

Species-specific bleaching trajectories during the 4th global coral bleaching event in northeastern Peninsular Malaysia

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Abstract

During the 4th global coral bleaching event (2023-2025), over 80% of the world's coral reefs experienced bleaching-level heat stress above 4 °C-weeks (DHW). Inevitably, the large spatial extent of this event substantially impacted coral reefs worldwide, and data are needed to quantify bleaching trajectories and coral mortality. In northeastern Peninsular Malaysia, heat stress accumulated to record levels by June 2024 (DHW=9.6 °C-weeks), resulting in severe mass coral bleaching. Here, we quantified species-specific bleaching and mortality trajectories for 12 abundant reef-building coral species of the genera *Acropora*, *Diploastrea*, *Echinopora*, *Heliopora*, *Montipora*, and *Porites*, by tracking 1850 tagged colonies from September 2023 to October 2024 using a novel Colony Bleaching Response Index (CBRI) that considers scales of discoloration and colony surface extent. In June 2024, 92.9% of all surveyed corals were bleached, resulting in 40.6% mortality by October 2024. However, bleaching trajectories varied across species, whereby the least bleached species in June were not the first to recover nor the least affected by mortality, suggesting inherent species-specific bleaching trajectories and recovery pathways. Mortality of *Porites* cf. *lobata* and *Diploastrea heliopora* was $\leq 1\%$, whereas severe mortality was recorded for *Acropora* species (five species, range 46.3-95.4%), *Echinopora* cf. *horrida* (44.7%), and *Montipora* cf. *aequituberculata* (27.8%). Among susceptible species was *Heliopora coerulea*, a species commonly considered heat tolerant. Our findings challenge previous regional studies that concluded a reversal of bleaching hierarchies of species over time, whereby historically ascribed heat tolerant species (i.e., slow-growing massive species) became susceptible and historically susceptible fast-growing species became heat tolerant. Importantly, bleaching severity did not decrease with depth. These data represent the first regional accounts of species-specific coral bleaching mortality in Malaysia, highlighting distinctive ecological bleaching and recovery trajectories of species.

Keywords: Coral bleaching, climate change, El Niño, Malaysia, Mortality, Ocean Warming

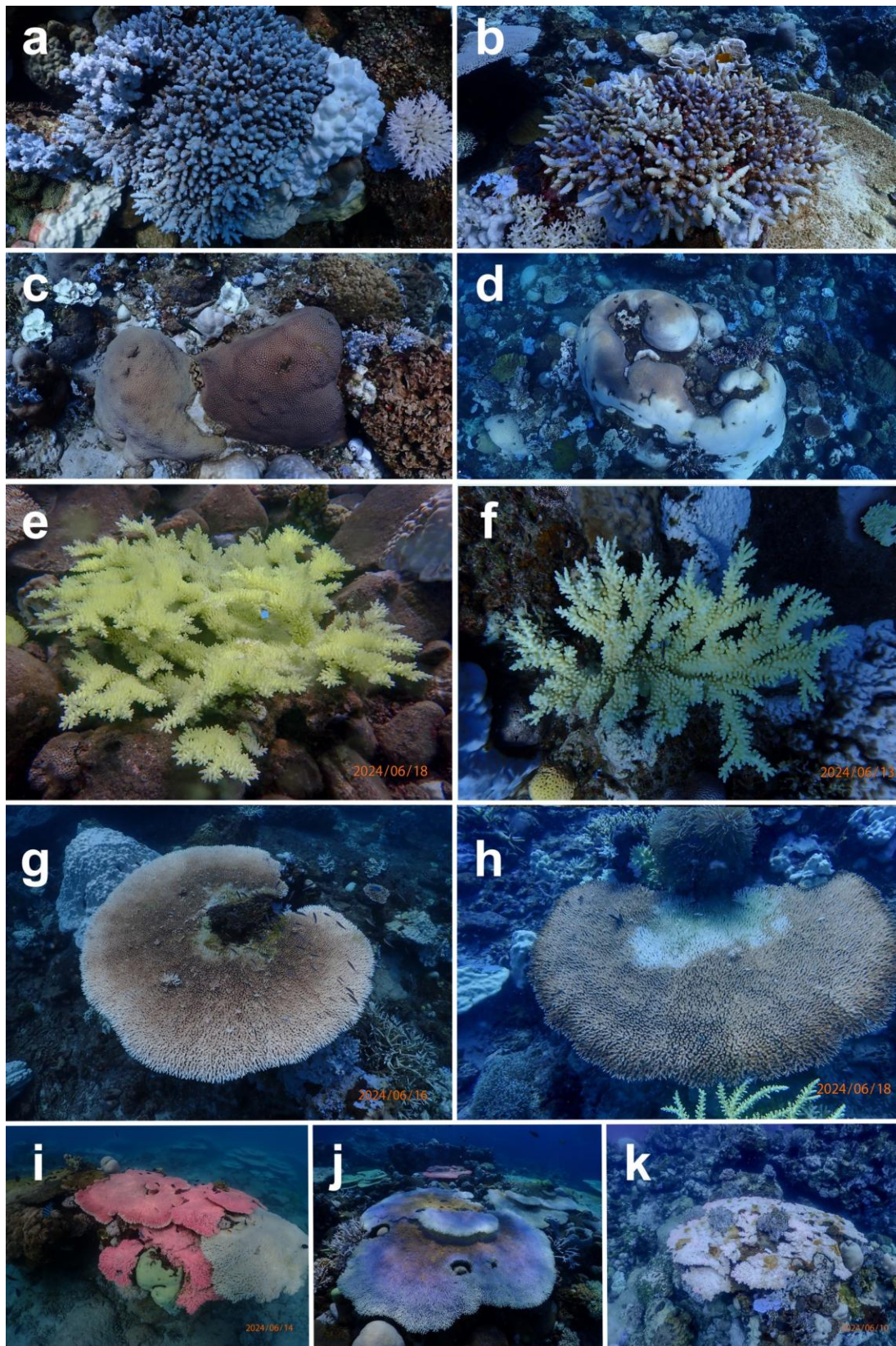


Figure 1. Example of coral bleaching categories. (a-b) *Acropora* cf. *gemmifera* colonies showing differential bleaching expressions: (a) severely pale and severe colourful bleaching vs. (b) severely pale, severe colourful bleaching, and fully bleached branches. (c) A pale *Diploastrea heliopora* colony (left colony) next to a healthy colony (right colony). (d) Partial bleaching of a *Diploastrea heliopora* colony. (e-f) Differential colourful bleaching example observed for *Acropora* cf. *florida* colonies: (e) pale and

mild colourful bleaching, and (f) severely pale and severe colourful bleaching. (g-h) within-colony bleaching variability seen for *Acropora* cf. *cytherea*: (g) inner part of the table is pale, becoming severely pale towards the outside, where the edge is fully bleached. (h) The fully pigmented edge of the colony becomes severely pale and bleached towards the inside of the colony. (i-j) show differential colourful bleaching among table coral species: (i) mild colourful bleaching of *Acropora* cf. *spicifera* (bright red-pink colony) and (j) severe colourful bleaching of *A. cytherea* glowing in bright blue. Image (k) shows a fully bleached *A. spicifera* colony with partial mortality from heat stress exposure. Images by Chew Kok Lynn and Sebastian Szereday.

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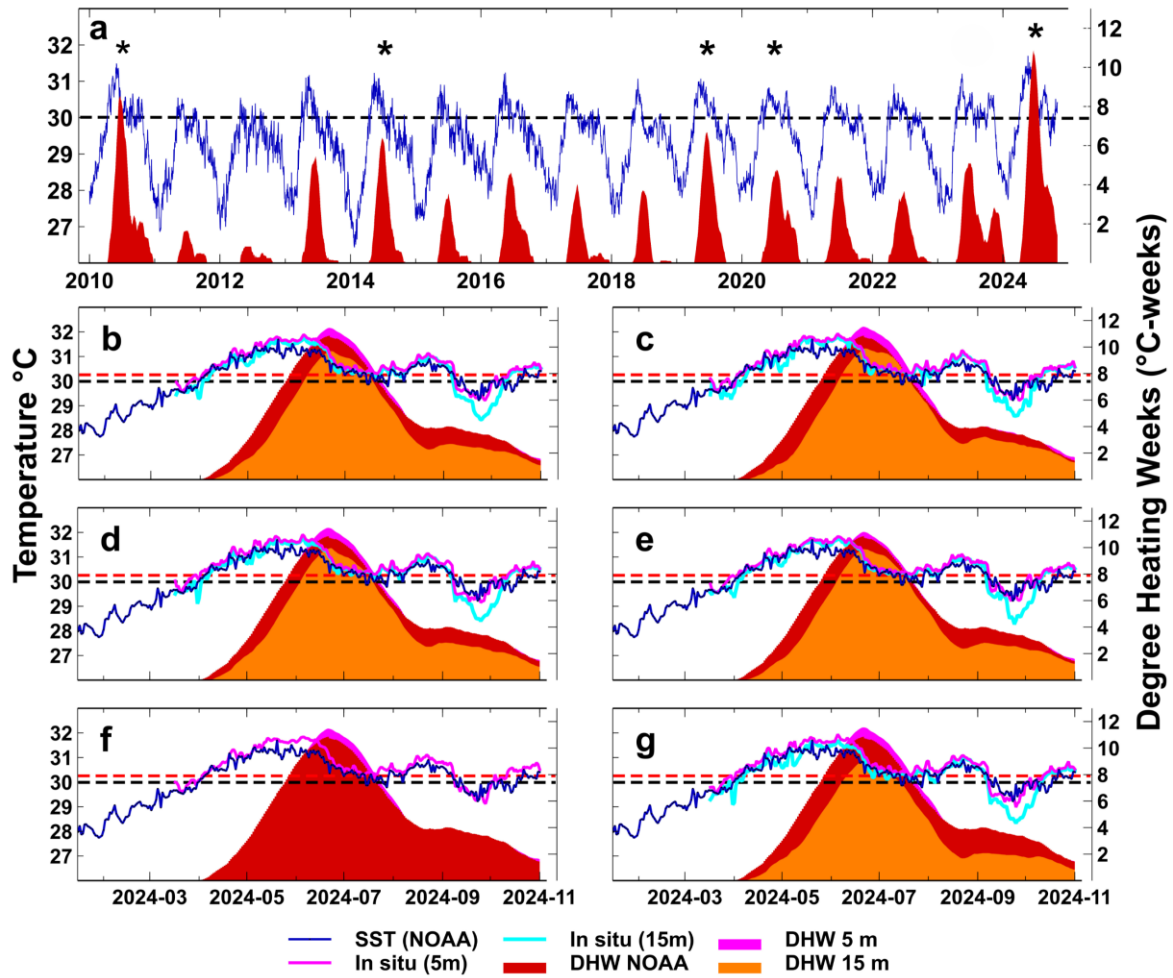


Fig. 2 Sea surface temperature (SST) and degree heating weeks (nDHW). The blue line shows the satellite-based nightly sea surface temperatures (SST °C) between 1 January 2010 and 31 October 2024, around Pulau Lang Tengah (5°46'30.0"N, 102°52'30.0"E), recorded by the National Oceanic and Atmospheric Association (NOAA), Coral Reef Watch (CRW) product, version 3.1. The black-dotted line shows the maximum monthly mean (MMM) temperature based on NOAA CRW satellite data (i.e., 29.94 °C). Heat stress based on satellite SST data (i.e., DHW NOAA) is shown in dark red to compare the severity of heat stress events since 2010. The asterisks in panel (a) highlight heat stress events that resulted in coral bleaching (identified from available literature and author observations). Panels (b-g) show site-specific temperature and heat stress data, where the mean daily 24h in situ sea temperature is shown for measurements at 5 m (cyan line) and 15 m (blue line) water depths, respectively. The red-dotted line highlights the MMM (i.e., 30.23 °C) based on in situ temperature data from five sites around Pulau Lang Tengah recorded between 2020 and 2022. nDHW based on in situ temperature data is shown for both depths (DHW 5m and DHW 15m). (b) – island average; (c) – Batu Bulan; (d) – Batu Kucing; (e) – House Reef; (f) – Karang Nibong (deep data missing due to logger malfunction); (g) – Tanjung Telunjuk.

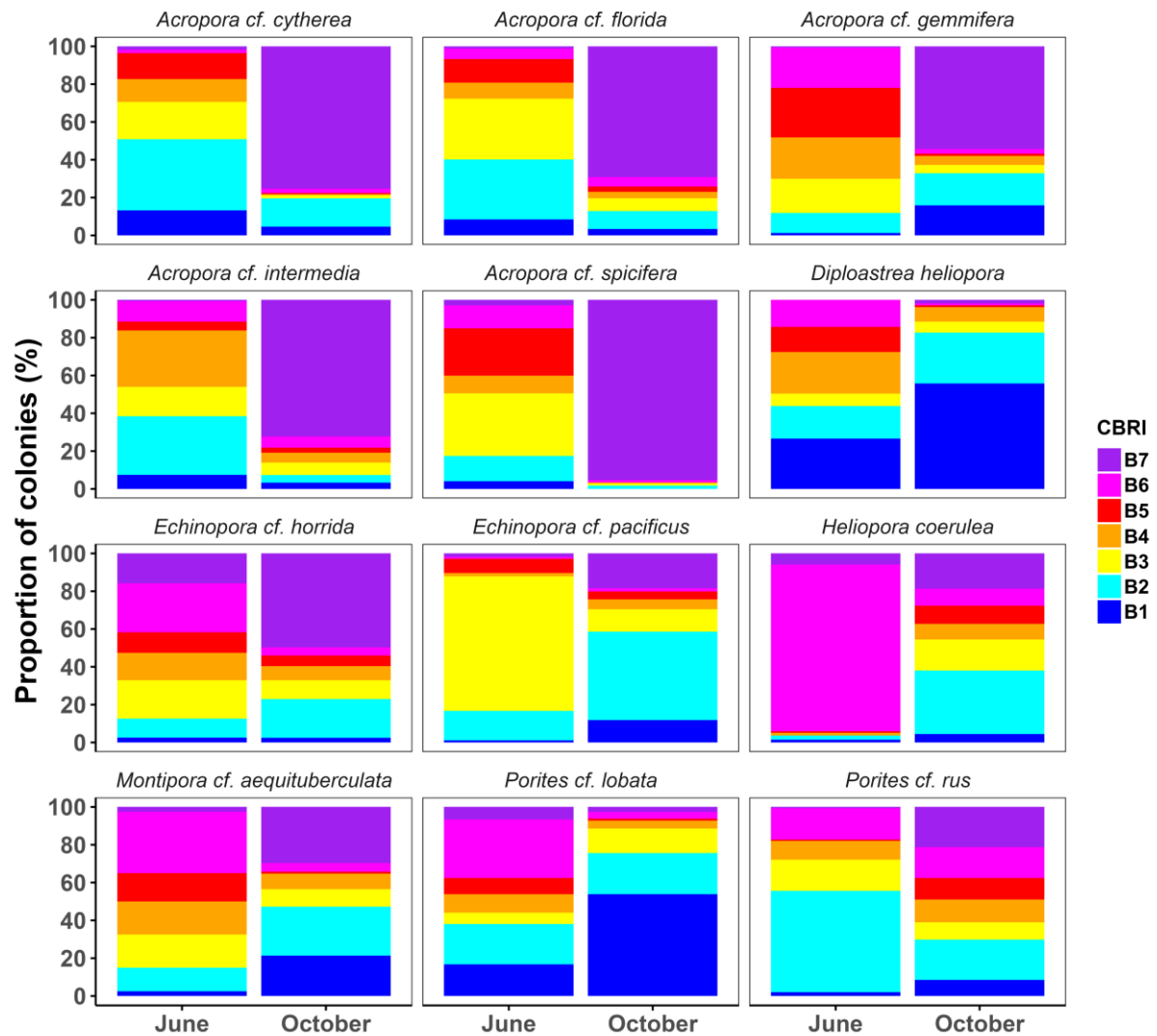


Fig. 3 Coral bleaching severity and recovery. The severity of bleaching on colony-level is expressed by the Colony Bleaching Response Index (CBRI) based on data recorded in June and October 2024. Higher CBRI scores indicate more severe bleaching. CBRI categories: B1 – no bleaching, B2 ≤ 16.7, B3 = 16.8-33.3, B4 = 33.4-50, B5 = 50.1-66.7, B6 = 66.8-83.3, B7 - CBRI > 83.3. Colour scale based on NOAA's CRW heat stress alert colour scheme.

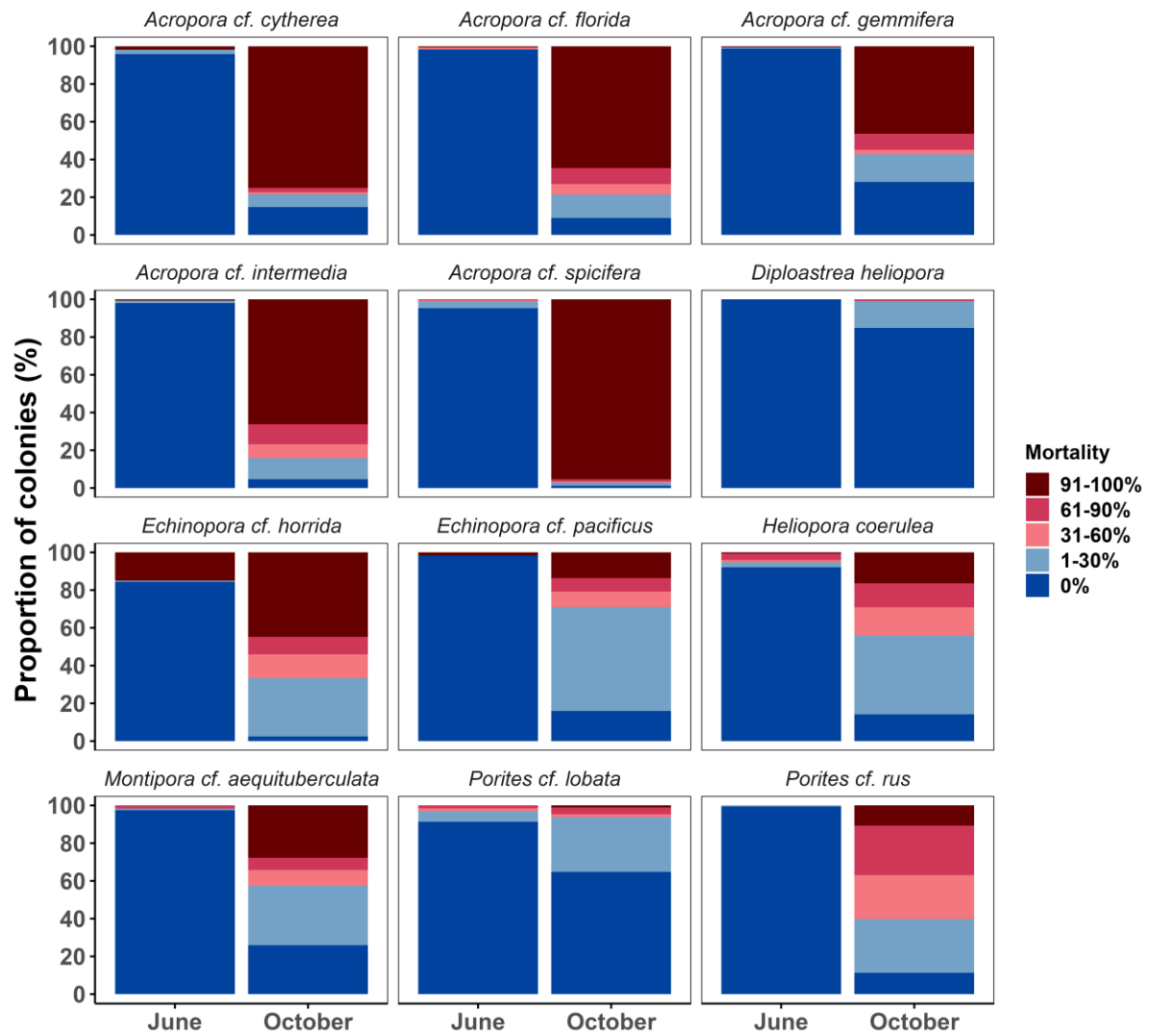


Fig. 4 Percentage of healthy, partially, and fully dead coral colonies during peak heat stress in June 2024 and four months later in October 2024.

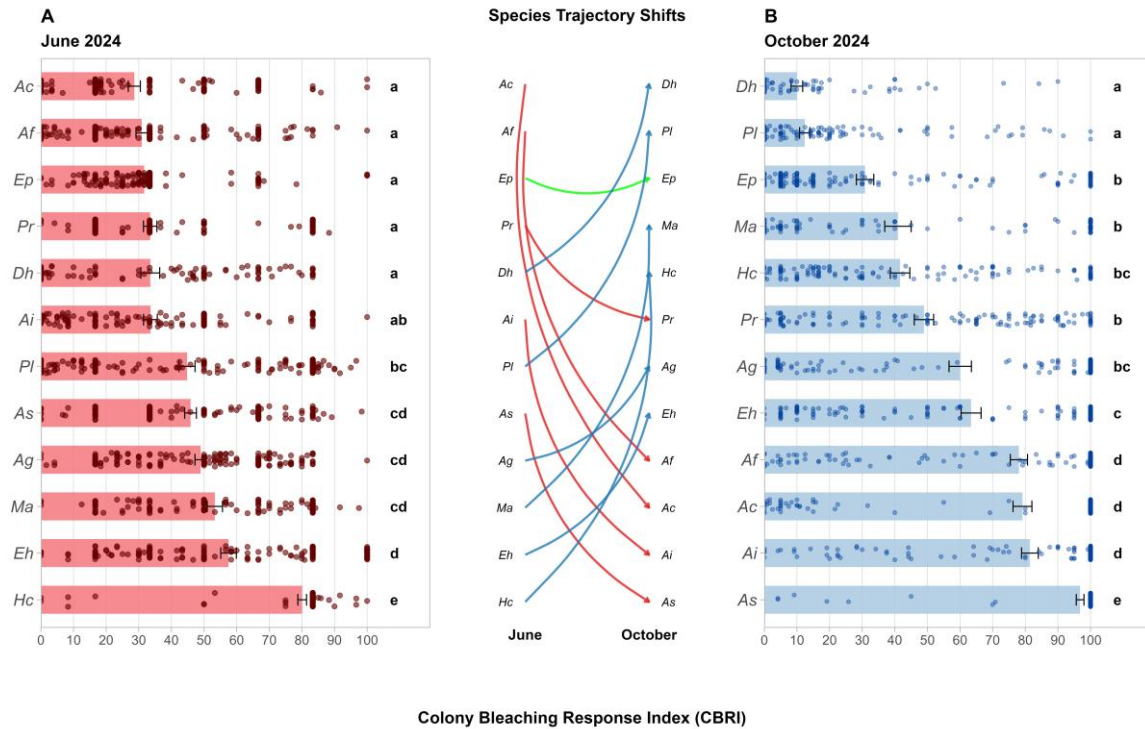


Fig. 5 Changes in bleaching trajectory among species across survey periods. Coral bleaching severity is expressed by the Colony Bleaching Response Index (CBRI). Dots represent individual data points of colonies and emphasize within species variability and data distribution. Error bars signify the standard measurement error. Species are plotted from least (top) to worst bleached (bottom) for each survey occasion to emphasize the distinct bleaching trajectories of species. Letter annotations represent results of pairwise Dunn's Tests conducted at significance levels of $p \leq 0.05$. Species abbreviations: Ac – *Acropora* cf. *cytherea*; Af – *Acropora* cf. *florida*; Ag- *Acropora* cf. *gemmifera*; Ai – *Acropora* cf. *intermedia*; As – *Acropora* cf. *spicifera*; Dh – *Diploastrea heliopora*; Eh – *Echinopora* cf. *horrida*; Ep – *Echinopora* cf. *pacificus*; Hc – *Heliopora coerulea*; Ma – *Montipora* cf. *aequituberculata*; Pl – *Porites* cf. *lobata*; Pr – *Porites* cf. *rus*.