BioEssays

PROBLEMS & PARADIGMS

Prospects & Overviews

Rebuilding relationships on coral reefs: Coral bleaching knowledge-sharing to aid adaptation planning for reef users

Bleaching emergence on reefs demonstrates the need to consider reef scale and accessibility when preparing for, and responding to, coral bleaching

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Abstract

Coral bleaching has impacted reefs worldwide and the predictions of near-annual bleaching from over two decades ago have now been realized. While technology currently provides the means to predict large-scale bleaching, predicting reef-scale and within-reef patterns in real-time for all reef users is limited. In 2020, heat stress across the Great Barrier Reef underpinned the region's third bleaching event in 5 years. Here we review the heterogeneous emergence of bleaching across Heron Island reef habitats and discuss the oceanographic drivers that underpinned variable bleaching emergence. We do so as a case study to highlight how reef end-user groups who engage with coral reefs in different ways require targeted guidance for how, and when, to alter their use of coral reefs in response to bleaching events. Our case study of coral bleaching emergence demonstrates how within-reef scale nowcasting of coral bleaching could aid the development of accessible and equitable bleaching response strategies on coral reefs. Also see the video abstract here: https://youtu.be/N9Tgb8N-vN0

KEYWORDS
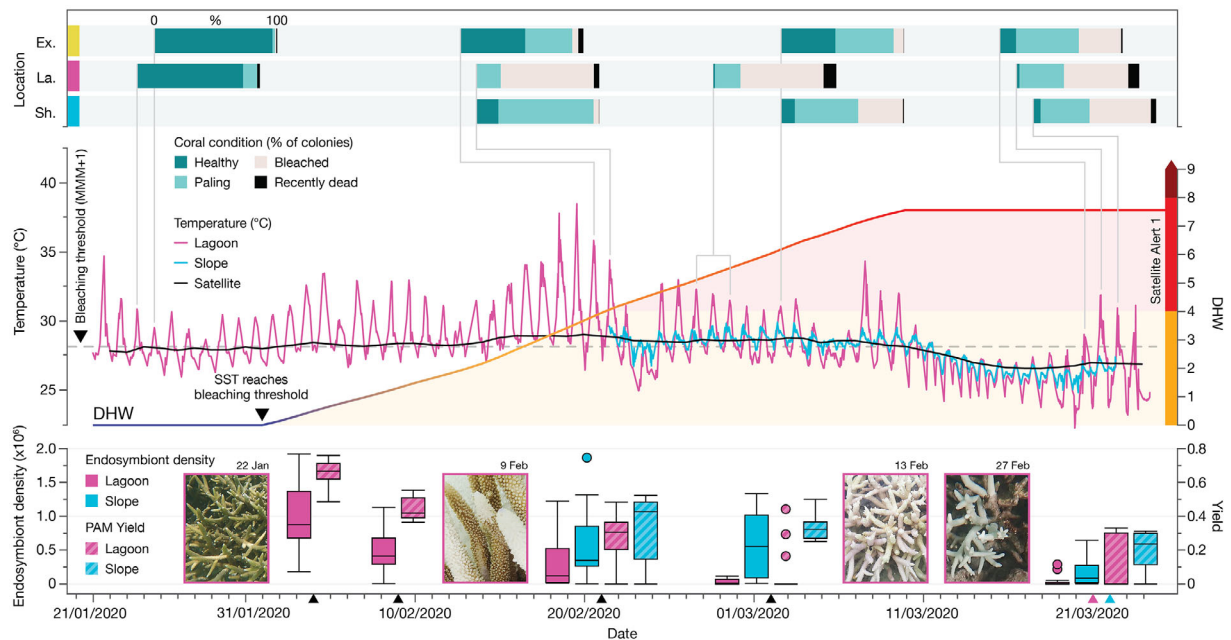bleaching alerts, climate adaptation, coral bleaching, coral reef

FIGURE 1 Bleaching impacts from heat stress vary across reef areas. Ecological surveys (top) of coral conditions in the reef lagoon (La.), and exposed (Ex.) and sheltered (Sh.) slopes of Heron Island reveal heterogeneity of bleaching emergence and severity. In situ temperature loggers (centre) indicate different variability between lagoon and slope sites, which is not detected by satellite temperature monitoring of ocean temperatures or integrated into satellite-based bleaching risk tools (DHW). Physiological data of endosymbiont density and photosynthetic yield (bottom) from lagoon and slope corals is consistent with ecological observations. Inset pictures provide representative images of branching *Acropora* colonies during the bleaching event. Arrows indicate dates when coral samples were collected on the reef for the corresponding plotted data of coral physiological responses, black arrows indicate both lagoon and slope collected on same day; pink and blue arrows indicate collections from sequential days

INTRODUCTION

The continuing coral reefs crisis

Coral reefs are now undergoing an unprecedented rate and severity of mass bleaching.[1–7] The first predictions of near-annual bleaching occurring globally by 2020 were published following the global mass bleaching event of 1998.[8] Bleaching studies since have documented that shallow reef environments, such as the lagoon, reef crest, and reef slopes to 6 m depth, are the most severely damaged as a result of bleaching.[9–13] These shallow-water reefs directly support the activities and livelihoods of millions of people worldwide[14–16] and bleaching disproportionally impacts these reef-reliant societies.[10,11] Given that different end-user groups utilize within-reef habitats in a variety of ways, usage-specific guidance of when and how to respond to, adapt, or intervene in, an impending bleaching event is not available for the vast majority of reef end-users. For example, temperature-based predictive tools[2,17,18] forewarned of the bleaching event on the GBR from early-2020, however the resolution of the satellite predictions was insufficient to forecast the variability in bleaching emergence across the within-reefs habitats of the over 3000 distinct reefs of the ecosystem. The contrast between documented variable bleaching emergence[10,11,19] and satellite-based predictions, that do not capture this variability, underlies a limitation between current forecasting capabilities and managers and end users in provision of

bleaching warnings at the smaller scales directly needed for local reef users. This disconnect, accentuated by the lack of accessible, targeted information for specific reef areas and end-users, would be substantially magnified in regions (and for reef users) heavily reliant on subsistence from shallow water coral reef ecosystems.

VARIABLE CORAL BLEACHING EMERGENCE

A case study

In all reef habitat types coral bleaching results from the combined effects of temperature and light stress, which lead to the breakdown of the symbiosis between habitat-forming corals and the single-celled algae that reside within their tissue.[20–22] Within a single coral reef there are also multiple drivers that influence the spatial and temporal variability of the bleaching response and its severity, including light exposure, tidal variation, ocean currents, waves, upwelling, turbulent mixing, water residence time, and lagoonal outflow.[11,23–25] The influence of these drivers varies across reef habitat types, affecting both the level of exposure to temperature stress and the corals' physiological susceptibility.[11]

Variable emergence of coral bleaching in response to these drivers was observed at Heron Island beginning in late January 2020 (Figure 1; for methods see Supplementary Material). Within 4 weeks, extensive

impacts were evident in the intertidal lagoon with over 80% of branching *Acropora* colonies (the predominant habitat formers) bleached or recently dead. Only 0.5% of *Acropora* colonies remained healthy within the coral lagoon 1 month after the start of the bleaching event. In contrast, at that time (February 21st) our surveys found only 9% and 5% of coral colonies on the exposed and sheltered reef slopes, respectively, were bleached or dead (Figure 1). Despite heat stress continuing throughout March (satellite temperature-based Degree Heating Weeks, DHW, peaked at 7.6°C-weeks) and into April, our surveys of the reef slope conducted 8 weeks after the onset of bleaching (late March 2020) found recent mortality rates of less than 5% and bleaching rates of approximately 35% and 50% on exposed and sheltered slopes, respectively (Figure 1). In contrast, we found over 15% mortality across the reef lagoon in late-March, affecting both thermally-susceptible and thermally-tolerant coral species. Coral bleaching emerged first in the reef lagoon, followed by the sheltered coral reef slope and then the exposed coral reef slope. The physiological impact of bleaching to the symbiosis of dominant reef corals was quantified by endosymbiont density and PAM fluorometry (Figure 1, Table S1 Table S2). The substantial differences in the timing and severity of ecological impacts among reef areas were mirrored in the corals' endosymbiont community density, with the average symbiont density for reef flat branching *Acropora* being 50-fold less than that of corals impacted by bleaching on the coral reef slope (2nd March, Figure 1). Variable bleaching emergence in different reef areas was also reflected in the distinct in situ temperature records on the coral reef lagoon and coral reef slope habitats (Figure 1). Importantly, the difference in thermal conditions on each of these reef habitats is not captured by the satellite temperature-based measures (see discussion below), the method relied upon to provide alerts of coral bleaching events to local end users (Figure 1).

Current limitations of bleaching predictions for reef end-users

While the broad uptake of globally available satellite monitoring products for bleaching risk has greatly benefited many scientific and coral reef management agencies, translation of these warnings into readily accessible information at a scale that is useable for non-scientific reef end-users currently doesn't exist. The spatial scale of satellite-based nowcasting (5 × 5 km^2 pixel) far exceeds the complexity of within within-reef habitats (as shown in Figure 1) and also exceeds that of typical reef usage across the broad spectrum of reef end-users. The nowcasts do not capture the spatial variability in temperature and in accumulated coral heat stress that occurs within coral reefs as a result of complex interplay of biophysical drivers of coral bleaching.[2,17,18] It is also important to recognize that satellite-derived temperature products represent night-time surface water temperature conditions across the pixel, and so do not necessarily reflect the daily peak temperatures that are experienced at the depth of corals within reef habitats. The difference between km-scale pixel-based, night-only surface temperature and within-reef daily peak temperate is evident when comparing

satellite sea surface temperatures (SST) and in situ lagoonal temperatures and is significant to the biological responses observed on coral reefs. Our in situ measurements of temperature reveal a far greater between-days variance on reefs than is evident in the satellite products (Figure 1); within-day variability is far greater and daily temperature peaks higher on the reef flat compared with those of the adjacent slope, driven by both diel and tidal changes (Figure 1). These factors of scale and temporal variability are critically important to the communication of coral bleaching risk translated from satellite products. Spatial variability in the onset and severity of coral bleaching across reef habitats can explain the contrasting snapshots of reported within-reef bleaching severity observed across the GBR in 2016.[11] Importantly, predictive heat stress tools (e.g. DHW) do not, as yet, incorporate site-specific variability in bleaching emergence, nor have these products been tailored towards the differing needs of reef end-users. The variability in the timing of bleaching emergence on different reef areas and the disparity in scale of bleaching occurrence and bleaching risk communication emphasizes the need for targeted, end-user accessible predictive tool development which incorporates spatial and temporal aspects of within-reef risk that ultimately influence bleaching impact and how end-users respond to bleaching on coral reefs.

In addition to the within-pixel (5 × 5 km^2) variability in timing described here, the rate and trajectory of warming leading into heat stress events, and the history of both temperature variability and prior bleaching, also influence the biological and ecological responses that are observed within a reef that in turn impact ecosystem services provided by the reef. For example, a rapid onset of heat stress has been observed to result in the dissolution of coral skeletons and reduction in 3D reef complexity,[26] consequences of which include the immediate loss of susceptible habitat forming species and long-term loss of coastal protection provided by complex reef structures.[27] In contrast, a gradual increase of heat stress accumulation, for example occurring over several tidal cycles, can allow for a greater chance of short-term acclimatization, reduce heat stress induced colony mortality, result in greater colony survival, and thereby facilitate near-term bleaching recovery.[28–30] As such, there is strong evidence from many coral reef ecosystems that thermal variance is a strong driver of bleaching tolerance.[31–35] An analysis of GBR heat stress events spanning almost three decades identified three characteristic temperature trajectories, among which the so-called 'protective' trajectory induced thermal tolerance not seen with the other trajectories.[36] However, it is also important to note that stress accumulation that is below the threshold for observable bleaching and below the threshold for heat-induced coral mortality can lead to long-term consequences to the reef ecosystem, such as increased disease occurrence, reduced growth, reduced wound healing in corals, and reduced reproductive output.[24,37–42] Additionally, past exposures to heat stress, as well as subsequent bleaching and/or mortality can result in ecological memory, modifying the response or corals and reefs to new stress.[43] Incorporating factors of within-reef thermal variance, the trajectory and rate of temperature increase, and the biological and ecological consequences at the within-reef scale into new predictive bleaching tools has the capacity to translate scientific knowledge and engage end-users into
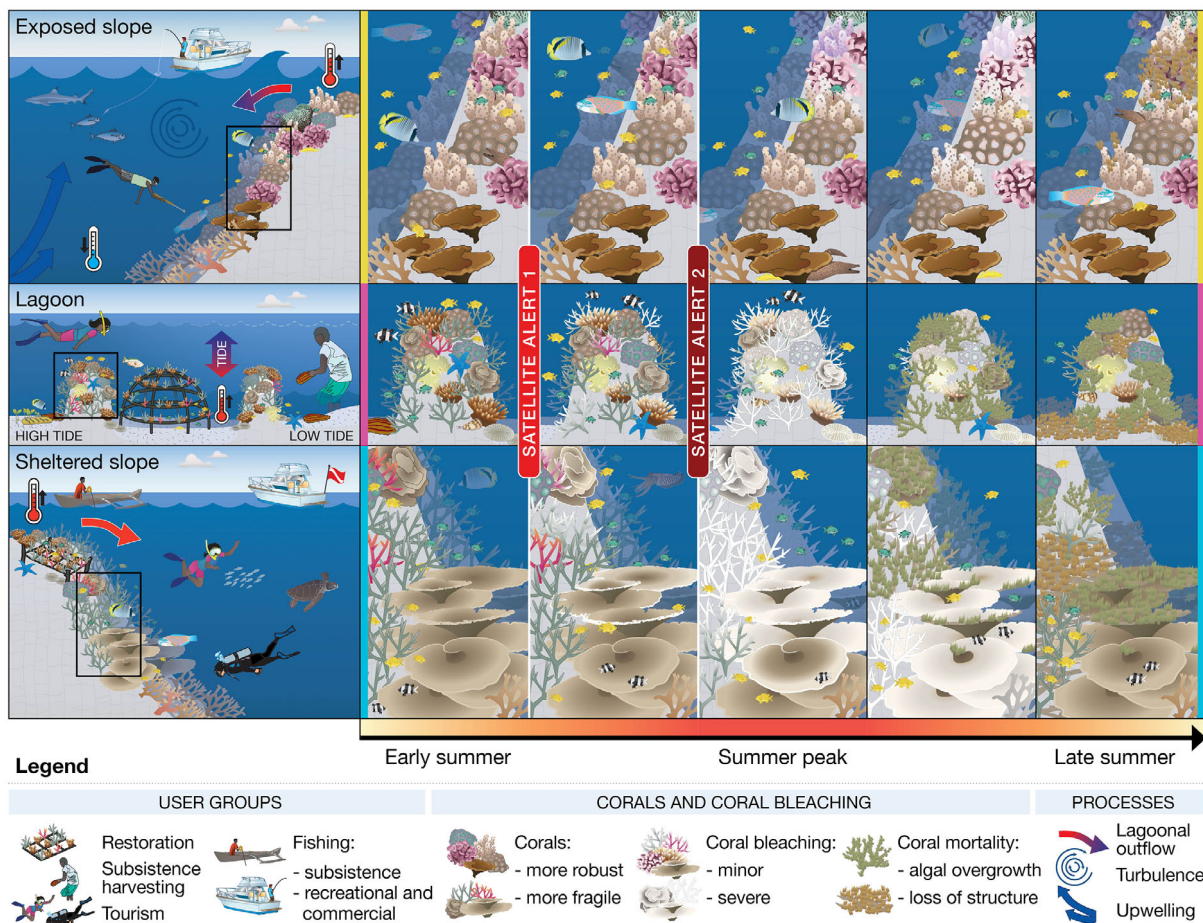
FIGURE 2 Coral reef usage by end-users varies between lagoon and slope areas, as does the emergence and severity of coral bleaching events. Lagoon corals typically experience bleaching impacts earlier in summer than reef slopes, influenced by relevant physical processes. Satellite monitoring of heat stress that causes bleaching cannot resolve small-scale variability between reef areas. Different end-users would benefit from specific guidance of differential timing and severity of impacts

knowledge-sharing at the scale of their use to build understanding of coral bleaching events.

Coral reefs, like other ecosystems, are utilized in different ways by multiple user groups. Uses for coral reefs around the world can include tourism (SCUBA and snorkeling), water sports (surfing, kitesurfing, boating), food sources (including subsistence, recreational, and commercial fishing), ecosystem repair and restoration, and culturally specific activities (ceremonies, festivals, culturally important sites or objects) (Figure 2). Coral reef lagoons are particularly important because they support a large proportion of these social-ecological usages including tourism activities, near-shore fisheries and local-scale coral reef restoration efforts. However, as we have demonstrated (Figure 1) reef lagoons are the first and most severely impacted reef areas during a bleaching event due to pooling of warm water over the reef and the high reflectance of light within the shallow waters that accelerates symbiosis breakdown.[44] In comparison, bleaching emergence on coral reef slopes and reef channel habitats is often delayed, occurs later in the summer peak thermal stress, and may even be entirely abated due to high water flow (Figure 1).[23,45] These factors can result in less disruption for end-users of exposed slopes, compared

with those on adjacent sheltered slopes and lagoon. For example, reef gleaning activities are restricted to the reef lagoon while subsistence fishing occurs across reef flats and upper and lower reef slopes; in contrast, deeper slope sites are more heavily exploited by both fishers and divers.[46] The heterogenic nature of bleaching emergence therefore results in a disproportionate impact to different reef end-users (Figure 2).

Links between bleaching emergence heterogeneity and impacts to reef user groups

The spatial and temporal variability in bleaching emergence can, in turn, substantially alter the within-reef habitats upon which different user groups rely. For example, exposed reef slopes with high water flow and wave action are sometimes less conducive to dive tourism and fishing, therefore, during bleaching events prioritizing use of less-impacted exposed slopes could reduce usage-associated stressors on sheltered slopes that experience more severe bleaching. In this instance, exposed slopes could be considered socio-ecological refuges.
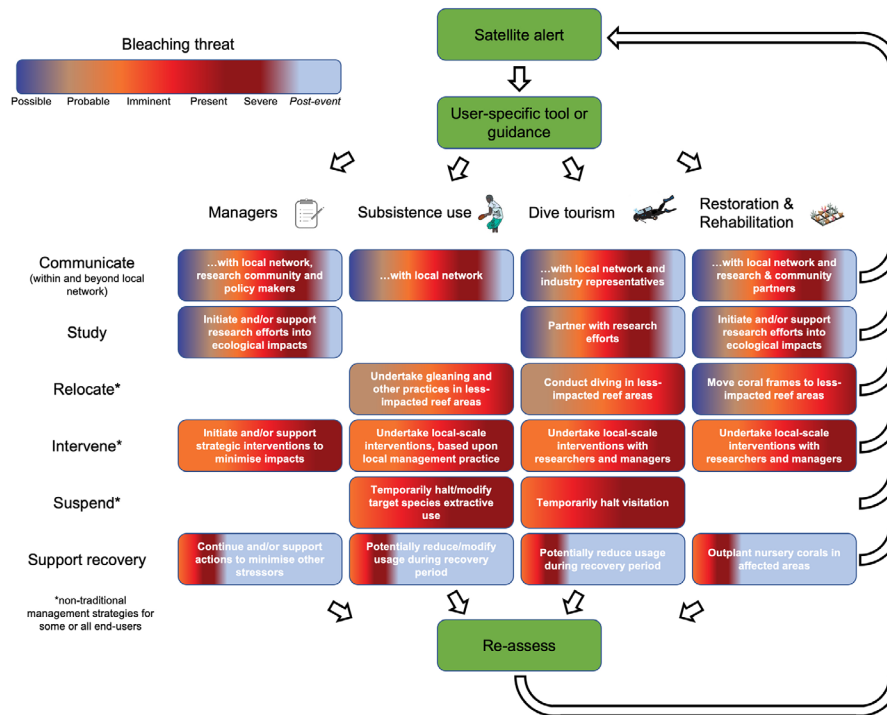
FIGURE 3 Habitat-specific coral bleaching alerts allow new response actions for end-user groups. Potential response options and the timing of their application vary for different end-users based on the within-reef areas they access and the level of bleaching threat (indicated by the color spectrum). In addition to traditional strategies, new opportunities to relocate activities (before/during stress), intervene to mitigate impacts (during stress) and to suspend usage (severe stress) will be presented with finer-scale tools and guidance. End-user groups should re-assess response decisions as satellite alerts are updated through a bleaching event

For millions of people in coral reef regions there is, and continues to be, a direct reliance on the goods and services provided by these increasingly impacted coral reef ecosystems.[47,48] However, this also points to inequality in both the impacts upon and options available to different sections of the global coral reef community. Many developed nations are now heralding, investing in, and testing high-cost adaption initiatives such as assisted evolution, ecosystem engineering, and climate engineering as strategies to address coral reef decline and species losses.[49–53] However, these strategies are generally expensive, require substantial infrastructure for development, require coordinated governance, and many are acknowledged as likely being decades from scalable implementation once developed and extensively tested.[49,54] As such these approaches remain out of reach for many reef managers, particularly those in developing nations where the majority of coral reefs are found, due to the lack of immediate implementation, high cost, and reliance on advanced technologies.[49,52,54,55] Many reef-reliant communities have limited livelihood alternatives to replace their immediate reliance on coral reefs and as such are disproportionally affected by the impacts of climate change and coral bleaching events.[53] Importantly there is currently no mechanism in place, or available in the immediate future, to support communities to prepare and respond in real-time to the impacts of bleaching events. This demonstrates a societal inequality in access to effective planning for intervention and rehabilitation between developed and developing nations. This inequality needs urgently to be addressed to improve how the impacts of coral bleaching

on societies into the future are communicated and strategies to mitigate, respond, and adapt to bleaching are developed. Providing reef-reliant communities with direct access to information to understand, prepare, and respond to the heterogeneity of bleaching impacts may be one such mechanism that can aid in the near-term adaption to coral bleaching events for reef end-users.

The provision of habitat-specific coral bleaching alerts

Habitat-specific bleaching nowcasts have the potential to enable end-users to adapt their reef-use practices during periods of heat stress and bleaching disturbance, and guide long-term action planning (Figure 3). The development of fine-scale predictions for end-users can also support new response actions at the local scale, beyond those that have traditionally been considered by reef managers and conservation planners.[56] To achieve this goal, it is necessary for next-generation alert systems to assimilate the within-pixel satellite data with common features of the coral reefs that influence difference in the bleaching risk in the region. This would enable reef users to access scientifically validated, customized alerts relative to their habitat use. For example, actions available to reef users are likely to vary based on the specifics of each end-user group and on the level of bleaching threat (Figure 3). Understanding the differential impacts of bleaching for end-users can facilitate the forming, or in some cases rebuilding, of trust and

relationships between groups such as tourism operators, scientists, and managers.

Fine-scale bleaching predictions can inform strategically timed mitigation, restoration, and adaptation strategies. For example, active interventions that modify the physical conditions (e.g. reducing temperature or light levels), and in turn the level of coral vulnerability, are being considered across a range of scales and stakeholders, but have had limited trials during bleaching episodes.[57] Local-scale interventions that could mitigate the impacts of bleaching events include relatively low-cost options, such as the use of shade cloth or sprinklers to reduce light exposure.[54,57] These interventions, used in conjunction with the pre-identification of especially vulnerable or valuable resources and spatiotemporally-specific bleaching alerts, have the potential to support more economically viable management options for some reef users. Mobile interventions may also be developed and deployed based on predicted location and timing of bleaching risk. Further, prioritizing the use of less-impacted areas during bleaching events, such as exposed slopes, could reduce dive tourism and fishing-associated stressors on sheltered slopes, which experience more severe bleaching. The relocation of end-user activities, such as a shift from sheltered to exposed slope areas during bleaching events, could create socio-ecological refuges where reef-associated activities can continue during bleaching, but are directed away from vulnerable areas. These examples, in tangent with our analysis, demonstrate that the within-reef location and timing of any intervention action is critical to conservation planning.

Facilitating knowledge-sharing relationships among reef users may aid in broadening the scope for uptake of response actions and communicating the limitations of some actions within particular reef habitats.[56] The development of habitat-specific bleaching alert tools would support decision making, such as for ecosystem repair or restoration planning, both during bleaching impacts and prior to their realization (Figure 3). The relocation of end-user activities, such as a shift from sheltered to exposed slope areas, could be implemented to minimize additional stress on corals within a heavily used reef and reduce other drivers of reef decline such as coral disease outbreaks. For example, cases for suspending end-user activities during the most extreme levels of threat and in severely impacted locations may be decisions that can be triggered directly in response to within-reef nowcasts.

Interdisciplinary multi-user dashboarding for bleaching alerts

Dashboarding (i.e. interactive online information portals) with multi-user input has become a widely recognized and successful tool for conservation planning and conservation community education and engagement.[58] There are many examples,[58–61] such as The Sustainable Seafood Guide (www.goodfish.org.au), Global Learning for Local Solutions (marinehotpsots.org)[62] and RedMap (www.redmap.org.au), that have a track record of successful community engagement with the public to support societal adaption and

community engagement in conservation outcomes,[58] as well as frameworks for establishing their success.[61,63] Tools such as Coral Reef Watch (https://coralreefwatch.noaa.gov) and The Adaptation Project Tool (https://pacificclimatechange.net) provide scientists, managers, and conservation planners with access to resources but these tools have not yet utilized local-scale knowledge and use of coral reefs, nor integrated local knowledge with scientific knowledge to aid multiple reef users in planning specifically for the impacts of coral bleaching on a local-scale. Recent increases in telecommunication connectivity and device affordability in developing nations (a 2019 survey of 11 emerging and developing nations, found a median of 53% of adults use personal devices[64]) demonstrates there is now increasingly widespread access for coral reef end-users in developing nations, suggesting that a phone-based alert system may be effective for targeted alert systems. A phone-based alert system could send information relevant to locally-specific intervention and management responses[65] directly to reef end-users and include the opportunity for direct engagement to disseminate information.[65] Similarly, relatively cheap temperature sensors placed in key end-user areas of the reef, linked to online dashboards would aid development of site-specific, scientifically supported bleaching alert systems. We propose that knowledge sharing between scientists, managers and reef end-users through the development and application of end-user-targeted coral bleaching dashboards could address current knowledge gaps and bridge inequalities in access to coral reef adaption planning.

Online dashboards capable of customizing bleaching alerts by within-reef habitat (e.g. reef slope vs lagoon) could be informed by a combination of scientific knowledge of bleaching susceptibilities, satellite data, in situ ocean temperature data (where available), and end-user knowledge of site use, resource value, and site-specific structure. The combination of multiple data types and disaggregation by reef sites would provide end-users with multiple benefits including real-time targeted bleaching alerts, capacity for forward planning of conservation efforts and bleaching intervention planning. Currently satellite-based heat stress accumulation alone underpins bleaching alerts, but integrating end-user knowledge (e.g. reef area used, exposed or sheltered site, depth of reef usage) into the dashboard could create a positive feedback loop which further improves spatial relevance, further aligning bleaching alerts with end-users.

Information on the immediate societal impacts of coral bleaching events is currently limited to regions of intensive scientific study, however reef user groups extend across a much larger areas of coral reefs in both developed and developing nations. The dashboard concept proposed here would seek to capitalize on this larger footprint of potential information from reef end-users while still ensuring the alerts are underpinned by science. Importantly, this combination would provide a means to investigate the distribution of reef use across coral reef ecosystems and enable equitable targeted science and management of bleaching risk. Critically, an integrated bleaching dashboard would support real-time decision making by both the reef end-users and scientists, helping each to understand implications and trade-offs of local conservation choices, and enabling global knowledge sharing for innovative in coral bleaching responses measures.

FUTURE OUTLOOK

The heterogeneous impacts of coral bleaching within-reefs, combined with the differing reliance of reef users on reef habitat types, illustrates the urgent need for better targeted management of coral reefs at the within-reef scale. Critically, sheltered lagoons, which are typically not differentiated from reef slopes in current bleaching alert systems, exhibit both a higher susceptibility to bleaching and a higher frequency of end-user engagement. Therefore, improved guidance at the spatial and temporal scales at which bleaching emerges within reefs is needed to inform responses to impending bleaching events. Bleaching alerts that recognize the different reef habitats and how they are used will also build trust among reef users, managers, conservation groups, members of the public and scientists, which can foster inclusive decision making (e.g. in prioritizing the design and implementation of interventions relevant to specific reef habitats). Access to habitat-specific guidance at times of coral bleaching alerts may therefore begin to address conservation inequality, particularly if these efforts are coupled with effective local-scale mitigation, restoration, rehabilitation, conservation, and conservation strategies.[66–69] This would provide developing nations and areas with fewer resources access to the data and support needed to track and respond with greater specificity to bleaching risk and at a finer resolution than provided by current satellite alerts. As we enter an era of near-annual bleaching events it is increasingly evident that coral bleaching will continue to impact both coral reefs and coral reef users in profound and irrevocable ways.

AUTHOR CONTRIBUTIONS

Conceptualization: Tracy D. Ainsworth, William Leggat, Brian R. Silliman and Scott F. Heron; methodology: Tracy D. Ainsworth, William Leggat, Coulson A. Lantz, Scott F. Heron; data collection: Coulson A. Lantz, Jessica L. Bergman, Alexander J. Fordyce, Charlotte E. Page, Juliana J. Renzi, Joseph Morton; formal analysis, Tracy D. Ainsworth, William Leggat, Coulson A. Lantz, Jessica L. Bergman, Alexander J. Fordyce, Charlotte E. Page, Scott F. Heron; data curation Coulson A. Lantz, Jessica L. Berman, Alexander J. Fordyce, Charlotte E. Page, Scott F. Heron; visualisation: Tracy D. Ainsworth, William Leggat, Scott F. Heron, initial draft: Tracy D. Ainsworth; editing Tracy D. Ainsworth, William Leggat, Brian R. Silliman, Coulson A. Lantz, Jessica L. Bergman, Alexander J. Fordyce, Charlotte E. Page, Juliana J. Renzi, Joseph Morton, C. Mark Eakin, Scott F. Heron.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

All data are available on FigShare via https://doi.org/10.6084/m9.figshare.12301673.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.