Massive Drift of Pumice Stones Might Trigger Coastal Ecological Transitions

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Abstract

An intensive underwater volcanic eruption occurred in the Ogasawara Islands on 13–15 August 2021, bringing unprecedented amounts of pumice to the coast of Okinawa Island in the Ryukyu Archipelago, 1,300 km west of the eruption site, approximately 2 months later. The coast of Okinawa Island, especially along the northern part, is home to many typical subtropical seascapes, including coral reefs and mangrove forests, so the possible impact of the large amount of pumice is attracting attention. Here, we report early evidence of ecosystem changes that may be the result of large-scale pumice shoaling on coastal beaches, estuaries, coral reefs, and mangrove forests. Massive pumice drift is a major obstacle to fishing activities and ship traffic, but possible future long-term changes in coastal ecosystems should also be noted. The phenomena observed on Okinawa Island are expected to occur not only in the Ryukyu Islands but also along the coasts of Kyushu, Shikoku, Honshu Islands, where pumice is expected to drift later.

Introduction

Okinawa Island is located in the southern region of Japan and has a high level of biodiversity along its coast, including coral reefs, mangroves, and tidal flats [1–3]. Okinawa is influenced by the warm Kuroshio Current (Fig. 1), which flows northward along the west side of the island [4, 5], making the marine environment suitable for tropical and subtropical organisms [1, 2]. The island is an attractive place for tourists because of its beautiful seascapes, but some areas are threatened by rapidly increasing tourism pressure [6–8] from ongoing coastal developments [1, 9, 10], in parallel with the global changes resulting from multiple human activities [11-13]. In contrast, little coastal development has occurred in the northern part of Okinawa Island, the site of Yambaru National Park, with mountain ranges, dense evergreen broad-leaved forests, and a high level of biodiversity on land as well as in the coastal marine environment. In 2021, the region, together with the Yambaru region and Amami Oshima, Tokunoshima, and Iriomote Islands, was named a World Natural Heritage Site [14].

The Japan Coast Guard reported that a large submarine eruption with high plumes of smoke occurred within the Ogasawara Archipelago (Fukutoku-Oka-no-Ba, Tokyo, Japan: 24.285°N, 141.481°E) on 13 August 2021. Volcanic information has been summarized in an article by the Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology [15]. The large amount of pumice stones produced by this eruption was carried by ocean currents for approximately 2 months before reaching the Ryukyu Islands, including the main Okinawa Island, which is located approximately 1,300 km away from the eruption site (Fig. 1).

Because it is difficult to observe a submarine eruption, details of the mechanism of the submarine eruption and the process of pumice formation are not fully understood [16, 17]. In general, however, pumice is created by intense quenching and vesiculation generated by a volcanic eruption [18]. It is commonly light colored, indicating that it is rich in silica content. Low-density pumice aggregates on the sea surface, forming mobile pumice rafts that can be detected by satellite [19], and a combination of drift calculations that incorporate ocean currents, wind, and wave action can usefully forecast raft dispersal [20].

Pumice rafts can cause widespread geological and ecological disturbances [21–25]. Scientific study of such events is rare, however, given their short duration and often distant location. Thus, few ecological studies have examined pumice rafts and coastal disturbance. In this initial report, we describe the effects of a massive pumice drift on natural systems in the coastal area of northern Okinawa Island (Fig. 1b; Supplementary Table 1) and infer how the ongoing presence of pumice rafts may impact the coastal ecosystem via biological responses to this novel habitat formation. Because of the ever-changing spread of the pumice raft, we report only limited observations carried out along the coast of the Yambaru region (Kunigami District), which is particularly rich in natural resources [14].

Results And Discussion

Massive drift of pumice along the northeastern coast of Okinawa Island

A large amount of pumice stones reached and aggregated along the northeastern coast of Okinawa Island, brought by strong seasonal northeasterly winds (Supplementary Video 1). Biofouling of the pumice has already been observed. These stones are thought to have been brought in by the Kuroshio countercurrent from sites near the Ogasawara Archipelago 1,300 km away [15]. Because the Kuroshio countercurrent is composed of various medium-sized eddies in the ocean, the current does not always flow in one direction and appears in the mean field rather than as a continuous flow [26]. The drift of pumice stones seems to have been affected by the combination of the Kuroshio countercurrent and seasonal northwesterly wind and transported to Okinawa over a long distance (Fig. 1a). The pumice raft reached the northern part of Okinawa approximately 2 months after the eruption (Fig. 2–4). Most of the pumice stones were grayish, but some stones had black lines on the surface, and others had completely black surfaces (Fig. 2d, e). These features are all identified as pumice stones produced in the submarine eruption at Fukutoku-Oka-no-Ba volcano in the Ogasawara Archipelagos [15]. The Kuroshio Current is faster than the Kuroshio countercurrent [26], so it is reasonable to assume that pumice rafts drifting in the waters around Okinawa will move northward at a faster rate and should spread to the main islands of Japan in the very near future.

Changes in the coastal landscape: natural beaches and estuaries

Marine calcifiers, including corals, calcareous algae, and foraminifers, produce white sandy beaches on Okinawa Island. However, the grayish pumice drifting ashore changed the white sand beach, especially along the northeastern coastline. We observed several lines of pumice aggregations, suggesting that pumice was brought ashore by wavefronts several times produced by a strong north wind (Fig. 2a). At the same sampling site, the thickest sedimentary depth was more than 30 cm from the original sand beach surface (Fig. 2b). Most of the pumice stones were from 0.5 cm to 3 cm in diameter, with a few black pumice stones included (Fig. 2c: yellow arrow). Pumice stones arrived at the estuaries of some brackish rivers (Fig. 8, Supplementary Fig. 1a) and mangrove forests in northwest Okinawa (Fig. 9). Our observations were conducted in a limited area, and it is likely that there are areas where more pumice stones have been deposited, depending on wind direction and wave action (Supplementary Video 2).

Pumice stones and pumice rafts show dynamic behavior in a short period. We captured photographs 24 h apart at two positions on the shore of Okinawa, which allowed us to compare the pumice dynamics during this period (Fig. 3). Within that time frame, there were two high tides. Note also that these photos were taken in the inner reef area, so the influence of the offshore current was not dominant. As seen in Fig. 3a, on the first day, the coast was covered with dark pumice stones, and floating pumice could be seen on the seafront. The north wind was strong that day, as shown by the relatively high waves near the shore as well as white-crested waves near the reef edge. By the following day, most of the pumice had been moved offshore by tidal forces (Fig. 3b), indicating that newly produced pumice rafts were removed from the same place they had been deposited. At another site on a gravelly beach, pumice fully covered the seawall on the first day, but all of the pumice stones washed away, leaving the original gravels, on the following day (Fig. 3c, d). These observations lead us to expect that the pumice rafts will disappear from the coast of Okinawa fairly quickly, but in fact, there have been many cases where they have come back again in a few days. These observed dynamics may contribute to the future prediction of drifted debris in coastal waters.

Biofauling of sessile organisms on pumice stones rafting near Okinawa Island

Some pumices observed on the Okinawa beach had already become habitats for sessile organisms (Fig. 4), as reported in previous studies [21–25]. Goose barnacles (*Lepas* sp.) without external damage to the shell were often observed on the pumice (Fig. 4b). *Lepas* is a common biofouling taxon distributed globally and plays a role in biofouling as a foundation organism [26]. The shell growth rate is more than 1 mm/day in some *Lepas* species [27]. We found that *Lepas* on pumice stones had grown in two weeks. Measurements of the shell size of *Lepas* attached to the pumice collections (Supplementary Table 2) conducted in the same area (Supplementary Video 2) showed a bias toward larger sizes in the second collection (5.92 ± 3.86 mm (average ± S.D.), n = 75, 13 November 2021) than in the first one (3.43 ± 1.08 mm, n = 21, 31 October 2021), and significant differences were detected between the measurement periods (Mann–Whitney U test, $p < 0.05$). These data imply that the barnacles settled on the pumice stones and started to grow near Okinawa. The shell size would be larger if the barnacles had settled and grown on the surface of the pumice as it traveled long distances because at least 50 days had passed since the formation of the pumice near Ogasawara. A cheilostome bryozoan was also found on the same pumice sample (Fig. 4c). Bryozoans are colonial marine invertebrates that construct an extrashell skeleton composed of aragonite and calcite [28]. Through elemental and isotopic analysis of the $CaCO_3$ skeleton [29], it may be possible to investigate how the organisms attached to pumice stones were transported to Okinawa Island.

Red autofluorescence was detected from the pumice pebbles surface (Fig. 4d), though to be derived from the chlorophyll of microalgae conventional extracted organic solvent (i.e., acetone and methanol, see Supplementary Fig. 2) with a diameter of several tens of micrometers (Fig. 4e, f). The texture of the pumice pebbles (Fig. 4d) and the bright spots of the red fluorescent signal (Fig. 4e) were not completely coincidental. As the pumice pebbles in the rafts are constantly rubbed and worn, only microorganisms are likely to survive on the surface on small pumice pebbles. Genetic studies have revealed the transport of larval corals [30] and crown-of-thorn starfish [31] between the Okinawa and Ogasawara Archipelagos, which are more than 1000 km apart, with no large islands in between. Integrating spatiotemporal information on the exact pumice movement on the sea surface with such genetic analytics studies may help to clarify the dispersal processes of marine organisms in greater detail.

Considering that small sessile organisms were often found on pumice rafts (Fig. 4), it is easy to imagine that pumice rafts transport not only multicellular organisms but also microorganisms such as bacteria. Some astrobiology studies have proposed that pumice might have functioned as a habitat for the earliest settlements of microorganisms [32, 33]. Considering this study, pumice rafts may serve a variety of functions in bacterial ecosystems, such as connecting populations over long distances and serving as a direct link between sandy beaches and the ocean (Fig. 3). Pumice has a large surface area with many vesicles [34]. When pumice stones rub together by wave action, they break apart, thus enlarging the surface area and leading to a dramatic increase in bacterial habitat; pumice may continue to serve as an ecosystem mediator for a long period of time. According to the different pore structures inside of pumice, they eventually sink to the bottom of the sea, which is estimated to occur over months to years [35, 36], the characteristics of the sea floor will change, and the original ecosystem will likely be altered. Filamentous algae grew well on the pumice stones in the brackish water observed during this study period (Supplementary Fig. 3). The same kind of biofilm will be formed on pumice that sinks to the bottom of the ocean in the very near future.

Impacts on fishes and other organisms in coastal waters

A pumice raft reached the Hentona fishing port (Fig. 5a), where more than 200 farmed Indian mackerel (*Rastrelliger kanagurta*) had died in the fishery cages in the bay by early November (Fig. 5b). Fish stomachs were filled with pumice stones (Fig. 5c), suggesting that they had confused pumice stones for food. The digestive system in the fish is filled with numerous pumice stones, and in places, the pumice stones are visible through the intestinal wall or are damaged, suggesting that the direct cause of death of the farmed fishes was not starvation but damage to the fish's digestive tissues caused by the pumice stones. This species of fish is a filter feeder swimming with its mouth open widely while feeding. The same feeding behaviour is also seen in the fin whale (*Balaenoptera physalus*) and basking shark (*Cetorhinus maximus*), two marine species studied with regard to environmental pollution by microplastic debris [37]. When marine wildlife such as turtles, seabirds, and whales mistake plastic waste for prey, most die of starvation, as their stomachs are filled with plastic debris [38]. We are concerned that a similar situation likewise occurs in the natural environment in the ocean, with filter feeding fishes consuming pumice stones.

Some migratory fishes must swim with their mouths open and breathe by constantly taking oxygen dissolved in the seawater passing through their gills (e.g., tuna, bonito, yellowtail, sardine, mackerel, and swordfish). If small pumice pebbles or particles were to pass through the gills, they would likely physically damage the tissue. This damage may affect the survival of these economically important fishes and perhaps alter their population dynamics. Thus far, it is unclear how the catches in the seas around Okinawa have changed since the arrival of the drifting pumice. If this hypothesis is correct, however, then pumice traveling on the Kuroshio Current could also affect fisheries in the seas around Japan. Through more research, the impact of large quantities of pumice on marine life will become clearer in the future.

Pumice rafts may also affect the upriver migration of fishes [39, 40], which move between rivers and the sea according to their life histories. Pumice covered the brackish area of the Oku River in northwest Okinawa (Oku River, Supplementary Fig. 1a), adjacent to the Oku harbor (Supplementary Fig. 1b), likely carried there by a combination of high tide and wind effects. Later, in this report, we note that pumice stones cover the river bottom as well as mangrove mudflats. Further studies are needed to assess the impacts of pumice rafts on anadromous and amphidromous fish populations.

Another possible influence of massive arrivals of pumice rafts is a decline in the dissolved oxygen concentration in seawater under the pumice-covered sea surface. Primary producers of marine ecosystems, such as phytoplankton in the water column and seagrasses and seaweeds in shallow waters, generate dissolved oxygen in seawater. However, the shoaling of massive pumice rafts can reduce their photosynthesis, inhibit gas exchange at the sea surface, and cause seawater to become anoxic. Prolonged disturbance would lead to the deterioration of the ecosystem in the worst-case scenario [41, 42].

Negative impact on reef-building corals: shading and ablation

Coral reefs are diverse ecosystems and provide coastal protection from waves [43]. Reef-building corals maintain photosynthetic algae (zooxanthellae) that live in their tissues and play a critical role in supplying the coral with glucose, glycerol, and amino acids, which are the products of photosynthesis under energetic consequences of flexible symbiont associations (i.e., mutualistic relationships) [44]. If the symbiotic relationship breaks down, the coral tissue will turn white (bleaching), and in the worst case, the coral will die [44, 45]. Previous studies discussed that pumice rafts contribute to coral dispersal [21–24], and rafts may support escape of juvenile coral from unfavorable conditions such as local stress [25]. But the negative aspects of pumice drift are still unclear. In the coastal area of Okinawa Island, pumice rafts washed ashore in inland bays such as beaches (Figs. 2, 3) and harbors (Fig. 5, Supplementary Fig. 1b, c), but such areas are not often inhabited by corals. Underwater photographs taken under the pumice raft show that the actual habitat of reef-building corals exists slightly far from the beach, such as reef lagoons or reef edges (Fig. 6a), which are reef-building areas. Underneath the pumice rafts, there is very little sunlight, and nothing can be seen (Fig. 6b). Light occasionally shines through the gaps in the waves (Fig. 6c), and the current disperses large quantities of pumice into the seawater (Fig. 6d). Here, we consider that the reef-building corals at the reef edge are shown to be photosynthesis inhibited by the drift of pumice rafts shading sunlight. If the symbiotic algae inside the corals do not receive sufficient light for a prolonged period, algae photosynthesis is inhibited, causing coral death. In the worst cases, corals at the reef edge would be damaged, which can affect the marine ecology of the area and potentially economic activity (attenuation of fishing, tourism, and wave protection effects).

A young *Acropora* coral colony survived at the reef edge under a strong wave current, with many pumice stones flowing through the water (Fig. 7a, Supplementary Video 4). In Fig. 7b-d, one of the pumice stones hit a coral branch tip of the colony. The pumice stones were abrasive and caused the coral branch tips to wear away. A pumice stone of more than a few centimeters in diameter may break fragile coral branches with a strong current. No corals with open polyps were observed at the reef edge when the pumice raft shored. This observation implies that coral surface ablation by pumice stones may become a stress factor for corals.

Reef-building corals have a fragile layer of soft tissue on a calcium carbonate skeleton. To protect and defend themselves from various kinds of foreign matter in the environment (e.g., sand and bacteria), coral tissues continuously produce mucus, which is thought to play a role in coral halobiont defense, possibly through the production of antimicrobial substances [46]. Microscopic scratches may be caused by drifting pumice stones, which could induce inner tissue exposure and the loss of mucus function. This situation may lead to infection of the coral surface by bacteria and other pathogens adhered to the pumice stones. Previous studies have reported that coral tissue can be lost in response to mechanical stress leading to the induction of coral diseases [47], and multiple environmental stressors could result in the expansion of harmful bacteria in the reef environment [48, 49]. Currently, the exact impact of the pumice on the coral reef ecosystems around Okinawa is unclear, but the systems should be closely monitored. Considering the most recent wave impact with pumice stones during repeating low tides, the damaged coral surfaces may not have enough recovery time to cover with new tissue. The images show that pumice rafts not only inhibit coral photosynthesis but also induce physical damage to coral tissue, causing combined stress to the corals (Figs. 6 & 7). Human-induced climate change has already led to a reduction in reef-building corals to the point that these ecosystems are becoming endangered [43]. The natural disaster of the drifting pumice on such weakened ecosystems is becoming a cause for further concern.

Impact on mangrove organisms caused by sudden changes in sediment properties

Here, we report on the appearance of pumice stones in the brackish water around Okinawa and discuss the possible effect on the mangrove ecosystem as an example of the Ibu River (Fig. 8). In the tropics and subtropics, mangrove ecosystems play critical roles in interactions between land and sea. In fact, mangrove ecosystems are linked to neighboring environments such as coral reefs and seagrass beds through the movement of organisms and the circulation of materials [50, 51]. Recent scientific advances have clarified the microbial environment of mangroves, and the composition of their unique microbiota suggests that they may perform several important functions in the ecosystem, such as functional gene diversity and metabolic potential of soil microbial communities [52].

A river flowing through a mangrove forest connects to Ibu Beach (Fig. 2a: white arrow points to the river mouth). In the brackish water of the river, approximately 100 m from the mouth, many pumice stones were found to have sunk, presumably because of the drop in salinity (Fig. 9a: dark colored area noted by a white arrowhead). By zooming in a little on the photo to observe the underwater conditions, we clearly see a large amount of pumice stones (each a few centimeters in diameter) that had sunk (Fig. 8b), showing a clear border with the original sandy riverbed. These stones were easily brushed off by hand, suggesting that the pumice had not completely lost its buoyancy, and some of the pumice stones at the bottom of the river swayed slowly in the water flow (Supplementary Video 5). For a goby (*Psammogobius biocellatus*), there does not seem to be any serious concern at the moment (Fig. 8c). Further up the river (approximately 200 m from the river mouth), floating pumice stones reached the point where orange mangrove (*Bruguiera gymnorhiza*) trees were growing (Fig. 8d). These observations indicate that the buoyancy of pumice differs among stones [35, 36]. It appears that sunken pumice stones could be easily removed. There was no heavy rainfall during the survey. If heavy rains occur and the flow rate of the river increases, however, pumice stones could flow back to the ocean. It will be necessary to monitor river substrate changes and to assess how pumice affects river ecosystems (e.g., fish migration) in the future [39, 40]. Within four months of the massive pumice adrift to Okinawa Island, we could easily observe green filamentous algae covering the pumice pebbles (Supplementary Fig. 3). The surface of the pumice is porous, which seems to be a good environment for organisms to attach to.

Pumice rafts also drifted onto the mangrove mudflats (Fig. 9a), which were almost completely covered with pumice pebbles (Fig. 9b). Although this area is covered with a massive amount of pumice, Y.O. did not note any smell of decay. Many of the crabs and gobies survived under these circumstances (Fig. 9c–i), and Y.O. did not find any evidence of mass die-offs in the pumice-covered mangrove at the beginning of this study period. However, the surface layer of the burrow was covered with pumice and was prone to collapse; in some cases, the crabs' burrows were blocked (Fig. 9g). Observations of behavior, with particular focus on a fiddler crab (*Uca lactea lacteal*) in Fig. 9c, showed that in some cases, it had given up trying to enter the burrow, which easily collapsed under the pumice stones (Supplementary Video 6). In another case, competition to acquire burrows emerged, making it difficult for smaller individuals to obtain a burrow even within the same species (Supplementary Video 7). The pumice-covered substratum is different from the original mud substratum, making it a particularly harsh environment for small crabs. To adapt to this environment, small crabs have already shown alternative behaviors, such as hiding in the spaces among pumice pebbles (Fig. 9h). Fiddler crabs use their claws to put substrate in their mouth and then sift through the substrate and eat the organic matter (e.g., algae, fungi, and tiny insects) [53]. As the substrate has been replaced by pumice instead of sand, feeding behavior may be inhibited, especially for smaller individuals. If pumice stones occupy a large surface area during the breeding season, however, they may interfere with the spawning and larval dispersal of these crabs. Three months after we started the survey, Y.O. could hardly observe the burrows of the fiddler crab or their population on the pumice cover mudflat. It is speculated that the environment where the fiddler crabs live was covered with pumice pebbles, hindering eating behavior, with the younger individuals being more affected.

Another observed mangrove inhabitant is the mudskipper (*Periophthalmus argentilineatus*), a fish that jumps on the surface of the water around a creek near the riverbank. However, when the pumice grains stuck to the fish's body, they did not move well and appeared to sink (Supplementary Video 8). The body surface had a pumice pebble attached to its head (Fig. 9i) because of the stones' adsorption properties. The mudskipper has relatively thin skin that is suitable for life on land and breathing oxygen [54], such that the fish's movement may result in the pumice on its skin surface causing microinjuries. A recent molecular study suggested that the expansion of innate immune system genes in mudskippers may provide a defense against terrestrial pathogens [55]. Because the bacterial composition of the sediment may also be changed by drifting pumice stones, the immune response of this fish may be altered if the pumice pebbles remain on the mudflats for a long time. We are also concerned about mudskippers' feeding activities as well as territorial and courtship behavior on pumice-covered mangroves [56]. In addition, the mudskipper has a special egg-laying behavior: the fish deposits eggs on the walls of an air-filled chamber within its burrow to provide air to the eggs in the lower oxygen conditions in the mud [57]. Likewise, the various behavioral patterns of gobies could also be affected by the drift of pumice in the mangrove. In addition to mangrove fishes, we assume that drifting pumice stones may especially affect fish communities inhabiting soft-sediment coastal areas where pumice pebbles easily sink.

As described above, the organisms living in the mangrove tidal flat have difficulty finding shelter due to the change in the substrate (Fig. 9c-i, Supplementary Videos 6–8). Thus, it is likely to be preyed upon by other wild animals, such as Okinawa rail (*Hypotaenidia okinawae*). *H. okinawae* is a flightless rail that is declared the National Natural Treasure (Agency for Cultural Affairs) and endemic to Yambaru region (Fig. 9j, Supplementary Videos 9, 10). The pumice-covered mangrove flats should provide an efficient feeding ground for the Okinawa rail or other birds for a while. On the island of Okinawa, pumice drift covers a wide area of the coast, which may alter the behavior patterns of various organisms associated with the area. Okinawa rail is not a seabird; however, the previous study reported that migratory birds ingest pumice stones when they were starving [58]. Changes in the behaviors of migratory birds in areas where pumice rafts have been washed ashore may require a little more attention.

Impact on local industries and countermeasures of massive pumice stone arrival

The local broadcast stations in Okinawa Prefecture reported that a large amount of pumice aggregated in some fishing harbors in northern Okinawa, alarming that pumice stones can damage the propellers of fishing boats and cause engines to overheat. Fishing boats are unable to operate because their drive systems are malfunctioning; for example, as the engine coolant system becomes clogged with pumice, the engine overheats. Thus, not only fishing but also the tourism industry is likely to be greatly affected if this situation continues for a very long period. The massive amount of pumice that entered an enclosed area not affected by the exchange of seawater or wind flow makes it difficult for the pumice stones to be removed via natural means (Fig. 5, Supplementary Fig. 1b, c), so the removal work is being done by heavy machinery. Oil fences have begun to be installed to prevent pumice from entering the harbor. However, even if the pumice rafts are successfully removed from the fishing harbor, new pumice rafts continue to invade it. To minimize the impact of pumice stone shoaling on human activities, it will be necessary to make advances in predicting the movement of pumice rafts as well as to develop countermeasures for events such as this natural disaster. Volcanic activity is common in Sakurajima (Kagoshima Prefecture), with one of Japan's most active volcanoes that smokes constantly, and minor eruptions often take place multiple times per day. Because of this situation, the local port has performed a workload analysis of how to remove drifting pumice after the likely event of a major volcanic eruption [59]. Likewise, assessing the effects of pumice drift will provide valuable information for planning disaster prevention in Okinawa and other areas in the future.

Here, we describe the possibility of pumice stones serving as a nutrient adsorbent material. Nitrate and phosphate from local and industrial wastewater are the main sources of nutrient loading in the marine environment [60, 61], and these compounds induce the reduction of dissolved oxygen in the ocean [62]. The large surface area of pumice traps nutrients, as reported in a study of its environmental purification properties [63]. Thus, pumice stones have been proposed as technically workable low-cost reusable adsorbents for the removal of nutrients (e.g., phosphate) during wastewater treatment to suppress nutrient loading in natural waters [64, 65]. If coastal nutrients are absorbed by the pumice rafts and transported offshore, nutrients may be reduced in areas where the pumice had washed ashore. We showed that large quantities of pumice stones moved from the beaches offshore within a short period of time (Fig. 3). These short-term behaviors of pumice stones may contribute to the transportation of nutrients from coastal areas to the open ocean. A study of coral revealed that phosphate accumulation in sand sediments inhibits coral calcification and reduces the coral growth rate [66]. In addition, high dissolved inorganic nitrogen and phosphate concentrations in seawater induce coral bleaching, which threatens the survival of corals with symbiotic dinoflagellates [67]. Possible roles of pumice stones in biogeochemical cycles are topics of future research. Later, the deposition of these nutrient-rich pumice stones on the sea bottom may alter the mineral balance of the ocean floor where they are deposited.

Conclusions

We reported some examples of early influences on a broad range of coastal organisms that may be the result of large-scale pumice shoaling on coastal beaches, estuaries, coral reefs, and mangrove forests. In addition to the impact on fishing activities and ship traffic as a natural disaster, possible future long-term changes in coastal ecosystems should also be noted. Drifting pumice stones are not only useful for dispersing marine organisms but also attracting attention for their multiple functions, such as a medium for dispersing the microbiome and the possibility of absorbing nutrients from seawater. Pumice has been carried by the Kuroshio Current and may affect the coastal environments of Kyushu, Shikoku, and Honshu Islands of Japan. Pumice rafts have also recently reached Taiwan and the Philippines, which are even further away from the sites of submarine eruptions. We hope this report of the situation will be helpful for additional research carried out in Okinawa and other places where pumice stones have been washed ashore, as further investigations are needed to clarify how the large amount of pumice affects both marine and shallow-water environments. Although the peak of pumice drift seems to have passed within the observation period, long-term investigation is necessary.

Within half a year of the large-scale submarine eruption that occurred at Fukutoku-Oka-no-Ba, an unprecedentedly large underwater eruption occurred at the Hunga Tonga-Hunga Ha'apai volcano, located in the South Pacific Kingdom of Tonga on 15 January 2022 (JST), and now Tonga and surrounding Islands are suffering from the volcanic disaster. The full extent of this natural catastrophe is still unclear. There is an urgent need for a comprehensive survey of the area, and a rapid study of this volcanic eruption's influence on marine organisms is strongly required. The impact of large-scale eruptions on climate change attracts attention. But, a massive amount of volcanic products were released, thus, future research is also needed on the effects of large amounts of pumice on marine ecosystems. The examples of pumice drifting from Fukutoku-Oka-no-Ba volcano would be a good reference.

Methods

Since the pumice rafts were found at Cape Hedo on 16 October 2021, we decided to start a survey focusing on the Yambaru region. Underwater photography at the reef edge was conducted on 14 November 2021. Drone photography (Fig. 5a) was conducted by Okinawa Times Co., Ltd., which is a local media outlet in Okinawa Prefecture. The images in Figs. 5b and c were provided by the Kunigami Fishing Association. A Coolpix w 300 (Nikon Co., Ltd.) was used to take the photographs. The latitude and longitude of the locations where the images were taken are listed in Supplementary Table 1. The shell length measurement of *Lepas* sp. was carried out on pumice that had just washed ashore on the beach. The first samples were taken from seven pumice stones (31 October 2021), and the second ones were from six pumice stones (13 November 2021). Statistical analysis of shell size of them were analyzed with R version 4.0.3 software. Pumice pebbles were collected from a pumice raft at Ibu beach on 15 January 2022. A Leica M165 stereo microscope was used for pumice pebble observation. Pebbles were excited 485/10 nm with ET GFP/CY3 band pass filter. The red autofluorescent signal from algae was detected by a color digital camera (also see Supplemental Fig. 2, 3). The green autofluorescence from pumice, which may have come from the mineral, is minimal or absent under fluorescent microscopy. Adobe premiere pro and image J software were used for audio video and image editing.

Declarations

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Authors’ contributions

Y.O., A.I., and A.S. designed the field study. Y.O. conducted the field work. A.I. performed statistical analysis. Y.O. made figures and videos. M.I., A.I., Y.O., and K.Y. conducted a microscopic observation. Y.O., A.I., M.I., K.Y., and A.S. wrote the paper. All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

Data availability

All data generated or analysed during this study are included in this published article and its supplementary information files.

Competing interests

The authors declare no competing interests.

References

1. Iguchi, A., & Hongo, C. (Eds.). *Coral reef studies of Japan* (Vol. 13). (Springer, 2018).
2. Reimer, J. D. et al. Marine biodiversity research in the Ryukyu Islands, Japan: Current status and trends. *Peer J.* **7**, e6532 (2019).
3. Kunishima, T., & Tachihara, K. Patterns in diversity and species composition in soft-sediment tidepool fishes across topographical types: Implications for conservation with spatial nuances. *Mar. Environ. Res.* **170**, 105442 (2021).
4. Andres, M., Park, J. H., Wimbush, M., Zhu, X. H., Chang, K. I., & Ichikawa, H. Study of the Kuroshio/Ryukyu current system based on satellite-altimeter and in situ measurements. *J. Oceanogr.* **64**, 937-950 (2008).
5. Japan Coast Guard. Quick Bulletin of Ocean Conditions No. 207 (published on 5 November 2021) https://www1.kaiho.mlit.go.jp/KANKYO/KAIYO/qboc/2021cal/cu0/qboc2021207cu0.html
6. Tada, O. Constructing Okinawa as Japan's Hawaii: from honeymoon boom to resort paradise. *Japanese. Stud.* **35**, 287-302 (2015).
7. Toyoshima, J., & Nadaoka, K. Importance of environmental briefing and buoyancy control on reducing negative impacts of SCUBA diving on coral reefs. *Ocean. Coast. Manage*. **116**, 20-26 (2015).
8. Lamb, J. B., True, J. D., Piromvaragorn, S., & Willis, B. L. Scuba diving damage and intensity of tourist activities increases coral disease prevalence. *Biol. Conserv.* **178**, 88-96 (2014).
9. Veron, J. E. N. Conservation of biodiversity: a critical time for the hermatypic corals of Japan. *Coral Reefs* **11**, 13-21 (1992).
10. Reimer, J. D. et al. Effects of causeway construction on environment and biota of subtropical tidal flats in Okinawa, Japan. *Mar. Pollut. Bull.* **94**, 153-167 (2015).
11. Hoegh-Guldberg, O., & Bruno, J. F. The impact of climate change on the world's marine ecosystems. *Science*. **328**, 1523-1528 (2010).

12. Henson, S. et al. Rapid emergence of climate change in environmental drivers of marine ecosystems. *Nat. Commun.* **8**, 14682 (2017).
13. Silvy, Y., Guilyardi, E., Sallée, J. B., & Durack, P. Human-induced changes to the global ocean water masses and their time of emergence. *Nat. Clim. Chang*. **10**, 1030-1036 (2020).
14. United Nations Educational, Scientific and Cultural Organization (UNESCO) Description https://whc.unesco.org/en/list/1574/ (2021).
15. Geological Survey of Japan. Fukutoku-Oka-no-Ba submarine volcano information. https://www.gsj.jp/en/hazards/volcano/fukutokuokanoba2021-e.html (2021).
16. Wright, I. C., Gamble, J. A., & Shane, P. A. Submarine silicic volcanism of the Healy caldera, southern Kermadec arc (SW Pacific). I. Volcanology and eruption mechanisms. *Bull. Volcanol.* **65**, 15-29 (2003).
17. Murch, A. P., White, J. D., & Carey, R. J. Characteristics and deposit stratigraphy of submarine-erupted silicic ash, Havre volcano, Kermadec Arc, New Zealand. *Front. Earth Sci.* **7**, 1 (2019).
18. Manga, M. et al. The pumice raft-forming 2012 Havre submarine eruption was effusive. *Earth Planet. Sci. Lett.* **489**, 49-58 (2018).
19. Jutzeler, M., Marsh, R., Carey, R. J., White, J. D., Talling, P. J., & Karlstrom, L. On the fate of pumice rafts formed during the 2012 Havre submarine eruption. *Nat. Commun.* **5**, 1-10 (2014).
20. Jutzeler, M. et al. Ongoing dispersal of the 7 August 2019 pumice raft from the Tonga arc in the Southwestern Pacific Ocean. *Geophys. Res. Lett*. **47**, e1701121 (2000).
21. Jokiel, P. L. Rafting of reef corals and other organisms at Kwajalein Atoll. *Mar. Biol.* **101**, 483-493 (1989).
22. Jokiel, P. L., & Cox, E. F. Drift pumice at Christmas Island and Hawaii: evidence of oceanic dispersal patterns. *Mar. Geol.* **202**, 121-133 (2003).
23. Bryan, S. E., et al. Pumice rafting and faunal dispersion during 2001–2002 in the Southwest Pacific: record of a dacitic submarine explosive eruption from Tonga. *Earth Planet. Sci. Lett.* **227**,135-154 (2004).
24. Bryan, S. E. et al. Rapid, long-distance dispersal by pumice rafting. *PLoS One*, **7**, e40583 (2012).
25. Velasquez, E., et al. Age and area predict patterns of species richness in pumice rafts contingent on oceanic climatic zone encountered. *Ecol. Evol.* **8,** 5034-504610 (2018).
26. Kagimoto, T., & Yamagata, T. Seasonal transport variations of the Kuroshio: An OGCM simulation. *J. Phys. Oceanogr.* **27**, 403-418 (1997).
27. Mesaglio, T. P., Schilling, H. T., Adler, L., Ahyong, S. T., Maslen, B., & Suthers, I. M. The ecology of Lepas-based biofouling communities on moored and drifting objects, with applications for marine forensic science. *Mar. Biol.* **168**, 1-16 (2021).
28. Taylor, P. D., & Sendino, C. Latitudinal distribution of bryozoan-rich sediments in the Ordovician. *Bull. Geosci.* **85**, 565-572 (2010).

29. Knowles, T., Leng, M. J., Williams, M., Taylor, P. D., Sloane, H. J., & Okamura, B. Interpreting seawater temperature range using oxygen isotopes and zooid size variation in *Pentapora foliacea* (Bryozoa). *Mar. Biol*. **157**, 1171-1180 (2010).
30. Nakajima, Y., Nishikawa, A., Iguchi, A., & Sakai, K. Regional genetic differentiation among northern high-latitude island populations of a broadcast-spawning coral. *Coral Reefs* **31**, 1125-1133 (2012).
31. Horoiwa, M., et al. Integrated population genomic analysis and numerical simulation to estimate larval dispersal of *Acanthaster* cf. *solaris* between Ogasawara and other Japanese regions. *bioRxiv* doi.org/10.1101/2021.03.25.436911 (2021).
32. Brasier, M. D., Matthewman, R., McMahon, S., Wacey, D. Pumice as a remarkable substrate for the origin of life. *Astro. Biol*. 11, 725-735 (2011).
33. Elser, J. J., et al. Community structure and biogeochemical impacts of microbial life on floating pumice. *Appl. Environ. Microbiol.* **81**, 1542-1549 (2015).
34. Whitham, A. G., & Sparks, R. S. J. Pumice. *Bull. Volcanol.* **48**, 209-223 (1986).
35. Fauria, K. E., Manga, M., & Wei Z. Trapped bubbles keep pumice afloat and gas diffusion makes pumice sink. *Earth. Planet. Sci. Lett.* **460**, 50-59 (2017).
36. Mitchell, S. J., et al. Sink or float: microtextural controls on the fate of pumice deposition during the 2012 submarine Havre eruption. *Bull. Volcanol.* **83**, 1-20 (2021).
37. Fossi, M. C., et al. Large filter feeding marine organisms as indicators of microplastic in the pelagic environment: the case studies of the Mediterranean basking shark (*Cetorhinus maximus*) and fin whale (*Balaenoptera physalus*). *Mar. Environ. Res.* **100**, 17-24 (2014).
38. Avio, C. G., Gorbi, S., & Regoli, F. Plastics and microplastics in the oceans: from emerging pollutants to emerged threat. *Mar. Environ. Res.* **128**, 2-11 (2017).
39. Iida, M., et al. Specific gravity and migratory patterns of amphidromous gobioid fish from Okinawa Island, Japan. *J. Exp. Mar. Biol. Ecol.* **486**, 160-169 (2017).
40. Milton, D. A. Living in two worlds: diadromous fishes and factors affecting population connectivity between tropical rivers and coasts. In *Ecological connectivity among tropical coastal ecosystems* (pp. 325-355). (Springer, 2009).
41. Cloern, J. E. Phytoplankton bloom dynamics in coastal ecosystems: a review with some general lessons from sustained investigation of San Francisco Bay, California. *Rev. Geophys.* **34**, 127-168 (1996).
42. Brierley, A. S., & Kingsford, M. J. Impacts of climate change on marine organisms and ecosystems. *Current Biology*, **19**, R602-R614 (2009).
43. Harris, D. L., et al. Coral reef structural complexity provides important coastal protection from waves under rising sea levels. *Sci. Adv.* **4**, eaao4350 (2018).
44. S. K. Davy, D. Allemand, V. M. Weis. Cell biology of cnidarian-dinoflagellate symbiosis. *Microbiol. Mol. Biol. Rev.* **76**, 229–261 (2012).

45. Baird, A. H., Bhagooli, R., Ralph, P. J., & Takahashi, S. Coral bleaching: the role of the host. Trends *Ecol. Evol.* **24**, 16-20 (2009).
46. Shnit-Orland, M., & Kushmaro, A. Coral mucus-associated bacteria: a possible first line of defense. *FEMS Microbiol. Ecol.* **67**, 371-380 (2009).
47. Lamb, J. B., et al. Scuba diving damage and intensity of tourist activities increases coral disease prevalence. *Biol. Conserv.* **178**, 88-96 (2014).
48. Harvell, D., et al. Coral disease, environmental drivers, and the balance between coral and microbial associates. *Oceanography*, **20**, 172-195 (2007).
49. Kubomura, T., Yamashiro, H., & Reimer, J. D. Appearance of an anomalous black band disease at upper mesophotic depths after coral bleaching. *Dis. Aquat. Org.* **131**, 245-250 (2018).
50. Alongi, D. M. Present state and future of the world's mangrove forests. *Environ. Conserv.* **29,** 331-349 (2002).
51. Meziane, T., & Tsuchiya, M. Fatty acids as tracers of organic matter in the sediment and food web of a mangrove/intertidal flat ecosystem, Okinawa, Japan. *Mar. Ecol. Prog. Ser.* **200**, 49-57 (2000).
52. Bai, S., et al. GeoChip-based analysis of the functional gene diversity and metabolic potential of soil microbial communities of mangroves. *Appl. Microbiol. Biotechnol.* **97**, 7035-7048 (2013).
53. Moruf, R. O., & Ojetayo, T. A. Biology of the West African fiddler crab, Uca tangeri (Eydoux, 1835) (Decapoda: Ocypodidae) from a mangrove wetland in Lagos, Nigeria. *Int. J. Aquat. Biol.* **5**, 263-267 (2017).
54. Zhang, J., Taniguchi, T., Takita, T., & Ali, A. B. A study on the epidermal structure of *Periophthalmodon* and *Periophthalmus* mudskippers with reference to their terrestrial adaptation. *Ichthyol. Res.* **50**. 310-317 (2003).
55. You, X., et al. Mudskipper genomes provide insights into the terrestrial adaptation of amphibious fishes. *Nat. Commun.* **5,** 5594 (2014).
56. Clayton, D., & Townsend, K. Territoriality and courtship behavior. In *Fishes out of water* (pp. 277-300). (CRC Press, 2017).
57. Ishimatsu, A., Yoshida, Y., Itoki, N., Takeda, T., Lee, H. J., & Graham, J. B. Mudskippers brood their eggs in air but submerge them for hatching. *J. Exp. Biol.* **210**, 3946-3954 (2007).
58. Roman, L., et al. Desperate times call for desperate measures: non-food ingestion by starving seabirds. *Mar. Ecol. Prog. Ser.* **662**, 157-168 (2021).
59. Asano, T., & Nagayama, A. Analysis of workload required for removal of drifting pumice after a volcanic disaster as an aspect of a port business continuity plan: A case study of Kagoshima Port, Japan. *Int. J. Disaster Risk Reduct.* **64**, 102511 (2021).
60. Borgesa, A. V., & Gypensb, N. Carbonate chemistry in the coastal zone responds more strongly to eutrophication than ocean acidification. *Limnol. Oceanogr. Lett.* **55**, 346-353 (2010).
61. Carpenter, S. R. Phosphorus control is critical to mitigating eutrophication. *Proc. Natl. Acad. Sci. U.S.A.* **105**, 11039-11040 (2008).

62. Rabalais, N. N., et al. Eutrophication-driven deoxygenation in the coastal ocean. *Oceanography*, **27**, 172-183 (2014).
63. Çifçi, D. İ., & Meriç, S. A review on pumice for water and wastewater treatment. *Desalin. Water Treat.* **57**, 18131-18143 (2016).
64. Makita, Y., et al. Preparation and phosphate adsorptive properties of metal oxide-loaded granular activated carbon and pumice stone. *Colloid. Surf. A-Physicochem. Eng. Asp.* **582**, 123881 (2019).
65. Karimaian, K. A., Amrane, A., Kazemian, H., Panahi, R., & Zarrabi, M.. Retention of phosphorous ions on natural and engineered waste pumice: Characterization, equilibrium, competing ions, regeneration, kinetic, equilibrium and thermodynamic study. *Appl. Surf. Sci.* **284**, 419-431 (2013)
66. Iijima, M., et al. Phosphate enrichment hampers development of juvenile *Acropora digitifera* coral by inhibiting skeleton formation. *Marine Biotechnology*, **21**, 291-300 (2019).
67. Rosset, S., Wiedenmann, J., Reed, A. J., & D'Angelo, C. Phosphate deficiency promotes coral bleaching and is reflected by the ultrastructure of symbiotic dinoflagellates. *Mar. Pollut. Bull*, **118**, 180-187 (2017).

Figures

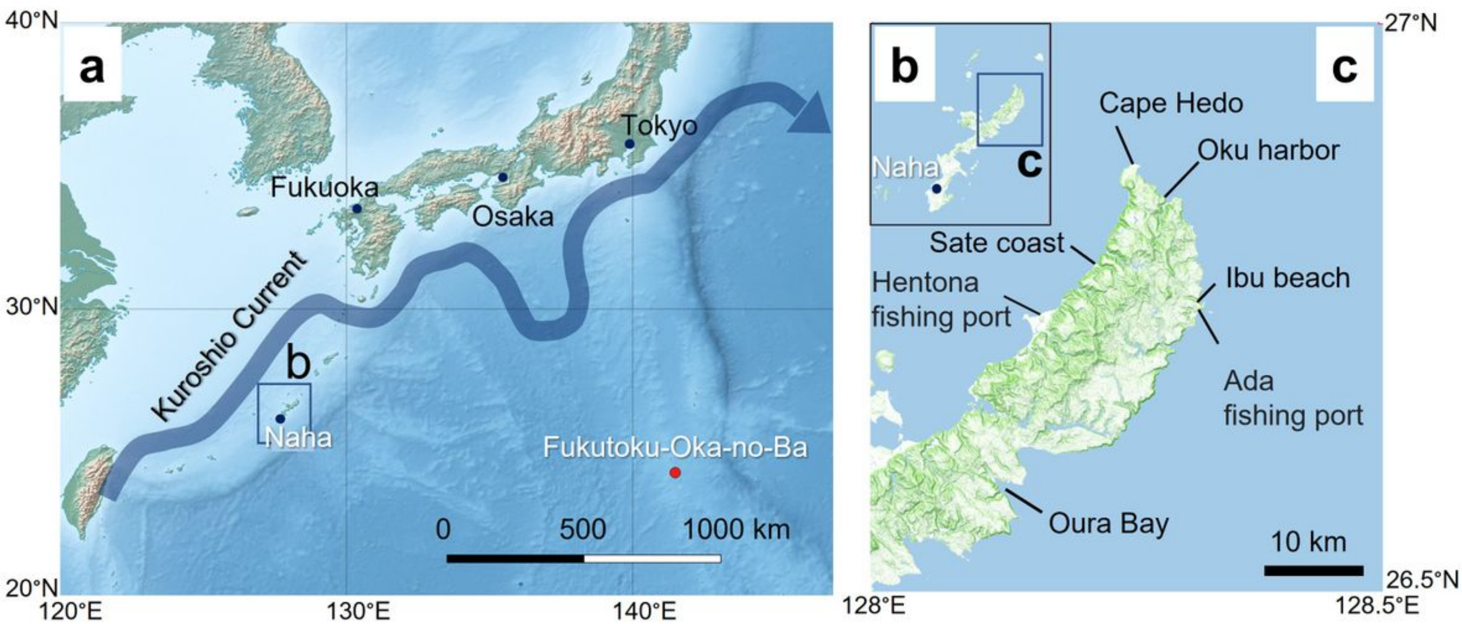

Figure 1

Locations of the eruption site, the island of Okinawa where the pumice drifted, and the observation sites. (a) Location of the eruption site at the Fukutoku-Oka-no-Ba submarine volcano (red circle, 24.285°N, 141.481°E), 60 km south of Ioto Island (Iwo Jima) in the Ogasawara Archipelago; the eruption occurred from 13 to 15 August 2021. Okinawa Island is approximately 1,300 km from the eruption site. Pumice from the eruption site was likely brought by the Kuroshio countercurrent, which flows westward to the south of the main path of the Kuroshio Current (meandering arrow). However, because of the slowness of the Kuroshio countercurrent and the complexity of its pattern, we do not show its path in this figure. (b) The main island of Okinawa and its surrounding islands. (c) Sampling sites of drifting pumice along the northern coast of Okinawa (Kunigami District). The flow path of the Kuroshio Current shown in (a) is based on the Quick Bulletin of Ocean Conditions of the Japan Coast Guard [**4**]. The Kuroshio Current is expected to transport pumice rafts from the Ryukyu Islands toward the coasts of Kyushu, Shikoku, and Honshu Islands of Japan. Panel (a) was made with Natural Earth (https://www.naturalearthdata.com). Topographic maps of panels (b) and (c) are based on the GSI Vector Tile Experiment (https://maps.gsi.go.jp/vector/) by the Geospatial Information Authority of Japan.

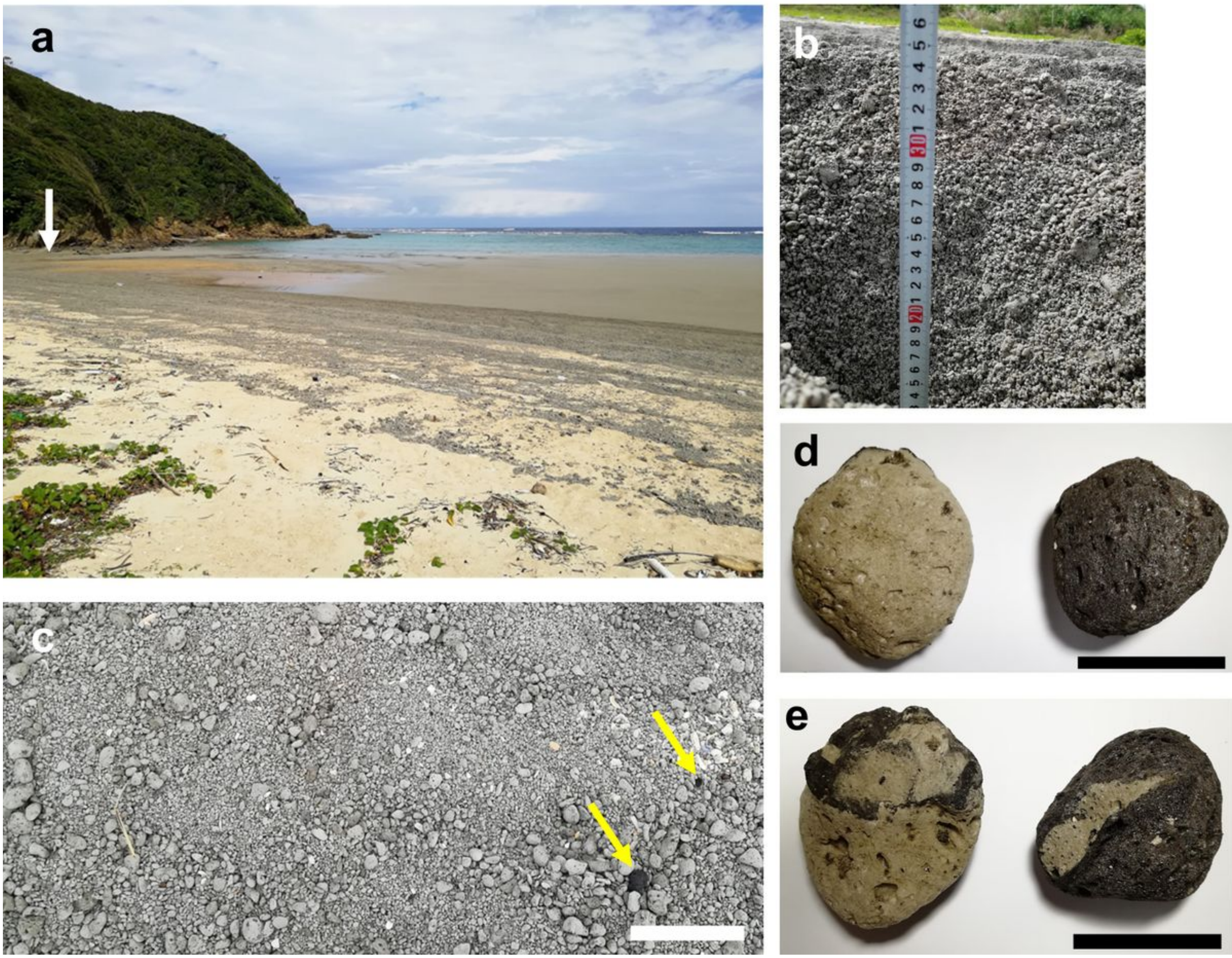

Figure 2

An example of a natural beach on Okinawa Island where pumice has washed ashore. (a) Appearance of natural sandy beaches on the northern part of Okinawa Island (Ibu beach, Kunigami District). Photo was taken on 24 October 2021. Pumice drifted onto the sandy beach and formed a striped pattern. Note the white-capped waves on the reef edge in the photo, indicating that a strong wind is blowing. The white arrow points to the mangrove river estuary corresponding to Figure 9. (b) Estimation of the pumice sedimentation depth on the original sand beach surface. (c) The high tide zone of the natural sandy beach is covered with pumice pebbles and stones. Yellow arrows indicate black pumice stones. Scale bar: 10 cm. (d, e) Front and back of examples of relatively large pumice stones from the same beach. The left image is mostly light brown, whereas the right image is almost black. Scale bars: 5 cm.

Figure 3

Short-term migration of pumice from beaches as revealed by stationary observations. These four photos were taken at two sites on northern Okinawa Island on two consecutive days, 23 and 24 October 2021. (a, b) A sandy beach along the Sate Coast. It was windy on the first day, and pumice stones were washed up with the waves. Almost all the pumice stones were removed from the beach and transported offshore on the following day. The black arrow in photo (a) indicates Cape Hedo, the northernmost tip of Okinawa Island. (c, d) At this gravelly beach, pumice fully covers the seawall on the first day, but all of the pumice stones washed away, leaving the original gravels, on the following day. The white arrow in each photo indicates an identical marker stone placed on the beach.

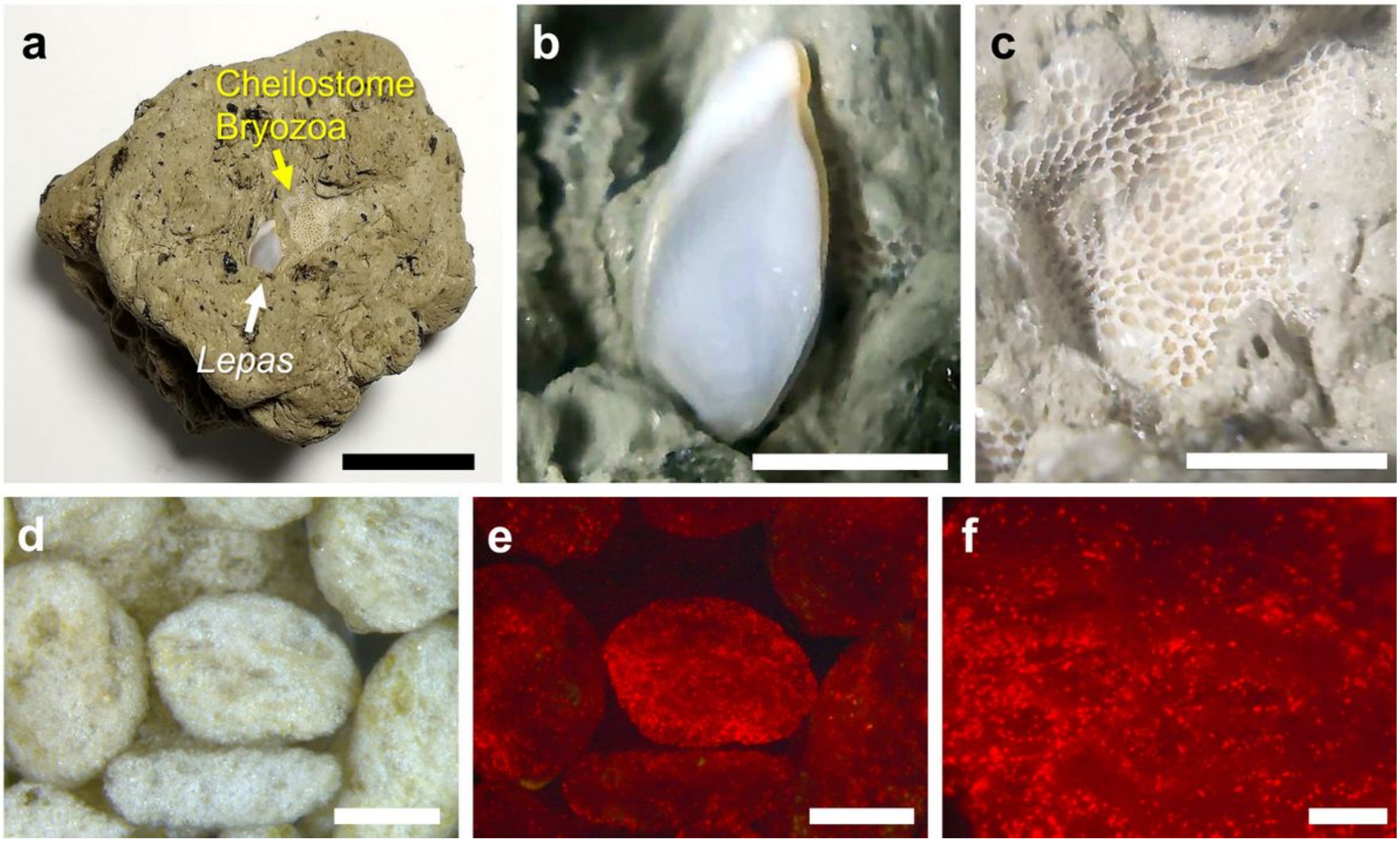

Figure 4

Pumice stones settled by marine organisms. (a) Pumice collected from Ibu beach on 31 October 2021. Two marine benthos coexist close together on a pumice stone. Scale bar: 1 cm. (b) Enlarged image of the *Lepas* barnacle. Scale bar: 3 mm. (c) Enlarged image of the bryozoan. Scale bar: 3 mm. (d) Stereo microscopic image of pumice pebbles of a few millimeters in diameter collected from Ibu beach on 15 January 2022. Scale bar 1 mm. (e) Red autofluorescence was detected from pumice pebbles. Image corresponds to (d). Autofluorescence from microalgae was confirmed by Supplementary Figure 2. Scale bar 1 mm. (f) Enlarged image of the center of the figure of (e) shows red autofluorescent signals with a diameter of 10-30 μm were observed. Scale bar: 200 μm.

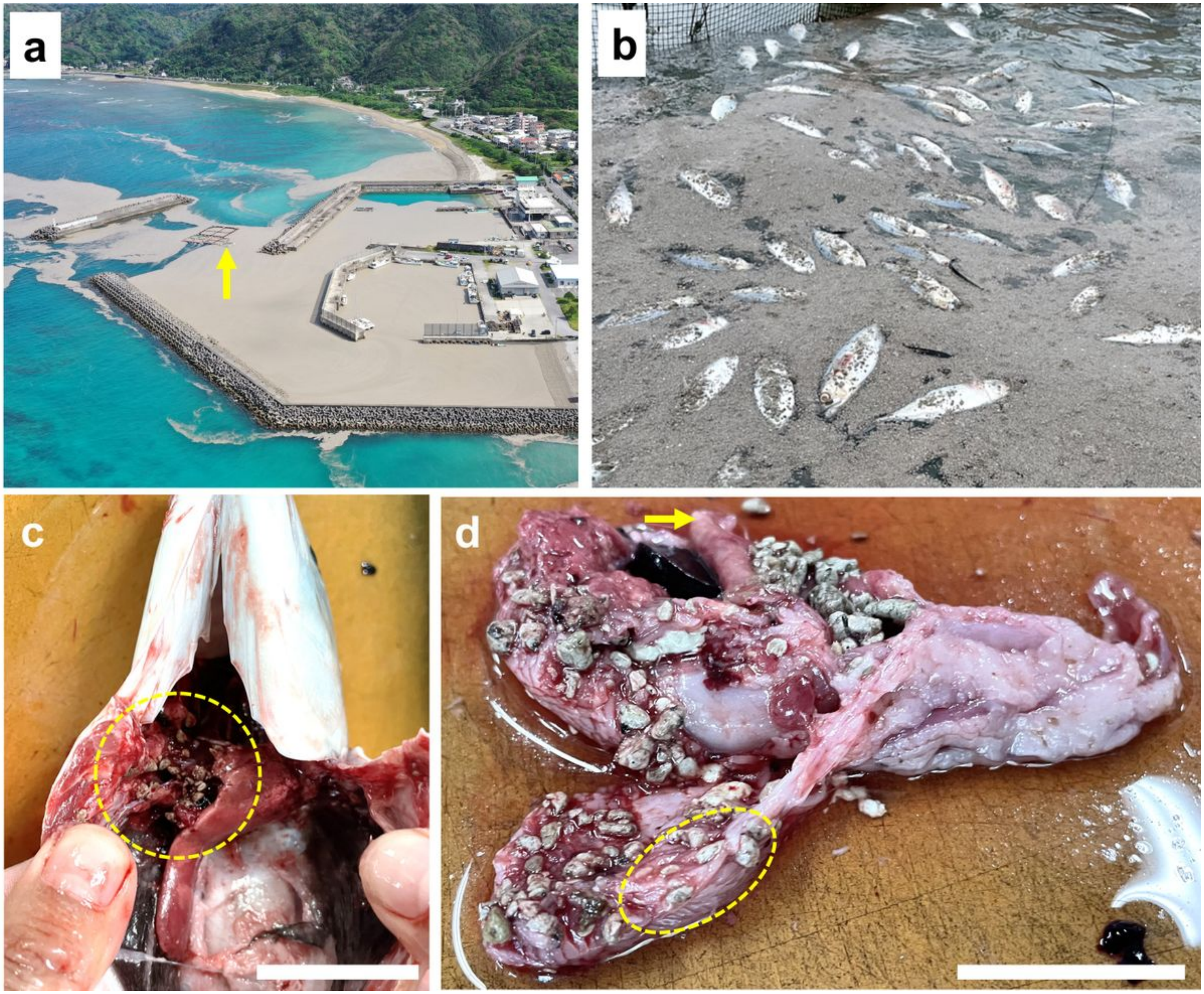

Figure 5

Large quantities of pumice drifted ashore, killing farmed Indian mackerel (*Rastrelliger kanagurta*). (a) Aerial image taken by a drone at the Hentona fishing harbor on 24 October 2021; yellow arrow points to the fish cage adjacent to the bay covered with pumice rafts. (b) A large amount of pumice washed ashore and cultured fish died in the fish cages. The local fishermen association estimated that more than 200 individuals had died by early November. (c) When fish were opened, they swallowed many pumice pebbles (yellow enclosed area: esophagus). (d) The appearance of the stomach to the intestines is shown. The yellow arrow indicates the part of the fish from the esophagus to the stomach. The appearance of the intestine is craggy due to the pumice pebbles stuck in the intestine. In the yellow circle, the pebbles in the intestine were transparent and partially came out from it.

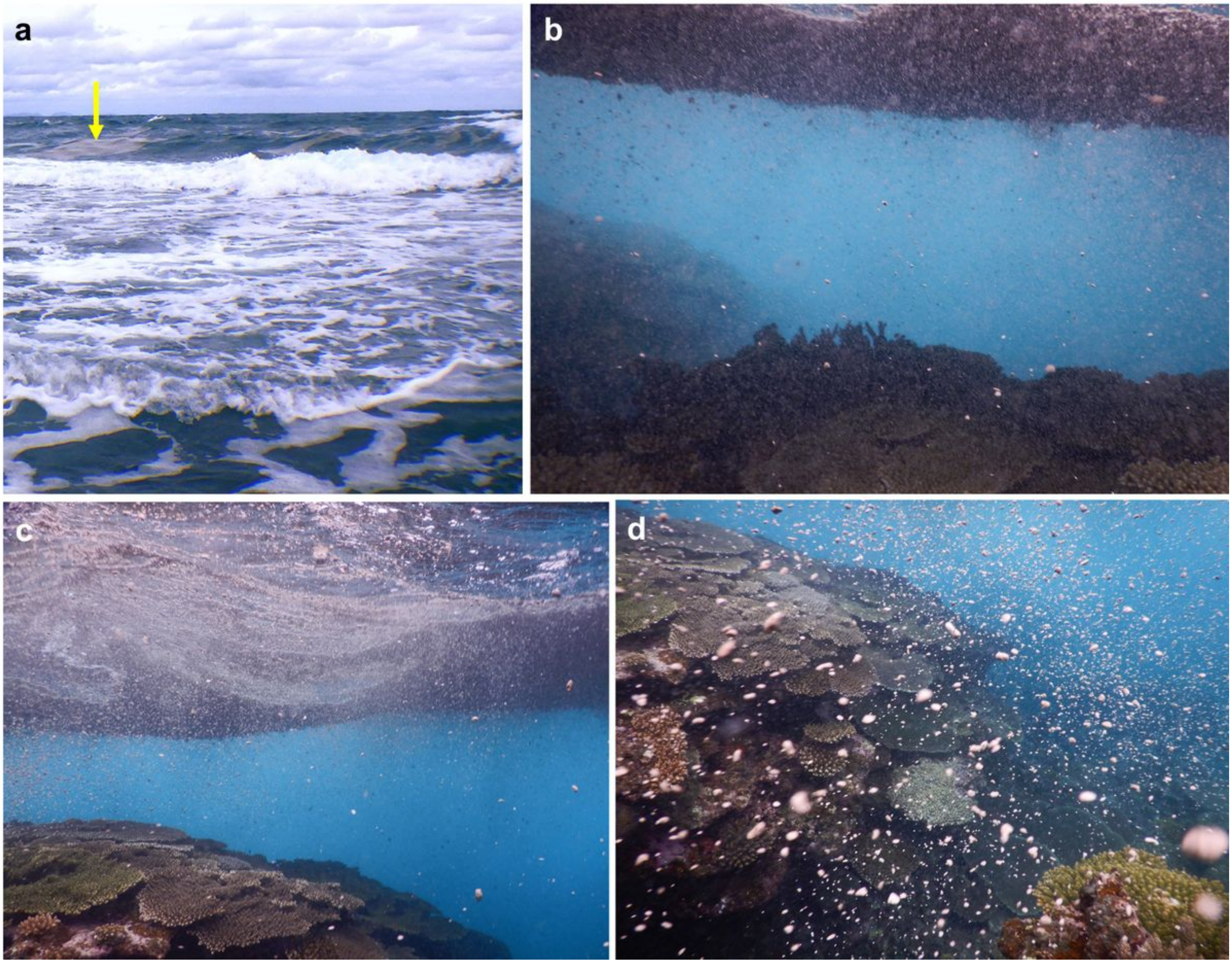

Figure 6

Pumice raft shading corals at the reef edge. Pumice rafts shading corals at the reef-edge. Photos were taken at low tide during the day on 14 November 2021, and the pumice raft floated approximately 50 cm from the top of the reef (see Supplementary Video 3). (a) View of the reef edge from the intertidal zone at low tide. The yellow arrow indicates that the pumice raft was drifting the reef edge. (b) It was dark under the pumice rafts. There were many coral colonies on the seabed, but they are hard to take in this water photograph. (c) The pumice rafts were shown to disperse as the waves came in, allowing sunlight to reach the coral through their gaps. (d) The waves crashed the pumice rafts, causing countless pumice stones to drift fast through the water.

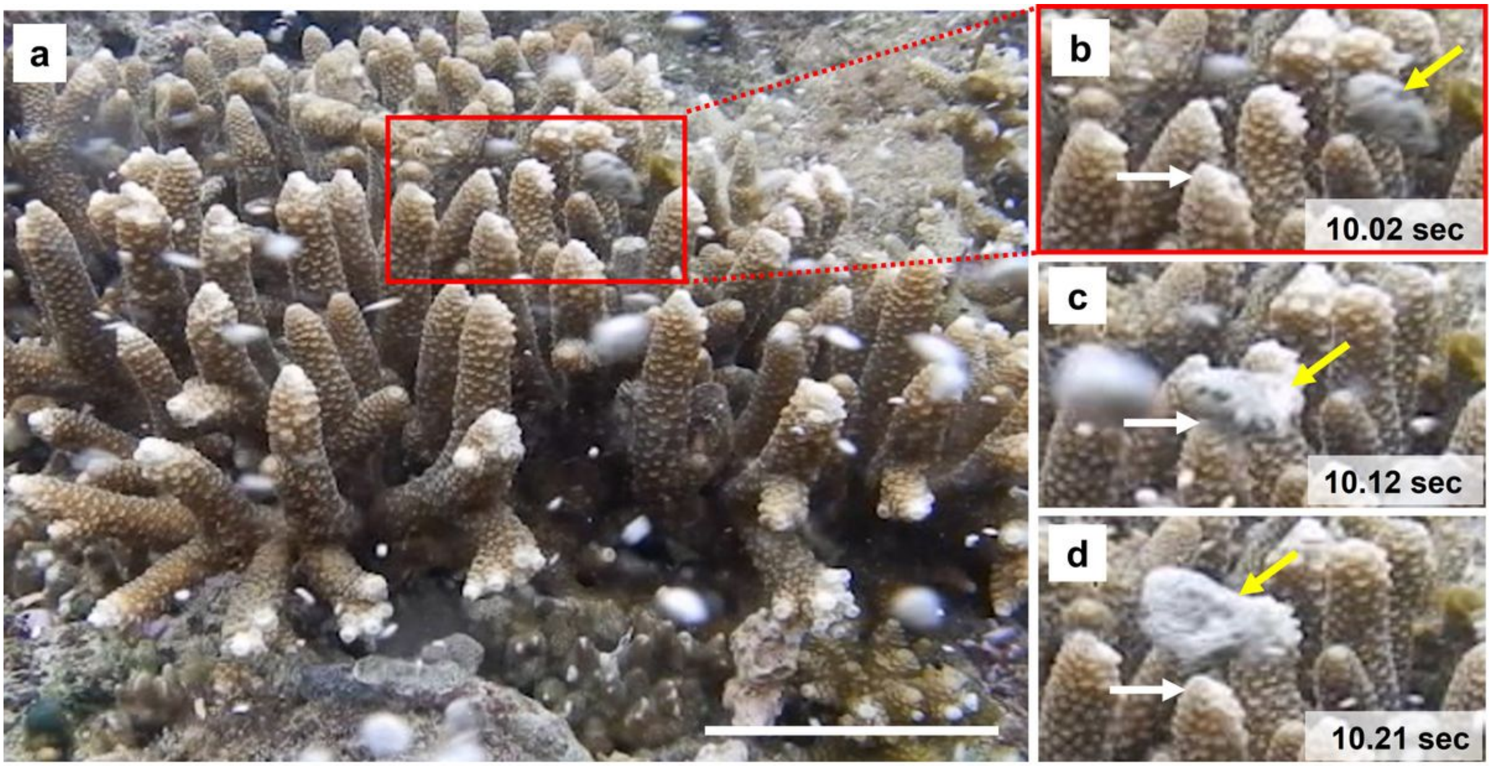

Figure 7

Underwater photography showing that corals were damaged by the pumice stones. Underwater photographs showing the possible damage of corals by the ablation of pumice stones in a shallow coral reef environment. (a) Pumice pebbles are shown drifting around the coral and driven fast by wave action. This figure corresponds to Supplementary Movie 4. Scale bar: 5 cm. (b-d) A pumice stone with a long axis of approximately 2 cm (yellow arrow) hit the tip of a coral branch (white arrow) and changed its direction within a short period. The images were taken less than 50 cm below the sea surface. These photos were taken on 14 November 2021.

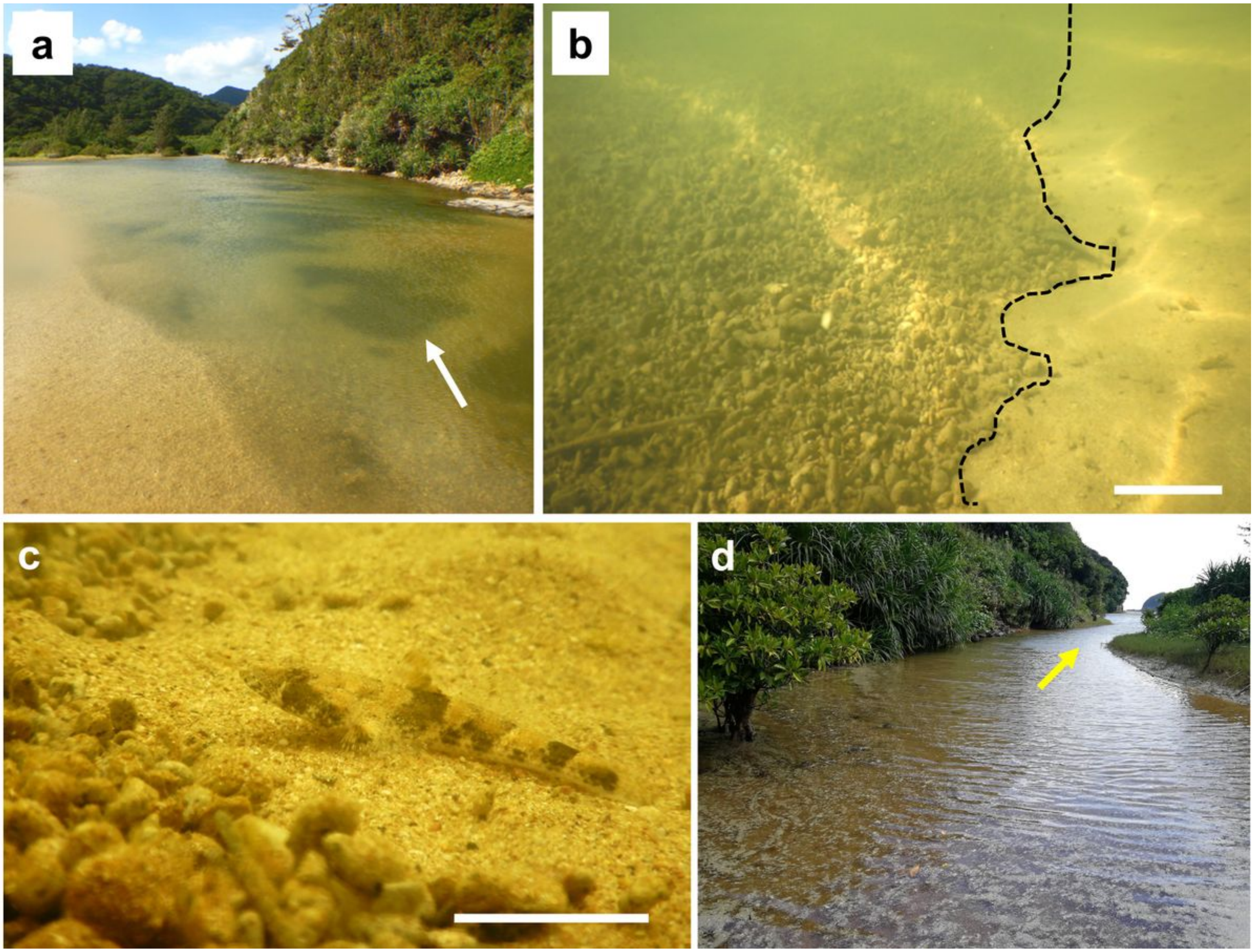

Figure 8

Pumice has begun to settle onto the bed of the brackish river. (a) In the lower reaches of the Ibu River, connecting to the coast north of the Ibu beach. Photo taken from the estuary side at low tide. The white arrow points to a dark gray aggregation of pumice on the bottom of the river. (b) Enlarged image of (a). The black dotted line marks the boundary between the pumice stones (left) and the original sandy river bottom (right). Supplementary Video 5, showing pumice stones swaying in the water, was recorded in this area. Scale bar: 10 cm. (c) *Psammogobius biocellatus* can be seen at the river bottom. Pumice stones were located left on this image. (d) A little further up the river, where mangroves can be seen to the left. Yellow arrow points toward the estuary. These photos were taken on 13 November 2021. At the same location, filamentous algae were growing rapidly on the pumice surface in mid-January (see Supplementary Figure 3).

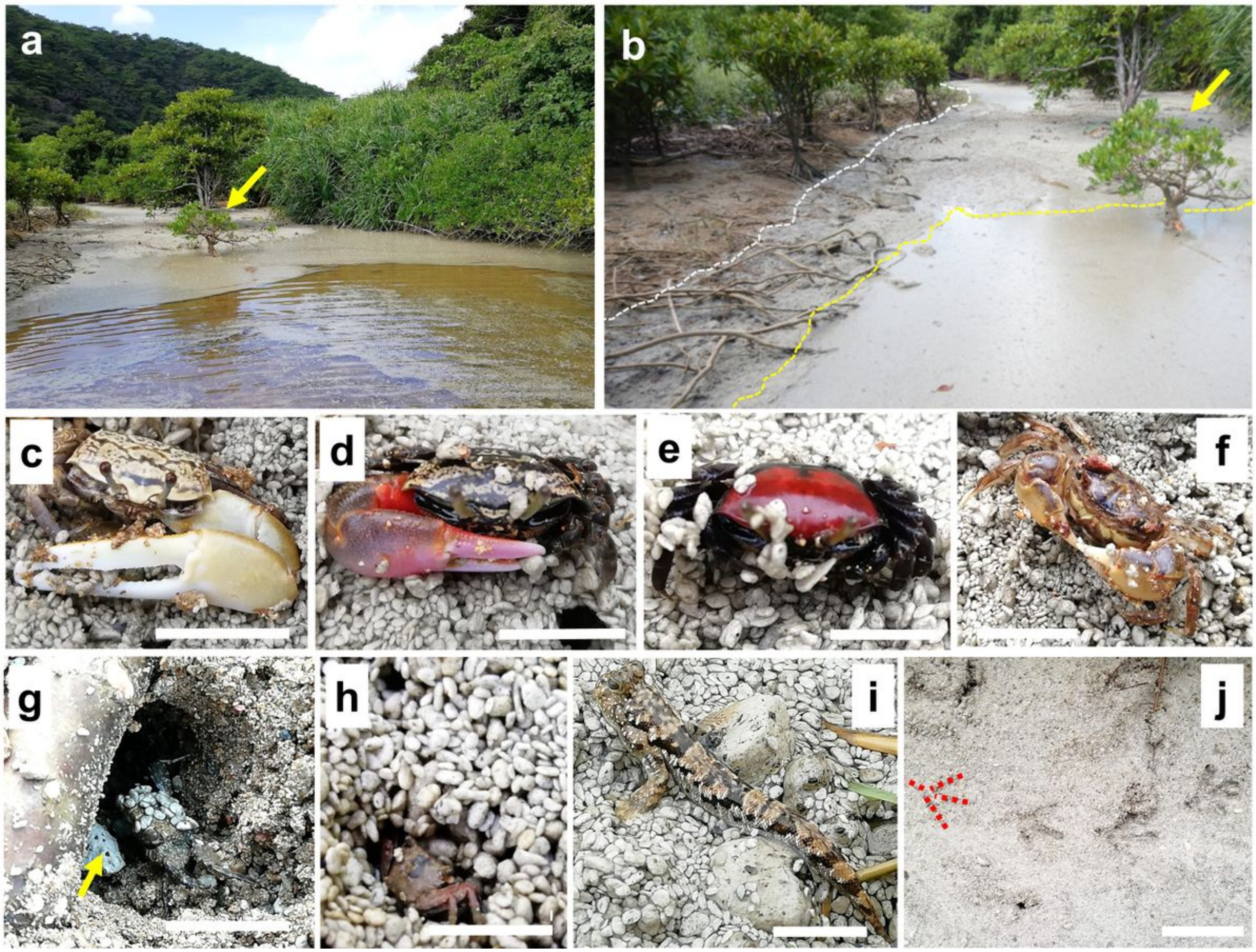

Figure 9

Behavior of mangrove organisms affected by drifting pumice. (a) Pumice raft adrift in a mangrove river, where a colony of *Kandelia obovata* (yellow arrow) and *Bruguiera gymnorhiza* trees coexist. (b) Enlarged image from (a), with the yellow arrow pointing to the same tree. The white dotted line indicates the boundary between the original mudflats and pumice-covered substrates, and the yellow dotted line marks the border of the water. (c) A fiddler crab (*Uca lactea lactea*) on the pumice pebbles. Video recording of the *U. lactea.* behavior on the pumice-covered sediment shows the crab's inability to return to its burrow, which had collapsed due to the pumice stones (Supplementary Video 6), and the competition between the species to acquire the burrow (Supplementary Video 7). Scale bar: 1 cm. (d) A fiddler crab (*Uca coaractata*) on the pumice pebbles. Scale bar: 1 cm. (e) A fiddler crab (*Uca chlorophthalma crassipes*) on the pumice covering mudflat. Scale bar: 1 cm. (f) A mitten crab (*helical epicure*) on the pumice substrate. Scale bar: 1 cm. (g) A sesarmid crab that cannot go back into its burrow because a pumice stone has blocked the entrance (yellow arrow); its body surface is covered with pumice grains. Scale bar: 1 cm. (h) A sesarmid crab tries to hide in a depression near the burrow; it is unable to hide in its burrow, which is blocked by pumice (red arrow). (i) A mudskipper (*Periophthalmus argentilineatus*) was placed on the pumice-covered water surface. It seemed difficult for fish to jump across the pumice-covered surface (Supplementary Video 8). Scale bar: 1cm. (j) Footprint of *Hypotaenidia okinawae* on the pumice-covered mangrove flat. The dashed line represents the shape of the bird's fingers. It seems to have been searching for food in this area until recently. There was a bird singing (Supplementary Video 9) near the bushes and observed a bird cautiously crossing the pumice-covered ground (Supplementary Video 10) on the left side of Fig. 9a. *H. okinawae* is categorized as the IUCN Red List of Threatened Species. https://doi.org/10.2305/IUCN.UK.2016-3.RLTS.T22692412A93352408.en

Supplementary Files

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