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Connectivity Between Areas Closed to Protect Vulnerable Marine Ecosystems in the NAFO Regulatory Area using a 3-D Lagrangian Particle Tracking Model

by

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Abstract

In support of the 2020 NAFO review of the closed areas to protect vulnerable marine ecosystems (VMEs) in the NAFO Regulatory area (NRA), connectivity among the areas closed to protect vulnerable marine ecosystems, and including Area 14 which was reopened to fishing in 2019, was assessed using Ocean Parcels, an interface to perform 3-D passive particle tracking simulations using output from an ocean circulation model, BNAM. Connectivity is an important property for evaluating the effectiveness of the closures, and especially so for the benthic invertebrates under protection, all of which are sessile as adults and rely on larval transport for dispersal. Here we evaluate the connectivity among areas closed to protect large-sized sponges, large gorgonian corals and sea pens. Overall, connectivity was generally weak with downstream interdependence and little redundancy. The largest area, Area 2 in Flemish Pass, showed some particle retention. For each receiving area the percentage of the total number of particles released (from all source areas) were presented and were generally small (< 10%). The exception is the connectivity between Areas 5 and 4 on the eastern and southeastern slopes of Flemish Cap which had a relatively high degree of connectivity with ~ 20% of particles connecting at all depths simulated. Those areas connect populations of large gorgonian corals and sponges.

Introduction

Connectivity among the areas closed to protect corals and sponges in the NAFO NRA is an important property for evaluating their effectiveness. The science of landscape ecology distinguishes between “structural connectivity”, i.e., physical fluxes and “functional connectivity”, defined as the movement of adults, gametes or larvae across space, connecting populations and habitats (Figure 1) (Hanski 1998). Effective connectivity further calls for successful settlement and recruitment to the population as not all larvae will survive early settlement conditions, while genetic connectivity requires further survivorship of those settled larvae through to sexual reproduction (Pineda et al. 2007). Different analytical tools are available to model each of these aspects of connectivity.

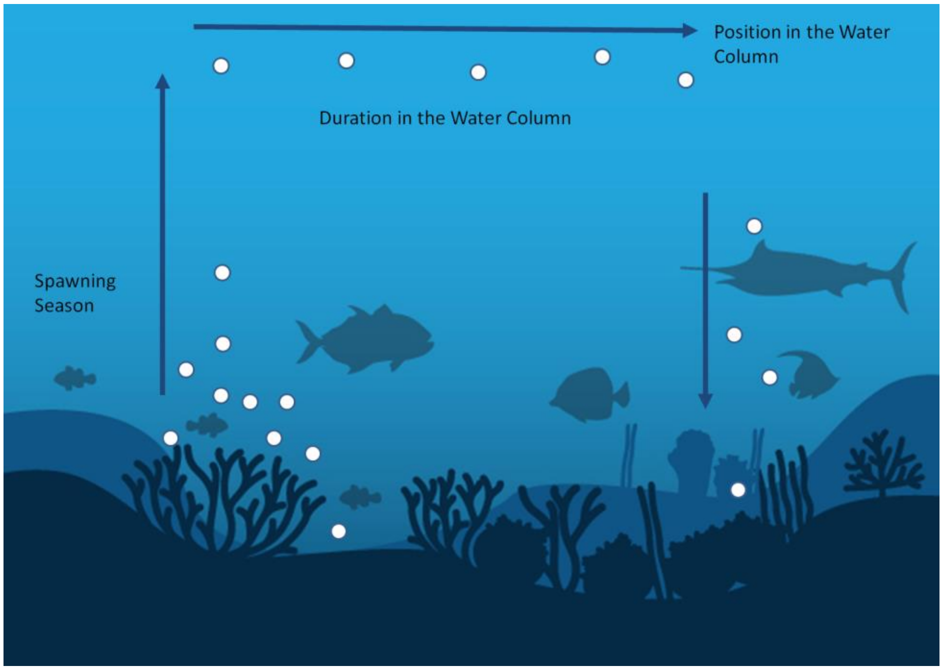

Figure 1. Illustration of the pelagic phase of dispersal for deep-sea corals and sponges and associated metrics needed for biophysical modeling.

Lagrangian particle tracking (LPT) models are considered an important tool for assessing structural connectivity in the deep sea (e.g., Xu et al. 2018, Bracco et al. 2019, Kenchington et al. 2019, Zeng et al. 2019). In such models, virtual particles are advected by the flow fields from numerical models (Lange and van Sebille 2017). Virtual behavior can also be added to the particles so that they can act as active drifters, i.e. larvae, and so can make predictions of functional connectivity. Recently, Kenchington et al. (2019) used a LPT model to evaluate structural and functional connectivity among the fourteen areas that were closed to protect Vulnerable Marine Ecosystems by the Northwest Atlantic Fisheries Organization (NAFO) in the high seas of the northwest Atlantic. That work was considered by NAFO and it was recommended that connectivity be included in the review of the NAFO closed areas (NAFO 2018).

A number of user interfaces are available to assess oceanic structural connectivity. These combine complex individual-level models of particles with a 3-D oceanographic model of the physics, and can be used to run forward/hindcast simulations, habitat connectivity calculations, comparison of physical circulation models, etc. Kenchington et al. (2019) used the Webdrogue Drift Prediction Model v.0.7 and the "Southern Labrador, Newfoundland Shelf" data set (http://www.bio.gc.ca/science/research-recherche/ocean/webdrogue/slns-tnls-en.php) to compute passive-particle drift trajectories. The ocean circulation model underlying the Webdrogue tracking algorithm was the Dartmouth Finite Element Model, Quoddy, a finite-element computer simulation program for coastal ocean circulation modeling (Lynch and Werner 1991). Details of the computation of the circulation components are provided by Hannah et al. (2000) and those of regional data sources by Han et al. (2008). The particle tracking algorithm used in Webdrogue is based on the DROG3-D program (Werner et al. 1993, Blanton 1995).

However, Webdrogue has a number of limitations when it comes to application to the NRA. Particle tracking is limited to relatively shallow depth zones using vertical averages of the velocity fields for each depth interval: 0-5 m (surface), 25-35 m (25 m), and 95-105 m (100 m). Further, the number of particles that can be seeded in a single run is limited to 50, random walk movement is not incorporated, and particle tracking can only be run with horizontal movement (2-D). After brief discussion of these limitations in WGESA at the November 2018 meeting, it was decided that additional work should be undertaken to evaluate the impact of these limitations on the connectivity results of Kenchington et al. (2019).

Re-evaluation of Structural Connectivity in the NRA

A number of alternative LPT models are available (e.g., Ariane (Blanke and Raynaud 1997), TRACMASS (Döös et al. 2017), Parcels framework (Lange and van Sebille 2017, Delandmeter and van Sebille 2019)) which allow for horizontal velocities to be calculated at greater depths than those available in Webdrogue, incorporate random walk, and allow for a greater number of particle seeds per simulation. We chose the relatively new Parcels framework version 2.1 (http://www.oceanparcels.org) to re-evaluate structural connectivity in the NRA. Parcels was developed to optimize computational efficiency and scalability and importantly can be run in 3-D.

Parcels was used in conjunction with the eddy-resolving Bedford Institute of Oceanography North Atlantic model (BNAM) (Wang et al. 2016, Z. Wang et al. 2019), which uses the NEMO 2.3 (Nucleus for European Modelling of the Ocean) model engine. BNAM used a nominal resolution of 1/12° in this application. The BNAM ocean model used with Parcels, and the Quoddy ocean model used by Kenchington et al. (2019) belong to different model families in terms of model horizontal grids and treatments of vertical layers. BNAM is a structured, z-level grid ocean model (Madec et al. 2016). δ grid models, such as Quoddy, tend to overestimate vertical mixing for regions with large bathymetry gradients, such as seen in the NRA. Due to the unavailability of the Quoddy results, a direct comparison with Parcels using the two different ocean models could not be done. However, comparison of BNAM surface currents with surface-drifter derived currents (Z. Wang et al. 2019) showed a strong correlation, supporting the use of the BNAM ocean model for this region.

S. Wang et al. (2019) found that BNAM demonstrated more connectivity between the closed areas than that in Kenchington et al. (2019) in comparable simulations where Quoddy was used. Considering the well–represented surface currents and water properties for the Flemish Cap area captured by BNAM, and potential issues with δ vertical grid models (such as Quoddy) for slope regions, they suggested that the connectivity determined with Parcels should be considered as more suitable for this region.

Connectivity Between Closed Areas using 3-D Parcels Simulations

Lagrangian particles were advected using the fourth-order Runge-Kutta method (Runge–Kutta 4 default option in Parcels) as the integration scheme (Lange and van Sebille 2017). Optimal parameters for the number of particles, particle spacing, and time step were separately determined such that computational time was minimized without introducing bias (S. Wang et al. 2019). Particles were deleted if they reached the boundary of the spatial domain represented by the 31.4° and 67.3°W meridians and by the 34.5° and 58.6°N parallels of latitude.

Table 1. Overview of 3-D particle tracking experiments performed.

Experimental Objective	Particle Release Depth	Season for BNAM extracts	Drift Duration
Vertical movements	Surface, 100 m, 450 m, 1000 m, 2250 m	Average, Spring, Summer, Autumn, Winter	2 weeks, 1 month and 3 months
Potential source populations	1000 m	Average	2 weeks, 1 month and 3 months
Connectivity	Benthic habitats (see Table 3)	Average, Spring, Summer, Autumn, Winter	2 weeks, 1 month and 3 months

Three different simulation experiments aimed at determining different aspects of a biophysical connectivity between closed areas on Flemish Cap were performed (Table 1). Within each experiment a number of scenarios evaluating different depths, seasons (through extraction of associated ocean model data) and drift-time durations were evaluated (Table 1). Season and drift-time duration (Figure 1, Table 2) were based on a previous review of the life-history characteristics of the coral, sponge and sea pen species that are protected by the closures (Kenchington et al. 2019) and allow model outputs to be interpreted as biophysical models to the degree possible (i.e., functional connectivity).

Table 2. Model scenarios for assessing functional connectivity among areas closed to protect sponges, sea pens and large gorgonian corals performed.

Model	Closed Areas	Season	Drift Duration	Particle Release Depth	Particle Release Numbers
Sponges	Areas 1-6	Summer, Autumn, Average	2 weeks	1245 m 1452 m 1684 m	8,472 5,373 2,998
Sea pens	Areas 2, 7-12, 14	Spring, Summer, Winter, Average	2 weeks, 1 month and 3 months	643 m 902 m 1062 m	7,203 6,374 5,667
Large gorgonian corals	Areas 2, 4, 5, 13	Average	2 weeks, 1 month and 3 months	643 m 1245 m 1684 m	11,686 7,091 2,768

3-D connectivity among closed areas was assessed with drift durations of 2 weeks (sponges), 1 month and 3 months using the average data from the model (Table 2) and seasonal averages for sponges and sea pens (Table 2) where some information on spawning time has been reported (Kenchington et al. 2019). All particles were released at depths that reflected the on-bottom depths for each closed area, given that the corals and sponges are benthic organisms and larvae would be released from near the seafloor. Particles were released at the bottom depth of each closed area for those areas protecting the same species (Table 2) using the minimum, middle and maximum depths of the mean depth ranges for the combined areas (Table 2). Model parameters for all scenarios were 60 minutes (time step); 100 $m^2 s^{-1}$ (horizontal mixing); 0.01° (particle space) (see S. Wang et al. 2019). For all scenarios, the total number of released particles were initiated inside all closed areas (uniformly positioned) and the models run for all closed areas under each scenario. Table 2 shows the particle numbers for sponges, sea pens and large gorgonian corals at different depths.

To quantify connectivity, two metrics were computed based on particle trajectories (Goldsmit et al. 2019): 1) arrival time (how long it takes particles from the release area to reach another area), and 2) the percentage of particles crossing over a closed area and/or ending in the same or another closed area (Figure 2). Both metrics were calculated for particles released from each of the closed areas (source areas). The percentage of particles crossing over a closed area but not terminating there is important to consider because we do not know the actual larval duration in the water column for any of these species. Further, the larvae of some species, such as oysters, respond to settlement cues (e.g., Anderson 1996, Lillis et al. 2013) and passing over an area of dense aggregations of conspecifics could trigger larval movement to the seabed.

Figure 2. Particle retention is illustrated in hypothetical Closed Area 1 where particles mimicking larvae move into the water column and are still there at the end of the model run time (duration). Particles crossing over another closed area are shown in hypothetical Closed Area 2 and particles terminating in another closed area are shown in hypothetical Closed Area 3. In this study we attribute connectivity from hypothetical Closed Area 1 to hypothetical Closed Areas 2 and 3 because we do not know the precise duration of the larvae in the water column.

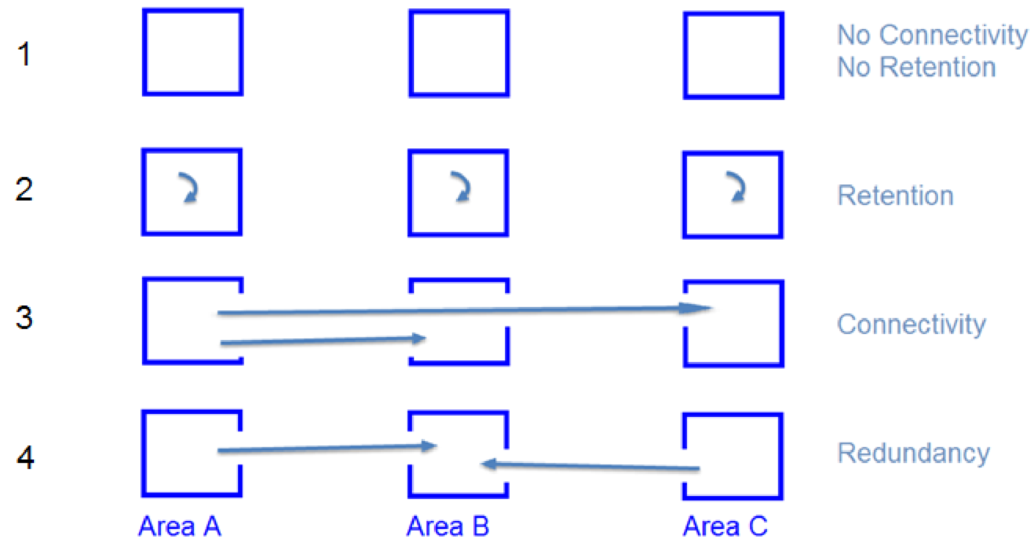

Figure 3. Hypothetical particle drift scenarios (1-4). Scenario 1: Model particles are exported from the area, there is no connectivity or retention. Scenario 2: Model particles released in Area A, Area B and Area C stay in their release areas. This is referred to as particle retention. Scenario 3: Model particles released in Area A connect to Areas B and C. Scenario 4: Model particles released in Areas A and C connect to Area B giving redundancy to Area B as it does not depend on a single source population.

We evaluated the connectivity among closed areas based on connectivity and redundancy (Figure 3). One outcome is particle retention where the particles are released from the source area and remain in the source area or return to it at the end of the run duration. Another outcome is that there is neither retention nor connectivity and particles terminate outside of any closed area. Areas can connect to one another in a variety of ways. When the currents and closed areas align, connectivity takes the form of a chain, linking successive closed areas downstream. When a closed area receives particles from two or more other closed areas it has a degree of redundancy, meaning that it does not depend on the larvae from a single source population to persist. Redundancy is an important property of networks of closed areas (Rayfield et al. 2011).

Large-Sized Sponges

The connectivity and retention of particles for Areas 1-6, closed primarily to protect large-sized sponges is presented in Table 3. Six connections were observed, effected at the minimum, and middle depths of the mean depth ranges for the combined areas, while only 5 of those were observed at the maximum depth where the connection between Area 6 and Area 4 was not found (Table 3). Retention increased with depth and was observed in Areas 2, 3, 4, 5, and 6 at different depths/seasons (Table 3). Those connections are summarized in Figure 4 using average currents and depicted on a map in Figure 5.

Some of the closed areas are large (Area 2, Area 5) with Area 2 showing some retention indicative of potential for self-perpetuation (Figure 4). The spatial configuration of the closures is good with respect to connectivity. There is a general clockwise flow pattern of downstream interdependence (Figure 5) with Area 6 (Sackville Spur) a potential source of recruitment to Area 5 and Area 4 (Figures 4, 5). Area 4 has some redundancy in that it potentially receives particles from both Area 6 and Area 5.

Table 3. Drift trajectories for modelled particle releases from within each closed area showing closed areas where particles first passed over as well as those with endpoints within the release area (Particle Retention), by depth, drift duration (2 weeks) and seasons (Summer, Autumn, Average) for sponges.

Drift Depth	Drift Duration	Particles Passing over/Ending in Closed Areas from Release Area (Summer, Autumn, Average)	Endpoints within the Release Area (Retention)
1245 m	2 weeks	Area 2 to Area 1 Area 3 to Area 2 Area 4 to Area 3 Area 5 to Area 4 Area 6 to Areas 5, 4	Areas 2, 4 (Summer) Areas 2, 4, 5 (Autumn) Areas 2 (Average)
1452 m	2 weeks	Area 2 to Area 1 Area 3 to Area 2 Area 4 to Area 3 Area 5 to Area 4 Area 6 to Areas 5, 4	Areas 2, 4, 5 (Summer) Areas 2, 4, 5 (Autumn) Areas 2, 4 (Average)
1684 m	2 weeks	Area 2 to Area 1 Area 3 to Area 2 Area 4 to Area 3 Area 5 to Area 4 Area 6 to Area 5	Areas 2, 3, 4, 5, 6 (Summer) Areas 2, 4, 5 (Autumn) Areas 2, 4, 6 (Average)

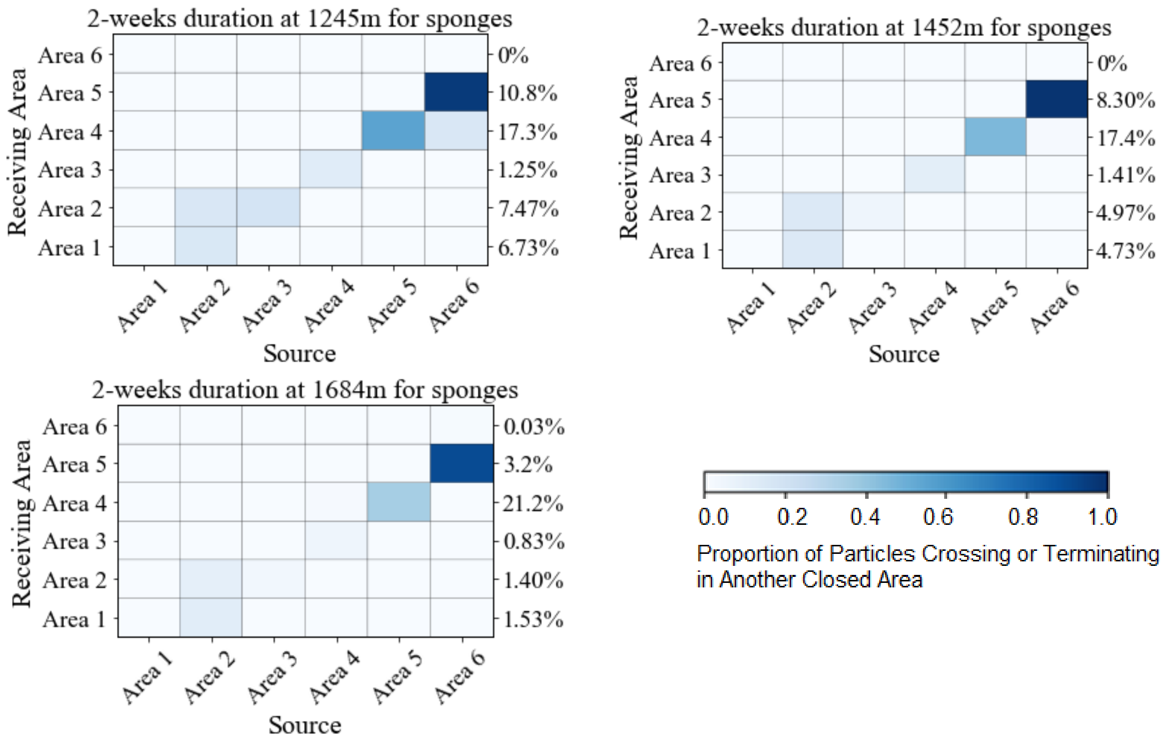

Figure 4. The proportion of modeled particles released from each of the 6 areas closed to protect large-size sponges (source areas; Areas 1, 2, 3, 4, 5, 6) and passing over or terminating in another area closed to protect large-size sponges (receiving areas). For each receiving area the percentage of the total number of particles released (from all source areas) are provided. Those values include particles that crossed, terminated or were retained in the receiving area. Drift durations were 2 weeks.

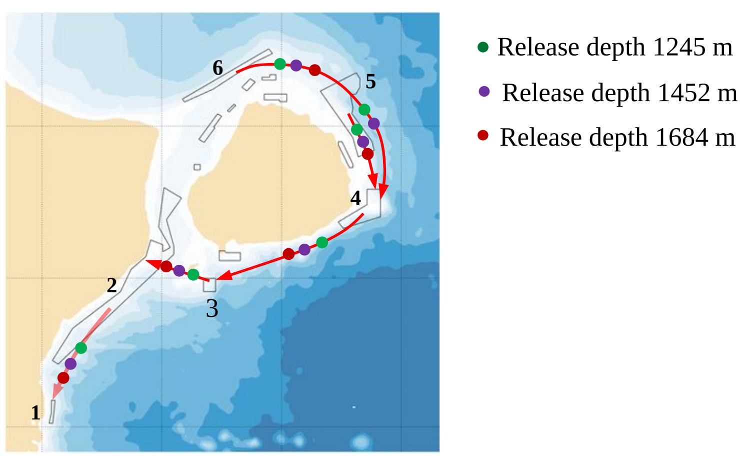

Figure 5. Connectivity pathways for particles released at 3 depths in each of the 6 areas closed to protect large-size sponges (Areas 1- 6) showing chain-linking with minimal redundancy in Area 4. Drift durations were 2 weeks. The closed circles over the lines indicates particles can reach another area when released from this depth.

Sea Pens

The connectivity and retention of particles for Areas 2, 7-12, 14, closed primarily to protect sea pens is presented in Table 4. The sea pens are connected between closed areas on Flemish Cap (Figures 6, 7) with all closed areas connecting to at least one other closed area under one or more drift duration/season/release depth scenarios. Areas 7, 8 and 9 connect to the most other closed areas (7 each and all the same ones, including to each other). Area 8 connects to 7 other closed areas, while Areas 12 and 14 connect to 4 areas, Area 10 to two areas and Area 11 to just one other area (Area 2). Nineteen connections were observed with 2-week drift durations, effected at the minimum depth of the mean depth ranges for the combined areas (Table 4). Of those, 6 were maintained with 1-month drift duration and another 8 were added (Table 4). Under 3-month drift durations no connections were in common with those seen at 2-weeks drift duration, but 10 connections were observed, 5 of those in common with the 1-month drift scenarios, and 5 new. The number of connections observed decreased with depth. At the middle depth of the mean depth ranges for the combined areas, only 13 connections were observed with 2-weeks duration, 9 with 1 month duration and 7 with 3 months duration. At the deepest scenario (maximum of the mean depth ranges for the combined areas) only 4 connections were observed, 3 with 2-week drift durations and 1 with 3-month drift duration (Table 4). The connectivity matrix between closed areas for 1-month durations is shown in Figure 6. Those connections are summarized in Figure 7 for the average currents with one benthic mean depth for each area. Retention decreased and changed with depth and was observed in Areas 2, 7, 8, 9, 10, 14 at different depths/seasons (Table 4). However, the proportion of particles effecting the connections are very low (< 2% for most receiving areas), the exception being Area 2 which received 7-8% of the total number of particles (Figure 6). A number of areas showed redundancy (Figure 6).

Table 4. Drift trajectories for modelled particle releases from within each closed area showing closed areas where particles first passed over/ended as well as those with endpoints within the release area (Particle Retention), by depth, drift duration (2 weeks, 1 month, and 3 months) and seasons (Spring, Summer, Winter, Average) for sea pens.

Drift Depth	**Drift Duration**	**Particles First Passing over/Ending in Closed Areas from Release Area**	**Endpoints within the Release Area (Retention)**
643 m	2 weeks	Area 7 to Area 8, 9, 12 (Spring) 8, 9, 10, 12 (Summer) 8, 9, 12 (Winter) 8, 9, 12 (Average)	Area 2, 7, 8, 9, 14 (Spring)
		Area 8 to Area 7, 9 (Spring) 9, 10, 12, 14 (Summer) 7, 9, 14 (Winter) 7, 9, 12 (Average)	Area 2, 7, 8, 9, 14 (Summer)
		Area 9 to Area 7, 8, 10, 12 (Spring) 8, 10, 12 (Summer) 7, 8, 10, 12 (Winter) 7, 8, 10, 12 (Average)	Area 2, 7, 8, 9, 14 (Winter)
		Area 10 to Area 2, 11 (Spring) 2, 11 (Summer) 2, 11 (Winter) 2, 11 (Average)	Area 2, 7, 8, 9, 10, 14 (Average)
		Area 11 to Area 2 (Spring) 2 (Summer) 2 (Winter) 2 (Average)	
		Area 12 to Area 10, 11 (Spring) 2, 10, 11 (Summer) 2, 10, 11 (Winter) 10, 11 (Average)	
	1 month	Area 7 to Area 10, 11, 14 (Spring) 2, 11 (Summer) 2, 10, 11, 14 (Winter) 10 (Average)	Area 2, 8, 14 (Spring)
Drift Depth	**Drift Duration**	**Particles First Passing over/Ending in Closed Areas from Release Area**	**Endpoints within the Release Area (Retention)**
		Area 8 to Area 10, 12, 14 (Spring) 2, 7, 11 (Summer) 10, 11, 12 (Winter) 10, 14 (Average)	Area 2, 7, 14 (Summer)
		Area 9 to Area 2, 11, 14 (Spring) 2, 7, 11, 14 (Summer) 2, 11, 14 (Summer) 2, 11, 14 (Average)	Area 2, 8, 14 (Winter)
		Area 12 to Area 2 (Spring) 2 (Average)	Area 2, 7, 14 (Average)
		Area 14 to Area 2 (Winter)	
	3 months	Area 7 to Area 2 (Spring) 2, 11, 14 (Average)	Area 2 (Spring)
		Area 8 to Area 2, 11 (Spring) 2 (Winter) 2, 11 (Average)	Area 2 (Summer)
		Area 12 to Area 8 (Spring)	
		Area 14 to Area 2 (Spring) 2, 8, 10, 11 (Summer) 2 (Average)	Area 2 (Average)

902 m	2 weeks	Area 8 to Area 9, 10, 12 (Spring) 9, 10, 12 (Summer) 9 (Winter) 9 (Average)	Area 2, 8, 9 (Spring)
		Area 9 to Area 8, 10, 14 (Spring) 8, 10, 14 (Summer) 8, 10 (Winter) 8, 12 (Average)	Area 2, 8, 9 (Summer)
		Area 10 to Area 2, 11 (Spring) 2, 11 (Summer) 2, 11 (Winter) 2, 11 (Average)	Area 2, 8 (Winter)
		Area 11 to Area 2 (Spring) 2 (Summer) 2 (Winter) 2 (Average)	Area 2, 8 (Average)
		Area 12 to Area 2, 10, 11 (Spring) 2, 10, 11 (Summer) 10 (Winter) 10 (Average)	
	1 month	Area 8 to Area 7 (Summer) 10 (Winter) 10,12 (Average)	Area 2, 8 (Spring)
		Area 9 to Area 2, 11 (Spring) 2, 11 (Summer) 2, 12 (Winter) 10 (Average)	Area 2 (Summer)
		Area 12 to Area 2, 11 (Winter) 2, 11 (Average)	Area 2, 8 (Winter)
			Area 2, 8, 10 (Average)
	3 months	Area 8 to Area 2, 7, 11 (Spring) 2, 14 (Winter) 2, 11 (Average)	Area 2 (Spring)
		Area 9 to Area 7 (Summer) 11 (Winter) 2, 7, 11 (Average)	Area 2 (Summer)
			Area 2 (Winter)
			Area 2 (Average)
1062 m	2 weeks	Area 10 to Area 2, 11 (Spring) 2, 11 (Summer) 2, 11 (Winter) 2, 11 (Average)	Area 2, 10 (Spring)
		Area 11 to Area 2 (Spring) 2 (Summer) 2 (Winter) 2 (Average)	Area 2 (Summer)
			Area 2, 10 (Winter)
			Area 2, 10 (Average)
	1 month	No new connections	Area 2 (Spring)
			Area 2 (Summer)
			Area 2 (Winter)
			Area 2 (Average)
	3 months	Area 9 to Area 2 (Spring)	Area 2 (Spring)
			Area 2 (Summer)
			Area 2 (Winter)
			Area 2 (Average)

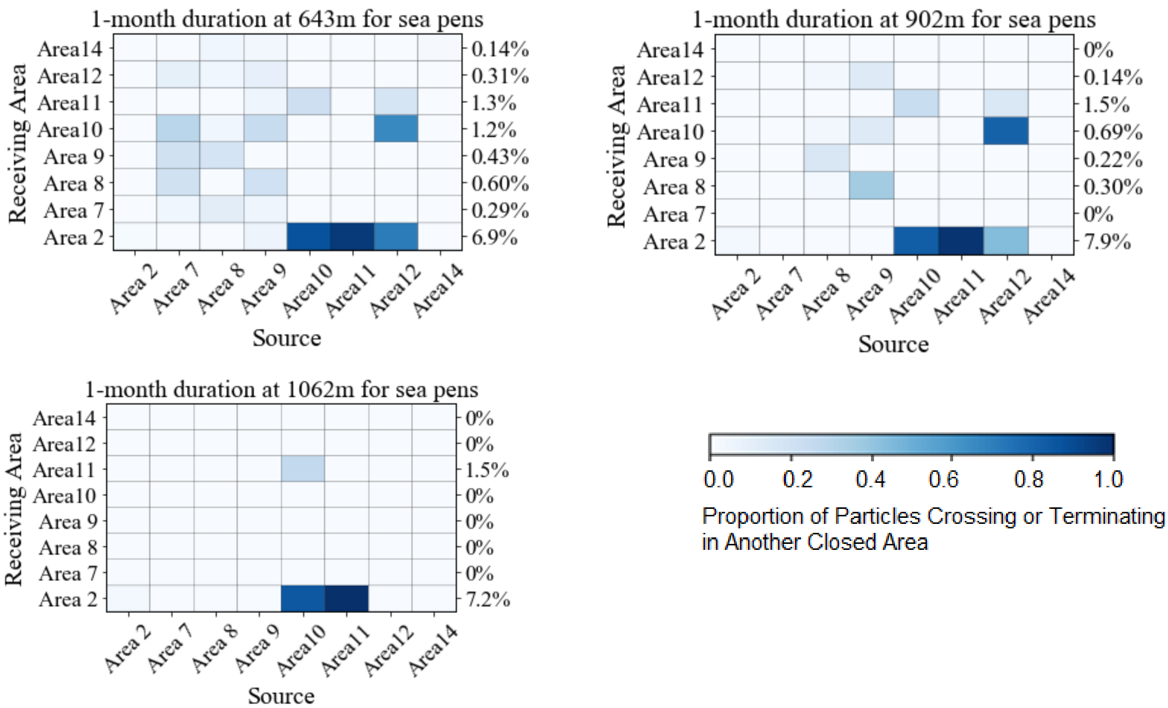

Figure 6. The proportion of modeled particles released from each of the 8 areas closed to protect sea pens (source areas; Areas 2, 7, 8, 9, 10, 11, 12, 14) and passing over or terminating in another area closed to protect sea pens (receiving areas). For each receiving area the percentage of the total number of particles released (from all source areas) are provided. Those values include particles that crossed, terminated or were retained in the receiving area. Drift duration was 1 month.

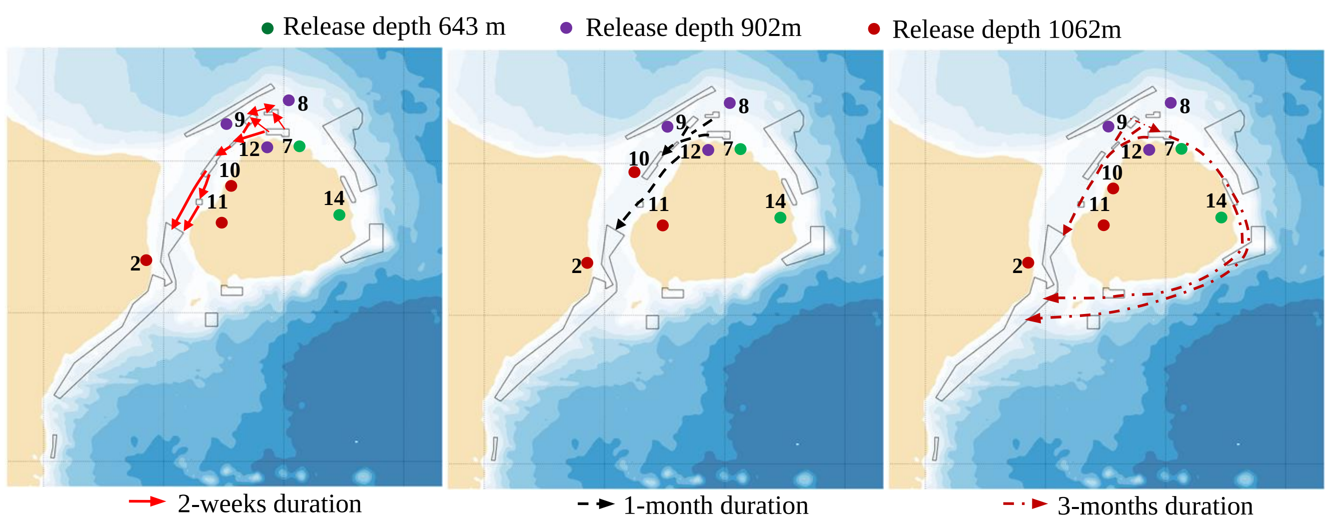

Figure 7. Connectivity pathways for particles released at 3 depths in each of the 8 areas closed to protect sea pens (Areas 2, 7, 8, 9, 10, 11, 12, 14). Drift durations were 2 weeks (left), 1 month (middle) and 3 months (right). The closed circles near the number code of some of the closed areas denotes that particles from this area are only released at this depth due to the depth of the closure, and the line indicates particles can reach another area when released from this depth.

Large Gorgonian Corals

The connectivity and retention of particles for Areas 2, 4, 5, 13 closed in part to protect large gorgonian corals is presented in Table 5. Six connections were made, 3 occurring with 2-week drift durations and 3 with 1-month drift durations. No added connections were seen with 3-month durations. The number of connections decreased with depth, more so at 1684 m than at the other depths. Three of the 4 areas (Areas 2, 4, 13) show particle retention with Area 2 showing retention at all depths. Those connections are summarized in Figure 8 for 1-month durations and mapped for 2 week and 1 month durations in Figure 9. With 1-month durations, Area 2 shows redundancy, receiving particles from 3 other areas closed to protect large gorgonian corals. With the 2-week duration, Area 13 has some redundancy (Figure 9).

Table 5. Drift trajectories for modelled particle releases from within each closed area showing closed areas where particles first passed over/ended as well as those with endpoints within the release area (Particle Retention), by depth and drift duration (2weeks, 1 month, and 3 months) for large gorgonian coral.

Drift Depth	Drift Duration	Particles First Passing over/Ending in Closed Areas from Release Area	Endpoints within the Release Area (Retention)
643 m	2 weeks	Area 4 to Area 13	Areas 2, 13
		Area 5 to Area 4, 13	
	1 month	Area 4 to Area 2	Areas 2, 13
		Area 5 to Area 2	
		Area 13 to Area 2	
	3 months	No new connections	No retention
1245 m	2 weeks	Area 4 to Area 13	Area 2
		Area 5 to Area 4, 13	
	1 month	Area 4 to Area 2	Area 2
		Area 5 to Area 2	
	3 months	No new connections	Area 2
1684 m	2 weeks	Area 5 to Area 4	Areas 2, 4
	1 month	Area 4 to Area 2	Areas 2, 4
		Area 5 to Area 2	
	3 months	No new connections	Areas 2, 4

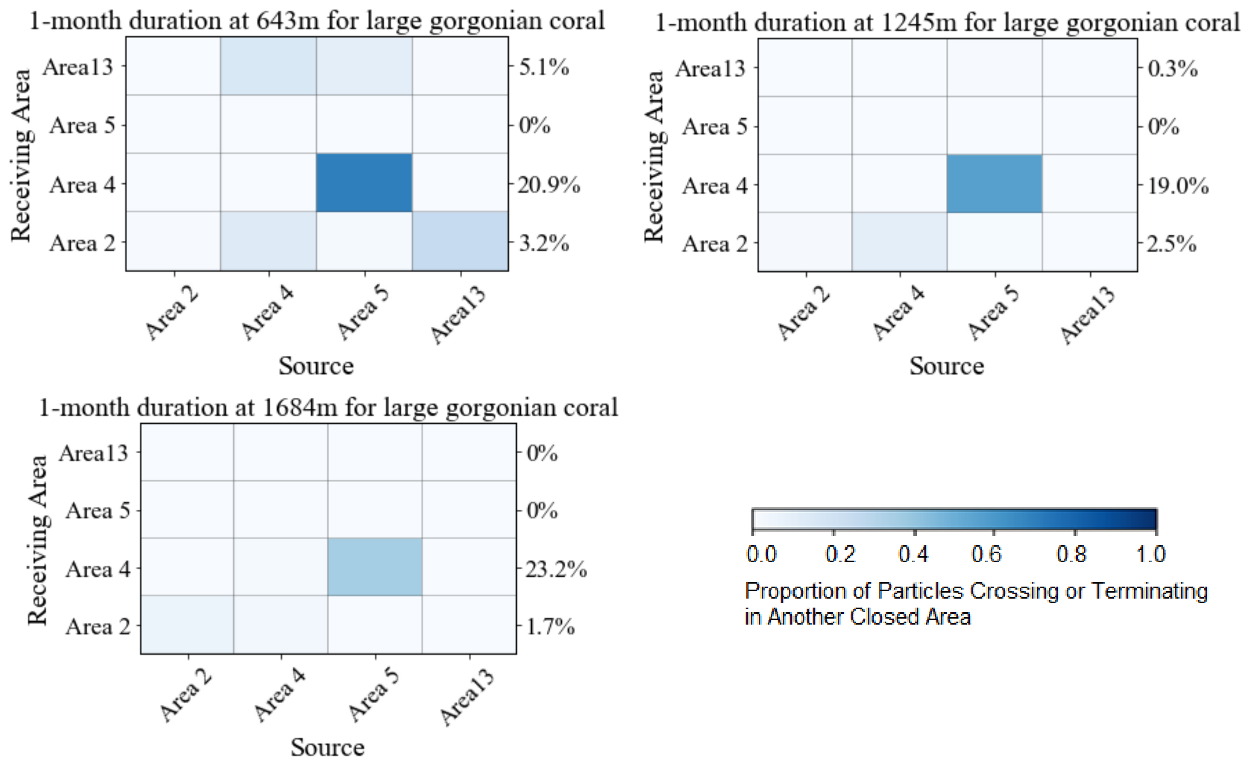

Figure 8. The proportion of modeled particles released from each of the 4 areas closed to protect large gorgonian corals (source areas; Areas 2, 4, 5, 13) and passing over or terminating in another area closed to protect large gorgonian corals (receiving areas). For each receiving area the percentage of the total number of crossed, terminated or were retained in the receiving area. Drift duration shown was 1 month.

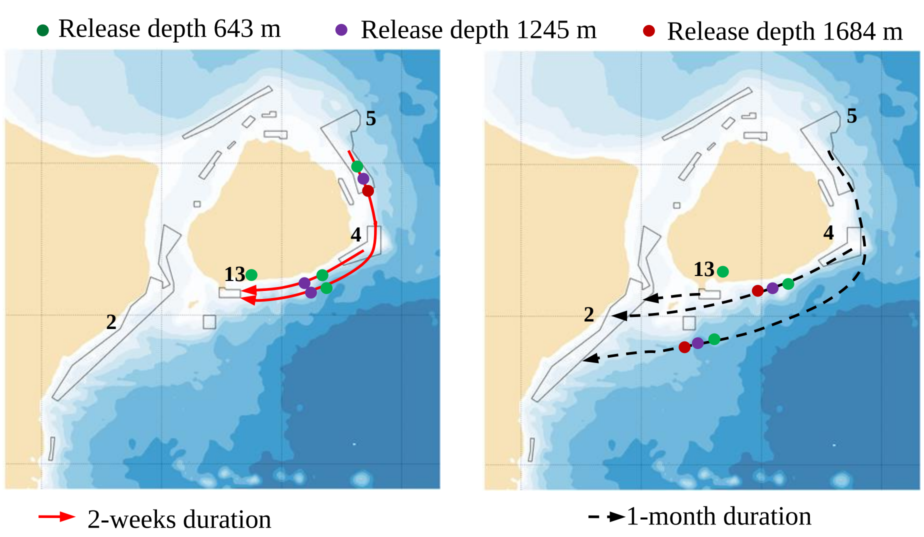

Figure 9. Connectivity pathways for particles released at 3 depths in each of the 4 areas closed to protect large gorgonian corals (Areas 2, 4, 5, 13). Drift durations shown are 2 weeks and 1 month. Area 13 shows some redundancy in 2-week durations and Area 2 shows redundancy in 1 month durations.

Summary Comments in Relation to the Closed Areas

The summary of the 3-D connectivity modeling is presented in Table 6. Five of the Closed Areas show that other areas connect to them and that they have some potential for retention. With one exception (Area 8) those closures are all for large sized sponges and large gorgonian corals. Area 1 has little to no retention predicted and appears to depend solely on Area 2 for recruitment. Similarly, Area 3, although it connects to another area, appears to depend solely on Area 4 for recruitment and retention is likely only at maximum depths in summer. Area 6 on Sackville Spur is also of concern. It is important to other areas and connects to Areas 5 and 4 but no other areas connect to it and retention may be limited to summer at the deepest depths only. Area 14 connects to other areas and other areas connect to it. It is clearly a fundamental part of the sea pen closed area network. Fishing this area could compromise recruitment to Areas 7, 8 and 9 which are key areas in the network but are all small and have limited in-coming connections (Table 6). The whole of the sea pen network (Table 6) is vulnerable because it depends on connections between closed areas with very limited retention in any of the areas but Area 8.

Table 6. Summary of connectivity evaluated between Closed Areas within functional groups and retention from the 3-D particle tracking studies.

Closed Area	Conservation Target	Summary
1	Sponge	Does not connect to any other area; Area 2 connects to it; no retention.
2	Sponge/Large Gorgonian Coral/Sea Pen	Connects only to Area 1; Areas 3, 4, 5, 7, 8, 9, 10, 11, 12, 13, 14 connect to it; retention at all depths/seasons due to large size.
3	Sponge	Connects only to Area 2; Area 4 connects to it; retention only at maximum depths in summer.
4	Sponge/ Large Gorgonian Coral	Connects to Areas 2, 3, 13; Areas 5 and 6 connect to it; retention observed.
5	Sponge/ Large Gorgonian Coral	Connects to Areas 2, 4 and 13; Area 6 connects to it; retention in summer and autumn only.
6	Sponge	Connects to Areas 5 and 4; no other areas connect to it; retention in summer and average models at deepest depths only.
7	Sea Pen	Well connected to Areas 2, 8, 9, 10, 11, 12, 14; Areas 8 and 9 connect to it; retention observed.
8	Sea Pen	Well connected to Areas 2, 7, 9, 10, 11, 12, 14; Areas 7, 9, 12 and 14 connect to it; retention.
9	Sea Pen	Well connected to Areas 2, 7, 8, 10, 11, 12, 14; Areas 7 and 8 connect to it; some retention with short durations.
10	Sea Pen	Connects to Areas 2 and 11; Areas 7, 8, 9, 12 and 14 connect to it; limited retention.
11	Sea Pen	Connects to Area 2; Areas 8, 9, 10, 12 and 14 connect to it; no retention.
12	Sea Pen	Connects to Areas 2, 8, 10, 11; Areas 7, 8 and 9 connect to it; no retention.
13	Large Gorgonian Coral	Connects to Area 2; Areas 4, 5 connect to it; retention in shallower portions of closure
14	Sea Pen	Connects to Areas 2, 8, 10, 11; Areas 7, 8, 9 connect to it; no retention.

Addendum

Since the preparation of this document, a paper has been published (Wang et al. 2020) which updates these results. This publication uses a shorter time step (20 min) and both forward and backward model runs based on comments from the reviewers. Wang et al. (2020) was used for incorporating connectivity into the WGESA 2020 discussions.

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