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Opinion

Rethinking atoll futures: local resilience to global challenges

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Atoll islands are often perceived as inevitably lost due to rising sea levels. However, unlike other islands, atoll islands are dynamic landforms that have evolved, at least historically, to vertically accrete at a pace commensurate with changing sea levels. Rather than atoll islands' low elevation *per se*, the impairment of natural accretion processes is jeopardising their persistence. While global marine impacts are deteriorating coral reefs, local impacts also significantly affect accretion, together potentially tipping the scales toward atoll island erosion. Maintaining atoll island accretion requires intact sediment generation on coral reefs, unobstructed sediment transport from reef to island, and available vegetated deposition sites on the island. Ensuring the persistence of atoll islands must include global greenhouse gas emission reduction and local restoration of accretion processes.

Highlights

Atolls islands are biogenic landforms that are intrinsically capable of adjusting their size, position, and elevation to changing sea levels.

The vulnerability of atoll islands to sea level rise is not intrinsically due to their low elevation but primarily due to the loss of their island building capacity.

The geophysical processes that control atoll island accretion are being impacted on global and local scales.

Protecting and restoring the natural geophysical processes of atoll island accretion through local conservation actions is key to unlocking nature-based opportunities for enhancing atoll resilience to global change.

The demise-of-atolls narrative

Throughout the 21st century, the environmental impacts of anthropogenic climate change will become increasingly apparent and steadily intensify [1]. The past decade has seen a surge in movements, initiatives, and media coverage advocating for actions against climate change. These global efforts have championed powerful symbolism to sharpen focus on the existential threats of climate change, such as the polar bear (*Ursus maritimus*), a symbol for the melting ice caps. Similarly, low-lying **atoll islands** (see Glossary) symbolise a loss of ecosystems due to sea level rise, with catastrophic consequences for the inhabiting plants, animals, and humans. This evolved into a narrative that depicts **atolls** as lost causes on an inevitable path to complete disappearance [2]. Numerous assertions of atoll people as 'environmental refugees' further reinforce this image, although these claims currently lack empirical evidence [3] and are problematic as they reinforce colonial behaviours whereby Western institutions 'decide' up to which point islands are inhabitable for Indigenous people [4].

That climate change is jeopardizing atoll islands through the combined effects of rising sea levels, sea-surface temperatures, ocean acidification, tropical cyclones, and marine heatwaves is indisputable. However, surrendering atoll ecosystems to climate change overlooks a nascent opportunity for many atoll islands that is currently arising from advances in atoll geoscience, ecology, and conservation. Globally promoting the inevitability of atoll 'drowning' also disempowers local communities and Indigenous knowledge systems from working toward place-based solutions.

To free Large Ocean atoll states from their current role as the 'canary' of climate change predictions [5], a call to identify nature-based solutions to atoll persistence has recently been voiced [6]. In this article, we argue that the key to unlocking nature-based solutions for building resilient atoll islands lies in the **accretion** processes through which atoll islands naturally adjust to changing

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sea levels and storm impacts (Box 1). By linking ecological with geophysical processes, it may be possible to increase resilience through immediate, local-scale restoration initiatives. These are not merely stop-gap strategies until global marine pressures become mitigated but rather essential long-term complements to reducing greenhouse gas emissions for ensuring the future of atoll islands.

Much is at stake for the over 320 atolls in the world, as they are home to Indigenous atoll cultures and independent atoll nations and host habitat of global significance for tropical seabirds, endangered marine turtles, and other emblematic island species [7]. Researching effective, immediate, and local-scale opportunities to maximise atoll resilience is therefore urgent and pivotal to preserve their unique cultural and ecological values beyond the Anthropocene.

Atoll islands and sea level rise: the common portrayal is overly simplistic

Atoll islands are accumulations of sand- to boulder-sized material, generated from surrounding coral reefs and deposited on coral reef flats of atoll rims by waves and currents. As wave-built structures, most atoll islands range in elevation 1–5 m above sea level. Sea levels are currently increasing at mean rates of 3.2–4.2 mm per year and are predicted by 2100 to reach 0.28–0.55 m (under SSP1–1.19 emission scenarios) and 0.63–1.01 m (under the SSP5–8.5 emission scenarios) over preindustrial levels [8]. As sea levels rise and storm surge increases, it has been commonly assumed that atoll islands will simply drown given a perception that they are static, inert landforms. The adoption of this ‘static landform’ assumption is the root of the misconception that atoll islands are on an inevitable path to submersion [9]. In reality, the relationship between rising sea levels and the threat to atoll islands’ persistence is more complex.

Atoll islands are dynamic landforms that continually adjust their size, location, and elevation (through accretion) in response to changing **boundary conditions** in which they exist [10] (Box 1). Naturally functioning and intact atoll islands can vertically accrete at rates commensurate with sea level rise (3–10 mm per year) [10–13], thereby maintaining a groundwater lens that supports terrestrial life [14]. Only by impairing these accretion processes do atoll islands become unable to keep pace with projected sea level rise. Therefore, the threat of sea level rise to atoll islands stems not from their low elevation *per se* but because the processes critical to maintaining atoll island accretion are increasingly undermined by both global and local human impacts [15]. This introduces a second, widely overlooked dimension to the consideration of atoll island persistence in the Anthropocene: local-scale opportunities that restore natural accretion and stabilise processes for leveraging climate change resilience.

Global climate change impacts interact with local impacts

Marine impacts of climate change are jeopardising atoll reefs worldwide and consequently the supply of sediment to, and stabilization of, atoll islands. Rising sea surface temperatures, ocean acidification, and the increasing frequency and intensity of marine heatwaves from ocean atmosphere oscillations (e.g., **El Niño Southern Oscillation**) are increasingly deteriorating coral reef health globally. The response of individual coral reefs to these global climate change impacts can be compounded by human disturbances on a local scale. Terrestrial anthropogenic runoff [16,17], intense fishing pressure [18,19], macroalgal blooms [20], and coastal dredging activities [21] significantly modulate coral reef responses to climate change impacts and recovery trajectories. Coral reef recovery to net accretion has been achieved on remote and actively protected atoll reefs within 2–6 years following past El Niño Southern Oscillation episodes [22–24], and within 14–16 years on urbanised densely populated atolls [25]. Local-scale anthropogenic stressors are in many cases what decisively tip the scales of individual atoll reefs from recovery to collapse [26,27] (Figure 1). Under ambitious greenhouse gas emission reduction

Glossary

Accretion: the process of vertical and lateral sediment accumulation on atoll islands by means of wind, wave, and current transport from the surrounding coral reefs and reef flats.

Atoll: a widely distributed ecosystem type across tropical oceans, consisting of (i) an annular coral reef structure that encloses (ii) a central lagoon, with (iii) up to several hundred low-lying atoll islands located on top of the reef flat of the atoll rim, together forming an ecologically connected system.

Atoll island: locally motu, cay, islet. Each atoll hosts up to several hundred individual atoll islands. They form the terrestrial part of the atoll ecosystem and are individual land masses of up to several hundred hectares in size, consisting of loosely consolidated reef-derived sediments locally deposited on top of the reef flat.

Boundary conditions: the minimum and maximum values of variables in which a system stably exists.

El Niño Southern Oscillation: an irregularly recurring variation in sea level, sea surface temperature, and winds over the tropical Pacific, which exerts strong impacts on marine and terrestrial ecosystems throughout the Pacific.

Box 1. The natural accretion process of atoll islands

Despite the dominant narrative that atoll islands are already succumbing to rising sea levels, global meta-analyses of over 700 atoll islands have identified that 88.6% of islands show no net loss in land area over the past half-century, many even increasing in size, despite sea levels having risen by up to 0.6 m [56,57]. This empirical evidence of persistence of atoll islands underscores their inherent dynamism under changing environmental conditions, including rising sea levels [10,11,58]. Atoll islands formed on top of atoll reefs once they had grown to sea level following the postglacial marine transgression and provided horizontal platforms for sediment deposition. Atoll islands are built from biogenic carbonate sediments generated on living atoll reef rims and comprise (i) coral fragments generated by mechanical breakdown, (ii) sediments generated by bioeroding organisms (e.g., parrotfish and sea urchins), and (iii) skeletal remains of calcifying reef fauna (e.g., foraminifera and echinoderms) [31] (Figure I). Active island accretion requires transport of these sediments from the reef across the reef flat to the island. This transfer is a highly selective process, with an unpublished study suggesting that only ~26% of sediment produced on reefs contributes to island accretion [59], while the remainder is exported off the reef or reincorporated in the reef framework [60]. Sediment transfer to islands is controlled by wave energy that drives across-reef currents that entrain sediment [12,44,61,62]. Importantly, the maximum height that waves reach when breaking against the shoreline (the wave run-up) dictates the maximum point of sediment deposition and, therefore, island height. As sea levels rise, water depth, current velocities, wave height, and run-up will increase, resulting in a continuously higher maximum point of sediment deposition, causing islands to rework shoreline sediments and increase in height (i.e., accrete) [13,58]. Once deposited on the island surface, sediment becomes trapped and consolidated within the stratified vegetation belt [63]. Internal soil mineralization processes can further stabilise island sediments [52]. As atoll islands are accumulations of unconsolidated sediments, they continuously adjust their shape, location, and elevation to the prevailing environmental conditions. Continued sediment transfer to island shorelines enables islands to maintain or expand their footprint on coral reefs [13]. Differential erosion and accretion around island shorelines, driven by storms [54], seasonal monsoons [46], or persistent changes in nearshore currents, also allow islands to move location on coral reef surfaces [9].

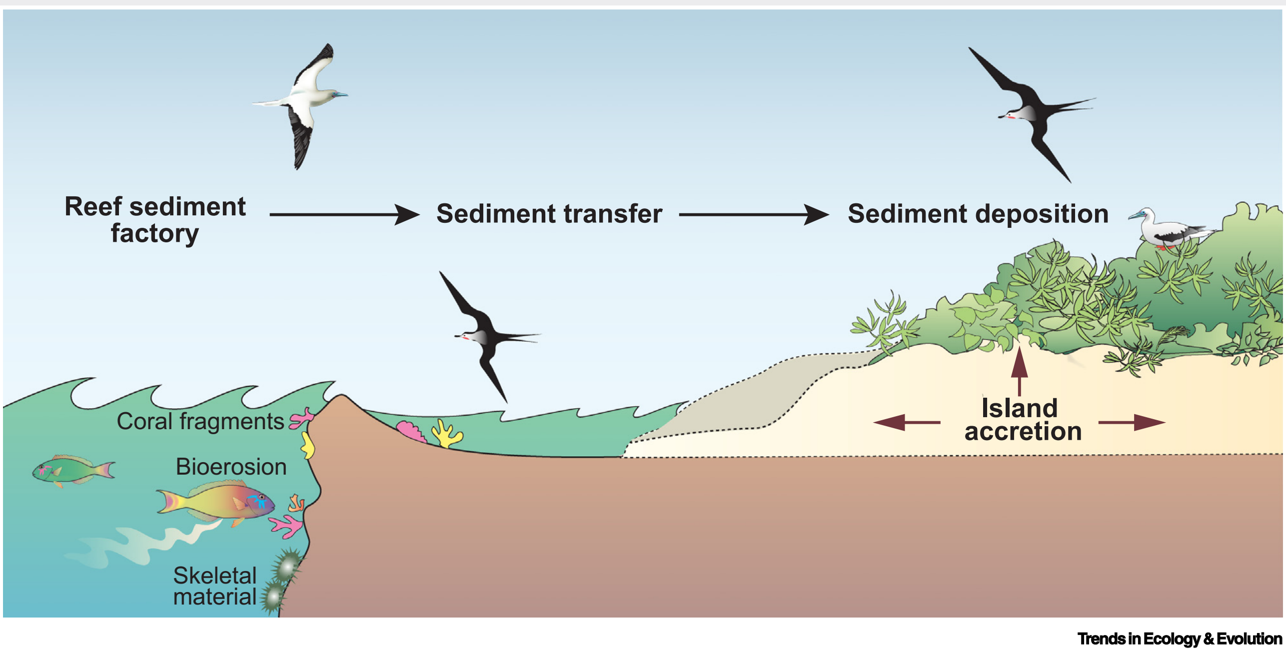

Figure I. The process of atoll island accretion.

pathways (SSP2–SSP4) [28], net growth of atoll reefs can be maintained, albeit at deteriorated capacity [29]. Thus, while reducing greenhouse gas emissions is essential to minimize global-scale marine pressures, atoll island persistence will only truly be achieved when the local-scale impacts that impair the natural accretion and stabilising processes of atolls are also addressed [15,21,26].

The pressing need to reduce greenhouse gas emissions is overwhelmingly clear. Similarly, degradation of coral reef ecosystems through localized stressors and their compounding impacts on coral bleaching events are well documented [18,27], and roadmaps toward protecting and restoring coral reef biodiversity are being developed [30]. Surprisingly, we still lack fundamental

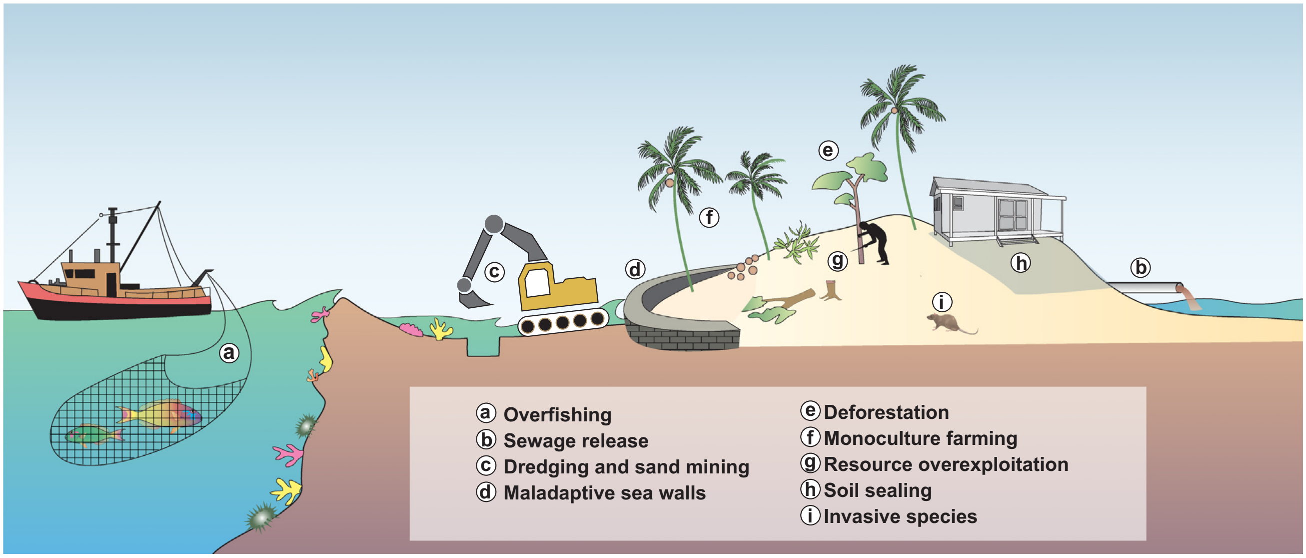

Figure 1. Local-scale impacts severely degrade the natural accretion and geophysical processes of atoll islands. Climate change is jeopardising coral reefs and thereby also the vital sediment factory for continuous atoll island accretion. At the same time, many local-scale human impacts also severely degrade or alter the geophysical processes in atoll island accretion (see Box 1). These local impact dimensions comprise the coral reef and its capacity to generate sediments for island accretion (a–b), land–sea connectivity between the reef 'sediment factory' and the island through altering the geophysical conditions required for sediment transport (c and d), and land-based disturbances that reduce the capacity of the island to trap and consolidate sediments (e–i) and adjust to changing environmental conditions in sediment deposition.

scientific evidence on if, and how, local conservation interventions translate into restoring accretion as the foundation to nature-based resilience building on atoll islands. To ensure the persistence of atoll islands, it is now essential to acknowledge the local impact dimensions on atoll island accretion processes and identify nature-based local opportunities that can leverage this inherent dynamism of atoll islands while also addressing the long-term effects of global climate change. Achieving this will require new interdisciplinary research efforts that aim to connect conservation interventions on coral reefs (the sediment 'factory'), land–sea connectivity (the sediment 'conveyor belt'), and atoll islands themselves (the deposition sites) to outcomes of geophysical accretion processes.

Restoring the sediment factory for atoll islands

Sediment for atoll island building is produced from the breakdown of coral and other calcifying organisms that inhabit the living coral reef and shallow lagoon system (Box 1). Maintenance of sediment supply at the island scale, therefore, places a premium on preserving the production of key island-building constituents [31,32]. The health of the coral reef carbonate sediment factory is directly compromised by a raft of local human impacts that include destructive fishing practices, sand mining, seagrass bed removal, sewage release, and resource overexploitation [15] (Figure 1). These impacts can be directly addressed through local-scale island-based management and community-driven conservation actions, which may be better viewed as essential nature-based solutions to restore sediment-generating processes for atoll island accretion. For example, in some settings, parrotfish bioerosion of coral substrate can generate up to 85–90% of the total sand-grade sediment on the reef flat for atoll island accretion [33]. Establishing well-managed marine protected areas can recover parrotfish and other keystone bioeroder populations [34]. Whether the ecological benefits of marine protected areas cascade to a meaningful improvement in the geophysical processes of atoll island accretion remains to be tested. Newly developed methods like 'SedBudget' [35] can aid in quantifying how coral reef restoration translates into sediment generation, which then potentially cascades to atoll island accretion. Additionally, direct intervention to restock coral populations through outplanting, although in its infancy as a restoration technique, is theoretically capable of restoring sediment production and island stabilisation sufficiently to sustain islands under forecasted sea level rise [36].

Conservation and restoration of keystone species critical for maintaining atoll nutrient cycles (e.g., sharks [37], seabirds [38], and land crabs [39]) may also link to accretion processes. For instance, in undisturbed systems, seabird guano is a critical subsidy to natural reef nutrient cycles. Protecting atoll seabird colonies (e.g., by means of regulating human consumption, restoring nesting and roosting habitat, and eradicating invasive predators) has been shown to translate to faster coral growth rates and higher bioerosion rates from grazing in the surrounding coral reefs [38,40]. Additionally, seabird guano enriches groundwater and soils of atolls [41], providing natural nutrient subsidies for atoll plant communities in an otherwise nutrient-poor soil environment [42]. Whether restoring the land–sea connectivity that recovers nutrient fluxes tied to coral reef and forest productivity also translates to enhanced atoll island stability awaits direct scientific evidence. If so, it would offer powerful nature-based conservation opportunities to enhance resilience [43].

Restoring the sediment conveyor: sediment transport and island linkages

The prospect of atoll islands keeping pace with sea level rise also depends on active sediment transport from the coral reef to island shorelines [44] (Box 1). Anthropogenic modifications to the coral reef structure, such as dredging channels and harbours, can significantly alter reef flat hydrodynamics that disrupt sediment transport pathways [15] (Figure 1). Furthermore, seawall constructions along island shorelines disconnect islands from their reef sediment reservoir, severely undermining the ability of islands to vertically accrete or adjust to changing boundary conditions [45]. Atoll islands are highly dynamic landforms that continually adjust their size and location on reef surfaces [9]. These adjustments occur due to differential erosion and accretion around island shorelines [46]; erosion on one sector of an island shoreline is, therefore, not *ipso facto* evidence of land lost to sea level rise but primarily indicates a natural process of island adjustment to changing boundary conditions. A case study on Tuvalu atolls revealed that coastal erosion on islands was prematurely attributed to sea level rise, when in fact coastal engineering projects disrupting sediment fluxes were later identified as the causal factor [47]. Active sediment transport from reef habitat to islands is critical to atoll island stability and should be considered a management priority for atoll conservation agendas. This especially applies to developed atoll islands, where coastal infrastructure is often built without considering whether natural sediment transport toward the island will still be maintained.

Island restoration: accretion and stabilising processes

Once deposited on an atoll island, unconsolidated sediments are colonised and stabilised by the terrestrial vegetation. Sediment accretion and a healthy stratified atoll vegetation are therefore tightly interlocked. A case study of cyclone impacts on Lighthouse Atoll in the Caribbean Sea showed that all 15 islands with an intact stratified native vegetation increased in height by 0.3–1.5 m due to cyclone-driven sediment deposition, whereas all 29 islands within the same atoll that had native forest replaced by a monoculture coconut palm plantation with no understory vegetation eroded by 0.9–2.7 m, with two islands disappearing entirely [48]. This finding suggests that the large-scale conversion of native atoll forests to monoculture coconut palm plantations by colonial powers likely undermined the stabilising processes for atoll island accretion on a basin scale. Additionally, monoculture coconut palm plantations are more susceptible to cyclones than native atoll tree species, thus further facilitating erosion [49]; have higher water demands, thus depleting the groundwater lens for native vegetation and humans alike [50]; and are associated with increased dissolved organic carbon runoff into the lagoon that might contribute to coral degradation [51]. The restoration of atoll vegetation toward its native, stratified forest or the return to intercropping and mixed-use cultivation of coconuts with understory vegetation (as practised by Indigenous atoll cultures for centuries prior to Western copra plantations) offers a key local-scale restoration opportunity on uninhabited, agricultural, or sparsely populated atoll islands. The interplay of the indigenous, dominant atoll forest tree species *Pisonia grandis* with seabird guano deposition is critical for *in situ* soil phosphate mineralization and soil and groundwater enrichment on atoll islands [52]. Diversifying atoll vegetation, reestablishing *P. grandis* forests, and restoring seabird communities would, together, likely not only help stabilise islands but also offer multiple benefits for groundwater and soil nutrients and bring beneficial knock-on effects for surrounding coral reef communities [53].

Reconciling natural accretion processes with human development

Ecosystem-based restoration of atoll island accretion processes has the potential to benefit atoll biodiversity conservation, maintain resilient landforms, and provide multiple cobenefits to human communities, yet it also creates complex dilemmas between natural processes and human habitation needs. On atolls, overwash and inundation of islands by extreme wave events can be destructive forces to human settlements but are also an essential component of the natural sediment delivery processes and accretion of atoll islands [54,55]. Nevertheless, finding nature-based solutions that enhance accretion through ecological restoration ultimately aligns human needs and biodiversity conservation (Box 2).

Most atoll islands are entirely uninhabited, used for agriculture, or sparsely inhabited by small local communities, and these atoll islands likely offer the most immediate opportunities to evaluate ecological restoration on island accretion. For the small minority of densely populated urban atoll islands, approaches need to be modified to include engineered solutions that ensure island persistence under climate change. However, engineered solutions to atoll habitability will only be sustainable if they consider the natural dynamics and accretion processes of atoll islands. For example, seawall defence structures are currently built around atoll islands to protect coastal

Box 2. Incorporating Indigenous knowledge systems

Atolls have been continuously inhabited by humans for sometimes thousands of years [64]. This alone suggests that the first human settlers accumulated substantial knowledge about the nature of atolls in order to inhabit them.

Incorporation of atoll dynamism into settlement planning and resource use was key to the survival of atoll communities [65]. For example, the Indigenous settlers of the Tuamotus, French Polynesia, the world's largest atoll archipelago, understood the atoll environment as dynamic and recognized that they needed to manage its limited resources sustainably in order to persist. The Paumotu language shows this recognition as placenames and a general nomenclature that is functional. There are different terms for semipermanent islets ('motu') and vegetated sandbars ('tahuna') that can shift seasonally. Placenames often indicate an island's suitability for habitation or resource acquisition, its susceptibility to natural hazards, or its ongoing accretion, with strict restrictions ('tapu' and 'rāhui') to human development or resource extractions on certain islands [66]. Indigenous atoll knowledge systems embrace and leverage the fact that atolls are organic landforms, and the islands and those that live on them are at the mercy of insurmountable atmospheric and oceanic forces.

However, atoll Indigenous knowledge systems are often omitted from modern resource management, as far back as the beginning of colonial expansion, when atolls were systematically developed into phosphate mines or copra plantations for continental markets. Still today, Indigenous perspectives and local interests remain widely excluded when discussing climate change mitigation and adaptive management on atolls. Current global management proposals for atoll islands tend to be technocratic, including engineered solutions and relocations of people to high islands or continents. A more just societal approach would be informed by Indigenous knowledge, aligning with how atoll inhabitants envision their own future. We argue that incorporating Indigenous knowledge systems and their lessons on traditional usage and management of atoll resources is essential to the reestablishment of the inherent resilience of atoll ecosystems.

infrastructure. However, seawalls mainly hinder natural sediment accretion rather than stop atoll island erosion [45]. Like ecological restoration, human infrastructure engineering on atolls should incorporate the geophysical processes of atolls. Indigenous atoll knowledge systems are thereby key to guiding the reconciliation of human adaptation with natural processes on atoll islands (Box 2).

Box 3. Biosphere–geosphere contact points that may yield opportunities for nature-based solutions

The key to unlocking nature-based solutions to mitigate climate change impacts on atolls and build local resilience lies in the natural accretion process of atoll islands (see Box 1). Identifying links between ecological restoration and atoll accretion creates opportunities for immediate, local-scale interventions aiming to increase the accretion and resilience potential of atoll islands (Figure I). We propose potential points of contact between current biological conservation interventions and the geophysical accretion processes. These comprise marine-based conservation actions, like marine protected areas or coral restoration, which are known to benefit bioeroder biomass or carbonate production rates [34], and island-based restoration actions, like reforestation, invasive alien species removal, or forest diversification. Other potential points of contact between atoll biosphere and geosphere are the land–sea connection and the nutrient fluxes between coral reef, groundwater, island, deep sea, and pelagic ecosystems [37,38,41,43,67], as restoring these nutrient pathways benefits coral reefs and atoll forests alike but might also translate to improved sediment generation (in the coral reefs) and sediment binding (on the island). In addition, other dominant biogeochemical processes of atoll lagoon systems should be incorporated, as phenomena like the flushing of nutrient-rich or alkaline waters from the lagoon over the reef crest ('atoll flushing') through tidal pumping [68] are likely strong controls of sediment generation and transport. Identifying the enabling conditions and environmental limits for atoll accretion and nature-based interventions in the marine and terrestrial spaces is also important. For example, large-scale cold water upwelling [67], the atoll mass effect [69], or fluctuating deep sea currents [70] may control the capacity and limits of sediment generation in atoll reefs. Likewise, terrestrial conditions like rainfall, drought intensity, or wind exposure may also control the capacity of vegetation and soil processes in sufficiently binding and consolidating deposited sand materials. While these enabling conditions cannot be changed, it is important to understand how they modulate ecological responses of atoll systems to ecological interventions, as this may guide prioritisation of restoration actions.

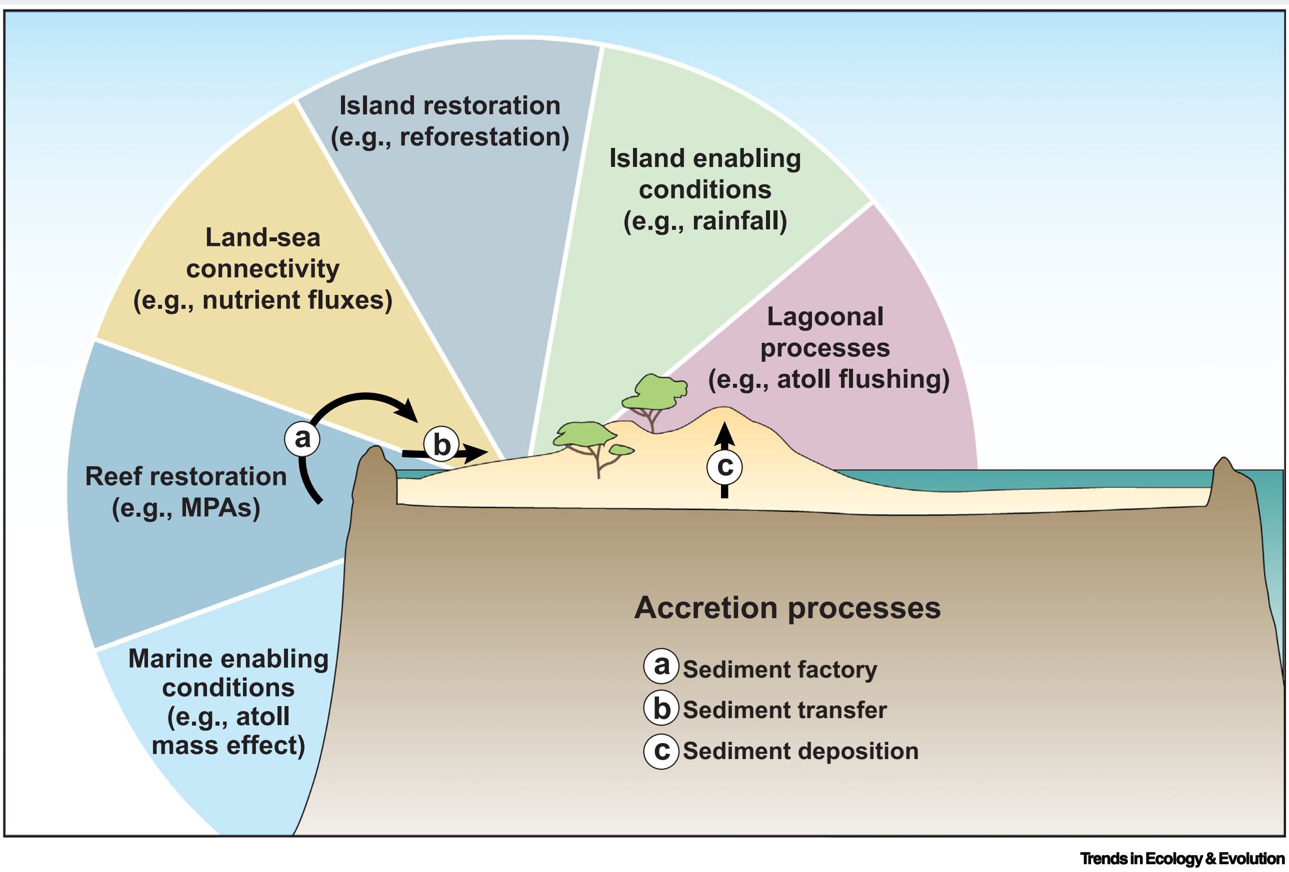

Figure I. Identifying biosphere–geosphere links is key for atoll island restoration. Abbreviation: MPAs, marine protected areas.

Concluding remarks

The dominant narrative of atoll islands evokes a fate of inevitable extinction, putting atoll nations and Indigenous atoll cultures entirely at the mercy of the Global North's will to cut greenhouse gas emissions. Cutting global greenhouse gas emissions remains the key endeavour for humanity to mitigate long-term climate change impacts for atolls. We argue that immediate nature-based interventions on atolls are important complements to this endeavour. Local-scale opportunities to restore the natural accretion of atoll islands can return ownership of the narrative on atoll persistence to Indigenous communities and atoll nations. These are not merely stop-gap strategies but are an essential second dimension to atoll persistence that should be acknowledged, better researched, and implemented. Key to unlocking nature-based solutions is linking ecosystem-based interventions (that span marine and terrestrial zones) with the inherent accretion processes of atoll islands (Box 3). The overarching goal for ecological and conservation research on atoll ecosystems should now be to identify how local-scale nature-based conservation interventions, paired where appropriate with traditional knowledge systems, translate to improved island accretion processes that immediately increase local resilience against climate change impacts (see Outstanding questions).

Outstanding questions

What ecological restoration actions best support atoll accretion, and what ecological (enabling) conditions and processes contribute to this outcome?

Where do these positive ecological enabling conditions exist elsewhere that allow replication of restoration methods for atoll accretion?

Up to what degree of human footprint can nature-based interventions create meaningful improvements to atoll accretion dynamics that can complement engineered solutions in urbanised settings?

What are the temporal lags between ecological interventions and measurable impacts on island accretion? Resolving such lags will inform restoration approaches.

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Declaration of interests

The authors have no interests to declare.

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