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Offshore oil and gas infrastructure plays a minor role in marine metapopulation dynamics

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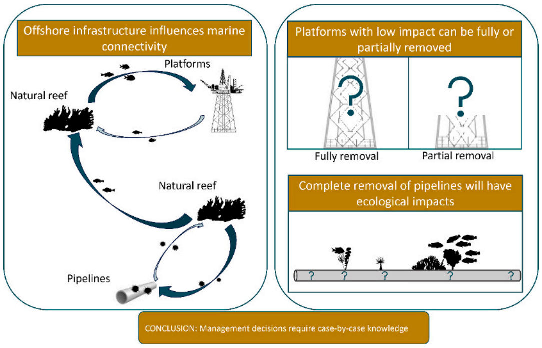
HIGHLIGHTS

- Offshore oil and gas structures may facilitate connectivity across the seascape.
- For the species modelled, platforms play a minor role in the metapopulation dynamics.
- Pipelines often served as important local stepping-stones.
- Decommissioning decisions should assess the contribution of individual structures.
- This is critical information to reduce domain-wide impacts from decommissioning.

GRAPHICAL ABSTRACT



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ABSTRACT

Decommissioning consequences of offshore oil and gas infrastructure removal on marine population dynamics, including connectivity, are not well understood. We modelled the connectivity and metapopulation dynamics of three fish and two benthic invertebrate species inhabiting the natural rocky reefs and offshore oil and gas infrastructure located in the Bass Strait, south-east Australia. Using a network approach, we found that platforms are not major sources, destinations, or stepping-stones for most species, yet act as modest sources for connectivity of *Corynactis australis* (jewel anemone). In contrast, sections of subsea pipelines appear to act as stepping-stones, source and destination habitats of varying strengths for all study species, except for *Centrostephanus rodgersii* (long-spined sea urchin). Natural reefs were the main stepping-stones, local source, and destination habitats for all study species. These reefs were largely responsible for the overall metapopulation growth of all study species (average of 96 % contribution across all species), with infrastructure acting as a minor contributor (<2 % average contribution). Full or partial decommissioning of platforms should have a very low or negligible impact on the overall metapopulation dynamics of the species explored, except *C. australis*, while full removal of pipelines could have a low impact on the metapopulation dynamics of benthic invertebrate species and a moderate impact on fish species (up to 34.1 % reduction in the metapopulation growth). We recommend that the decision to

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remove offshore infrastructure, either in full or in-part, be made on a platform-by-platform basis and consider contributions of pipelines to connectivity and metapopulation dynamics.

1. Introduction

Offshore oil and gas (O&G) infrastructure, which has been installed in most oceans to access resources, often results in an extensive network of platforms supported by subsea pipelines, wells, and other submerged infrastructure (Bugnot et al., 2021; Gourvenec et al., 2022). Ongoing research is focused on understanding how this submerged infrastructure impacts surrounding marine ecosystems (e.g. Koppel et al., 2023; Redford et al., 2021), particularly as this information is fundamental to informing decommissioning decisions to remove or leave structures in place after they have depleted the energy reserves. In Australia, investigations are underway to determine which decommissioning options are in line with current regulations (NOPSEMA, 2022), which requires environmental risks and impacts to be reduced to a level that is as low as reasonably practicable (ALARP). Complete structure removal in Australia is predicted to cost $13 billion per year as 2000 offshore projects are decommissioned between 2021 and 2040 (Advisian, 2021; Sommer et al., 2019).

Offshore O&G infrastructure and associated activities have both negative and positive effects on marine ecosystems (Burdon et al., 2018). Infrastructure may act as artificial reefs, enabling the development of complex heterogenous communities including diverse biota (Love et al., 2019; Todd et al., 2020), and increasing the diversity and biomass of demersal, and pelagic fish species (Claisse et al., 2014; Fujii, 2015; Meyer-Gutbrod et al., 2020). They may also act as settlement habitat or stepping-stones for invasive species (Da Silva et al., 2014; Sammarco et al., 2014, 2010; Schulze et al., 2020), introduce artificial lights and noise that alter species behaviour (Barker and Cowan, 2018; Rich and Longcore, 2006; Todd et al., 2020), and introduce contaminants and nutrients (Henry et al., 2018; Koppel et al., 2023; MacIntosh et al., 2021). One of the most significant decommissioning knowledge gaps and priorities globally, however, is a need to understand how offshore O&G infrastructure influences seascape connectivity of mobile and sessile species at different life history stages (McLean et al., 2022a; Watson et al., 2023).

Connectivity is a fundamental ecological process for sustaining and replenishing marine populations and communities. Limited evidence of offshore infrastructure facilitating seascape connectivity exists for larvae and mobile adult invertebrates, fish and megafauna (Cowen and Sponaugle, 2009; Kool et al., 2013; McLean et al., 2022a; Nishimoto et al., 2019). This includes threatened and commercially important species (Fox et al., 2016; Henry et al., 2018) as well as the establishment and spread of non-native species (Page, 2019; Sammarco et al., 2014). The degree to which offshore structures represent a beneficial or detrimental net impact remains unclear, will vary by region and through time, structure, the extent of infrastructure, and species, and requires targeted research to determine the conditions and the extent to which offshore structures may be (positively and/or negatively) influencing multi-species connectivity and ecological flows across the seascape of interest (McLean et al., 2022a).

Understanding the role offshore infrastructure plays in seascape-scale marine population dynamics is particularly important when the time comes to decommission. It has been suggested that complete removal of these structures may have negative ecological implications for surrounding ecosystems, in particular reef-associated species (van Elden et al., 2019). Offshore O&G structures are often designated as production safety zones and therefore act as de facto marine protected areas that boost local abundances of target species, enhancing their reproductive capacity and the replenishment of fished populations via enhanced recruitment (Fowler et al., 2018; Love et al., 2019; Meyer-Gutbrod et al., 2020; Pondella et al., 2022). Structure removal could potentially lead to the loss of established biological communities, elevated turbidity and sound during the removal process (also applicable to partial removal), and increased pollution risk (Birchenough and Degraer, 2020; Fowler et al., 2018). Lifting of vessel access restrictions could also expose commercially important and threatened species to increased fishing pressure (Birchenough and Degraer, 2020; Fowler et al., 2020). On the other hand, complete structural removal may allow for the restoration of natural habitat that existed prior to O&G facility installation (Birchenough and Degraer, 2020; Schläppy et al., 2021). The many perspectives on whether the removal of offshore O&G infrastructure has net negative or positive implications for the environment requires a critical consideration of risks and benefits for marine ecosystems to evaluate whether other decommissioning options, including partial removal or in situ abandonment of selected structures, may be beneficial (Fowler et al., 2020; NOPSEMA, 2022).

Our study aims to address a significant knowledge gap regarding the role of offshore infrastructure in shaping the strength and direction of connectivity in key marine populations for a section of the Bass Strait region in south-east Australia, thereby contributing to decommissioning decisions. We use biophysical models that combine estimates of 3D ocean current dynamics with information on the larval biology and behaviour of three indicator reef fish species and two invertebrate species present within the system. This biological-physical modelling approach estimates species-specific potential connectivity within and between natural reef habitats and offshore infrastructure. Through this, we aim to estimate the influence infrastructure may have on population connectivity and metapopulations dynamics in these and other species with similar life history traits and ecological requirements. For example, we aim to infer whether infrastructure is likely to act as a source, destination, or as stepping-stones/corridors linking various populations of marine biota through larval dispersal. We also aim to provide insights as to whether infrastructure provides a net positive or negative contribution to the overall metapopulation dynamics of these species. Further, we estimate the relative importance of individual structures (e.g. differences between various platforms) and different structural types (e.g. platforms vs. pipelines) on population connectivity. Our main objective is to improve understanding of subsea infrastructure as either a settlement habitat or source population for larvae of fishes and benthic organisms which utilise oceanic currents for dispersal and connectivity within the Bass Strait region. As such, our study is designed to inform decommissioning decisions (better understanding of the impact of removal or retention on connectivity pathways) for pipelines and platform facilities, both individually and as a network.

2. Materials and methods

We examine the dispersal-based population connectivity of larvae of selected marine biota between artificial habitats created by Esso Australia Pty Ltd. (EAPL) offshore infrastructure (19 production platforms, 2 auxiliary facilities and 38 subsea pipelines of total length approximately 885 km), non-EAPL pipelines (approximately 300 km), and natural reef habitats across the Bass Strait, south-eastern Victoria (see Appendix A for regional description and Fig. S1). The offshore O&G field operated by EAPL for more than 50 years is coming to the end of its productive life. The locations of facilities range from near coastal waters to 78 km offshore in water depths of 38–100 m with pipelines connecting them to the shore (Tables S1, S2).

2.1. *Biophysical modelling of larval dispersal*

A biophysical modelling approach (adapted from Cecino and Treml, 2021; Treml et al., 2015, 2012) was used to simulate larval dispersal between 199 natural and artificial habitat patches. Larval production within habitat patches was scaled by available habitat area (described in Appendix A Methods), where the habitat patch size was the explicit proxy for each species' reproductive output from the subpopulation (Cecino and Treml, 2021; Treml et al., 2012; Urban and Keitt, 2001). The relative proportion of natural and artificial habitat area was calculated for each 500 × 500 m cell in the biophysical dispersal model (and maintaining mixed habitat patches, as required). Habitat cells were aggregated into unique subpopulation patches at a resolution of ~10 km, whereby neighbouring habitat cells within this distance are clumped into the same patch. Every habitat patch (199 in total) was assigned a unique identification number (ID) to track source-destination connections explicitly. In total, 101 unique natural rocky reef patches (170.5 km^2 total habitat), 20 platform patches (0.32 km^2 total habitat including subsea completion facilities and where Marlin A and Marlin B platforms were clumped into the same habitat patch due to close proximity) and 78 pipeline patches (1.91 km^2 total habitat), were included. The area of habitat within each biophysical model cell was calculated based on true-area estimates for nearshore reefs as described above assuming 100 % habitat cover for nearshore reefs (Lucieer et al., 2019), and 5 % habitat cover for offshore reefs (cover approximated from Bax and Williams, 2001 Plates I & II). All offshore infrastructure was represented in the biophysical model as true-area estimates derived from the spatial data (e.g. platform infrastructure and footprint data (m^2) and pipeline surface areas derived from actual diameter, length, and burial data for individual pipelines provided by EAPL; Table S1, Table S2). Within this model, 98.7 % of all hard habitat was from natural reef patches, with the remaining 1.3 % from artificial structures.

Larval movement was determined by species-specific biological parameters and oceanographic data, both described in Appendix A Methods. The selected life histories broadly represent taxa across a range of species commonly found on reefs and structures. Our results may be applicable to other taxa with similar life histories. The dispersal simulation released a "cloud" of virtual larvae that were then tracked as they move through the seascape for all spawning seasons between the years 1994 and 2003 inclusive. Virtual larval clouds were allowed to drift in the seascape and be transported by ocean currents throughout the entire larval duration. Settlement into habitat was governed by the life-history data (competency, behaviour, etc.; Table S3). Through time, the quantity of larvae that survived and settled on individual habitat patches was recorded from every source patch and to every destination (including the source patch) for each dispersal event across all spawning seasons and years of data. This was repeated for all patches within the seascape until all larval connections were quantified. The model output produced two types of connectivity matrices: a probability matrix and a migration matrix. The probability matrix quantifies the likelihood that larvae released from each source successfully survives and settles at a suitable habitat patch (a source-based connectivity matrix). The migration matrix quantifies the likelihood that individuals at a destination patch came from each source patch (a destination-focused connectivity matrix), with the diagonal representing self-recruitment. Both matrices were used for differing types of analysis (see below on patch-level metrics and metapopulation model). A connection strength threshold of 0.001 (0.1 %) was applied to migration matrices which retained only ecologically meaningful connections contributing >0.1 % of the settling larvae to a destination site. The values below this threshold were set to zero. We did not account in our biophysical model for larval response to external cues which can cause directional swimming towards light, diurnal vertical migration, noise emitted by platforms, or other natural physical and chemical cues that may attract larvae. We address some of those caveats in the discussion section.

2.2. Network and metapopulation analysis

We combined network and metapopulation analysis to characterise and visualise patterns of multi-species biophysical dispersal, represented by the connectivity matrices described above (Jordán et al., 2003; Minor and Urban, 2008; Treml et al., 2012; Urban and Keitt, 2001). A geographic dispersal network was built for each species where nodes represented the various habitat patches (e.g. natural reefs and offshore infrastructure) and connections (also called links or edges) quantified the dispersal likelihood (direction and strength) between all habitat patches. The network represented the ecologically significant dispersal connections between all habitat patches, including all those containing natural reefs, offshore O&G structures, and pipelines. This allowed us to clearly show connectivity patterns and patch importance across all habitat types and quantify the impacts associated with decommissioning specific types of infrastructure as well as the impact of partial decommissioning of the platforms (e.g. decommissioning top section of platforms to a depth of 55 m below sea surface). For each network and across all species, we calculated three local-scale (subpopulations) metrics and an additional broad-scale (metapopulation) metric which together characterise the influence offshore O&G structures have on connectivity and dynamics.

To quantify and map the influence of offshore O&G structures and natural reefs on population connectivity, we used three network-based metrics. To identify the degree to which structures or reefs act as strong local source or destination for population connectivity, we calculated weighted out-degree and weighted in-degree respectively. Weighted out- and weighted in-degree sums the dispersal strengths of all outgoing or all incoming connections, respectively from each habitat patch (Cecino and Treml, 2021; Minor and Urban, 2007). A strong local source habitat patch has a high weighted out-degree resulting from many strong connections flowing out from that habitat patch (or O&G structure). A habitat patch which has a high-weighted in-degree results from many and/or strong dispersal connections coming into that destination node. It is often useful to consider out-degree and in-degree together to gain a clearer view of an induvial patches' contribution to local connectivity through source and settlement dynamics (Minor and Urban, 2007; Zamborain-Mason et al., 2017). Similar to these two local-scale connectivity measures, we also quantified the role that each habitat patch may serve as a stepping-stone in the seascape, that is the degree to which each patch facilitates connectivity across the entire system. To identify important stepping-stone patches, we used a betweenness centrality which counts the number of shortest dispersal paths that use each habitat patch in connecting the broader network (Urban and Keitt, 2001). An O&G structure, or habitat patch, which has a high betweenness centrality measure is an important stepping-stone resulting in many pathways using this habitat patch. Simply, this metric helped to identify important nodes that maintain connectivity across the full network by acting as critical stepping-stones (Minor and Urban, 2007; Zamborain-Mason et al., 2017). All network analysis was completed in R using the igraph package (Csardi and Nepusz, 2006).

Metapopulation analysis quantifies how spatially separated subpopulations of the same species interact with each other through migration, colonisation, and extinction. It is a way of understanding how species persist and evolve in fragmented habitats such as the combination of natural reefs and adjacent O&G infrastructure. To examine the influence of offshore O&G infrastructures on the metapopulation dynamics, we used a simple metapopulation model that explicitly accounts for connectivity (Cecino and Treml, 2021; Figueira and Crowder, 2006) to estimate metapopulation persistence and the contribution each subpopulation makes to the instantaneous metapopulation growth rate (λ_C, Eq. (12) in (Figueira and Crowder, 2006). We calculated the instantaneous growth rate (λ_M) using Eigenanalysis and the metapopulation model and extracted the proportion of individual patch contributions (λ_C) to that growth rate, as well as the aggregate contributions for all natural reefs and infrastructure patches (e.g. summed contributions for all platform/pipeline patches). This approach implicitly assumes initial population sizes are low and explicitly assumes population densities per area are the same (i.e., variations in habitat quality are unknown). We calculated these metapopulation dynamics across the entire network, and then again under two decommissioning scenarios: 1) with complete removal of all platforms and pipelines, and 2) with the partial removal (to 55 m depth) of all platforms. In the metapopulation model, all habitat patches (described above) were considered unique subpopulations. Each subpopulation was characterised by its location and area of available habitat, reproductive output of adult population (fecundity), survival rates of produced larvae and a proportion of larvae in each subpopulation that disperse to another patch immediately following birth (Figueira and Crowder, 2006; Hale et al., 2015; Hanski, 1998). Because horizontal beam length of platforms increases with depth, area of available habitat for platforms was calculated by taking into account the difference in platform dimensions at water surface, at depth of 55 m (to account for partial decommissioning scenario), and at the seafloor using the formula for a truncated pyramid (Table S1; O'Leary, 2010). The surface area for pipelines was calculated from actual diameter, length, and burial rates data provided by EAPL (Table S2). We explored how pipeline burial estimates may affect metapopulation dynamics by completely removing the burial for all pipelines (i.e. completely exposed pipelines) and again by applying 90 % burial estimate (i.e. mostly buried pipelines) for all pipelines. We then calculated the metapopulation instantaneous growth rates (λ_M) for each of those alternative scenarios.

Estimating individual patch contributions, λ_C, ranked all habitat patches (natural and artificial habitat) according to the proportional contribution each patch makes to the metapopulation growth rate (Figueira and Crowder, 2006). Patch contribution results can therefore quantify the importance of a patch and consequences of removal of the patch or group of patches (e.g. due to decommissioning activities) to the persistence of a metapopulation. For metapopulation growth rate (λ_M), survival and fecundity values were kept the same across all species and for all networks as these values are unknown for the taxa in this study and most marine taxa. However, we performed a simple sensitivity analysis to explore the influence of increase in platform habitat area, a proxy for reproductive output, on the metapopulation growth. Similarly, there was no difference in survival rates for taxa recruiting to natural reefs or artificial habitats due to lack of published literature on this topic. Our previous metapopulation modelling and sensitivity analysis suggests that the impact of these (unknown) metapopulation parameters on results is minimal when these values are not expected to vary greatly across the seascape (Treml et al., 2015). Therefore, the differences across species in metapopulation growth rate and patch contribution can be attributed largely to differences in connectivity via inward and outward migration of larvae (other influences are larval characteristics, spawning times and durations).

3. Results

In total, we completed 927 dispersal simulations (~ 1500 days of CPU time consumed) across five species and all years between 1994 and 2003. This allowed us to develop robust and representative metapopulation connectivity networks for each study species, as defined by the migration matrices. The metapopulation networks were used to map the geographic structure, directionality, and strength of dispersal pathways for all study species. These maps also illustrate dispersal connections among source and destination subpopulations in the study domain (Fig. 1). For all species, connectivity was strongest coming from the western habitat patches in the study area, moving towards the east. This was largely driven by regional currents and the increased density of nearshore natural reef patches along Wilson Promontory located at the western boundary (Figs. 1, S1). A small cluster of offshore natural reefs around Deal Island in the south-western part of the study area was also strongly connected for all species except for *Notolabrus tetricus* (bluethroat wrasse). The vast majority of connectivity, across all species, was quite weak across all natural and artificial habitat patches, with a primarily eastward flow nearshore and westward flow offshore (but varies seasonally).

We did not find evidence that offshore O&G platforms act as critical stepping-stones for any of the study species (negligible or low betweenness centrality). In contrast, patches of pipeline habitat, especially nearshore pipeline patches or patches in the west of the study area, had medium to high betweenness centrality values for *Helicolenus percoides* (reef ocean perch), *N. tetricus*, and *Caesioperca lepidoptera* (butterfly perch), indicating sections of pipelines act as important local stepping-stones for these species (Fig. 1a–c). Similarly, there were sections of pipelines that had medium to high betweenness centrality for *Corynactis australis* (jewel anemone; Fig. 1d). Many natural reef patches in the eastern part of the study area were identified as important stepping-stones for connectivity of *C. australis* and *Centrostephanus rodgersii* (long-spined sea urchin; Fig. 1d, e) with some of those patches also acting as important stepping-stones for the connectivity of *N. tetricus* and *C. lepidoptera* (Fig. 1b, c). The nearshore natural reefs in the western part of the study area had medium to high betweenness centrality for *H. percoides* and *C. australis* (Fig. 1a, d) while a small cluster of natural reef habitat patches in the center of the study area (otherwise known as south-east reef), near to the offshore O&G infrastructure, also had high betweenness centrality for *C. australis* (Fig. 1d).

The 170 km^2 of natural reefs were the main source habitat for connectivity of all study species (patches identified by high weighted out-degree in the networks; Fig. 2). Pipelines were mainly characterised by a very low to low out-degree for all species with exception for *C. australis* and *C. rodgersii* where out-degree for all pipelines was very low (Fig. 2d, e). Majority of platform habitat patches had medium weighted out-degree for *C. australis* (Fig. 2d). All other platform habitat patches were characterised by a low to very low weighted out-degree for all other species, indicating a low source habitat potential for all platforms.

The main destination patches for all species were natural reef habitats, especially in the eastern part of the study area (high weighted in-degree in the networks; Fig. 3). The nearshore sections of pipeline patches had medium to high in-degree for all species except *C. rodgersii* (Fig. 3). No platforms were identified as major destinations for the metapopulation connectivity of the study species, yet all species have the capacity to reach platforms through weak and/or intermittent dispersal connections.

The contribution of individual habitat patches (λ_C) to the overall metapopulation growth rate (λ_M) in the study domain and across all species is presented in Fig. 4 and summarised in Table 1 for individual habitat types. The main contributors to the overall population growth were natural reefs contributing between 92.2 and 98.5 % to the population growth in this region (and representing 98.7 % of the total habitat area included in this study). All artificial infrastructure habitat patches contributed <3 % to the overall metapopulation growth of the study species with notable exception of platform patches contributions to the population growth of *C. australis* where platform patches contributed up to 7.5 % (all platform patches medium to high contribution; Fig. 4d and Table 1). In addition, Marlin A/Marlin B platforms habitat patch provided medium contribution for the metapopulation growth (λ_C) of *C. lepidoptera* (Fig. 4c). Nearshore pipeline patches were higher contributors to the metapopulations dynamics than the offshore pipeline patches across all species. Typically, the contribution of pipeline patches in the western part of the study area was higher than their contribution in the eastern part (Fig. 4). The overall metapopulation impact of O&G infrastructure in this seascape is robust to several factors of magnitude variation in the effective area of infrastructure, our proxy for reproductive output (10× increase in effective area of platforms increased their overall metapopulation influence by 10 %).

The modelled mean metapopulation impact of full or partial removal decommissioning of platforms and subsea facilities of all study species, except *C. australis*, was found to be very small (average < 1.5 %; Table 1). For *C. australis*, the metapopulation growth will decrease between 3.3 and 5.9 % in case of partial or full decommissioning of the

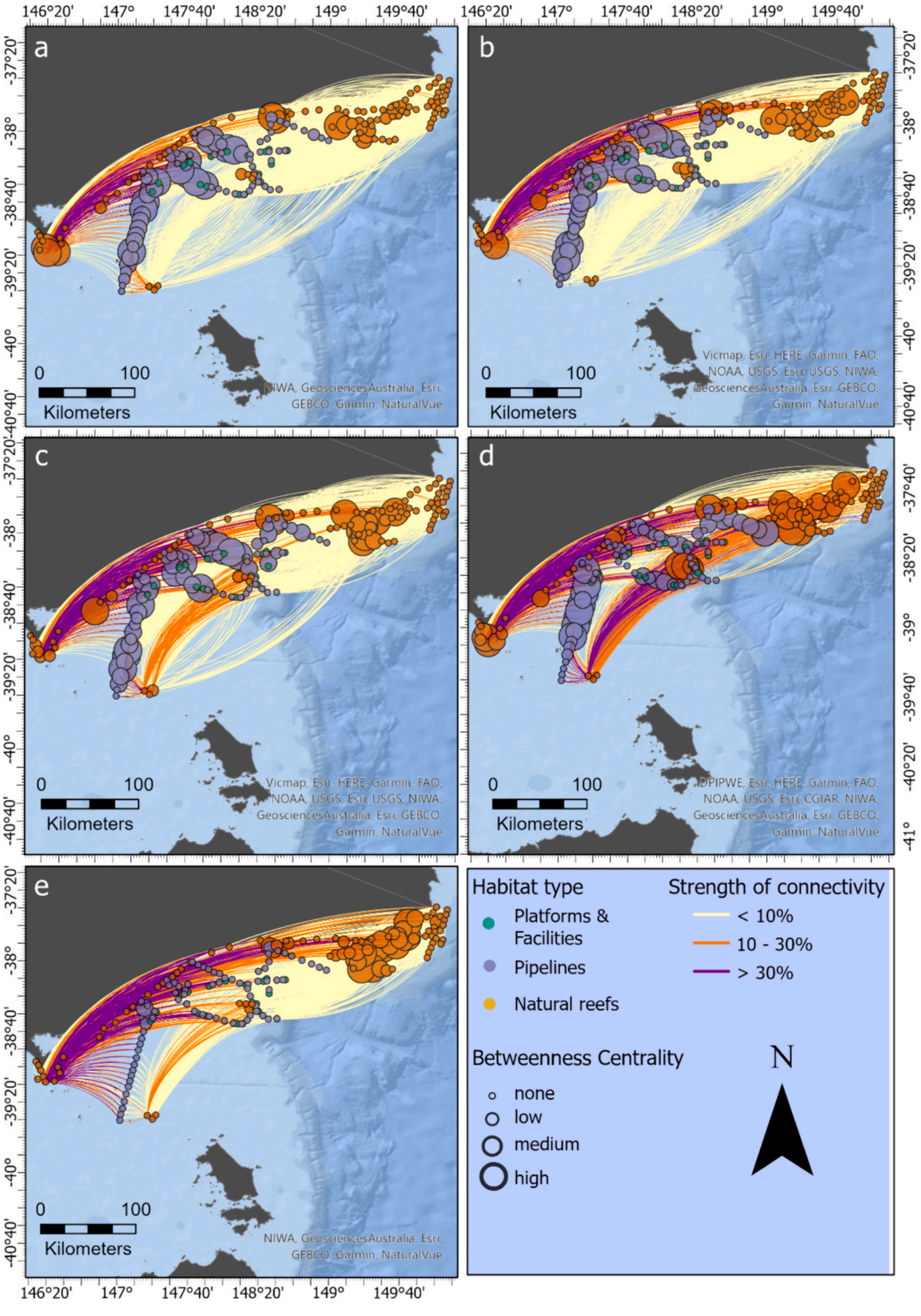

Fig. 1. Spatial distribution, direction, strength of metapopulation connectivity (the average proportion of larvae arriving to a destination habitat patch from all upstream sources as summarised in the migration matrices) and patch-level betweenness centrality metric in the study domain (see Fig. S1 for boundary and geographical settings) for all study species: a) *Helicolenus percoides* b) *Notolabrus tetricus* c) *Caesioperca lepidoptera* d) *Corynactis australis* e) *Centrostephanus rodgersii*. The directionality of dispersal between habitat patches is implied by following the arcs in a clockwise direction. High betweenness centrality measure indicates an important stepping-stone resulting in many pathways using this habitat patch whereas 'none' indicates that a given patch does not act as a network-side stepping-stone.

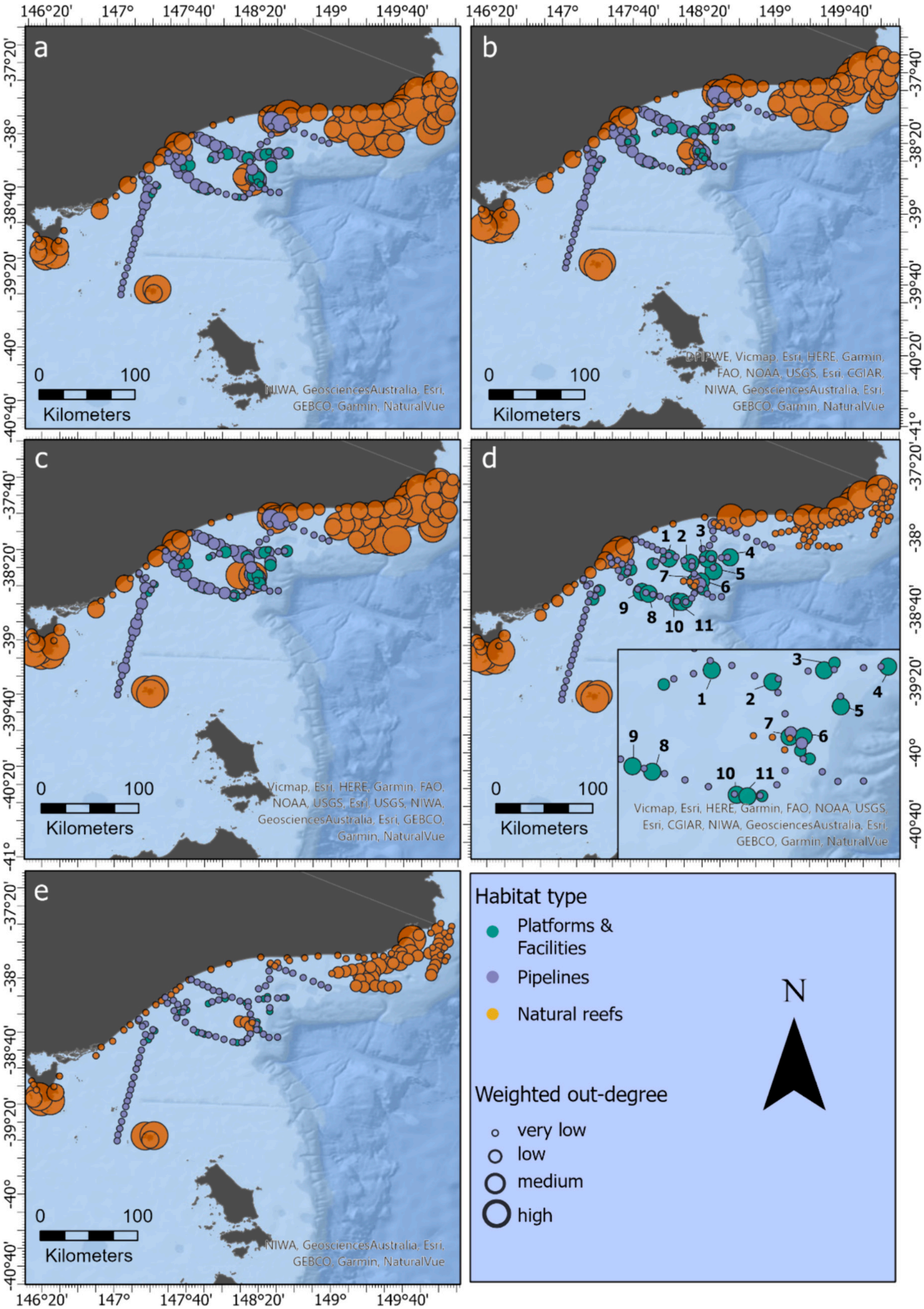

Fig. 2. Spatial distribution and patch-level weighted out-degree in the study domain (see Fig. S1 for boundary and geographical settings) for all study species: a) *Helicolenus percoides* b) *Notolabrus tetricus* c) *Caesioperca lepidoptera* d) *Corynactis australis* e) *Centrostephanus rodgersii*. Panel d), numbers refer to the habitat patches created by platforms: 1) Snapper; 2) a complex of platforms Marlin A and Marlin B; 3) West Tuna; 4) Kipper; 5) Flounder; 6) Halibut; 7) Fortescue; 8) Bream B; 9) Bream A; 10) West Kingfish; 11) Kingfish A. Inset presents a zoomed view on the key platforms with medium values of weighted out-degree for *C. australis*. High weighted out-degree identifies structures or reefs that act as a strong local source for population connectivity.

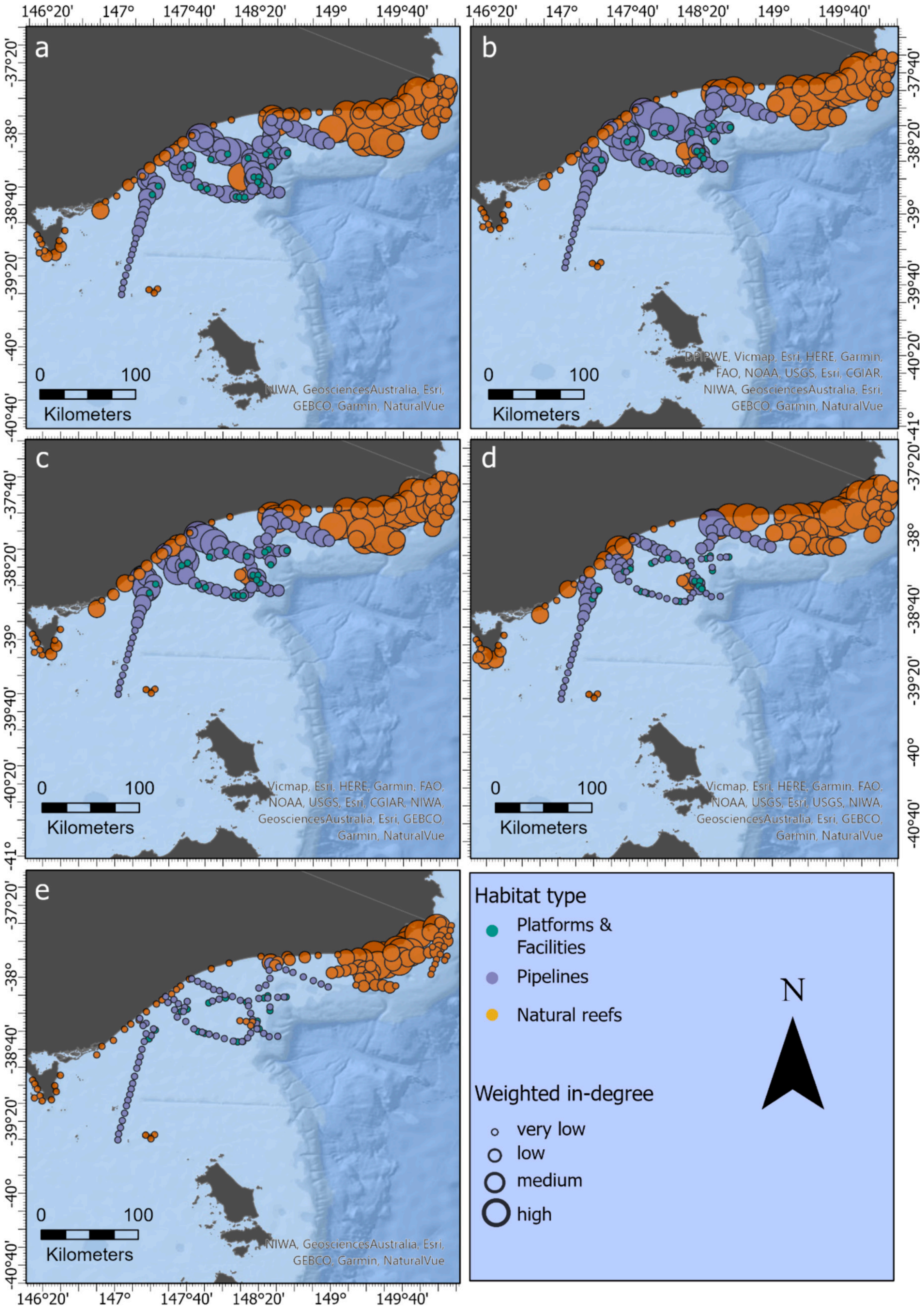

Fig. 3. Spatial distribution and patch-level weighted in-degree in the study domain (see Fig. S1 for boundary and geographical settings) for all study species: a) *Helicolenus percoides* b) *Notolabrus tetricus* c) *Caesioperca lepidoptera* d) *Corynactis australis* e) *Centrostephanus rodgersii*. High weighted in-degree identifies structures or reefs that act as a strong local destination for population connectivity.

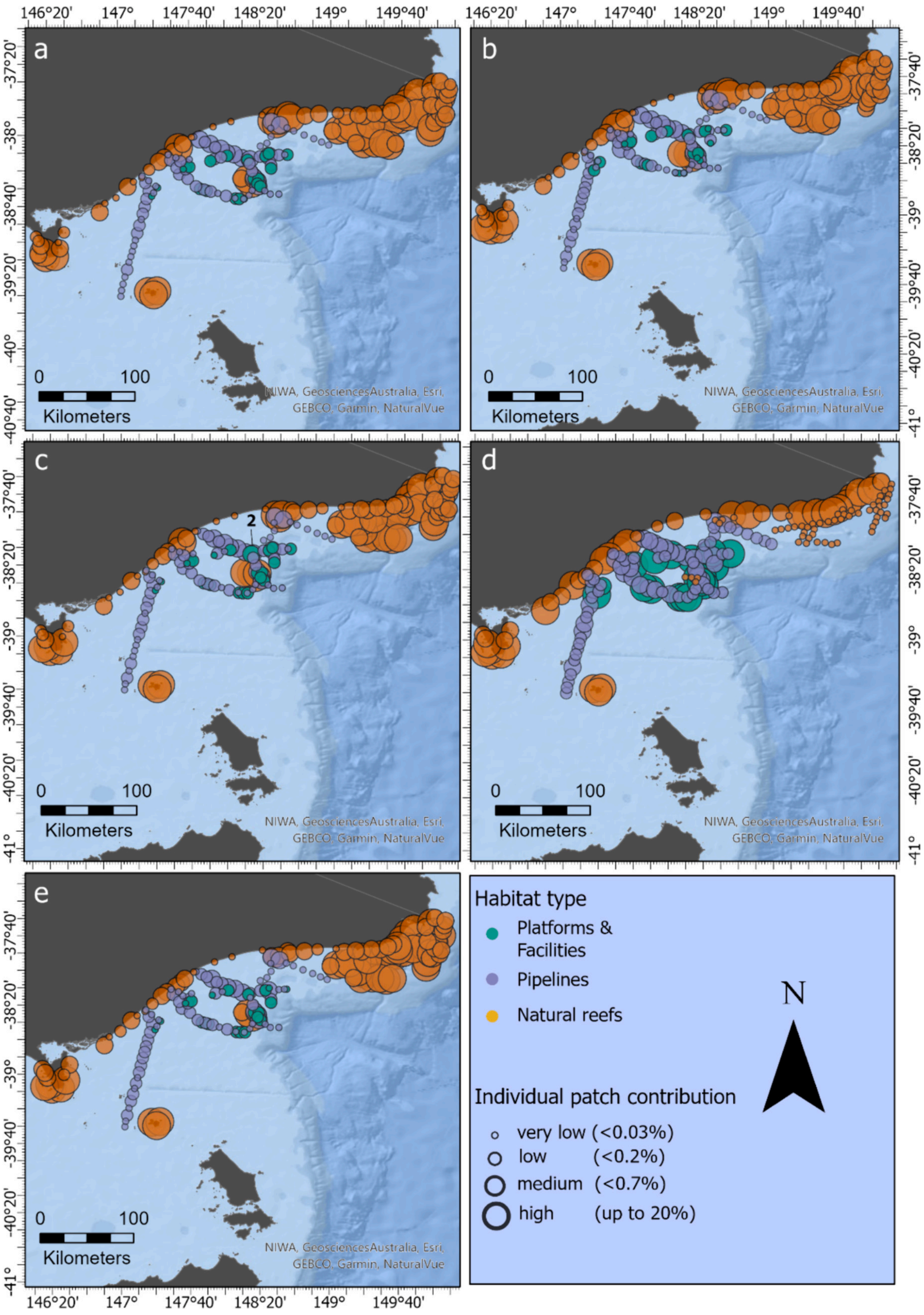

Fig. 4. Spatial distribution and individual patch-level contribution (λ_C) to overall metapopulation growth in the study domain (see Fig. S1 for boundary and geographical settings) for all study species: a) *Helicolenus percoides* b) *Notolabrus tetricus* c) *Caesioperca lepidoptera* d) *Corynactis australis* e) *Centrostephanus rodgersii*. In panel c), 2) indicates a complex of platforms Marlin A and Marlin B.

Table 1

The importance of habitat and infrastructure type, decommissioning and pipeline burial rates on the overall metapopulation growth rate (λ_M) of the study species. Partial removal refers to decommissioning to 55 m below mean sea surface level. Impact refers to per cent change in λ_M if structures are fully or partially removed from the seascape or pipelines fully exposed/mostly buried. Green colours indicate increase in the overall metapopulation growth rates, red colours indicate reduction in the overall metapopulation growth. Mean values across all species are provided in bold in far-right column. Silhouettes obtained from https://www.phylopic.org/ under Creative Commons licenses.

Parameter	*Helicolenus percoides* (reef ocean perch) 	*Centrostephanus rodgersii* (long-spined sea urchin) 	*Caesioperca lepidoptera* (butterfly perch) 	*Corynactis australis* (jewel anemone) 	*Notolabrus tetricus* (bluethroat wrasse) 	Across all species
Total natural reef contribution to λ_M	96.8 %	98.5 %	96.5 %	92.2 %	97.1 %	**96.2 %**
Platforms & facilities contribution to λ_M	0.4 %	0.2 %	0.5 %	7.5 %	0.4 %	**1.8 %**
Pipelines contribution to λ_M	2.8 %	1.3 %	3.0 %	0.3 %	2.5 %	**2.0 %**
Impact of full removal platforms & facilities	0.5 %	0.1 %	0.5 %	5.9 %	0.4 %	**1.5 %**
Impact of full removal pipelines	27.7 %	1.6 %	26.6 %	3.9 %	34.1 %	**18.8 %**
Impact of partial removal platforms & facilities	0.2 %	0.0 %	0.2 %	3.3 %	0.1 %	**0.8 %**
Fully exposed pipelines contribution to λ_M	0.4 %	0.1 %	0.4 %	0.1 %	0.4 %	**0.3 %**
High burial pipelines contribution to λ_M	0.9 %	0.3 %	1.2 %	0.4 %	0.9 %	**0.7 %**

platform patches, respectively. However, a higher impact of full removal of pipelines was found, with a mean decrease in metapopulation growth across species of 18.8 %, with higher-than-average decreases in metapopulation growth for *H. percoides* (27.7 %), *C. lepidoptera* (26.6 %), *N. tetricus* (34.1 %) (Table 1). Partial removal of platform patches and burial rates of pipelines (e.g. fully exposed or majority buried pipelines) may create relatively low impacts on metapopulation growth across all species (all modelled impacts <3.5 %; Table 1).

4. Discussion

Offshore O&G infrastructure are located in many ocean basins around the world with many approaching end of field life and requiring decommissioning. Decommissioning decisions need to minimise environmental risks and impacts to as low as reasonably practicable levels whilst complying with legislation. Our study provides critical information for evaluating decommissioning strategies by modelling and quantifying regional metapopulation dynamics among natural reef habitats and O&G infrastructure (platforms and pipelines) for key marine fauna in south-east Australia's Bass Strait region. Since most marine taxa have the capacity to disperse during early larval stages, network-based approaches can be especially powerful for understanding metapopulation dynamics and structure where connectivity is used as an important criterion in decision-making process (e.g. Berglund et al., 2012; Cecino and Treml, 2021; Goetze et al., 2021). With this spatial-ecological knowledge it is possible to identify specific offshore O&G structures whose partial or full removal should have minimal impact on population connectivity.

The direction of connectivity was primarily from western habitat patches towards the east, especially from nearshore natural reef patches in the western part of the study area towards natural and artificial habitat patches in the east. There was some westward connectivity from natural reefs, largely involving offshore habitat patches. However, given the age and uncertainty of the published benthic habitat maps (estimating reef cover and extent), we recommend future habitat surveys target these areas using contemporary mapping and benthic survey methods e.g. hydroacoustic and benthic video surveys. The vast majority of this connectivity, across species, was quite weak across the domain. Ocean currents and seasonality are well-known factors in shaping larval dispersal and survival (Cowen and Sponaugle, 2009; Kool et al., 2013; Nishimoto et al., 2019). The broader Bass Strait region is characterised by a complex oceanography where a seasonally wind-driven eastward current meets the southern extent of the East Australian Current (EAC) (Sandery and Kämpf, 2007). However, the EAC in this region manifests in the form of a seasonal and discontinuous field of mesoscale eddies rather than as a single continuous strong current system (Oke et al., 2019). As a result, currents transported from the west have a greater relative influence than currents from the east (Sandery and Kämpf, 2007), particularly for our study domain focus. Our high-resolution hydrodynamic model showed residual eastward currents of approximately 0.1–0.15 ms^{-1} on the continental shelf through the study area. This flow continued northeast to the VIC-NSW state border and strengthened to approximately 0.3 ms^{-1} with similar current patterns towards the northeast that are weaker in summer months than in winter months (Appendix A Hydrodynamic modelling).

Important stepping-stones are habitat patches that facilitate connectivity across the seascape and can be critical for connecting source habitat patches to other smaller or lower quality patches and whose removal could break the metapopulation into smaller, unconnected sections (Minor and Urban, 2007). We did not find evidence that platforms act as key stepping-stones for the connectivity of the five study species as measured by the betweenness-centrality metric in this study. Artificial hard substrates, such as O&G platforms or renewable energy structures, have been previously documented to act as stepping-stones for a range of native and invasive marine biota in other systems (Adams et al., 2014; Coolen et al., 2020; Page, 2019). By providing suitable settlement habitat where it was previously absent, artificial structures could improve survival rates of larvae transported offshore, away from original habitats, thus improving gene flow between subpopulations or facilitating range expansions (e.g. Adams et al., 2014; Coolen et al., 2020). The capacity of offshore infrastructure to act as important stepping stones, will depend largely on the proximity, spatial arrangement and quality of habitat patches, species' life-history parameters and larval dispersal strategies where oceanic flow patterns often play a major role (Coolen et al., 2020; Treml et al., 2008). In our study, the pre-competency period and maximum pelagic larval durations (PLDs) most likely played an important role for the observed stepping-stone capacity of platforms where, due to long pelagic larval stages (40–120 days), our study species were capable of traversing large distances. Similar patterns were previously documented for other connectivity studies on sessile invertebrates on infrastructure (Coolen et al., 2020; Page, 2019). Likewise, the same has been noted during connectivity simulations for renewable energy infrastructure (Adams et al., 2014) which found that species with longer pelagic stages did not need to rely on offshore habitats for connectivity, because they were able to cover large distances during dispersal. We expect that for the Bass Strait region, marine species with shorter pelagic larval stages (hours to days; e.g. Mayorga-Adame et al., 2022; Young et al., 2020) will likely be utilising offshore structures as stepping-stones to facilitate their connectivity across the seascape. One such species is *Scorpis lineolatus* (silver sweep) which is thought to have a short larval duration (Neira et al., 1998; Silberschneider and Booth, 2001) in conjunction with strong larval swimming capabilities (Dudley et al., 2000).

Our research outcomes suggest that nearshore sections of pipelines may act as important local stepping-stones for the connectivity of *H. percoides*, *N. tetricus* and *C. lepidoptera*. This is a novel finding as the role of pipelines as stepping-stones in connectivity of marine organisms was only hypothesised but not quantified in the literature. Given that these species are among the most common and abundant species on natural reefs in the region (Bax and Williams, 2001; McLean et al., 2022b; Williams and Bax, 2001), it is reasonable that they utilise this seascape extensively. It is possible that *C. lepidoptera* recruits on pipelines and shifts to platforms during ontogenetic development. ROV imagery analysts noted the presence of juvenile *C. lepidoptera* on pipelines, hovering close to sponge biota growing on the pipelines and moving quickly among this biota as the ROV approached. Previous studies observed high abundance of adults and sub-adults of *C. lepidoptera* on platforms in the Bass Strait (Birt et al., 2023; Neira, 2005). Similarly, sections of pipelines in the western part of the study area may act as important stepping-stones for the connectivity of *C. australis*. While extremely ubiquitous on platforms in this region, there were limited documented sightings of *C. australis* in previous biota surveys of pipelines (McLean et al., 2022b). This may be because the abundance of adults of this species is very low, similar to the abundance of this species on the natural low relief reefs in this region (e.g. Dürr, 2003). Alternatively, they may be hidden by larger more conspicuous biota, or they are out-competed, or simply that pipelines do not provide suitable habitat for *C. australis*. In contrast, a previous study found anemones from a range of different genera to *C. australis* to be among the most frequently observed taxa on pipelines in the North Sea (Redford et al., 2021).

Source and destination populations play a critical role in determining the overall connectivity of the network. Natural reefs, that make up 98 % of all hard substrate habitat in the system, were the main source and destination habitats for the network connectivity of all study species. All platforms (0.32 km^2 habitat) were found to act as low to medium strength source patches for the connectivity of *C. australis*. Other modelling studies have found that platforms can function as source habitats for larval production by reef fishes and invertebrates which can benefit regional populations if the larvae are able to survive through the dispersive phase and contribute to production in natural areas (Henry et al., 2018; Nishimoto et al., 2019; Thorpe, 2012). Pipelines (1.91 km^2 of total habitat) were discovered to have nearshore sections that can be relatively strong sources for all three fish species in this study. Habitat patches with large weighted out-degree are important local source hubs of larvae supply to other neighbouring patches and are critical for ensuring successful reproduction and increasing the gene pool size by dispersing across a wide area (Cecino and Treml, 2021). Notably, platforms and pipelines were not found to act as regionally important sources or destinations for local connectivity of the invasive *C. rodgersii*, most likely due to the extended larval dispersal capacity and the oceanic currents in the region which primarily enhances west-east connectivity (as described above). *C. rodgersii* originates from the NSW coast (Byrne et al., 1998; Underwood et al., 1991) so regional flow patterns may not promote its dispersal to the infrastructure in the region. Pipelines, however, acted as destination patches of varying strength for all other species in our study, particularly the nearshore or eastern pipeline patches were quite important destination patches. The pipelines may be supporting some highly abundant species or allowing for the settlement of competent larvae. For example, *H. percoides* was one of the most abundant species on the nearshore pipelines and its abundance increased with increased total pipeline length (McLean et al., 2022c).

Natural hard substrate reef habitat patches were the main contributors to the overall metapopulation growth of all study species in this region, largely driven by the total habitat area (98.7 % of all habitat included for this study in the region). Platforms and pipeline habitat patches all contributed on average <2 % to the overall metapopulation growth in this region. The overall contribution of platform patches to the metapopulation growth was low but these dynamics differed between study species. All platforms contributed to the metapopulation growth of *C. australis*. This is perhaps to be expected given that platforms had a very high percent cover for this anemone (average ~ 73 % cover up to ~95 % in depths <55 m; McLean et al., in prep). Anemones, such as *C. australis*, are quick colonisers of available space and are important in structuring species assemblages (Hartnoll, 1998). It is likely that the flat surfaces of these platforms may benefit this sessile filter feeding species (in contrast to more complex surfaces) through enhanced water flow, likely promoting growth and reducing mortality (Lenihan, 1999). In addition, the Marlin A/Marlin B habitat patch had medium contribution to the metapopulation growth of *C. lepidoptera*. Offshore O&G platforms have been shown to have the highest fish production per unit area of seafloor of any other studied marine habitat, which is likely attributed to the unique complex vertical structure of these platforms (Claisse et al., 2014). However, we are currently unsure whether platforms in this study produce more larvae than the surrounding natural reefs, which could be the focus in future research (see Appendix A Study Limitations for a discussion of the limitations of this study). Nearshore pipeline patches (closer to natural reefs) typically contributed more than offshore patches, and western pipeline patches typically contributed more than the eastern patches. This pattern is most likely dictated by the dominant currents in this region and the proximity to natural reefs, as described above. In addition, it appears that the long continuous linear structure provided by pipelines, and the relative placement of these habitat patches within the seascape, uniquely benefit the metapopulations dynamics of some of the study species. This is also supported from the community study in this region where longer pipelines and those that were more exposed (less buried) had higher fish abundance (McLean et al., 2022c).

We did not find evidence that, under prevailing long-term regional hydrodynamic circulation, O&G structures are being used as important stepping-stones for the invasive *C. rodgersii*, and a similar outcome might be assumed for other marine invasive species with similar life-histories and dispersal capacities. The species has been observed on offshore infrastructure, but in very low numbers on both platforms and pipelines (McLean et al., in prep). We note that marine invasive or non-native range shifting species can use offshore infrastructure as stepping-stones or settlement habitat in other places around the world (Adams et al., 2014; Coolen et al., 2020; Sammarco et al., 2014, 2010). With the current pace of climate change accelerating and affecting oceanic flow patterns in south-east Australia and elsewhere in the world (Cai et al., 2005; García Molinos et al., 2017; Poloczanska et al., 2016), future invasions and range shift in this region may be possible. To appropriately explore future climate-driven dynamics and the connectivity impacts in this system, a new hydrodynamic model would be required (well beyond 1994 to 2003 data used in the current study). This effort would greatly benefit from targeted in situ data collection of oceanographic parameters and facilitate a novel comparison within a global hotspot of marine climate change.

The ultimate decision to partially or fully remove infrastructure should take into consideration the role that offshore structures have on marine population dynamics across the seascape and how those components interact with the surrounding natural habitats. Our study demonstrated that, even though decommissioning of platforms or pipelines in the Bass Strait may have negligible to minor effects on the overall metapopulations of the study species, some facilities might be more important than others or some species may be more severely impacted by the decommissioning activities than others. For example, Marlin A/Marlin B platforms habitat patch contributed more to the metapopulation growth of *C. Lepidoptera* and *C. australis*, and acted as source populations, albeit mostly weak, for three of the fish species. Similarly, nearshore pipeline patches had an important role for network connectivity or metapopulation growth across three fish species used in this study. We demonstrated that full or partial removal of platforms will have virtually no difference on the overall metapopulation growth of most study species except for *C. australis*. In contrast, complete removal of all pipelines may reduce the metapopulation growth of some of the species using the pipelines up to 34.1 %. Removing these pipeline habitats would theoretically increase the risk for domain-wide metapopulation impact. We recommend that the decision to remove offshore O&G infrastructure fully or partially be made on platform-by-platform basis and consider contributions of pipeline sections to connectivity and metapopulation dynamics in Bass Strait.

5. Conclusions

Our main findings indicate that for the species evaluated: 1) platforms are not major sources, destinations, or stepping-stones for most of the study species, except acting as low to medium sources for connectivity of *C. australis*. Platforms do not contribute substantially to the region's metapopulation dynamics, except somewhat to the metapopulation of *C. australis*; 2) natural reefs, which make up >98 % of the region's hard substrate habitat, were the main stepping-stones, source and destination habitats for all study species (but sections of pipelines could act as stepping-stones, source or destination habitats of varying strengths); 3) natural reefs were largely responsible for the overall metapopulation growth, with artificial structures as a minor contributor; 4) full or partial decommissioning of platforms should have a very low or negligible impact on the overall metapopulation dynamics of all species explored (except *C. australis*), whereas full removal of pipelines could have a low impact on the metapopulation dynamics of benthic species in the region and a moderate impact on fish species, and 5) variability in pipeline burial estimates has a negligible effect on the metapopulation dynamics of all study species. Our findings support previous studies which found local-scale influence of offshore infrastructure and a negligible regional influence of pipelines and platforms on the distribution and abundance of fish communities in north-west Australia (Galaiduk et al., 2022).

CRediT authorship contribution statement

Ronen Galaiduk: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization. **Dianne L. McLean:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization. **Conrad W. Speed:** Writing – review & editing, Writing – original draft, Visualization, Data curation. **Dougal Greer:** Writing – review & editing, Writing – original draft, Visualization, Methodology. **Rhys McIntosh:** Writing – review & editing, Writing – original draft, Visualization, Methodology. **Eric A. Treml:** Writing – review & editing, Writing – original draft, Validation, Methodology, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

Ronen Galaiduk reports financial support was provided by Esso Australia Pty Ltd (EAPL). Dianne McLean reports a relationship with EAPL that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Hydrodynamic model outputs are stored on the AIMS data portal (Data|AIMS; https://doi.org/10.25845/8YN0-6N04). Data on the location of all habitat patches and the species-specific connectivity matrices pertaining to the results of this study can be provided upon request to the corresponding author. All functions for the network analysis are contained within the igraph package. The full metapopulation math follows that contained in Figueira and Crowder (2006, Eqs. (1) to (13)).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.172981.

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