

RESEARCH ARTICLE

Limited source–sink connections shape south-western Pacific coral reef resilience under current and future warming

Elise Dehont^{1,2}  | Severine Choukroun³ | Alana Grech⁴  | Kate M. Quigley^{4,5,6} 

¹Centre for Fisheries Ecosystem Research, School of Fisheries, Fisheries and Marine Institute, Memorial University, St. John's, Newfoundland and Labrador, Canada; ²Station Marine de Wimereux, Département de la Faculté des Sciences et Technologies de l'Université de Lille, Wimereux, France; ³Centre of Tropical Water and Aquatic Ecosystem Research, James Cook University, Townsville, Queensland, Australia; ⁴College of Science and Engineering, James Cook University, Townsville, Queensland, Australia; ⁵Minderoo Foundation, Perth, Western Australia, Australia and ⁶University of Western Australia, Perth, Western Australia, Australia

Correspondence

Elise Dehont

Email: elisedehont@aol.com

Kate M. Quigley

Email: katemarie.quigley@myjcu.edu.au**Funding information**

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Abstract

1. Current and future coral reef resilience will depend heavily on larval connectivity between reef systems, enabling populations to recover from repeated disturbance. However, climate warming is rapidly reducing larval dispersal, threatening reef recovery potential following mass bleaching.
2. Using a stochastic biophysical Lagrangian particle-tracking model, this study examined large-scale dispersal of coral larvae across the southern Pacific Ocean, focusing on reefs classified using an eco-evolutionary framework ('resistance, recovery, avoidance'). Dispersal was simulated across 850 reefs in the southwestern Pacific (2011–2024) for two coral species representing branching or massive corals under three warming scenarios (+1°C, +2.5°C, +4°C), and analysed for source–sink dynamics.
3. We identified key stepping-stone reefs in the Coral Sea and show that resilient, heat-tolerant reefs have limited source–sink connectivity within this larger region.
4. Lord Howe Island (LHI) may represent a potential refugium in a future of significant larval dispersal limitation under projected climate warming. However, its limited connectivity constrains its natural contribution to regional larval supply, making it simultaneously a conservation priority and a candidate for managed intervention.
5. *Synthesis and applications.* Our results demonstrate the importance of integrating connectivity into conservation planning by highlighting that the current marine protected area networks across the southwestern Pacific should be managed as an interconnected network rather than as isolated reserves. Additionally, a prioritisation of the enhanced protection of Coral Sea reefs and LHI is warranted given their importance as stepping-stone reefs bridging distant reef systems or isolated dispersal, respectively. Finally, the intentional movement of larvae from resilient, heat-tolerant reefs to other locations could be investigated given their lower relative

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outward connectivity, with the aim to boost heat tolerance in surrounding reefs. Taken together, these results show that a potential expansion of transboundary management frameworks will be critical to maintain important larval corridors between the southern Great Barrier Reef, New Caledonia and LHI to sustain regional metapopulation resilience under the pressure of a warming world.

KEYWORDS

biophysical model, climate change, connectivity, coral reefs, dispersal, Great Barrier Reef, larvae, Lord Howe Island

1 | INTRODUCTION

Connectivity is a fundamental ecological process that determines the ability of organisms to move and adapt across habitats (Cowen & Sponaugle, 2009). Connectivity also influences the resilience of communities by facilitating gene flow, re-colonisation after disturbance and the maintenance of demographic and genetic diversity across spatially structured populations (McManus et al., 2021; Palumbi, 2003). Understanding patterns in connectivity is essential for understanding functional differences across landscapes and seascapes as it reveals critical source–sink dynamics and identifies key pathways that enable organismal movement across habitats (Green et al., 2015; Saint-Amand et al., 2023). This can include stepping-stones, defined as critical locations that allow organisms to move effectively across networks (Olds et al., 2012). Connectivity can also inform populations' persistence over time (Hastings & Botsford, 2006), and the patterns of maintenance of genetic and demographic stability over time (Palumbi, 2003). As climate change accelerates and disturbances become more frequent and intense, understanding connectivity through the lens of pathways of dispersal is essential to predict the future outcomes of ecosystems.

To this end, dispersal and connectivity metrics are being increasingly incorporated into applied conservation actions in the oceans, particularly for the design of marine protected areas (MPA) and within restoration programs. On coral reefs, well-connected locations are more likely to benefit from larval supply from healthy 'upstream' populations, whilst also serving as sources to support recovery areas after impacts (McCook et al., 2010). Identifying and protecting these critical locations—sources, sinks and stepping-stones—is essential for maintaining ecosystem function, especially under scenarios of increasing disturbance (Magris et al., 2014). In this way, incorporating connectivity information into marine spatial planning can enhance the resilience of reef systems by promoting ecological redundancy, genetic diversity and the persistence of metapopulations across broad spatial scales (Carr et al., 2003; Almany et al., 2007).

Major connectivity sources, by definition, contribute large numbers of propagules across seascapes (Dibacco et al., 2006). Sinks, in contrast, rely heavily on external input for regeneration and may therefore be particularly vulnerable to upstream disturbances (Watson et al., 2012). Alternatively, connectivity hubs can act as central locations linking different reef areas and may be essential

for maintaining overall network cohesion (King et al., 2023; Vogt-Vincent et al., 2023). Understanding where these locations are and their drivers is vital (Urban & Keitt, 2001) given well-connected reefs may be better able to recover from disturbances, whereas poorly connected or isolated locations are more vulnerable (McManus et al., 2021; Wang et al., 2022).

In marine ecosystems such as coral reefs, connectivity is predominantly mediated by larval dispersal, which is strongly influenced by ocean currents and to a lesser extent by larval behaviour, especially for corals (Fiksen et al., 2007; Michie et al., 2024). Several stepping-stone locations have been identified, including across critical regions in the Pacific (Wood et al., 2016). Stepping stones are especially important for oceanic archipelagos and marginal reefs, where direct dispersal between distant sources and sinks may be unlikely or unfeasible due to larval duration limits or current dynamics (Gilpin, 1980). As climate-driven changes in ocean circulation speed up, these locations may buffer the effects of altered dispersal routes or reduced connectivity from increased mortality (Greiner et al., 2022). Furthermore, incorporating connectivity models into climate projections is essential to more fully build out projections of future patterns of ecosystem resilience and adaptive capacity (Quigley et al., 2019).

Connectivity in coral reef systems has also been extensively studied as a key driver of population dynamics, biodiversity maintenance and ecosystem resilience. Coral larvae, which are primarily broadcast-spawned and planktonic (Baird et al., 2009), have the capacity to disperse over short to very long distances depending on their average life-spans and the prevailing ocean conditions (Graham et al., 2008). Within major reef systems such as the Great Barrier Reef (GBR), empirical studies and biophysical models have revealed strong spatial heterogeneity in connectivity (Feng et al., 2016) and have highlighted the existence of critical source reefs being those that exhibit greater than average larval export to surrounding reefs (Hock et al., 2017). In the Western Pacific, modelled large-scale larval dispersal patterns demonstrate marginal or potentially isolated reefs, such as those near Lord Howe Island (LHI), may be more connected than previously thought, due to ocean currents acting as long-distance dispersal corridors (Saint-Amand et al., 2023; Wood et al., 2016).

Climatic processes, including inter-annual fluctuations like the El Niño–Southern Oscillation (ENSO), also impact oceanographic dynamics (Wood et al., 2016). Along the east Australian shelf, the East Australian Current (EAC) influences dispersal at both large and

fine temporal scales (Vogt-Vincent et al., 2023). Seasonality is also critical, as it modulates current intensity, eddy formation and vertical stratification (Choukroun, 2010; Choukroun et al., 2010; Roch et al., 2023). Moreover, ecological and biogeographic differences exist between northern and southern reef complexes (Harriott & Banks, 2002), which are further shaped by large-scale current systems such as the EAC and the North and South Caledonian Jets (NCJ and SCJ) (Cetina-Heredia et al., 2014; Choukroun et al., 2010). At the biological level on reefs, seasonality cues also influence the timing and synchronicity of coral reproduction (spawning) events, creating inter-annual variability in larval supply and dispersal potential (Storlazzi et al., 2017). Together, these interacting environmental and biological factors create a complex and dynamic connectivity landscape that must be understood to effectively model, predict and manage coral reef resilience in the face of global change.

Molecular and modelling evidence for larval exchange across the GBR is present (Miller & Ayre, 2008; Quigley et al., 2019; Rodriguez-Lanetty & Hoegh-Guldberg, 2002; van Oppen et al., 2011). However, connectivity between the southern GBR and LHI—the southernmost coral reef in the world—is thought to be relatively limited, likely due to its oceanographic isolation and the meandering nature of the EAC in this region (Woodroffe et al., 2005). There is evidence, however, of some potential for long-distance dispersal in this region, including from drifter data (Wood et al., 2014), and for other reef associated fish (Williamson et al., 2016). These results underscore the potential for long-distance larval transport under favourable oceanographic conditions to locations like LHI. In parallel, New Caledonia has also been identified as a potential key source for the southern GBR and southern Pacific region, with the Queensland plateau serving as a stepping-stone along this dispersal pathway (Trembl et al., 2008).

Despite these insights and substantial research on large-scale connectivity across the southwest Pacific (Trembl et al., 2008; Wood et al., 2016), few studies have explicitly evaluated connectivity dynamics between the southern GBR, LHI and New Caledonia, particularly at regional spatial scales. The lack of integrated biophysical analyses at this scale, and without the use of an eco-evolutionary and future forecasting framework, thereby limits our understanding of how these reef systems interact and support the long-term ecological resilience of the region. To this end, we examined large-scale larval dispersal patterns in the southern Pacific for two distinct coral functional groups and under future warming scenarios within an eco-evolutionary framework. We used a combination of oceanographic modelling combined with a diversity of ecological parameters, including coral species with different life histories, within the 'avoidance, resistance and recovery' reefs framework (McClanahan et al., 2012). Connectivity across the region was strongly influenced by both species-specific biological parameters and prevailing current systems, with evidence of long-distance larval dispersal across the region that broke down with climate warming. Taken together, this study fills critical gaps in our understanding of coral reef connectivity in this region, with implications for predicating resilience in a warming climate. It also provides spatial prioritisation information for

conservation planning and action across this critical region, which includes two globally important World Heritage coral reefs.

2 | METHODS (SUMMARY)

We analysed larval connectivity across 850 reefs in the southwestern Pacific (17°–32°S, 149°–168°E) encompassing the southern GBR, LHI Marine Park, New Caledonia and the Coral Sea, over a 13-year period (2011–2024). This study did not involve fieldwork or the collection of biological samples. No permits or ethical approvals were therefore required.

Using a biophysical dispersal model parameterised with oceanographic data, we modelled dispersal for *Acropora yongei*, a fast-growing branching coral, as the primary species. To assess the sensitivity of connectivity patterns to species-specific biological parameters, we additionally modelled *Dipsastraea* spp., a slow-growing massive coral serving as a proxy species for *Porites*. A number of biological differences exist between these two species, including five key parameters in our models (Table S1). These include differences between pre-competency periods for *Acropora* versus *Dipsastraea* (2 vs. 3 days, respectively), pelagic larval duration (96 vs. 195 days), peak spawning timing (November vs. January at high-latitude sites), optimal temperature range (18°C–30°C vs. 18°C–29°C) and optimal salinity range (20–35 vs. 25–40 PSU). Additional Methodological detail, including critical references and values can be found in Appendix S1 in the Supporting Information. These differences resulted in the simulated particles being assigned different survival probabilities and resulting simulation windows. Reefs were classified into an eco-evolutionary framework (McClanahan et al., 2012). Overall, this framework distinguishes reefs by their respective capacities for post-disturbance regeneration (recovery), genetic thermal tolerance (resistance) and oceanographic cooling (avoidance). To apply an eco-evolutionary context to patterns in connectivity, we classified each reef into a recovery, avoidance, resistance framework (McClanahan et al., 2012). Here we define recovery reefs ($n = 112$) as those that demonstrate a high capacity to regenerate after environmental shocks, which were derived from Hock et al., 2017. This study used particle tracking models to identify reefs with consistently high connectivity (ability to supply larvae to multiple reefs under variable oceanographic conditions) and lower exposure to thermal stress and crown-of-thorns starfish outbreaks. Avoidance reefs ($n = 337$), derived from Sun et al. (2024), are defined as thermal refugia due to their specific location in regions where upwelling frequency is providing cooler waters, and generally were found to have sea surface temperature (SST) greater than 1°C cooler than surrounding waters. To do this, Sun et al. (2024) used high-resolution ocean modelling (4 km) to detect thermal refugia where SST is persistently $\geq 1^\circ\text{C}$ cooler than surrounding waters due to localised upwelling, validated through RCP8.5 modelled projections up to the 2080s. These occur along the outer shelf edge of the GBR, off the Whitsundays and from Pompeys to the Swains. Finally, resistance reefs ($n = 18$) are those

with an underlying genetic predisposition to confer thermal tolerance, derived from Quigley and van Oppen (2022). Specifically, these authors developed machine learning models with experimental data derived from heat stress experiments. Combining these models with remotely sensed environmental parameters enabled the prediction of reef locations housing adult coral colonies with high heat tolerance and high heritability of thermal tolerance.

A fourth category of unclassified reefs, hereafter referred to as 'additional reefs' were also included ($n=382$), encompassing two distinct groups: (1) GBR reefs that were evaluated in previous models (Hock et al., 2017; Quigley & van Oppen, 2022; Sun et al., 2024;) but did not meet the statistical thresholds for recovery, resistance or avoidance; and (2) reefs located in the Coral Sea, LHI and New Caledonia that were geographically excluded from those original GBR-centric analyses. A full list of reefs with their classification, coordinates and data sources is provided in [Dataset S1](#).

We applied this eco-evolutionary framework derived from independent model outputs sourced from Sun et al. (2024), Hock et al. (2017) and Quigley and van Oppen (2022) to a connectivity framework because any systematic structure could have direct implications for how resilience mechanisms operate in space. We did not assume differences in connectivity a priori. As an example, if genetically resistant reefs are weakly connected, adaptive variants may remain spatially confined, whereas if environmentally buffered (avoidance) reefs are highly connected, they may disproportionately export larvae adapted to cooler conditions, potentially shaping the adaptive landscape of downstream connected populations. Thus, testing connectivity among recovery, avoidance and resistance reefs provides a conceptual link between spatial dispersal, demographic persistence and evolutionary potential, rather than a purely descriptive correlation.

Connectivity was quantified using Lagrangian particle tracking based on BRAN2020 oceanographic data (0.1° horizontal resolution, 2.5 m depth). We simulated five larvae per reef per year ($n=55$, 250 total larvae per reef). For each of the 13 years, larvae were released on 20th November for GBR, New Caledonia and Coral Sea reefs and 20th January for LHI. This reflected differences in regional spawning phenology (see [Appendix S1](#)). Species-specific biological parameters (larval competency, pelagic larval duration, optimal salinity and temperature for survival) were used to assess sensitivity to dispersal assumptions. Mortality increased outside the optimal salinity and temperature ranges following a Gaussian function. Connections were defined as either direct colonisation events or the presence of live larvae within 1 km of a target reef.

Five larvae were released per reef per year over 13 years, generating a total of 55,250 larval trajectories across 850 reefs, including a daily time-step resolution and species-specific tracking periods of 96 days for *A. yongei* and 195 days for *Dipsastraea* spp. Given the scale of this study—encompassing 850 reefs, two species, 13 annual releases and three future warming scenarios—this number represented a pragmatic balance between computational feasibility and the primary objective of identifying dispersal pathways and connectivity routes rather than quantifying absolute larval flux, consistent with the approach of Wood

et al. (2014), which also only modelled a subset of larvae. The 13-year simulation period also allowed us to capture substantial inter-annual variability in ocean currents, including ENSO cycles and mesoscale eddy dynamics, which is more critical for identifying stable versus ephemeral pathways than increasing larval numbers within a single year. A sensitivity analysis using an alternative larval release number ($n=50$ larvae per reef) was also conducted to assess the robustness of this approach (See [Appendix S1](#) for full Methods).

Source-and-sink reefs are defined by their degree of connectivity, as defined by Minor and Urban (2008) and Cecino and Trembl (2021). Specifically, source reefs are defined as those reefs that exported ≥ 1 of larva/larvae to other reefs (threshold of outgoing degree ≥ 1), and sink reefs are those that received ≥ 1 larva/larvae from another reef (threshold of incoming degree ≥ 1). Both source and sink reefs exhibited incoming and outgoing connections (threshold of total degree ≥ 2). Isolated reefs are defined as those that had no connections either as a source or as a sink (threshold of total degree = 0). Critical reefs were defined as those falling within the 90th percentile of connectivity metrics, representing the most highly connected nodes in the network.

Future warming scenarios were modelled by applying uniform temperature anomalies during spawning periods: $+1^\circ\text{C}$ (analogous to SSP1-2.6, mean SST $\sim 30^\circ\text{C}$), $+2.5^\circ\text{C}$ (SSP2-4.5, mean SST $\sim 32^\circ\text{C}$) and $+4^\circ\text{C}$ (SSP5-8.5, mean SST $\sim 33^\circ\text{C}$). Larval mortality was recalculated under each scenario using temperature-dependent survival functions. Full methodological details, including study area, classification of reef categories, larval transport modelling, parameterisation and connectivity analyses, are provided in [Appendix S1](#) in the [Supporting Information](#). A Methods Summary Box with key parameters and thresholds is also provided at the beginning of this [Appendix S1](#).

3 | RESULTS

3.1 | Patterns in larval dispersal for *Acropora* across the western Pacific Ocean

We found that over the 96-day dispersal period in most years, connectivity was driven by a dominant southward current along the Australian continental shelf within our study region ([Figure 1](#)). Further offshore, larval dispersal patterns were more variable, indicating the presence of numerous mesoscale eddies. Of particular interest to this region, westward currents were observed to the north and south of New Caledonia, which deviated from the overall southward flow from this location across most years, extending down into the region around the southernmost reefs of the Coral Sea as well as LHI (after more than 75 days). Larvae originating at LHI dispersed in an eastward direction, out to Norfolk Island (taking between 25 and 100 days to reach the island), which also received larvae from southern New Caledonia over a shorter dispersal period (25–50 days). About 75–100 days of dispersal were needed for larvae originating from the southern GBR and Coral Sea to reach LHI, which is within the mean dispersal ability of *Acropora* ([Table S1](#)).

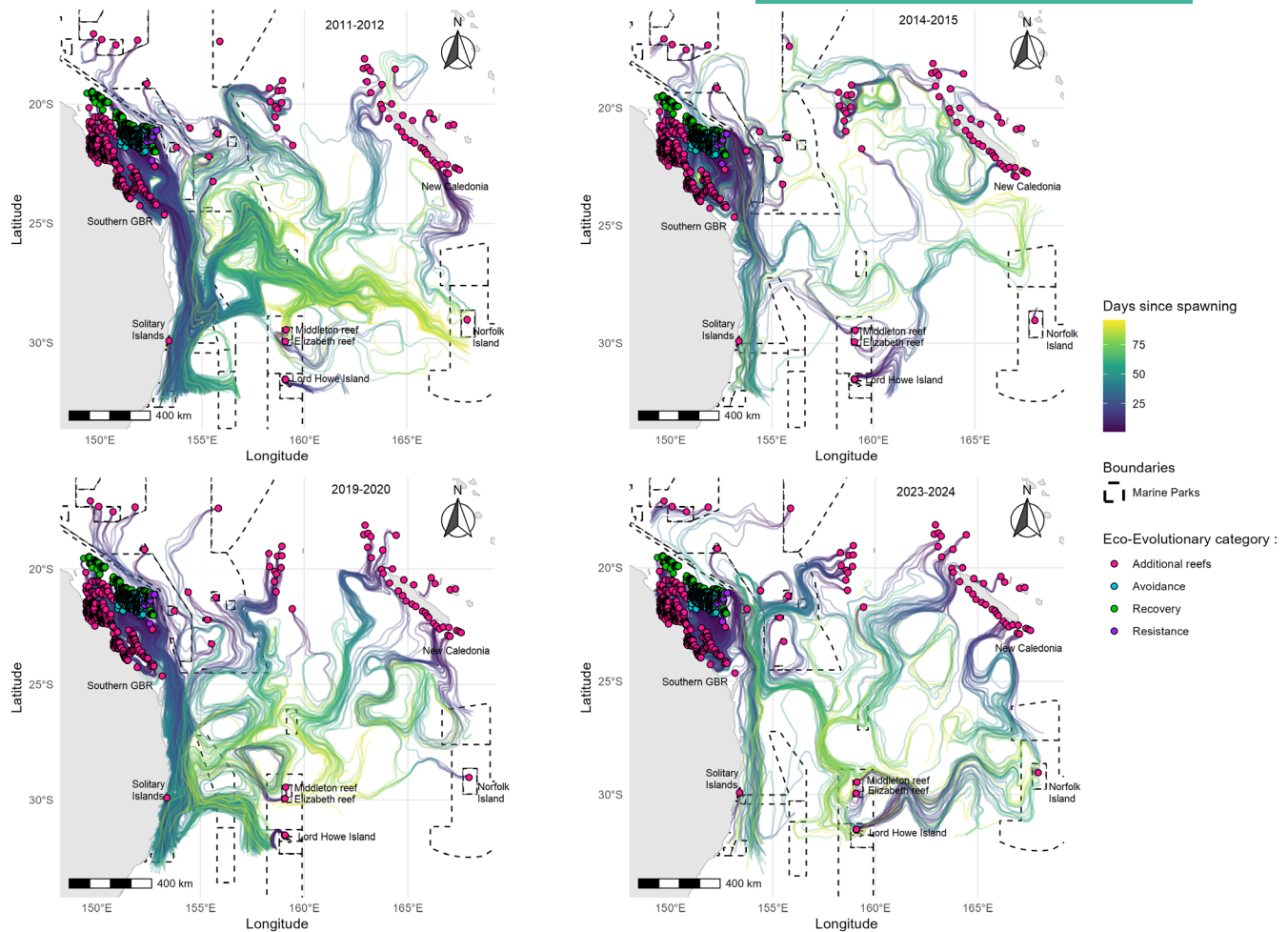


FIGURE 1 Larval dispersal trajectories modelled across the south-western Pacific Ocean. Trajectories represent 96-day spawning periods starting in November for 2011, 2014, 2019 and 2023 (from top left to bottom right), modelled for life-history traits of *Acropora*. Coloured dots indicate reef locations according to their category within the eco-evolutionary framework. Trajectories are coloured along a gradient of days since spawning, with darker colours representing fewer number of days, with increasing number of days in yellow. Marine Park boundaries are indicated by dashed black lines.

Analysis of the cumulative simulated larval trajectories over the 13 years revealed that the most highly connected reefs were predominantly located along the east coast of Australia. Most larval exchanges occurred within the southern GBR, accounting for approximately 91.25% of all connections with the study region ($n=14,781$ larvae). Across this region of the western Pacific, 88.2% of all source reefs, 60% of all sink reefs and 12.7% of sources/sink reefs were located outside the GBR (Figure 2a). Specifically, 2.92% of all dispersal connections occurred between reefs located outside the southern GBR ('External \rightarrow External'; $n=431$ larvae) and 5.83% occurred between the southern GBR and non-GBR reefs like New Caledonia, LHI and the Coral Sea ('GBR \rightarrow External'; $n=575$ larvae and 'External \rightarrow GBR'; $n=287$ larvae). This included larval dispersal from the southern GBR to LHI ($n=20$ larvae) (Figure 2a,b).

Within the southern GBR, 98.5% of reefs were identified as both sources and sinks (Figure 2a), with a smaller percentage of sink reefs (1.1%) or sources (0.4%). Most larval dispersal was concentrated in the southern GBR, with several well-defined dispersal pathways

extending beyond this core area and contributing significantly to larval dispersal to the Coral Sea and New Caledonia and LHI from the southern GBR (Figures 1 and 2b).

Of the locations examined here, New Caledonia exhibited the most diversity of source and sink dynamics, with 18.9% of reefs acting exclusively as sources, 10% as sinks, 36% functioning as both sources and sinks and 35% classified as isolated (i.e. no dispersal; Figure 2a). Whilst most larval exchange occurred among reefs in southern New Caledonia, long-distance dispersal from this location was observed toward the central Coral Sea reefs (Figure 2b), aligning with the previously identified eastward currents driving dispersal pathways over different years (Figure 1).

Some reefs functioned solely as sinks over this 13-year period. These reefs were located in the northern LHI Marine Park (Elizabeth and Middleton reefs) and in the Solitary Islands, which received larvae only from the southern GBR (Figure 2a,b), but it did not contribute to outward dispersal over the simulation period. Notably, LHI was the only location in which connectivity occurred exclusively

between local reefs, with no larval arrivals recorded from more distant regions over the 13-year simulation period (Figure 2b).

When examined from an eco-evolutionary framework, there were also differences in dispersal between 'avoidance, resistance, recovery' reefs (Figure 1). Avoidance reefs exhibited the highest number of incoming and outgoing connections in this region (Figure 3a). Recovery and resistance reefs showed lower larval exchange in both an inward

and outward direction, although most reefs within these two categories still functioned as both sources and sinks (98.1% and 100%, respectively; Figure 3b). Recovery reefs predominantly exhibited outward larval flows ranging from approximately 5% to 90%, whilst inward flows remained more limited (around 5%–50%), indicating that they primarily functioned as sources for other reefs (Figure 3a). Resistance reefs presented more balanced but consistently lower

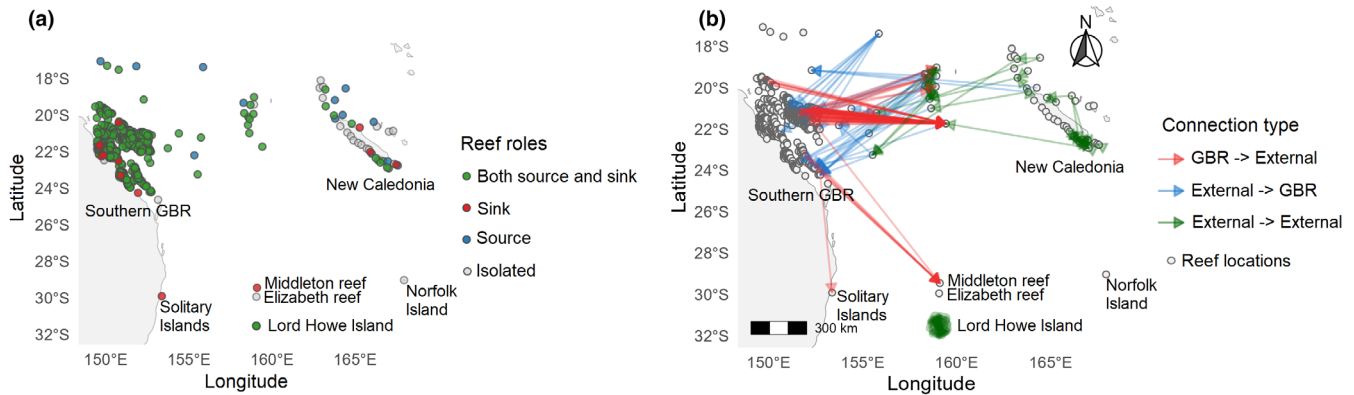


FIGURE 2 Cumulative larval connectivity modelled across the south-western Pacific for *Acropora* larvae simulated during yearly spawning events occurring between 2011 and 2024. (a) Spatial distribution of source, sink or both source and sink reefs coloured accordingly (blue, red or green) as determined by connectivity metrics. Reefs that did not classify within these three categories are represented as grey dots. (b) Cumulative dispersal trajectories, where arrows represent larval connections across reefs, coloured by directional flows relative to the southern Great Barrier Reef (GBR). For clarity of the figure, only long-distance connections are shown and connections found only within the southern GBR were omitted.

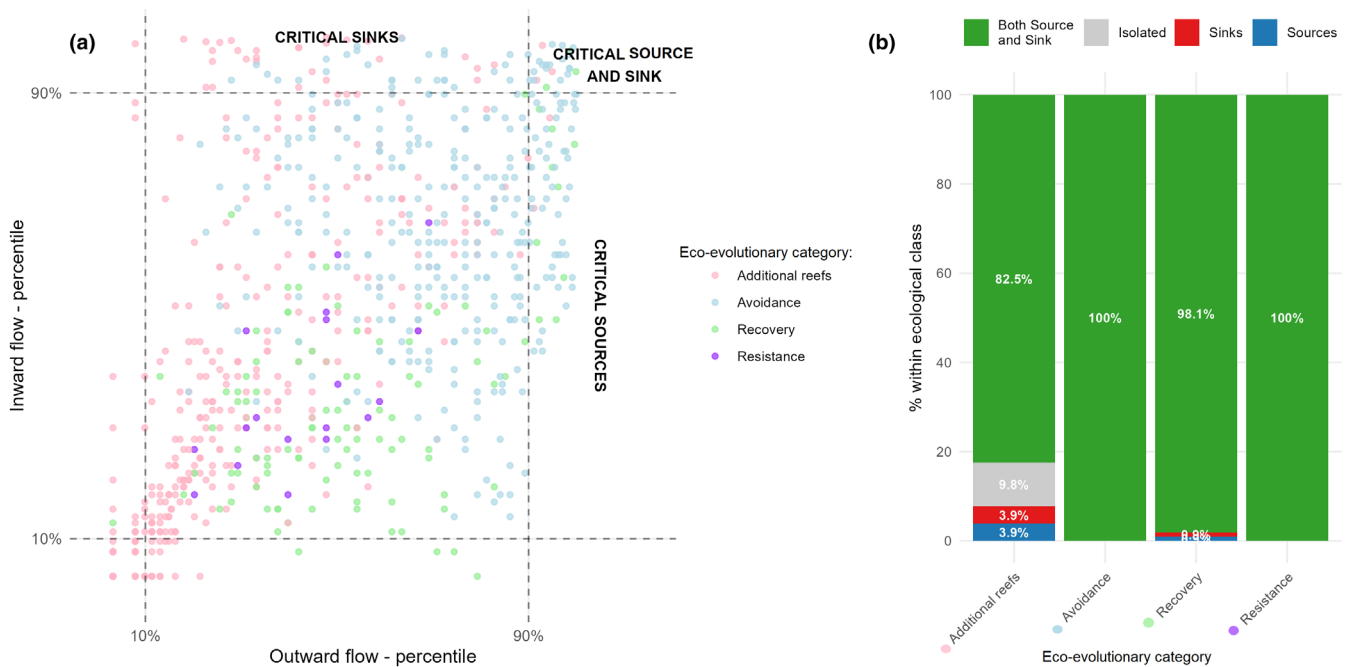


FIGURE 3 Identification of functionally important reefs based on directional larval connectivity and eco-evolutionary framework. (a) Scatterplot of outward (x-axis) versus inward (y-axis) larval percentage flow (%). Each point represents a reef ($n = 850$), coloured using the eco-evolutionary framework of 'avoidance, recovery, resistance' reef. Non-categorised reefs are labelled as 'additional'. The position of each point reflects the relative percentage (%) of larvae exported to and received from other reefs. Reefs falling within the 90th percentile of inward, outward or both flows are classified as critical sinks, sources or source and sink reefs, respectively. (b) Barplot showing the percentage of each eco-evolutionary role within each category.

levels of both inward and outward larval flows (between 10% and 50%), indicating a dual role as both sources and sinks, but with less overall connectivity. In contrast, reefs not classified into avoidance, resistance and recovery ('additional reefs') had the highest proportion of reefs characterised by weaker incoming and outgoing larval flows (Figure 3a), with 9.8% of these additional reefs identified as isolated from the connectivity network (Figure 3b), with only 82.5% of these reefs classified as both source and sink.

Critical sources, sink and source/sinks were identified, defined as reefs falling within the 90th percentile of inward, outward larval flow trajectories or both. Of the critical sources, 82.7% were avoidance reefs, with some (17.3%) recovery reefs (Figure 3a). The critical sinks were again mostly avoidance reefs (54%) or additional (46%). Critical source and sink reefs were mostly avoidance (75%), recovery (10%) or additional (15%) reefs. No resistance reefs were classified within the critical 90th percentile of any category.

Approximately ~71% of the variance in total degree of connectivity when the relationship between reef connectivity and reef categories was examined whilst also accounting for spatial effects (GAM, adjusted $R^2=0.709$, $n=850$). Geographic location was also a dominant driver of patterns in connectivity, as indicated by the significant spatial smooth term ($s(\text{lon}, \text{lat})$) from the GAM ($\text{edf}=27.95$, $F=37.18$, $p<2e-16$). It also accounted for the majority of the explained variance (adjusted $R^2=0.709$). In contrast, whether reefs were classified as avoidance, resistance or recovery was comparatively weaker in explaining variation in connectivity, with only recovery reefs showing a statistically significant relationship with connectivity ($\beta=-9.78$, $\text{SE}=4.45$, $p=0.028$).

3.2 | Patterns in larval dispersal for *Dipsastraea* across the western Pacific Ocean

These patterns were also examined for a different functional group of corals. Analysis of the cumulative simulated larval trajectories

over the same 13-year period revealed a total of 18,885 successful dispersal events for *Dipsastraea*, representing an increase of 16.59% in larval dispersal success compared to *Acropora* ($n=16,198$ larvae). As with *Acropora*, connectivity remained strongly concentrated along the east coast of Australia, with 91.89% of all larval exchange occurring within the southern GBR. Within this region, 99.1% of reefs functioned simultaneously as both sources and sinks (Figure 4a).

Although larval dispersal remained largely centred around the southern GBR, more distinct and extended dispersal pathways were observed beyond this region (Figure 4b). In contrast to *Acropora*, reefs that served as both sources and sinks were less frequently found outside the southern GBR: 100% of source reefs and 40% of all sink reefs were located outside the southern GBR, but only 2% of reefs that were both sources and sinks were found outside GBR boundaries (Figure 4a,b).

Long-distance dispersal events were also more common for *Dipsastraea*, compared to *Acropora*, particularly reaching reefs at LHI (a 530% increase in connectivity, $n=126$ larvae; Figure 4b). New Caledonia again exhibited the most diverse set of functional roles (Figure 4a). Unlike in the previous scenario with *Acropora*, LHI was not completely isolated but received larval input from the southern GBR (2.47%, $n=3$ larvae), New Caledonia (1.65%, $n=2$ larvae) and parts of the Coral Sea (7.44%, $n=9$ larvae).

When analysing connectivity across the region, 0.34% of all connections occurred between the southern GBR and LHI ($n=64$ larvae), whilst 5.84% connected the southern GBR with reefs outside the GBR system ('GBR → External' and 'External → GBR'; $n=1102$ larvae). Compared to *Acropora*, *Dipsastraea* larvae were more connected between the southern GBR and New Caledonia (+700%), as well as between the southern GBR and other reefs in the Coral Sea (+27.8%). Additionally, 1.74% of connections ('External → External', $n=329$) were exclusively between non-GBR reefs, and 0.11% ($n=20$) occurred within LHI itself.

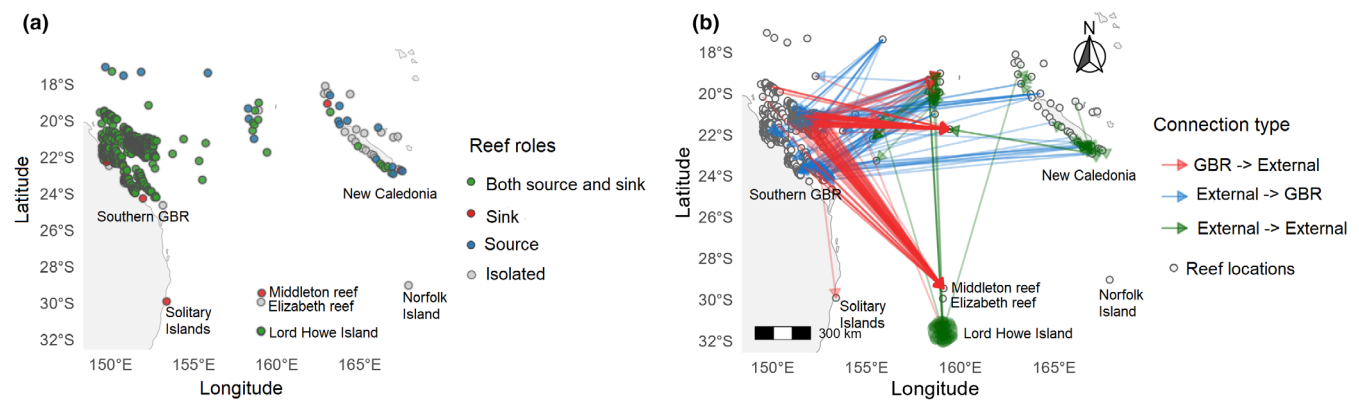


FIGURE 4 Cumulative larval connectivity modelled across the south western Pacific for *Dipsastraea*. Larvae simulated during yearly spawning events between 2011 and 2024. (a) Spatial distribution of source, sink or both source and sink reefs coloured accordingly (blue, red or green) as determined by connectivity metrics. Reefs that did not classify within these three categories are represented as grey dots. (b) Cumulative dispersal trajectories, where arrows represent larval connections across reefs, coloured by directional flows relative to the southern Great Barrier Reef (GBR). For clarity of the figure, only long-distance connections are shown and connections found only within the southern GBR were omitted.

3.3 | Changes in patterns of connectivity under future warming scenarios

Overall, a sharp decline in larval connectivity was observed under all projected warming scenarios in comparison with baseline connectivity measured from the 13-year dataset (2011–2024; [Figure 5](#)). Under historical conditions, larval dispersal (the percentage of larvae leaving a reef and arriving at another reef during its competency period), was estimated at 29.3% for *Acropora*. Under future warming scenarios, this dispersal rate declined with increasing temperature anomalies, falling to less than 1%. Under a low-emission scenario of approximately +1°C, only 9.6% of larvae successfully reached a new reef location ($n=5348$). This declined further to 4.9% ($n=2739$) with +2.5°C of warming and to 0.29% ($n=165$) under a high-emissions scenario of warming at +4°C.

Patterns of spatial connectivity were also markedly altered under future warming scenarios for *Acropora*. In the +1°C scenario ([Figure 5a](#)), 97.8% of all connections in this dataset occurred within the southern GBR ($n=5231$), with 1.6% representing exchanges between the southern GBR and external reefs ($n=88$), and 0.5% occurring between the southern GBR and New Caledonia, LHI and the Coral Sea ($n=29$). Under the +2.5°C ([Figure 5b](#)), 98.7% of connections were retained within the GBR ($n=2704$), with no exchange between the southern GBR and external reefs. Only 1.3% of connections ($n=35$) occurred among external reefs, of which 20 were directed toward LHI. Under extreme warming of +4°C ([Figure 5c](#)), connectivity further declined. 91.5% of the remaining connections occurred within the southern GBR ($n=151$), with 8.5% restricted to external reefs, exclusively within the LHI region. No connections between the GBR and external reefs were detected under this scenario.

Overall, future warming scenarios ([Figure 5](#)), relative to present day ([Figure 2](#)), represented a -67.2% decline in all dispersal connections at +1°C of warming, -83.2% for +2.5°C and -99% for +4°C. This also represents a -84.7% decline for +1°C and -100% decline

for both +2.5°C and +4°C or connections between the southern GBR and other reefs in this region (GBR > External). It also represents a -93.3% decline at +1°C, -91.9% decline at +2.5°C and -96.8% decline at +4°C decline for all remaining connections ('External → External').

3.4 | Sensitivity to larval number

Network connectivity patterns showed moderate to high stability across the three tested years (2013, 2016, 2019) when comparing 5 versus 50 larvae simulations ([Table S2](#)). Jaccard similarity coefficients ranged from 0.68 to 0.79 (mean = 0.73 ± 0.06), indicating that 68%–79% of connections identified with either larval number were common to both scenarios. The number of total connections increased by 32%–48% with 50 larvae (mean increase = $42 \pm 8\%$), primarily due to detection of rare or occasional routes, as expected. However, network density and mean connectivity degree showed proportionally similar increases (35%–42% and 33%–46%, respectively), indicating that the relative connectivity structure remained stable.

Reef classifications (source, sink, source-and-sink, isolated) were consistent for 81%–87% of reefs across scenarios (mean $84 \pm 3\%$). Status changes predominantly involved transitions from isolated to sink status (62%–71% of changes) or from sink-only to source-and-sink (18%–24% of changes), reflecting detection of additional incoming or bidirectional connections with increased larval sampling rather than fundamental shifts in reef roles.

Critical reefs identified in the top 10% of connectivity showed 71%–83% overlap between scenarios (mean = $76 \pm 6\%$), and connectivity rankings were highly correlated (Spearman's $\rho = 0.87$ – 0.92 , $p < 0.001$ for all years). Connections detected exclusively with 50 larvae (31%–39% of total connections in that scenario) had significantly lower intensities than connections detected in both scenarios (Wilcoxon test, $p < 0.001$ for all years), with median values of 1–2 larvae per connection versus 3–6 larvae for stable connections.

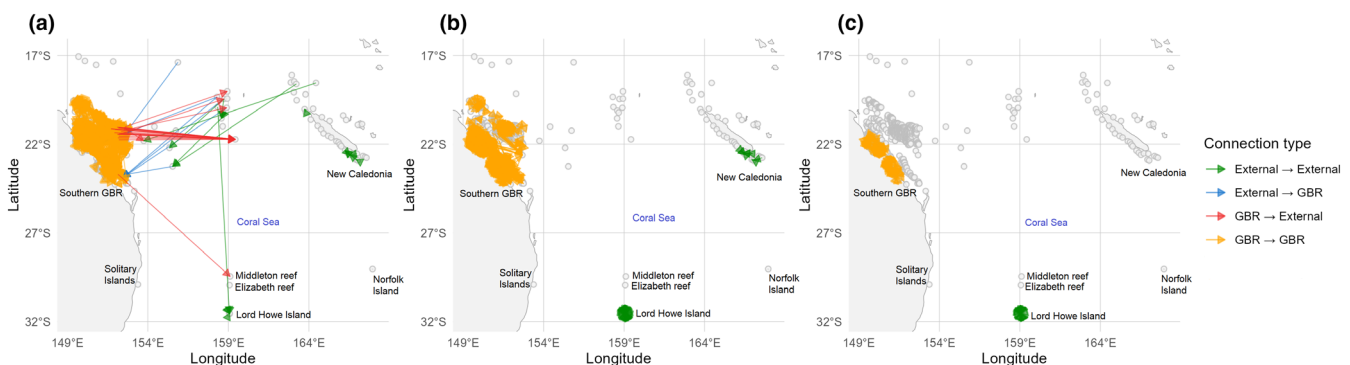


FIGURE 5 Larval connectivity modelled across the south-western Pacific for *Acropora* larvae under projected future warming scenarios. The arrows in each panel (a–c) represent larval connections between reefs, coloured according to directional flows relative to the southern Great Barrier Reef. (a) Scenario SSP1-2.6, representing the moderate warming scenario with +1°C of sea surface temperature (SST) anomalies. (b) Scenario SSP2-4.5, representing intermediate warming with +2.5°C SST anomalies. (c) Scenario SSP 5-8.5, representing extreme warming with +4°C SST anomalies.

4 | DISCUSSION

4.1 | Broadscale connectivity patterns reveal stepping-stone reefs across the south western Pacific Ocean

Here, larval dispersal modelled across the south-western Pacific revealed marked inter-annual and seasonal variability, likely reflecting the dynamic nature of oceanographic processes in the southern GBR across to New Caledonia and LHI. Despite this variability, large-scale trends emerged across these locations, as previously supported by results from Trembl et al. (2008). These patterns were likely driven by the EAC, which dominates the circulation along the south-east coast of Australia, whilst the NCJ and the SCJ also both influence larval transport across this region. In addition, cyclonic and anticyclonic eddies, such as the Capricorn-Bunker eddy, likely play a key role in shaping larval trajectories here as well (Cetina-Heredia et al., 2014; Choukroun et al., 2010). Capturing these trends is critical and suggests that these mesoscale features are trapping larvae, increasing retention time or redirecting them, thereby extending dispersal distances and/or favouring larval return to natal reefs.

The reefs of the southern GBR showed the highest connectivity overall, likely due to their increased density and influences of the nearby reef systems that may feed into them. This is especially true from New Caledonia, which appears to play a critical role in this network. Interestingly, despite their apparent geographical isolation, reefs in the Coral Sea also acted as stepping-stones in this region, which aligns with previous trends noted by Trembl et al. (2008) and Wood et al. (2014), by both releasing and receiving a substantial proportion of larvae. These reefs may thereby be bridging distant reef systems and enabling long-distance dispersal for both of the coral functional groups studied here. It is important to note that although our model simulated the dispersal of only five larvae per reef per run, spawning events can involve the release of millions of larvae over the course of only a few nights. This suggests that our results here may greatly underrepresent the full potential of larval dispersal and that the connections we show may have even greater ecological significance in nature.

The EAC and associated jets act as major dispersal highways (Cetina-Heredia et al., 2015), whilst eddies modulate small-scale dispersal and retention. These dynamic interactions highlight the complexity of predicting connectivity patterns, particularly over long distances and over inter-annual time scales. Similar observations have been made in other ocean basins, including in the western Indian Ocean, where larval dispersal distances of up to 1902 km have been estimated (Gamoyo et al., 2019), confirming the plausibility of long-distance connectivity events in favourable oceanographic regimes. These results reinforce the idea that even isolated reef systems can maintain functional linkages over large spatial scales when aligned with the major circulation pathways of currents.

4.2 | Resilient reefs have limited source-sink connectivity

The eco-evolutionary categorisation of reefs here using the recovery, avoidance, resistance framework revealed critically important reefs in each of these categories. In particular, critical (>90%) sinks were mostly made up of avoidance and some recovery reefs, critical sources were mostly avoidance reefs, and the rare source and sink reefs were mostly avoidance and recovery reefs. Moreover, resistance reefs were mostly found at middle ranges of inward and outward flow. Taken together, these results suggest that the heat-tolerant resistant reefs are not necessarily receiving above average numbers of larvae or importantly, likely not exporting them either. Hence, the transport of heat-tolerant larvae around these regions may be limited, which aligns with previous evidence using genetic models (Quigley et al., 2019). Importantly, if most of the critical larval sources come from avoidance reefs, which may lack the climate readiness required for future temperatures due to their lack of exposure to warming conditions, this may signal a more general lack of adaptation to warming regionally. Finally, most of the sink reefs were not found to be recovery reefs, which suggests that the reefs most in need of additional larvae (i.e. those under recovery), are not receiving the most larvae. Overall, our findings underscore the importance of spatial configuration of reefs in explaining ecological patterns. For example, the higher connectivity measured for avoidance reefs may reflect their exposure to current corridors (Fontoura et al., 2022), which may spur their dispersal across this region. Importantly, their classification may change under shifting environmental conditions, including climate-driven alterations to oceanographic regimes and ocean warming. Taken together, these results suggest a mismatch between the optimal conditions for recovery in a warming southwestern Pacific and what is currently occurring.

By overlaying patterns in connectivity and dispersal with these eco-evolutionary categories, our findings also highlight critical conservation priorities. These priorities are consistent with current recommendations, including the design and management of MPA networks that preserve larval corridors and sustain metapopulation persistence, as advocated by Beger et al. (2010) and Krueck et al. (2017). Specifically, our findings suggest three immediate management priorities for this region. First, despite their physical isolation, Coral Sea stepping-stone reefs should receive enhanced protection status given their disproportionate role in bridging connectivity between the southern GBR and New Caledonia. This function cannot be replaced by other reef systems locally. Second, avoidance reefs along the outer GBR shelf edge, which currently serve as critical larval sources, may require targeted monitoring and adaptive management given their low climate readiness but high potential for export. Third, collaborative frameworks should be expanded to explicitly incorporate larval connectivity corridors into international management planning across this region. This will ensure the maintenance of these critical larval corridors, which are

likely essential for regional metapopulation stability. It also underscores that whilst the southern GBR here serves as the dominant centre of connectivity in this region, peripheral and intermediate reefs, although fewer in number, likely play strategic roles in maintaining gene flow and metapopulation stability across these three eco-evolutionary categories. Although each of these locations individually is protected, these results highlight it may be essential to consider their protection as a network in an adaptive design and management plans of the MPAs of the southern Pacific.

4.3 | LHI may be a potential refugium under future climate warming

Incorporating climate warming into our connectivity models also revealed predicted significant declines in larval connectivity in the near and more distant future. Importantly, dramatic changes to connectivity occurred even under only +1°C of warming. Strikingly, at +2.5°C and +4°C of warming, there were dramatic collapses in connectivity, with only a few short-distance connections remaining. Outside the southern GBR, these remaining connections were mainly located in the southern Coral Sea and around LHI. Given these results, it is important to again note that only five larvae were released per reef per replicate run in our models, which likely underestimates the total dispersal potential in the region. However, the dramatic relative changes between scenarios highlight future risks to reef connectivity, regardless of the total realised dispersal and even if overall dispersal is underestimated. Finally, these results also underscore that understudied locations in the Coral Sea and LHI may represent valuable climatic refuges in the future.

LHI is characterised by cooler annual SSTs relative to the southern GBR (Harriott & Banks, 2002), which may explain its increased persistence compared to other locations situated in the southern GBR. Indeed, LHI maintains lower absolute temperature profiles below local maxima even under 2050 and 2100 warming scenarios compared to other reef regions like the GBR (Quigley & Baird, 2024). In essence, the cooler water may act as a buffer against climate-induced warming. This may allow for the maintenance of the relatively smaller degrees of larval exchange in this location to persist despite the increase in the projected number of extreme marine heatwave events. Indeed, some localised areas of the GBR are predicted to serve as thermal refugia that may persist even under some climate warming (McWhorter et al., 2022). Importantly, however, at +3°C of warming, even these refuges are predicted to disappear. This highlights that even climate refugia will eventually be at risk of collapse if climate warming is not brought under control.

It is important to note that our climate simulations only use increases in SST as a proxy for climate change impacts; they do not incorporate projected changes in ocean circulation. By not considering changes in ocean circulation patterns, including the potential weakening in currents such as NCJ and SCJ, and intensification of others such as the EAC (Schlaefter et al., 2024), it is unclear if our

dispersal estimates are under- or overestimated. Future work should combine the influence of both warming and changes to circulation to more fully estimate future larval dispersal in the region.

Looking to the future, high-latitude reefs like LHI may serve as climatic refuges, act as future sources for dispersal or assisted movement of individuals and may be future locations for colonisation as a result of ocean warming (Beaugrand et al., 2002). It should also be noted that under climate change, the volume transports of both the EAC and its extensions (EAC-Extension and the Tasman Front) are projected to increase, and the mean latitude at which the EAC separates from the coast is expected to be displaced further south (Cetina-Heredia et al., 2015; Suthers et al., 2011). Given these projected changes, it could enhance the poleward advection of coral larvae originating from the southern GBR, potentially facilitating the colonisation or reinforcement of cooler-water reefs at higher latitudes, including those near LHI. These locations should be a focus of priority conservation. This suggests that, from a management perspective, LHI warrants additional priority protections as an important climate refuge within the Australian marine estate. This should include enhanced protections from local stressors to maximise climate resilience, the establishment of monitoring to detect early changes in local abundances, and inform adaptive management responses. Given that LHI may represent one of the last viable coral reef systems in this region under extreme warming scenarios (+4°C), its protection represents a critical insurance policy for regional biodiversity persistence.

4.4 | Variation in connectivity patterns across two important coral functional groups

By using different coral species with contrasting life-history characteristics, our results highlight how important differences in traits can drive connectivity outcomes. Using *Dipsastraea* as a proxy for massive coral like *Porites* (Sadler et al., 2014), compared to a fast-growing group like *Acropora*, we found connectivity was ~17% greater across our study region in the massive species. This may have been due to the longer pelagic larval times (~2x) or higher predicted survival rates. This also resulted in a greater number of long-distance dispersal events, especially to isolated reef systems. Hence, slower-growing species with longer dispersal potential (Darling et al., 2012; Harrison & Wallace, 1990) may play a disproportionate role in maintaining genetic exchange and facilitating recovery following disturbances in this region. Interestingly, New Caledonia and LHI emerged as major centres of connectivity for *Dipsastraea*, highlighting their ecological importance for maintaining regional larval dispersal pathways in this region. It may also suggest that in the future, these locations may become increasingly dominated by species with slower-growing massive life histories, transitioning from branching dominated locations to massive dominated. From a conservation perspective, safeguarding these connectivity hotspots could therefore benefit both fast-recruiting corals like *Acropora* and more persistent taxa such as *Porites* (Hughes et al., 2003; Trembl et al., 2008).

4.5 | Limitations of the study

Although our biophysical model provides valuable information on larval dispersal routes in the south-western Pacific, several limitations must be recognised. Firstly, the model was designed to give priority to ecological interpretation and population level resolution in the reconstruction of larval trajectories. A simplification was applied by releasing only five larvae per reef, which is a considerable underestimate given that coral species such as *Acropora* can release up to 10,000 larvae per square metre (Álvarez-Noriega et al., 2016). Our sensitivity analysis (Table S2) demonstrated that whilst increasing to 50 larvae per reef detected 32%–48% more total connections across three representative years, these additional connections were predominantly rare dispersal events (median intensity 1–2 larvae), whereas all major dispersal corridors remained stable (Jaccard similarity 0.68–0.79). Critical reef identification showed 71%–83% overlap between scenarios, and reef-level classifications were consistent for 81%–87% of reefs. These results suggest that our approach is sufficient for identifying dominant connectivity patterns and spatial network structure, which was the primary objective of this study. The 13-year temporal coverage capturing inter-annual oceanographic variability contributes more substantially to robustness than increasing larval numbers within individual years.

Another limitation is that the underlying hydrodynamic dataset has a spatial resolution of approximately 10km, which is too coarse to resolve local circulation in areas such as the Swains reef group of the southern GBR and does not incorporate tidal dynamics (Saint-Amand et al., 2023). Because of this, we have restricted most of our interpretations of the model to the region or sub-region level.

These models also did not take into account empirical timing of spawning events or their variability year to year. These small variations are influenced by environmental cues such as the lunar cycle, sea temperatures and photoperiods. However, coral spawning is known to follow remarkably consistent phenological patterns, which may mitigate this uncertainty to some extent (Kaniewska et al., 2015; Sorek & Levy, 2014). Future studies can improve on this work by incorporating more detailed estimates of larval release per reef, higher-resolution tidal dynamics and yearly variation in spawning timing to better capture small-scale dispersal dynamics at the sub-regional level and refine estimates of connection strength.

5 | CONCLUSION

This study provides a regional scale assessment of larval connectivity patterns across the south Pacific using an eco-evolutionary perspective under current and future scenarios and different coral life histories. Importantly, we show critical stepping-stone locations for coral dispersal vary by species and that resilient heat-tolerant reefs may not be well connected across the region, with potentially important implications for the spread of heat tolerance around the southern Pacific. Future warming scenarios also revealed a

substantial threat to the connectivity in this region, leading to the collapse of long-distance larval connections and the maintenance of only some isolated short-distance connections. Interestingly, these connections were focussed around high-latitude reef systems like LHI. This work underscores the critical need to protect climatic refuges for their role in supporting biodiversity in the warming future.

AUTHOR CONTRIBUTIONS

Elise Dehont and Kate M. Quigley conceived the study. Elise Dehont analysed the data and drafted the initial manuscript. Elise Dehont, Severine Choukroun, Alana Grech and Kate M. Quigley reviewed the study design and manuscript and provided supervision. All co-authors edited and approved the final draft.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data are available from the Dryad Digital Repository <https://doi.org/10.5061/dryad.g1jwstr6h> (Dehont et al., 2026).

ORCID

Elise Dehont  <https://orcid.org/0009-0004-3457-8588>

Alana Grech  <https://orcid.org/0000-0003-4117-3779>

Kate M. Quigley  <https://orcid.org/0000-0001-5558-1904>

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SUPPORTING INFORMATION

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

Appendix S1. Detailed methods.

Figure S1. Map of the western Pacific study area, including the southern Great Barrier Reef, Lord Howe Island, the Coral Sea and New Caledonia.

Figure S2. Spatial distribution of reefs and coral spawning periods in the Western Pacific.

Table S1. Biological parameters used in the larval dispersal model.

Table S2. Sensitivity analysis comparing connectivity metrics between 5 and 50 larvae simulations across 3 years.

Data S1. Reef classifications.

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