Assessing the Planktonic Connectivity of the Channel MPA Network

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Cohérence

PANACHE

Protected Area Network Across the Channel Ecosystem

Assessing the Planktonic Connectivity of the Channel MPA Network

Coherence

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Assessing the Planktonic Connectivity of the Channel MPA Network

Evaluation de la connectivité planctonique du réseau d'aires marines protégées en Manche

ABSTRACT

While Work Package 1 of the PANACHE project aims at assessing the ecological coherence of the current network of MPAs designated to date across the Channel area, the current report studies more particularly the planktonic connectivity among the Channel MPA network through the simulation of eggs and larvae drift by Lagrangian models. Two complementary approaches were used: the first one considers as many species as possible but with a coarse representation of biological processes, and the second approach focuses on MPA connectivity through the larval transport of the well-known common sole species, for which knowledge of biological processes and associated parameters exist. Results allow the identification of clusters of highly connected MPAs that should be managed together, or conversely isolated areas for which local management measures will prevail. Finally, areas of cross-Channel connectivity appear to be limited, and concern mostly species with long larval transport.

KEYWORDS: connectivity, larval transport, particle tracking IBM, Channel MPA network

RÉSUMÉ

Si l'axe de travail 1 du projet PANACHE a pour objectif d'évaluer la cohérence écologique du réseau actuel d'AMP dans l'espace Manche, ce rapport étudie plus en détail la connectivité planctonique du réseau d'AMP de la Manche grâce à la simulation du déplacement des oeufs et des larves par des modèles lagrangiens. Deux approches complémentaires ont été utilisées : la première examine autant d'espèces que possible mais avec une représentation grossière des processus biologiques, et la seconde approche se concentre sur la connectivité des AMP par le transport au stade larvaire de l'espèce commune de la sole pour laquelle les processus biologiques et les paramètres associés sont parfaitement connus. Les résultats permettent d'identifier des ensembles d'AMP très connectées qui devraient bénéficier d'une gestion commune ou, au contraire, des aires isolées pour lesquelles des mesures de gestion locales sont plus appropriées. Enfin, les aires de connectivité transmanche semblent être limitées et concernent surtout des espèces avec un transport larvaire sur de longues distances.

MOTS-CLÉS : connectivité, transport au stade larvaire, modèle individu-centré de suivi de particules, réseau d'AMP de la Manche

Table des matières

List of Figures

List of Tables

I. Introduction

While English and French MPAs have been implemented separately in the Channel, the overall aim of the PANACHE project is to develop transnationally a stronger and more coherent approach to the management, monitoring and involvement of stakeholders of MPAs in this region. Dealing with the first of these aspects, Work Package 1 (WP1) studies more particularly the ecological coherence of the current network of MPAs designated to date across the Channel area, using criteria and methods put forward by OSPAR (2006, 2008) and others. The results of the work produced by WP1 are gathered in a larger report (Foster et al. 2014). The following criteria are used to assess ecological coherence of the Channel MPA network: representativity, replication, viability, adequacy, connectivity and management status (previously referred to as level of protection) (Sciberras, 2013).

As part of the criteria for ecological coherence, connectivity represents the extent to which the populations in different parts of a species' range are linked. Understanding the extent to which populations and sites are connected is critical both for the design of MPA networks to protect biodiversity, and for the development of conservation strategies to protect species associated with degrading and fragmenting habitats (Jones et al., 2008; Kritzer and Sale, 2004; UNEP-WCMC, 2008). This linkage can include several mechanisms at different life stages, such as larval dispersal (eggs, larvae or other propagules) or movement of juveniles or adults, and/or through functional linkages between communities, ecosystems and ecological processes.

Part of the connectivity assessment has been presented in the larger WP1 report (Foster et al. 2014), and is based on a simplified modelling approach using geographical distance among habitat patches and MPAs in order to provide preliminary information on the most- and least-connected areas of the MPA network. To complement these results, the present report assesses the connectivity of MPAs within the Channel network induced by larval dispersal. Whereas movement of juveniles and adults can be driven by various mechanisms according to the species and the season (foraging random walk, spawning migration, following a habitat preferendum gradient), larval dispersal is mostly driven by oceanography in the majority of cases. Furthermore, for most marine species, eggs and larvae are critical stages with high mortality rates and represent the bottleneck of population renewal (e.g. Anderson, 1988; Leggett and Deblois, 1994). In a conservation perspective, it is critical to take into account the dispersal of egg and larval stages when designing MPAs in a coherent network. An applied objective of the present report is to inform managers of the origin of eggs and larvae arriving in a particular area, and where the eggs and larvae produced in a protected area are susceptible to go within the Channel MPA network. To assess the connectivity of the Channel MPA network in terms of larval dispersal, the studies presented here use Lagrangian drift models forced by currents and aim to better identify clusters of highly connected MPAs, or conversely isolated areas, as well as areas of cross-Channel connectivity.

II. Methodology

With the aim of assessing the planktonic connectivity among MPAs in the Channel, a Lagrangian model was used to simulate the trajectories of eggs and larvae. Lagrangian-type methods follow the evolution of a particle subject to currents and computes its precise location at each time step following: $P(t+\Delta t) = P(t)+U(P(t))$, with P being the location of a particle and U a vector of currents. The main advantage of such models is their high flexibility. For example, they allow to take into account a high variety of biological processes. The drawbacks compared to Eulerian models are the reduction of a certain consistency and the requirements for important computing time and calibration tests.

In the context of connectivity assessment in a MPA network, two complementary approaches have been used, both based on Lagrangian modelling of eggs and larval drift. The first approach is a holistic perception of the planktonic connectivity of the Channel MPA network where we attempt to quantify the connectivity of the drifting first life stages among MPAs for as many species as possible. This follows the *a priori* statement that MPAs are expected to yield indirect benefit to the whole ecosystem, translated here as considering a high number of species. The scientific knowledge required to parameterize the model were not be available for all the species considered, which led to simplifications in the representation of biological processes in this multi-species approach. Conversely, the second approach computed the connectivity of the Channel MPA network for one well-known species, the common sole (*Solea solea*), for which a wealth of associated literature allowed a more refined representation of biological processes and more specific results.

2.1 The generic approach

2.1.1 Extent of the Channel MPA network considered

The Channel MPA network is composed of several categories of protected areas, including areas with a terrestrial component. Among the 222 MPAs identified in the Channel (Foster et al. 2014, Figure 1), some are too small or located too far inshore to be considered in this modeling study. Indeed, using a hydrodynamic model limits both the inshore coverage and spatial resolution of MPAs that can be included. The boundaries and spatial resolution of the hydrodynamic model used here (model MARS-3D, see below) allows us to considered only 100 MPAs.
Furthermore, as already described in the report of PANACHE WP1 (Foster et al. 2014) some MPAs are overlapping and needed to be merged for the current study. As we aimed to assess the connectivity between MPAs, we considered areas with a strong overlap to be a unique zone to study. Indeed, while studying connectivity we only consider the geographical position and physical characteristics (habitat, water temperature, depth) of the MPAs. The expected protection effects

arising from conservation measures set by law are not studied here, so two areas with identical geographical boundaries will not present any differences in this study. By grouping overlapping areas, we ended up with 53 zones of release for the first life stages (see Table 1 and Figure 2).

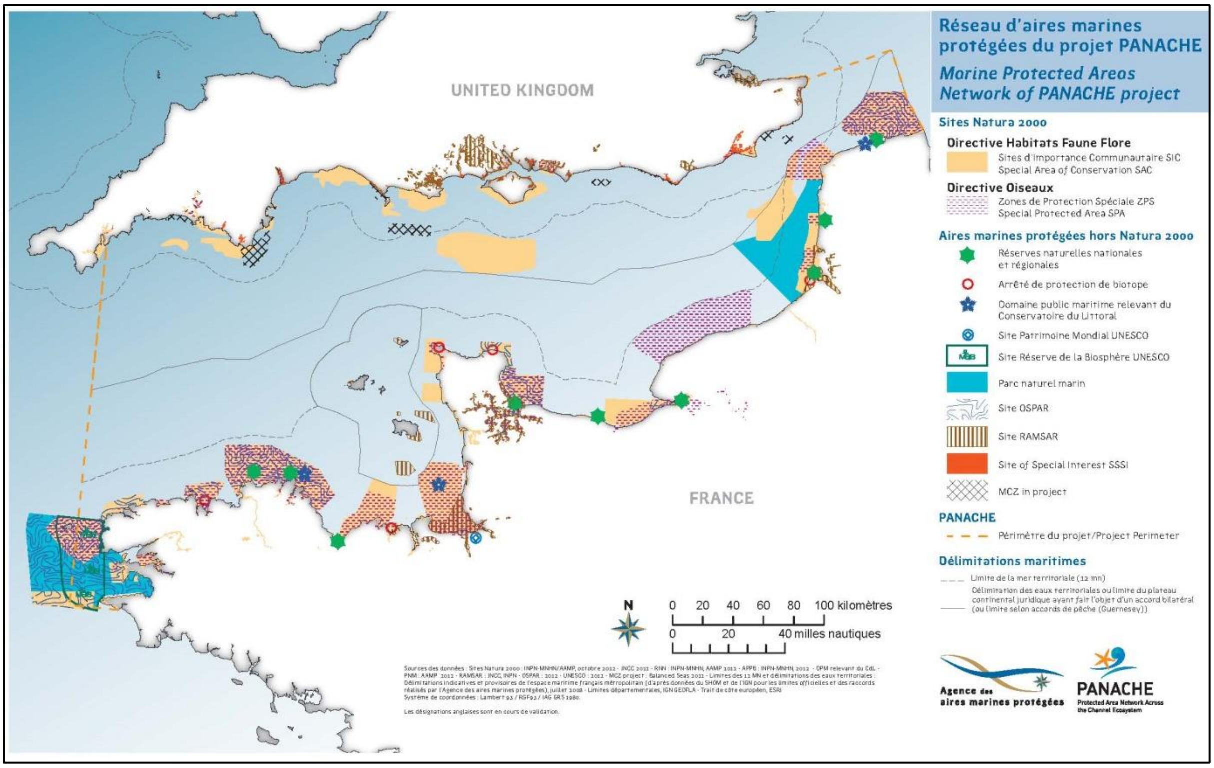


Figure 1: The PANACHE study area highlighting the range of MPA designation types within the network.

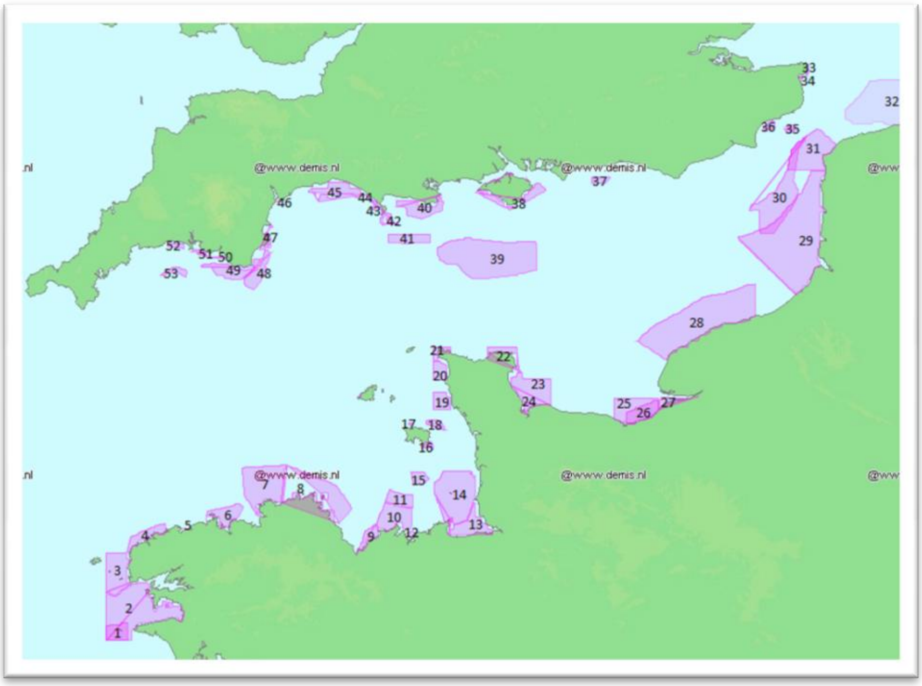


Figure 2: Location of the 53 areas considered in this study, resulting from merging overlapping MPAs and removing those MPAs that were too small or within inshore protected areas. See Table 1 for details.

Table 1: List of the Channel MPAs included in the 53 areas considered in this study.

Number of Zone	Country	Name	Type	Overlap (Yes / No)
1	FR	Parc marin d'Iroise	Parc naturel marin	No
2	FR	Iroise	• Zone marine protégée • parc naturel marin • OSPAR	Yes
3	FR	Ouessant - Molène	• Site d'importance communautaire (N2000,DHFF) • Zone de protection spéciale (N2000, DO)	Yes
4	FR	Abers - côtes des Légendes	• Site d'importance communautaire (N2000, DHFF) • OSPAR	Yes
5	FR	Anse Goulven - dunes de Keremma	• Zone spéciale de conservation (N2000, DHFF)	No
6	FR	Baie de Morlaix	• Site d'importance communautaire (N2000, DHFF) • OSPAR • Zone de protection spéciale (N2000, DO)	Yes
7	FR	côte de granit rose - Sept-îles	• Site d'importance communautaire (N2000, DHFF) • Zone de protection spéciale (N2000, DO) • OSPAR	Yes
		Sept-îles	• réserve naturelle nationale	
8	FR	Trégor - Goëlo	• Site d'importance communautaire (N2000, DHFF) • OSPAR • Zone de protection spéciale (N2000, DO)	Yes

9	FR	Baie de Saint-Brieuc est	• Site d'importance communautaire (N2000, DHFF) • Zone de protection spéciale (N2000, DO)	Yes
		Baie de Saint-Brieuc	• réserve naturelle nationale • OSPAR	
10	FR	cap d'Erquy - cap Fréhel	• Site d'importance communautaire (N2000, DHFF)	No
11	FR	cap d'Erquy - cap Fréhel	• Zone de protection spéciale (N2000, DO)	No
12	FR	îles de la Colombière, de la Nellière	• Zone de protection spéciale (N2000, DO)	No
13	FR	Baie du Mont-Saint-Michel	• Site d'importance communautaire (N2000, DHFF) • RAMSAR • Zone de protection spéciale (N2000, DO)	Yes
14	FR	Chausey	• Site d'importance communautaire (N2000, DHFF) • Zone de protection spéciale (N2000, DO)	Yes
15	Channel Isands	Les Minquiers, Jersey	• RAMSAR	No
16	Channel Islands	SE Coast, Jersey	• RAMSAR	No
17	Channel Islands	Les Pierres de Lecq, Jersey	• RAMSAR	No
18	Channel Islands	Les Ecrehou and Les Dirouilles, Jersey	• RAMSAR	No
19	FR	banc et récifs de Surtainville	• Site d'importance communautaire (N2000, DHFF)	No
20	FR	anse de Vauville	• Site d'importance communautaire (N2000, DHFF)	No
21	FR	récifs et landes de la Hague	• Site d'importance communautaire (N2000, DHFF)	No
22	FR	récifs et marais arrière	• Site d'importance communautaire (N2000, DHFF) • OSPAR	Yes
23	FR	baie de Seine occidentale	• Site d'importance communautaire (N2000, DHFF) • OSPAR • Zone de protection spéciale (N2000, DO)	Yes
24	FR	marais du Cotentin et du Bessin	• Site d'importance communautaire (N2000, DHFF)	Yes
		marais du Cotentin et du Bessin - baie de Veys	• OSPAR • RAMSAR	
		domaine de Beauguillot	• Reserve naturelle nationale • OSPAR	
		basses vallées du Cotentin et baie	• zone de protection spéciale (N2000, DO)	
25	FR	baie de Seine orientale	• Site d'importance communautaire (N2000, DHFF)	No
26	FR	littoral augeron	• Zone de protection spéciale (N2000, DO)	No
27	FR	estuaire et marais de la basse Seine	• Zone de protection spéciale (N2000, DO)	Yes
		estuaire de la Seine	• Réserve naturelle nationale • OSPAR • Site d'importance communautaire (N2000, DHFF)	

28	FR	littoral seino-marin	• Zone de protection spéciale (N2000, DO)	No
29	FR	estuaires picards et mer d'Opale	• Parc naturel marin	Yes
		estuaires et littoral picards	• Site d'importance communautaire (N2000, DHFF)	
		estuaires picards : baie de somme	• Zone de protection spéciale (N2000, DO)	
30	FR	ridens et dunes hydrauliques	• Site d'importance communautaire (N2000, DHFF)	No
31	FR	récifs Gris-Nez Blanc-Nez	• Site d'importance communautaire (N2000, DHFF)	Yes
		Cap Gris-Nez	• Zone de protection spéciale (N2000, DO)	
32	FR	Bancs des Flandres	• OSPAR • Site d'importance communautaire (N2000, DHFF) • Zone de protection spéciale (N2000, DO)	Yes
33	GBR	Thanet Coast	• Special Area of Conservation	No
34	GBR	Thanet Coast and Sandwich Bay	• Special Protection Area; OSPAR; RAMSAR	No
35	GBR	Folkestone Pomerania	• Marine Conservation Zone	No
36	GBR	Hythe Bay	• Marine Conservation Zone	No
37	GBR	Kingmere	• Marine Conservation Zone	No
38	GBR	South Wight Maritime	• Special Area of Conservation; OSPAR	No
39	GBR	Wight - Barfleur Reef	• candidate Special Area of Conservation	No
40	GBR	Studland to Portland	• candidate Special Area of Conservation	No
41	GBR	South Dorset	• Marine Conservation Zone	No
42	GBR	Studland to Portland	• candidate Special Area of Conservation	No
43	GBR	Chesil Beach and Stennis Ledges	• Marine Conservation Zone	No
44	GBR	Chesil Beach and the Fleet	• Special Area of Conservation • OSPAR • Special Protection Area • RAMSAR • Site of special scientific interest	Yes
45	GBR	Lyme Bay and Torbay	• Site of Community importance • OSPAR	Yes
46	GBR	Exe Estuary	• Site of Special Scientific interest • Special Protection Area • OSPAR • RAMSAR	Yes
47	GBR	Lyme Bay and Torbay	• Site of Community importance • OSPAR	Yes
48	GBR	Skerries Bank and surrounds	• Marine Conservation Zone	No
49	GBR	Start Point to Plymouth Sound and Eddystone	• Site of Community importance • OSPAR	Yes
50	GBR	Start Point to Plymouth Sound and Eddystone	• Site of Community importance • OSPAR	Yes
51	GBR	Plymouth Sound and Estuaries	• Special Area of Conservation • OSPAR • Site of special scientific interest	Yes
52	GBR	Whitsand and Looe Bay	• Marine Conservation ZOne	No
53	GBR	Start Point to Plymouth Sound and Eddystone	• Site of Community importance • OSPAR	Yes

2.1.2 Set of species considered

Although some MPAs in the Channel have specific conservation purposes, whatever conservation measure taken (except maybe protecting bird colonies) may indirectly benefit to other species and other MPAs in the network through passive or active dispersal processes. In order to take passive transport of planktonic life stages into account, we aimed to assess the connectivity among MPAs for as many species as possible. However, due to the methodology used, we faced some constraints regarding the choice of species considered:

- Intertidal species would not be well represented in the model (due to uncertainties linked to boundary conditions, plus because of the relatively low spatio-temporal resolution of the model for these species)
- Some species do not rely on current dispersion at larval stages, so connectivity among MPAs for these species cannot be computed from larval dispersal simulations
- Information required to parameterize the model is not always available for all species

Taking these constraints into account these, we conducted a literature review on a set of 158 species known to be present in the Channel in order to determine – when possible – the following information for each species:

- the spawning period (to assess the time of release of particles in the model)
- the spawning depth (to parameterize the depth of release of particles in the model)
- the duration of egg and larval stages (to estimate the duration of drift to model)
- possible knowledge about egg density and/or larval behavior (including vertical migration)
- possible adult distribution in the Channel (to determine preferential areas of release of particles in the model)
- Preferential habitat (to determine potential release areas and preferential recruitment zones)

For a few species (e.g. for sole and king scallop), some studies concerning larval dispersal have already been conducted (Rochette et al. 2012; Nicolle et al. 2013), thus, their behavior is well-known, especially concerning vertical migration, preferential habitats and egg location in the Channel. However, for most species, the current state of knowledge did not allow us to gather all the information listed above. As the objective of the current connectivity study is to assess the ecological coherence of the Channel MPA network for as many species as possible, we only considered the minimal information required to simulate larval dispersal: duration of egg and larval stages, and spawning depth and period. Furthermore, we grouped some species that are considered to have similar larval dispersal (both in term of duration and spawning) so we could use parameters of associated species. In doing so, we ended up with 53 groups of species for which we could conduct larval dispersal simulations (Table 2).

Table 2: Literature review gathering parameters of fish and invertebrate species (respectively on the left and right of the table) for larval dispersal simulations. Additional information concerning spawing and/or larval behaviors, when available, can be found in appendix 1.

Latin name	Spawning season	Spawning depth	Dispersion duration
Ammodytidae	december-january	Bottom	90 days
Aspitrigla cuculus	april- august	Surface	24 days
Buglossidium luteum	mai-august	Surface	24 days
Callionymidae	April-august	Surface	7 days
Chelidonichthys gurnardus	february - august	Water column	13 days
Clupea harengus	december - february	Bottom	60 days
Dicentrarchus labrax	february-june	Water column	35 days
Echiichthys vipera	june - august	Water column	18 days
Engraulis encrasicolus	April - august	Surface	34 days
Gadus morhua	December - May	Bottom	167 days
Limanda limanda	february - april	Bottom	20 days
Lotidae	january - september	Water column	120 days
Merlangius merlangus	march - june	Water column	30 days
Microstomus kitt	march - august	Surface	12 days
Mullus surmuletus	may - july	Water column	40 days
Platichthys flesus	february - june	Water column	17 days
Pleuronectes platessa	december - march	Surface	70 days
Sardina pilchardus	March - august and september-december	Water column	16 days
Scomber scombrus	june-july	Surface	26 days
Solea solea	February - june	Water column	25 days
Spondyliosoma cantharus	april - september	Bottom	70 days

Latin name	Spawning season	Spawning depth	Dispersion duration
Aequipecten opercularis	june - october	Bottom	35 days
Alcyonium digitatum	december - february	Bottom	17 days
Ascidiacea	may - october	Bottom	2 days
Asterias rubens	february - april	Water column	90 days
Astropecten irregularis	may-june	Water column	30 days
Cancer pagurus	november - january	Bottom	60 days
Crangon	march - december	Bottom	49 days
Crepidula fornicata	february - september	Bottom	30 days
Flustra foliacea	august - april.	Bottom	90 days
Homarus gammarus	July - december	Bottom	30 days
Hyas	august - september	Bottom	85 days
Hydrozoa	october - february	Bottom	3 days
Inachus	january - june	Bottom	105 days
Liocarcinus depurator	january - june	Bottom	55 days
Liocarcinus holsatus	april - august	Bottom	55 days
Macropodia	all year	Bottom	30 days
Maja brachydactyla	March - june	Bottom	21 days
Metridium senile	august - september	Water column	32 days
Necora puber	october - january and May-june	Bottom	39 days
Opisthobranchia	march - june	Water column	23 days
Ostrea edulis	june - october	Water column	24 days

Table 2 : continued

Latin name	Spawning season	Spawning depth	Dispersion duration
Sprattus sprattus	december - march	Water column	25 days
Trachurus trachurus	May - september	Water column	18 days
Trisopterus luscus	february - june	Water column	25 days
Trisopterus minutus	february- may	Bottom	17 days
Zeus faber	June - august	Water column	25 days

Latin name	Spawning season	Spawning depth	Dispersion duration
Pagurus bernhardus	december - march	Bottom	35 days
Pagurus prideaux	all year	Bottom	30 days
Pecten maximus	May - september	Water column	37 days
Psammechinus miliaris	April - september	Water column	70 days
Sponges	april - november	Water column	5 days
Urticina	april - june	Water column	8 days

2.1.3 Model description

In order to simulate larval dispersal, we use the Lagrangian model Ichthyop, forced by hydrodynamic outputs from the MARS-3D model. Particles representing eggs and/or larvae were released in this model and their location was followed at each time step until the end of the simulation.

The MARS 3D model (Lazure and Dumas, 2008), developed by IFREMER, has been used in this study for the domain defined by latitudes 47 and 52°N, and longitudes 5.865°W and 2.6°E (Figure 3). The hydrodynamic model MARS-3D provides input data for the larval drift model Ichthyop, and particularly models, via instantaneous or averaging computation, the following variables:

- fields of horizontal currents (U and V components) and the eulerian residuals
- water elevation, averaged levels and harmonic components of the tide
- salinity
- discharge components
- sediment transport and sedimentation.

The MARS-3D configuration used in this study is characterized by a 4km spatial resolution, 30 vertical layers and three processes considered for computing currents: tide, wind and density gradient (coming from water temperature and salinity). Although several years of hindcast have been simulated with MARS-3D, we only use the model output corresponding to the year 2012 for the current study, due to computing time limitation.

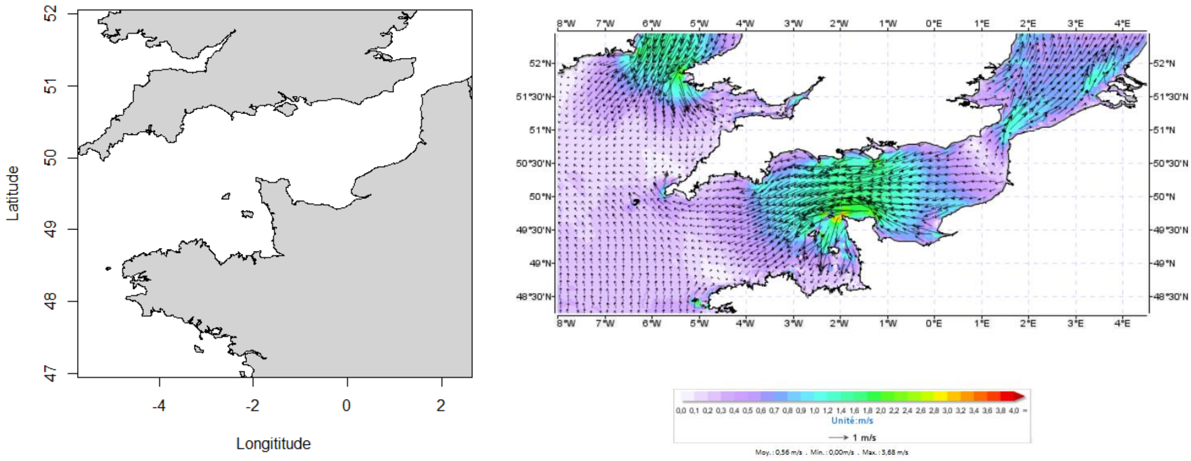


Figure 3: Representation of the domain considered (left) and currents as simulated by MARS 3D (right).

Ichthyop is an individual-based model of larval drift, developed by Lett *et al*. (2008). This software, written in Java, is a Lagrangian tool for modeling ichthyoplankton. It allows the simulation of individual trajectories in a given area, using forcing variables provided by a hydrodynamic model (MARS-3D in the current study) through NetCDF input files. In addition to larval drift, this tool can integrate diverse applications, such as simulating egg buoyancy, larval growth (according to temperature and/or food availability), behavior of horizontal and vertical dispersion, and behavior of vertical migrations. Spawning can be simulated following two schemes of spatial distribution, either a random distribution in a delimited area or on the contrary at positions and depths set by the user (for instance, for spawning at sea surface or on the bottom).

The software has a graphic interface that allows the user to set simulation parameters and visualize the simulated results via animations, possibly by selecting a particular variable of interest (size, development stage, temperature, etc.) (Figure 4). It is also possible to run the model using command lines on a terminal, an option that was used here when launching several parallel simulations on the “Caparmor” computing cluster hosted by IFREMER. Simulated results are saved as NetCDF files, readable with data analysis software such as R or Matlab. Variables are updated at each time step (in this study 200 s) and interpolated between two time steps.

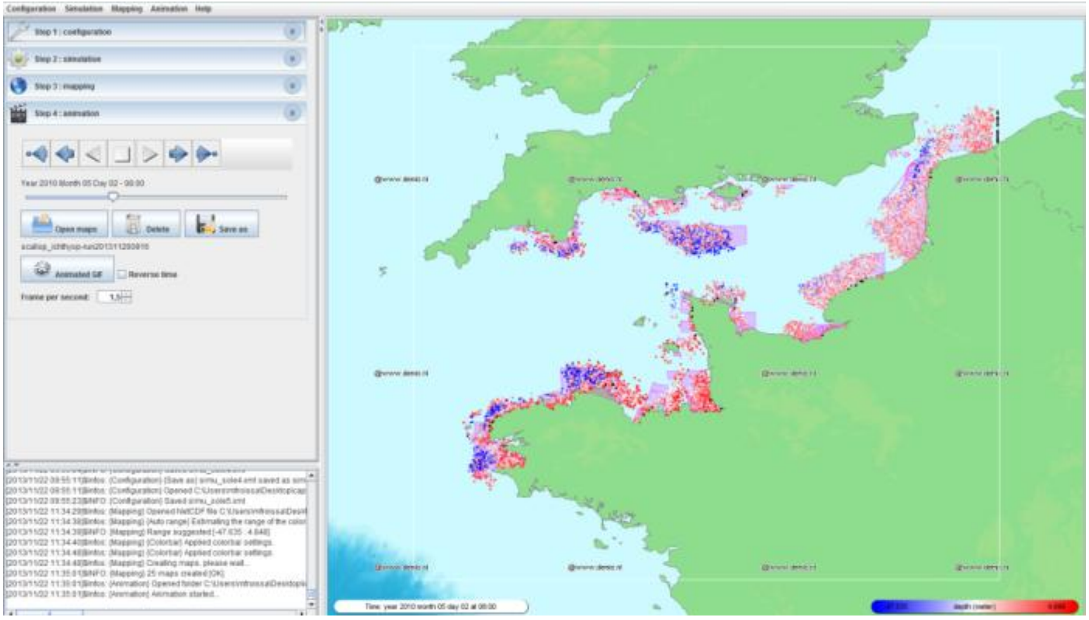


Figure 4: Graphical interface of the software Ichthyop 3.2b

a. Characteristics of particle transport and larval behavior

Simulations of passive transport were conducted by taking into account only advection due to currents and horizontal dispersion. For advection, numerical estimation involved the basic Euler approximation method, which solves first order differential equations. Concerning horizontal dispersion, the dissipation rate was set to the standard value of 10^{-9} $m.s^{-1}$. It was hypothesized that particles beach when arriving at the coastline. Due to a lack of precise information, vertical migration of individuals was not taken into account, neither was egg buoyancy nor any wind effect on the surface drift of particles. Species particularities were not taken into account during the transport of particles, but rather during the release phase and simulation duration.

b. Time and duration of simulations

For each species or group of species, simulations were run every 15 days during their spawning period. For each simulation, 50 000 individuals were released over the Channel MPAs, this number being a compromise between simulation precision and associated simulation time and required memory. The density of released particles was constant, i.e. the number of particles released was proportional to the size of the MPAs. Simulation duration corresponded to the duration of egg incubation (if they are subject to drifting) and duration of larval stages.

Because of limited information on spawning location and recruitment habitat, the released particle density could not match the actual release pattern over all the English Channel area. Therefore it is rather a potential connectivity pattern for each species across the MPA network that is evaluated here.

2.2 The detailed approach: the Sole case study

This section presents the use of an existing sole larval transport model to study the connectivity among MPAs and sole nursery grounds. The following paragraphs provide some details about this model, but for more information, please refer to Rochette et al (2012).

2.2.1 Hydrodynamical modelling

The three-dimensional (3D) ocean circulation model MARS (hydrodynamic Model for Application at Regional Scale; Lazure and Dumas, 2008) was used to simulate hydrodynamics in the Eastern and Western Channel, and the southern North Sea over 26 years (1982–2007). The model used a 4 km horizontal resolution with 30 vertical sigma layers. A time step of about 2 min allowed the model to solve the strong tidal currents occurring in the Channel with respect to stability criteria.

2.2.2 Spawning

a. Interannual number of eggs

The total number of eggs released each year in the area was calculated from: the number of adults of each age, the sex ratio, the number of eggs per female and the proportion of mature females (ICES, 2010).

b. Spawning season and peak

In the eastern Channel, the sole spawning period starts in February–March when sea surface temperature reaches 7°C and ends in June with a spawning peak in April–May, correlated to sea surface temperature. For each year, a dome-shaped curve was defined from a model established using the egg survey conducted in 1991 in the eastern channel by the UK Centre for Environment, Fisheries and Aquaculture Science (ref. in Rochette et al, 2012). Based on bibliography, a fixed 15 day precession was set for the western Channel, while a 31 day lag was applied in the North Sea (refs. in Rochette et al, 2012).

c. Spatial distribution

Based on the available data (egg surveys described in Rochette et al, 2012), the relative spatial distribution of eggs varied throughout the spawning season but was assumed to be constant over years.

The number of eggs spawned in a given cell of the grid at a given date of a given year is the product of: (1) the total number of eggs spawned this year (variable), (2) the proportion of it spawned at this date (variable), and (3) the proportion of it spawned in this cell at this time of the season (constant). As a result, although the relative spatial distribution of eggs is constant from year to year, the absolute distribution varies because (1) the number of eggs spawned per year varies; (2) the timing of the spawning varies.

In the case of this project, the resulting egg distribution was superimposed on the MPA map to extract the number of eggs spawned within each of them (Figure 5). For this purpose, we only considered the MPAs larger than 100 km².

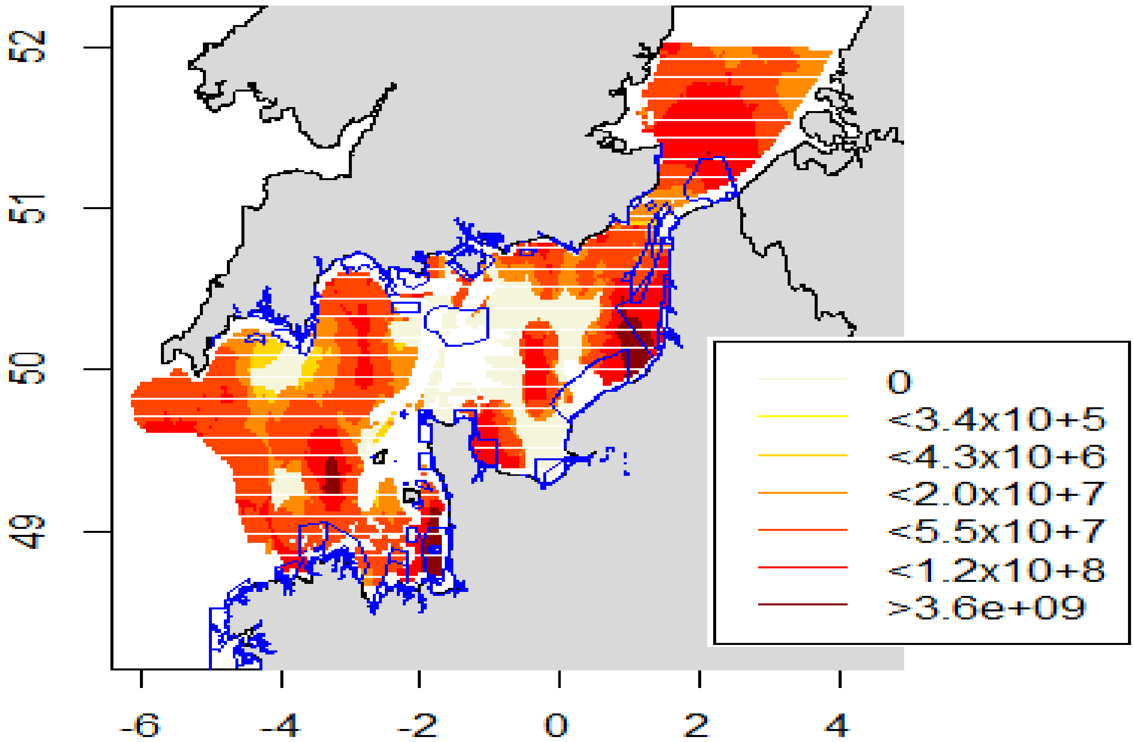


Figure 5: Distribution of the total number of eggs spawned in 1982. The MPAs are represented in blue.

2.2.3 Particle modelling

A particle-tracking module was coupled online to the 3D hydrodynamic model with a random-walk to account for vertical turbulent mixing. This module included an individual based modeling framework simulating trajectories and life traits of released particles from spawning areas to nursery grounds.

a. Life traits of drifting particles

Particle status evolved during drift through five successive development stages: passive transported eggs, passive transported larvae at development stage 1, vertical migrating larvae from stage 2, larvae at metamorphosis, and settled larvae. Transitions between these size-specific development stages and mortality rates vary depending on water temperature along the trajectories. Details are provided below on how the different stages were modelled, but please refer to Rochette et al (2012) for more information.

Eggs -> Larvae 1*:* Four egg development stages were distinguished. The durations of egg stages are temperature dependent Eggs tend to ascend to the surface during the first three development stages through buoyancy but they are also subject to vertical mixing with the model random-walk. Vertical advection is fully passive for the fourth development stage.

The survival of eggs varied depending on the temperature encountered as well as the egg diameter (related to the age of females and the spawning time).

Larvae 1 -> Metamorphosis: The duration of larval stage 1 is temperature-dependent. Larvae are unable to swim actively during this stage.

At stage 2, larvae acquire a swimming capacity and go through vertical nycthemeral migrations which are triggered by luminosity thresholds. Thresholds are defined as a function of the developmental stage (decrease with age). Suspended matter is accounted for in the calculation of the target depth (corresponding to a given luminosity threshold). The modelled irradiance is used to derive luminosity.

Survival probability during the larval stages depended on a fixed mortality rate (0.09 day^{-1}) and the duration of the entire larval stage until metamorphosis, specific to each trajectory.

b. Larval settlement and end of simulations

From stages 2 to 4, larvae are able to use selective tidal stream transport combined with nycthemeral migrations to reach the coasts (see refs in Rochette et al, 2012). However, this behaviour only appears when larvae approach settlement zones (see refs in Rochette et al, 2012). Besides, no metamorphosed larvae or juveniles were ever found outside nursery areas (see refs in Rochette et al, 2012), which suggest that larvae die reaching the size of metamorphosis when out of nursery grounds. Therefore, to avoid the spurious simulation of larval behaviour over coastal areas, the model simply tested whether larvae reach the coastal strip before metamorphosis. **Hence, the final destination to the nursery grounds was not targeted and larval supply was estimated at the scale of each nursery area as a whole.** For this reason, we cannot extract the amount of larvae settled within each MPAs (as we did for the spawning area).

In the model, larvae are transported until they reach the coastal area within the 20-m isobath with a soft bottom (i.e. nursery ground; Figure 6) or until they reach metamorphosis. If they reach a nursery ground at stage 2 or later before metamorphosis, they are considered to settle in this area but the larval mortality is still applied until metamorphosis. If they attain metamorphosis outside these coastal sectors, a 0% survival is applied.

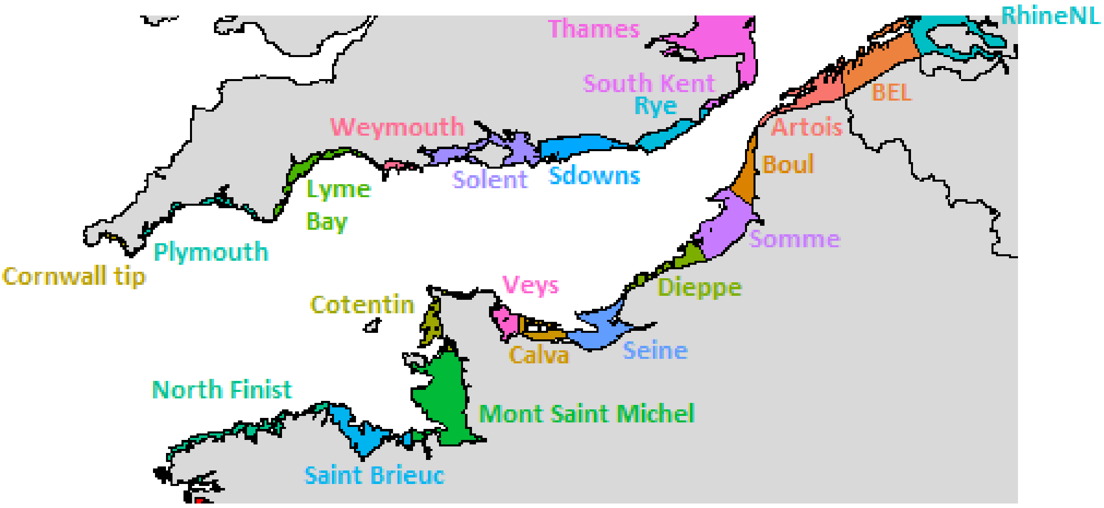


Figure 6: Sole nurseries in the English Channel as they are defined in the model: All the soft bottoms within the 20 m isobath.

III. Results

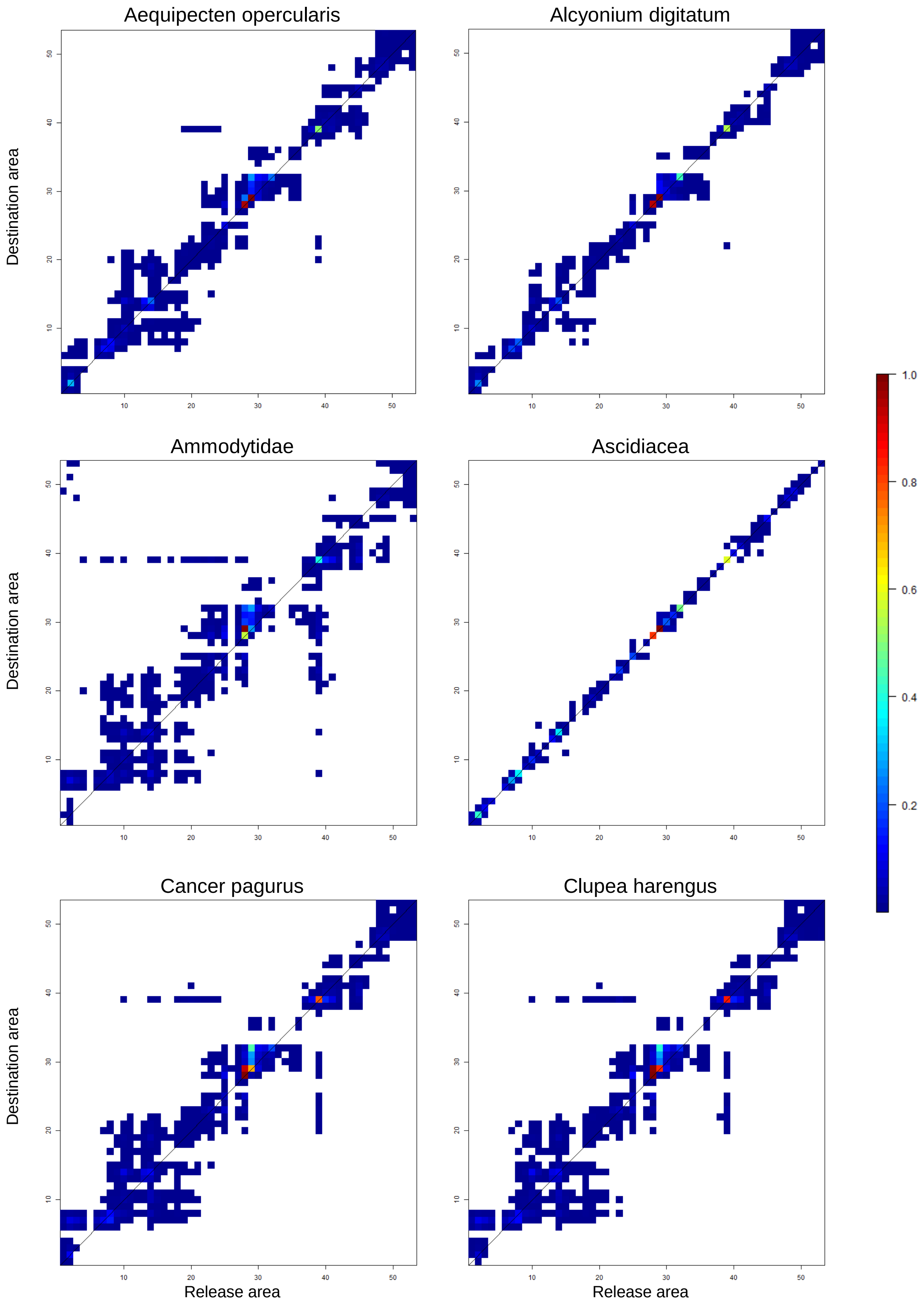
3.1 The generic approach

The results are presented as connectivity matrices, which represent the proportion of the particles released in zone *i* (on the x-axis), that arrived in zone *k* (on the y-axis) at the end of the simulation, i.e., at the end of dispersal. A high value on the i:i diagonal indicates a strong retention in the considered MPA. Connectivity matrices have been computed for each species and each release date (every 15 days during their spawning period, lasting from 2 months to the year according to species considered). This resulted in 534 connectivity matrices, which have been averaged by species in order to be presented in this report (section 3.2.1 ; Figures 5, 6 and 7) but see section 3.2.2 and its figures for examples of seasonal evolution of connectivity.

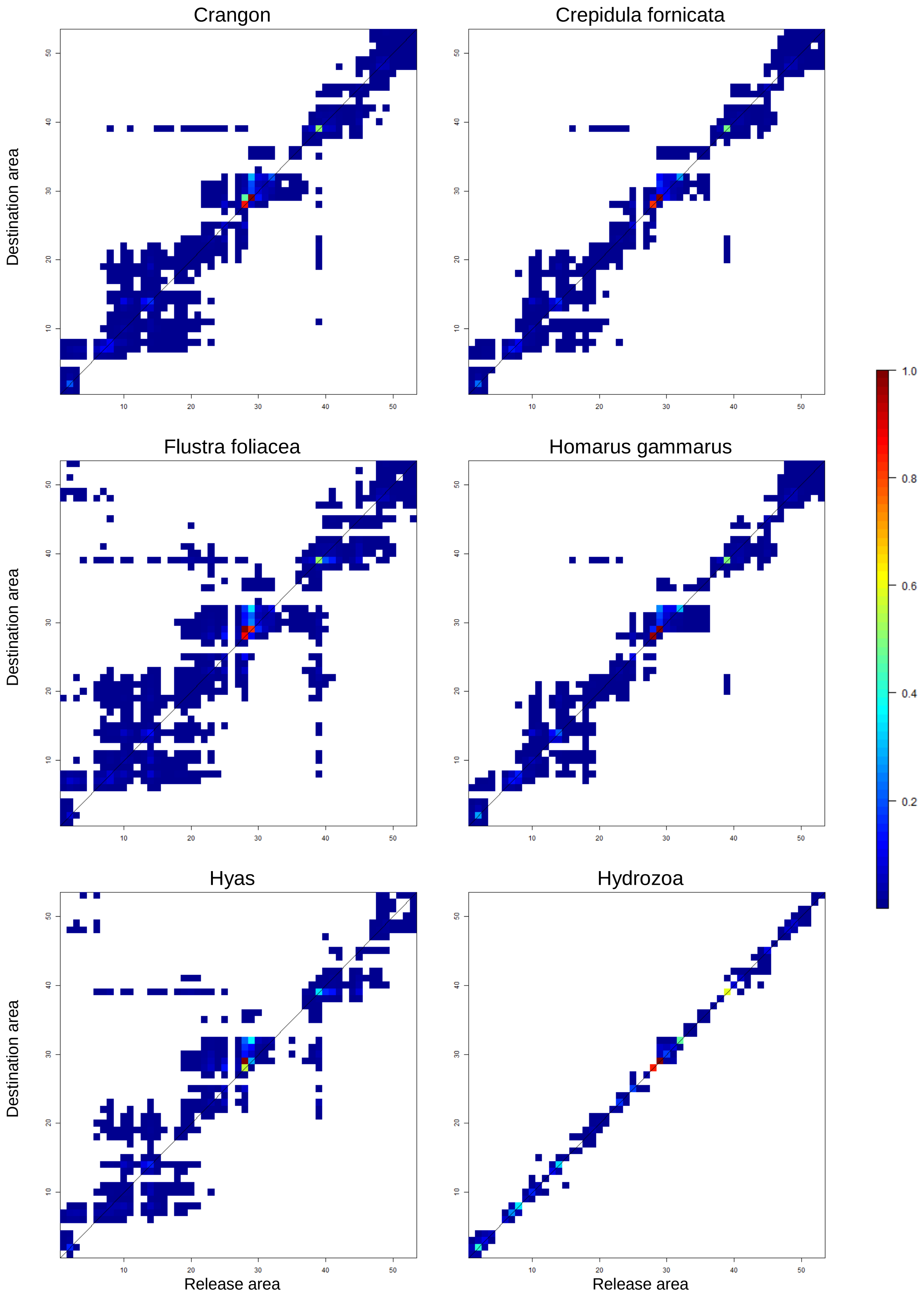
3.1.1 Connectivity among the MPA network for each species

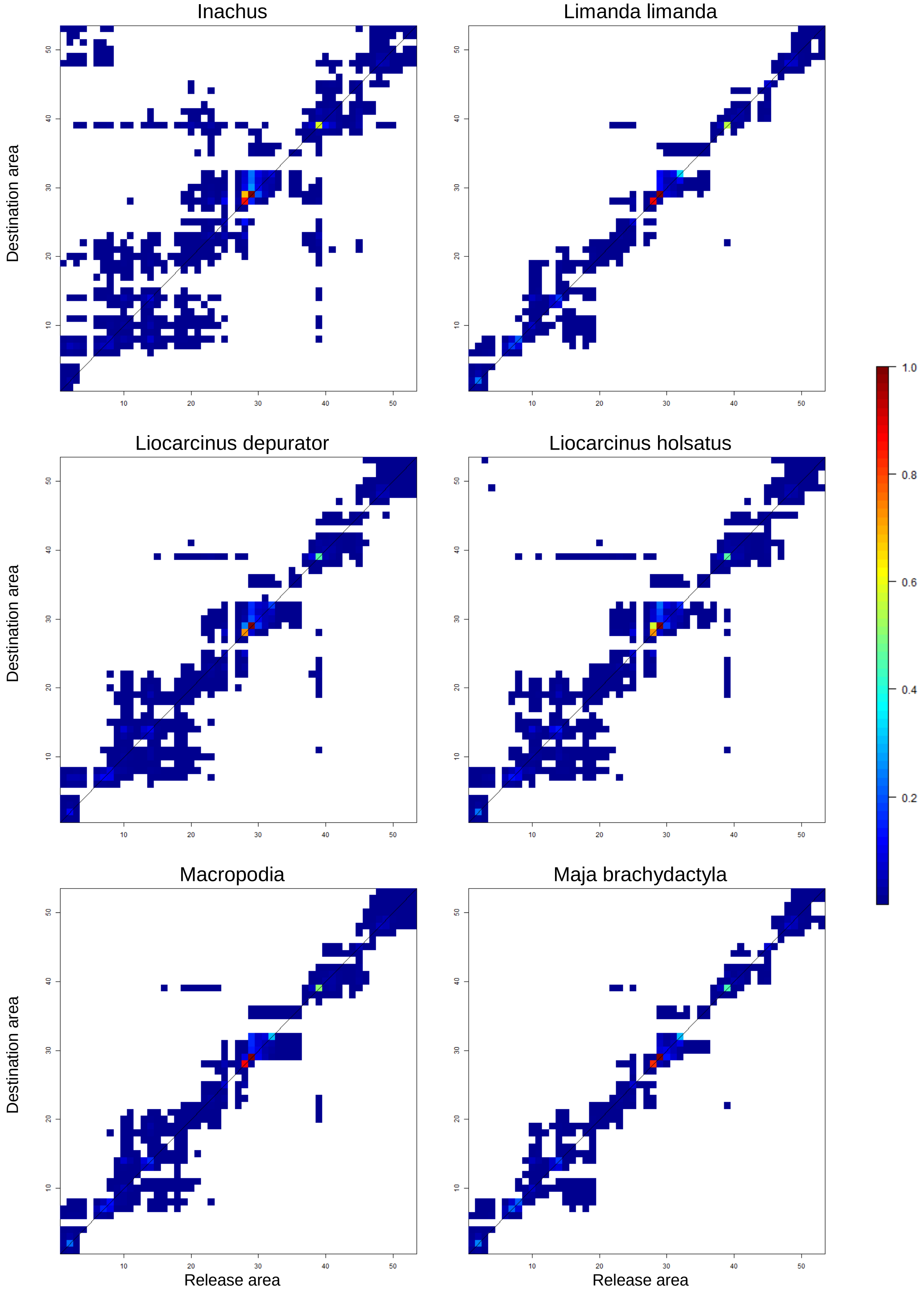
Connectivity among MPAs differs according to the species considered, i.e. depending on the vertical position of egg or larvae release (on the bottom – Figure 7; at the surface –
Figure 8; in the whole water column – Figure 9), the time of release and on drift duration. Particularly, it can be noted that connectivity among MPAs is very low for Ascidiacea (Figure 7), which has the smallest dispersal duration (only 2 days), and on the contrary very high for Lotidae (Figure 9), which has a longer dispersal duration (120 days).

For species with significant dispersal duration, connectivity matrices highlight the role of particular MPAs, such as area 39 (the offshore Wight - Barfleur Reef MPA), which allows exchange of particles between France and the UK. Some species (e.g., ammonitidae, *Flustra, Hyas, Inachus*) have dispersal parameters potentially allowing for a connection from the western French MPAs towards the western English MPAs (zones 1, 2 and 3, i.e. close to the Parc Marin d'Iroise and Ouessant – Molène, towards zones 49-51 and 53, i.e. Start Point to Plymouth Sound and Eddystone – see Figure 2 for location of these areas).



Aequipecten opercularis
Alcyonium digitatum
Ammodytidae
Ascidiacea
Cancer pagurus
Clupea harengus
Destination area
Destination area
Destination area
Release area
Release area
10
20
30
40
50
1.0
0.8
0.6
0.4
0.2


Crangon
Crepidula fornicata
Flustra foliacea
Homarus gammarus
Hyas
Hydrozoa
Destination area
Destination area
Destination area
Release area
Release area
10
20
30
40
50
1.0
0.8
0.6
0.4
0.2


Inachus
Limanda limanda
Liocarcinus depurator
Liocarcinus holsatus
Macropodia
Maja brachydactyla
Destination area
Release area
10
20
30
40
50
1.0
0.8
0.6
0.4
0.2

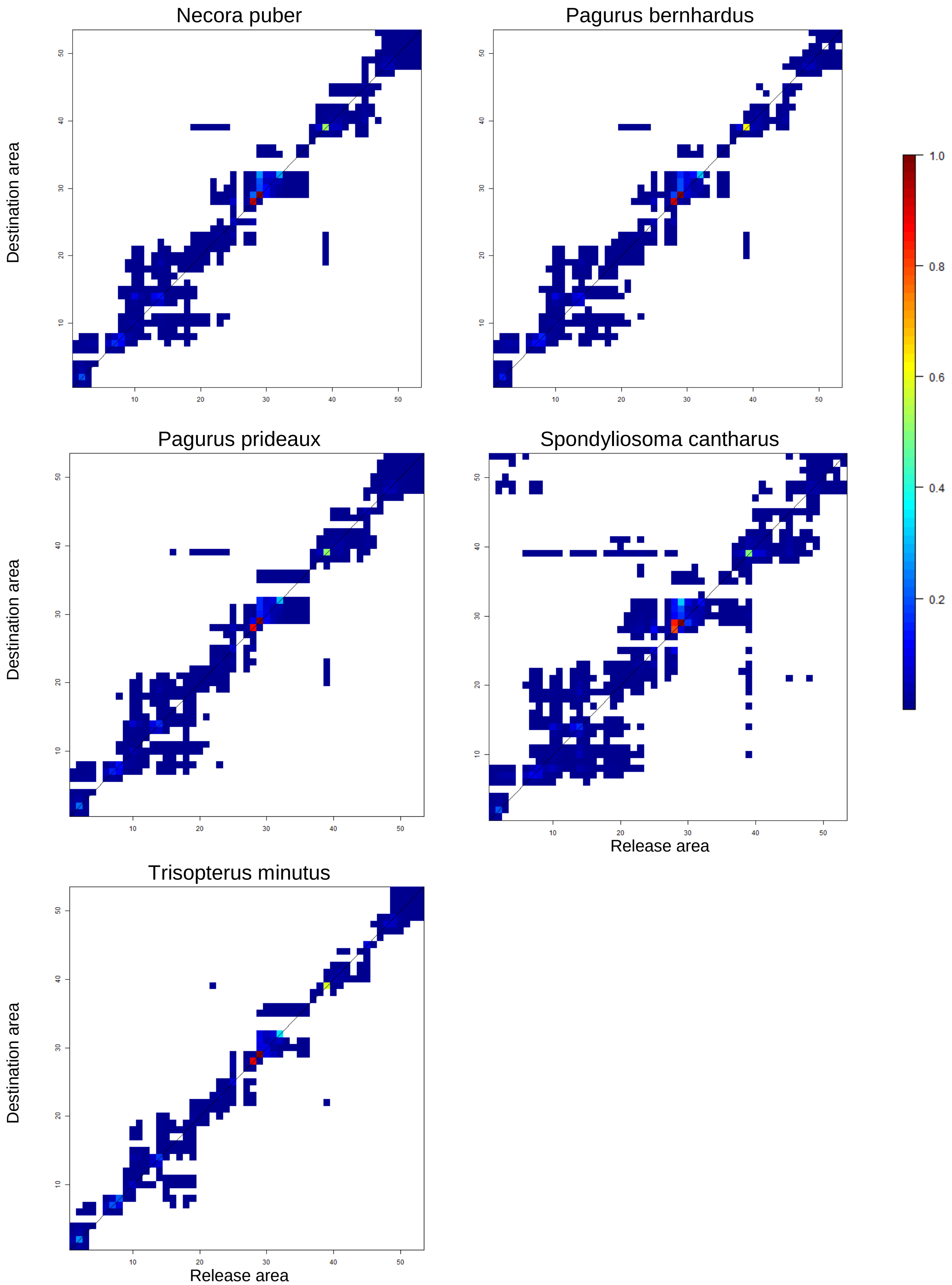
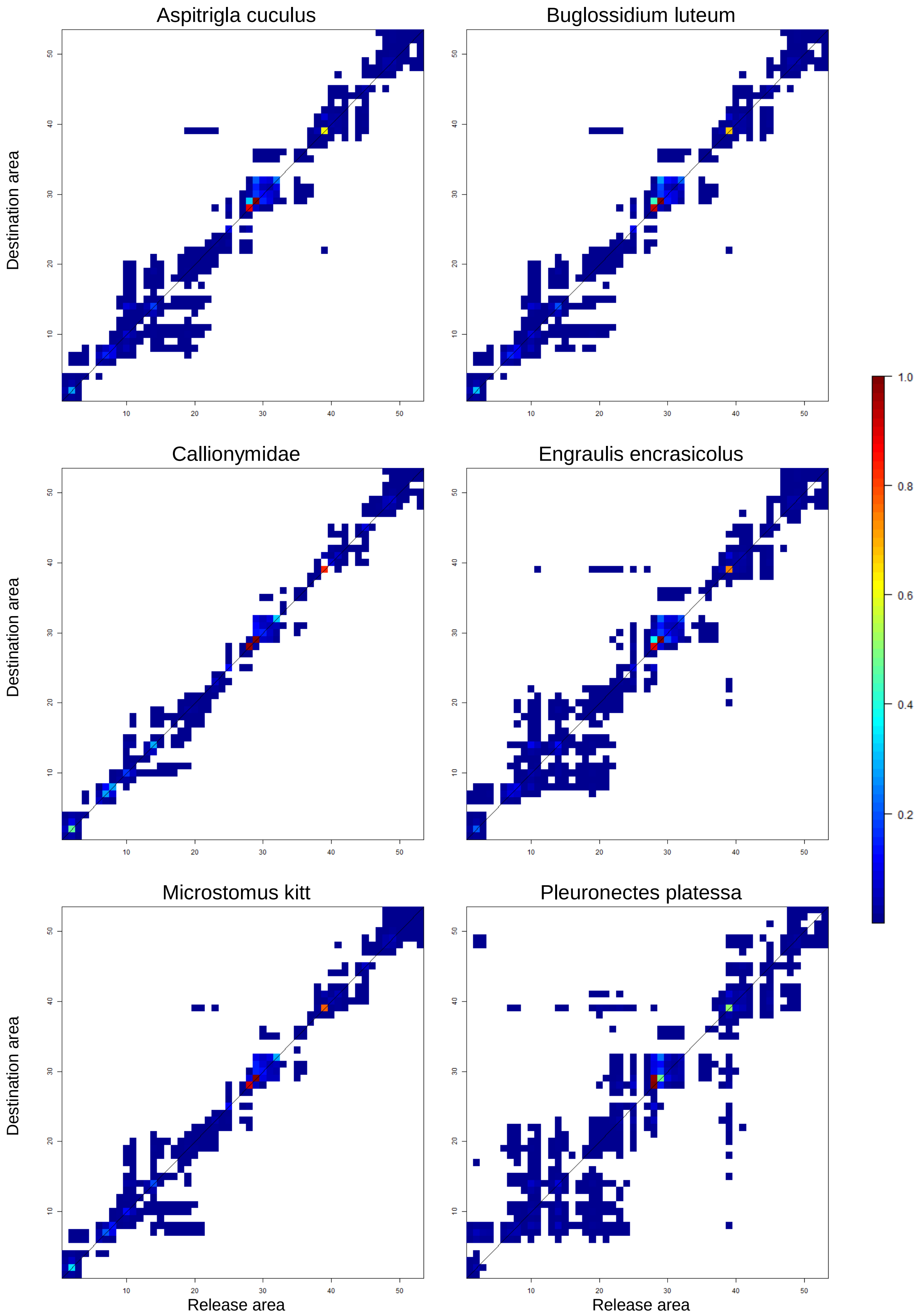


Figure 7: Connectivity matrices for species with egg release on the bottom. Species connectivity matrices are averaged over the entire spawning period (release event every 15 days). The color indicates the proportion of the particles released in zone i (on the x-axis), that arrived in zone k (on the y-axis) at the end of the simulation.


Aspitrigla cuculus
Buglossidium luteum
Callionymidae
Engraulis encrasicolus
Microstomus kitt
Pleuronectes platessa
Destination area
Release area
10
20
30
40
50
1.0
0.8
0.6
0.4
0.2

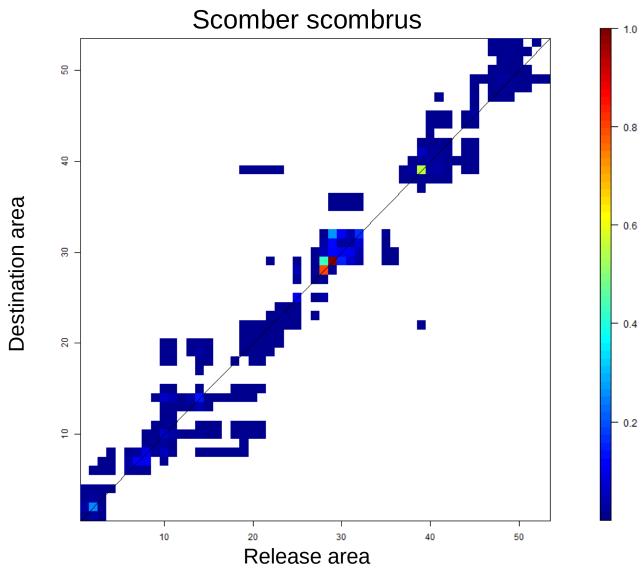
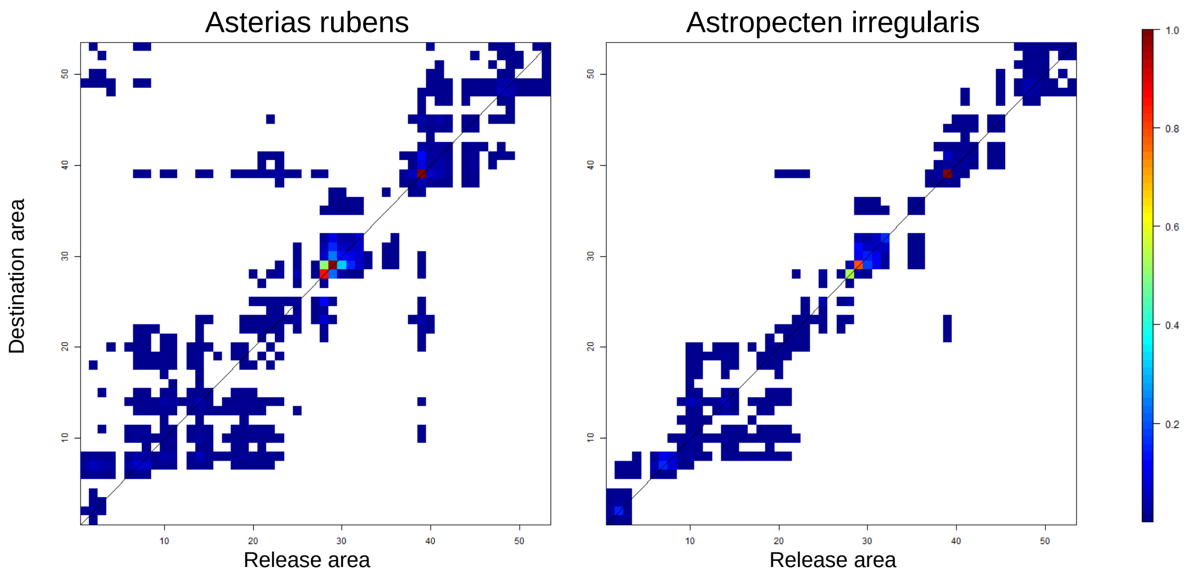
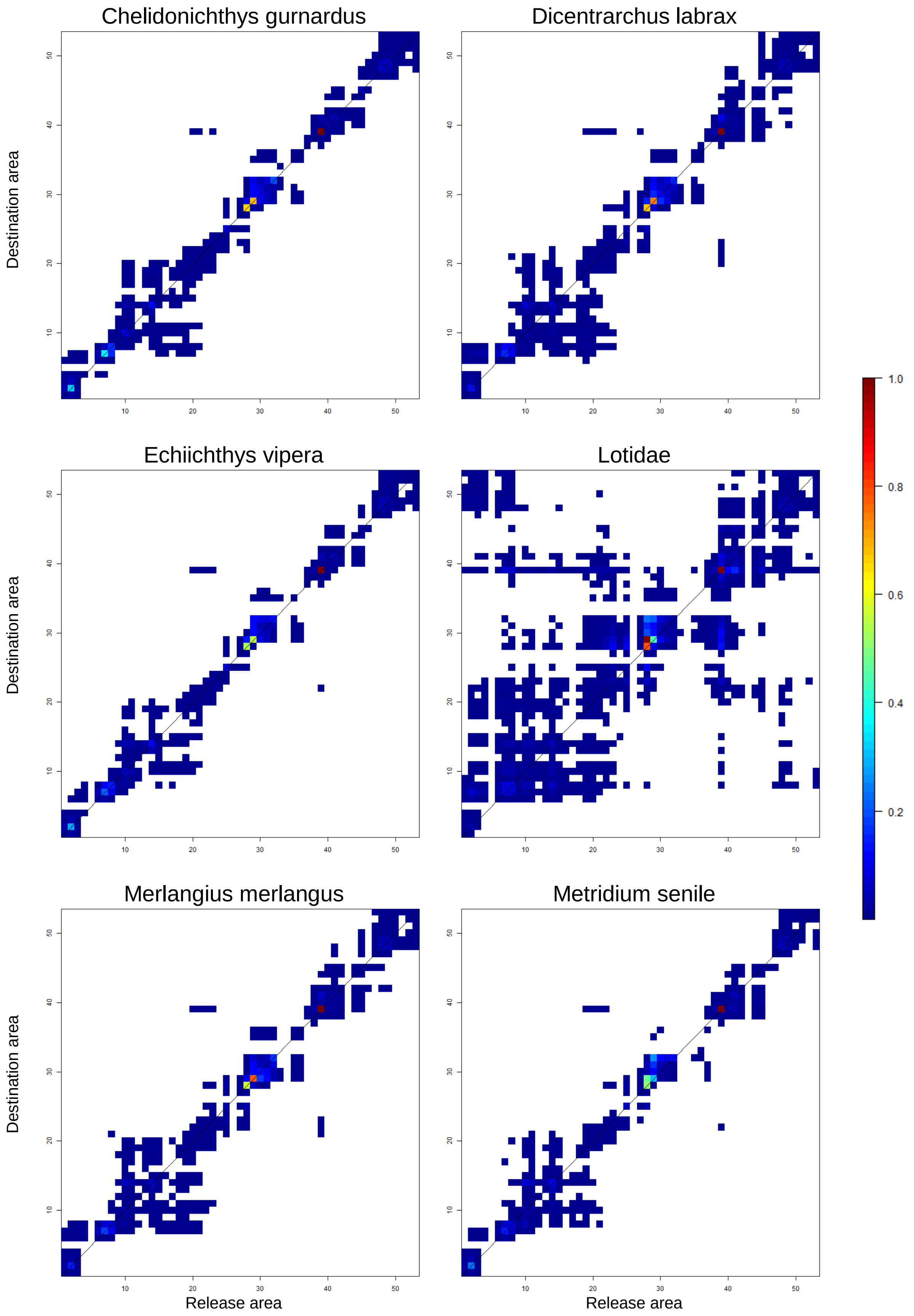
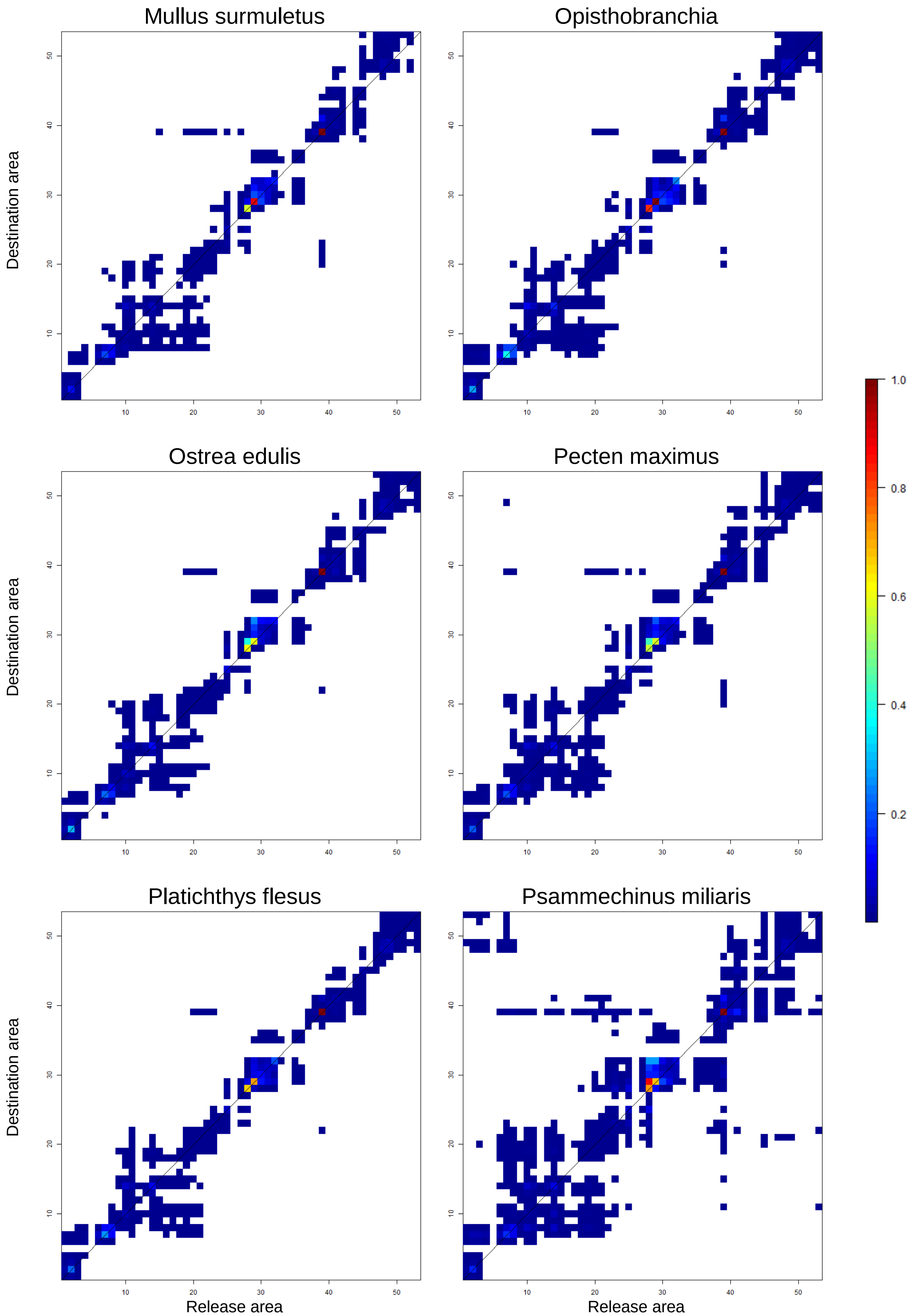


Figure 8: Connectivity matrix for species with egg release at sea surface. Species connectivity matrices are averaged over the entire spawning period (release event every 15 days). The color indicates the proportion of the particles released in zone i (on the x-axis), that arrived in zone k (on the y-axis) at the end of the simulation.

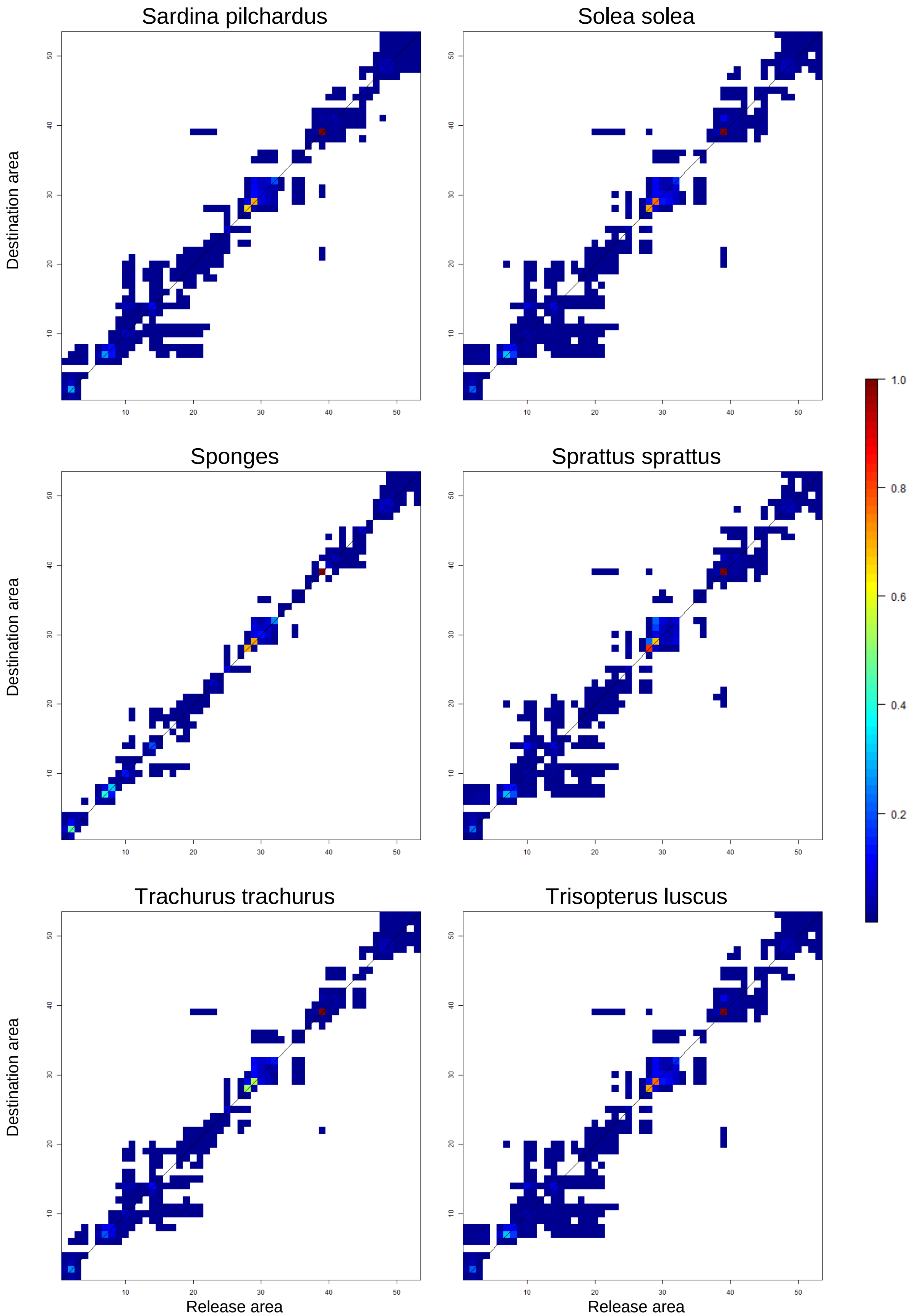




Chelidonichthys gurnardus
Dicentrarchus labrax
Echiichthys vipera
Lotidae
Merlangius merlangus
Metridium senile
Destination area
Release area
10
20
30
40
50
0.2
0.4
0.6
0.8
1.0



Mullus surmuletus
Opisthobranchia
Ostrea edulis
Pecten maximus
Platichthys flesus
Psammechinus miliaris
Destination area
Release area
10
20
30
40
50
1.0
0.8
0.6
0.4
0.2


Sardina pilchardus
Solea solea
Sponges
Sprattus sprattus
Trachurus trachurus
Trisopterus luscus
Destination area
Release area
10
20
30
40
50
0.2
0.4
0.6
0.8
1.0

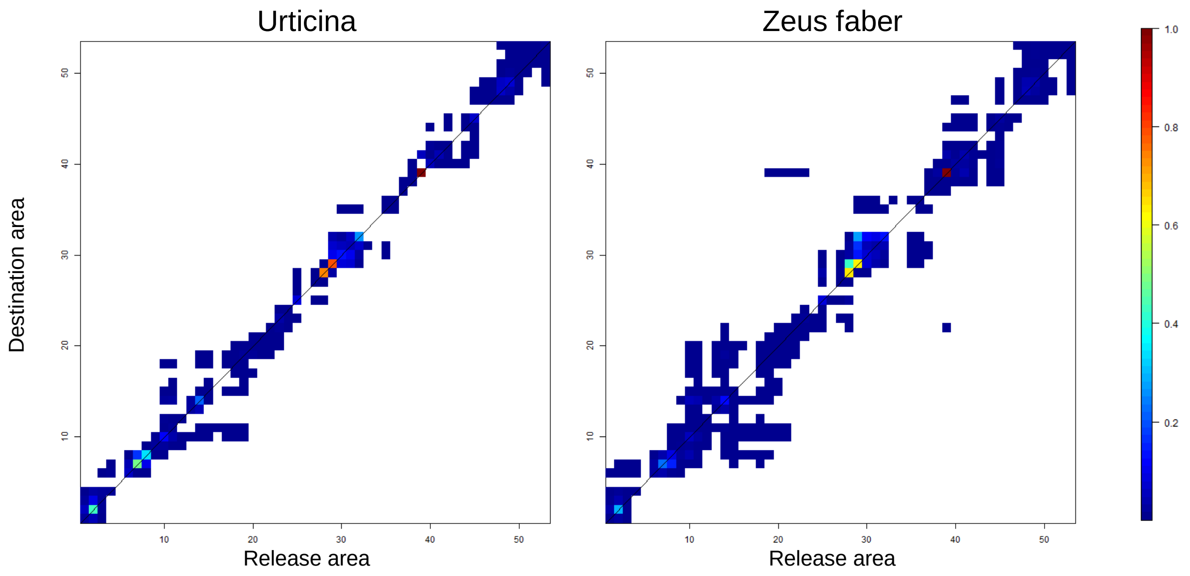
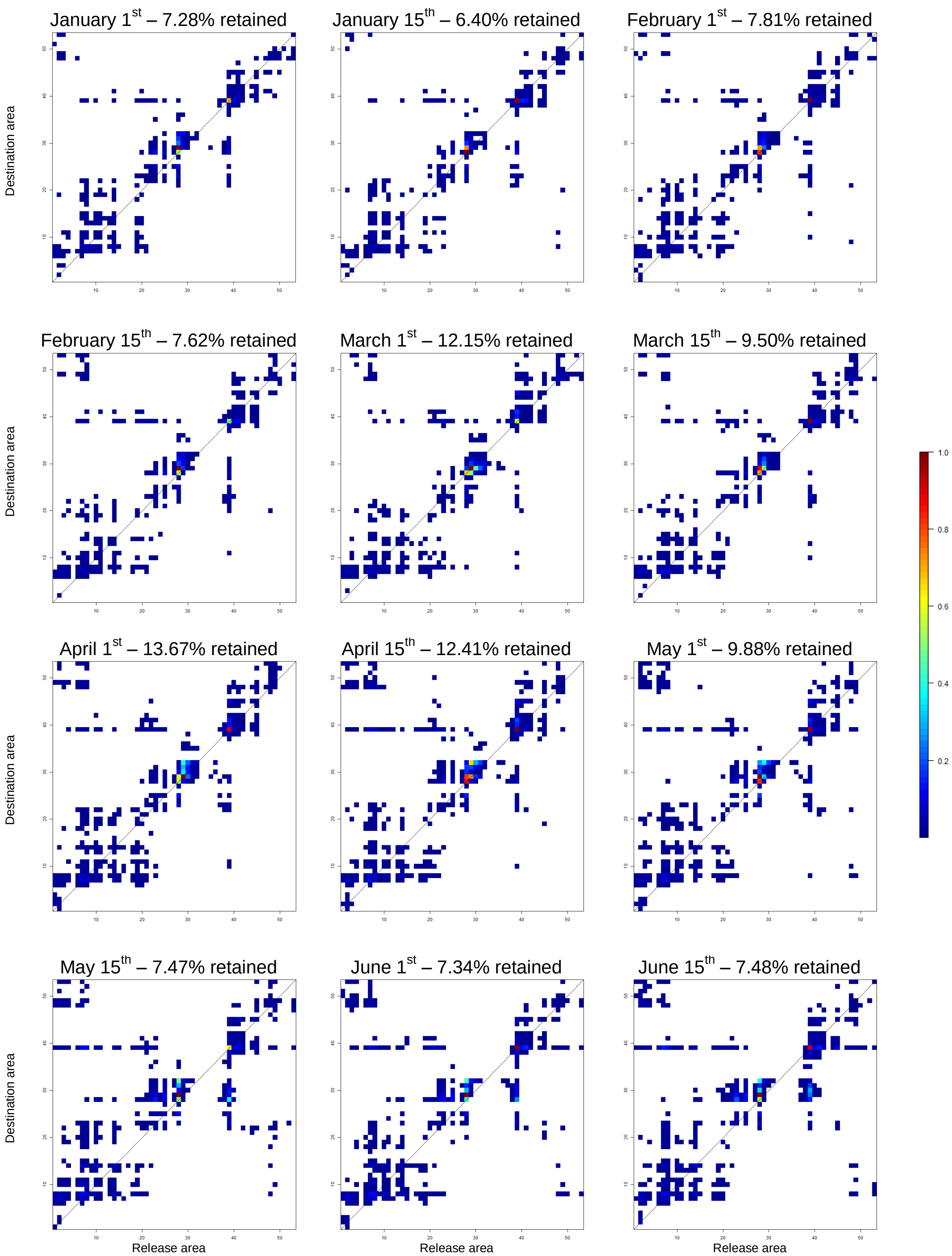


Figure 9: Connectivity matrices for species with egg release in the water column. Species connectivity matrices are averaged over the entire spawning period (release event every 15 days). The color indicates the proportion of the particles released in zone i (on the x-axis), that arrived in zone k (on the y-axis) at the end of the simulation.

3.1.2 Seasonal patterns in connectivity among MPAs

Connectivity matrices have been computed for each release event, i.e. every 15 days over the spawning period. As stated previously, due to the number of species and the length of their spawning period this computation resulted in 534 connectivity matrices. For clarity, they are not all presented in this report, but two examples of the long drifting species lotidae (Figure 10) and the commercial species sole (Figure 11) illustrate the effect of the period of release. According to the release date, the percentage of larvae that are retained in the Channel MPA network, i.e. larvae arriving in whatever MPA at the end of the drift, varies from 4.74% to 13.67% for lotidae and from 20.50% to 33.47% for sole. This variation of particles retention within the Channel MPA network does not seem to be associated with a drastic change of the global connectivity pattern observed between MPAs. Increase in this percentage is linked to the extension of connectivity between particular MPAs, for example for Lotidae from April to July with an increase in connectivity among western French and English MPAs (left upper corner of the connectivity matrix in Figure 10).


January 1st – 7.28% retained
January 15th – 6.40% retained
February 1st – 7.81% retained
February 15th – 7.62% retained
March 1st – 12.15% retained
March 15th – 9.50% retained
April 1st – 13.67% retained
April 15th – 12.41% retained
May 1st – 9.88% retained
May 15th – 7.47% retained
June 1st – 7.34% retained
June 15th – 7.48% retained
Destination area
Release area
1.0
0.8
0.6
0.4
0.2

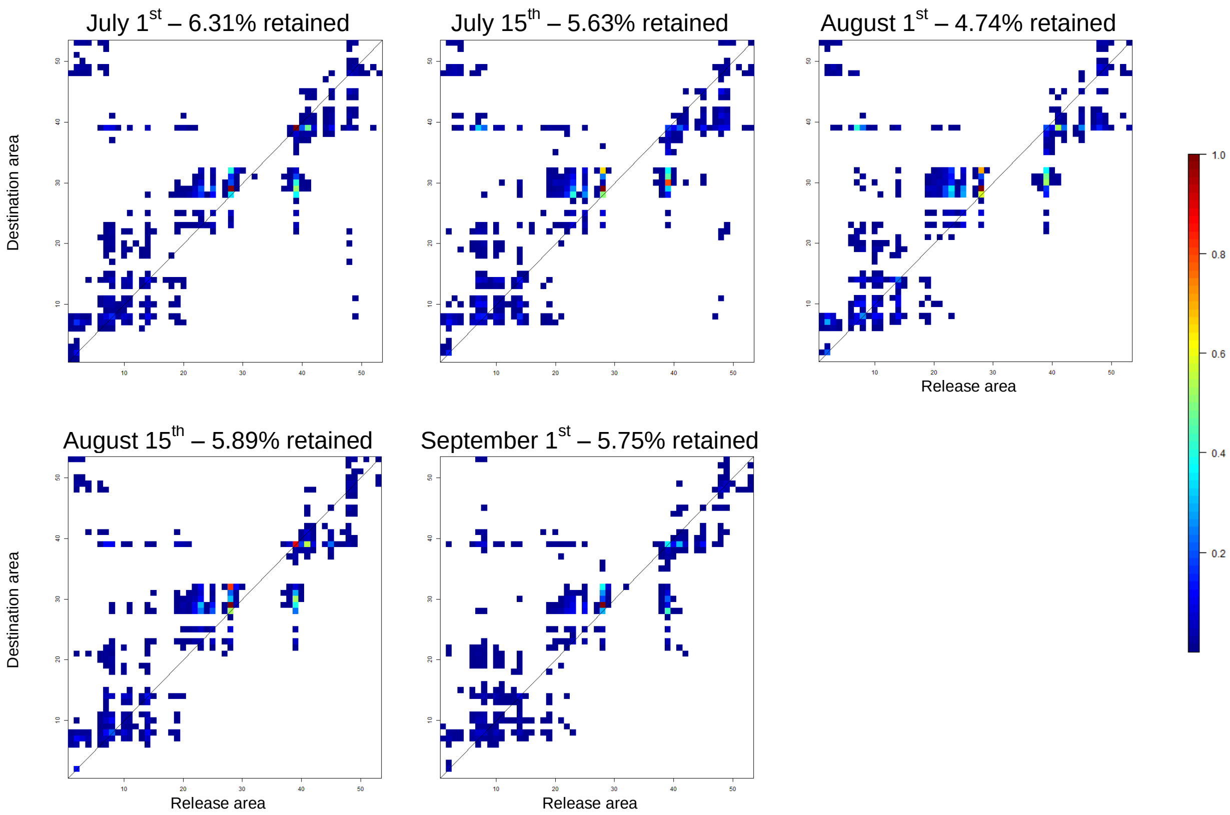


Figure 10: Connectivity matrices for Lotidae computed for each release event, from January to September. The color indicates the proportion of the particles released in zone i (on the x-axis), that arrived in zone k (on the y-axis) at the end of the simulation. The percentage of particles retained in the MPA network at the end of the simulation is also indicated.

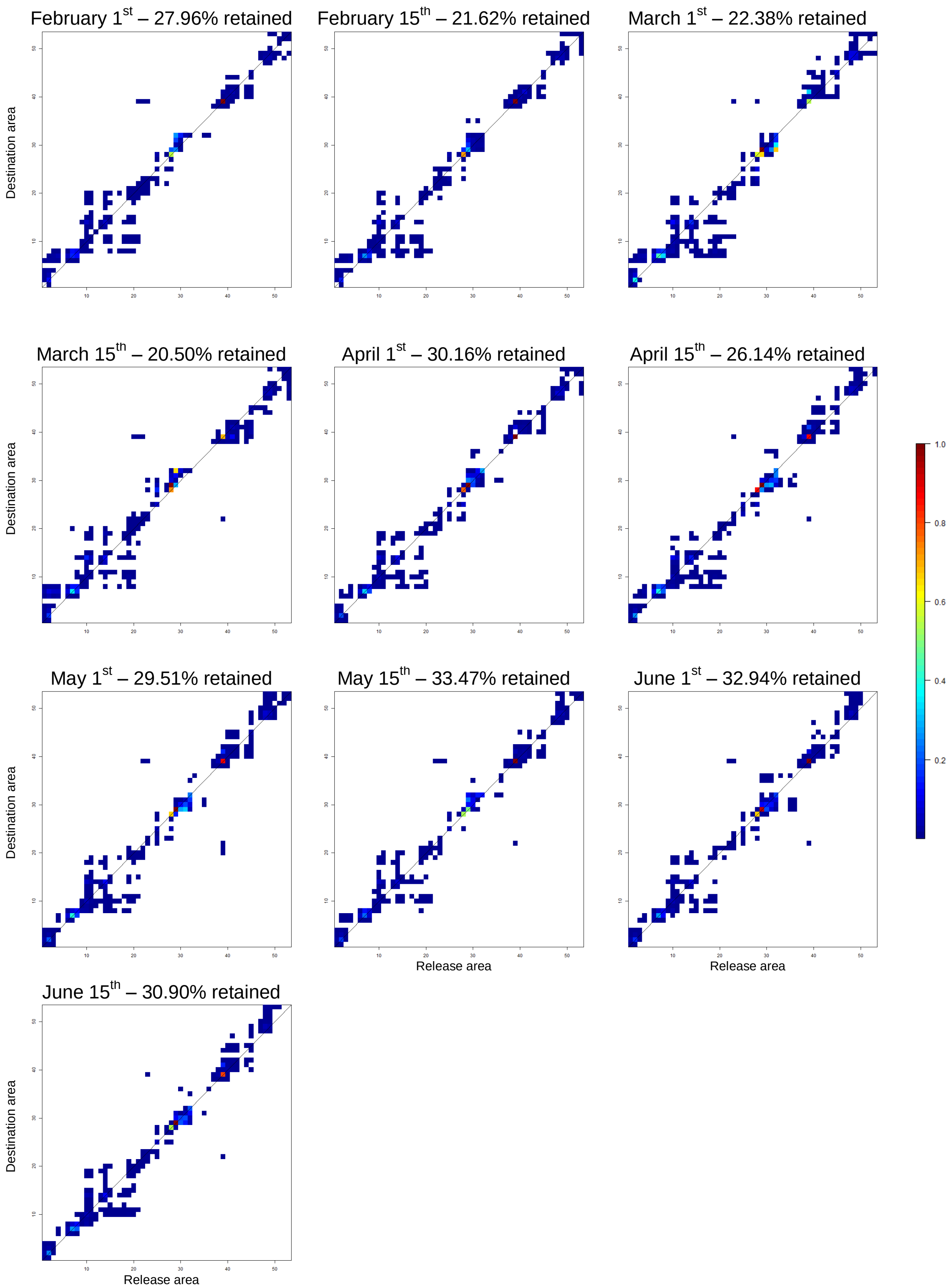


Figure 11: Connectivity matrices for Sole computed for each release event, from February to June. The color indicates the proportion of the particles released in zone i (on the x-axis), that arrived in zone k (on the y-axis) at the end of the simulation. The percentage of particles retained in the MPA network at the end of the simulation is also indicated.

Because currents vary throughout the year, partly due to changes in meteorological conditions, connectivity among the MPA network may be affected by the timing of spawning. In order to assess this effect, the percentage of particle retention among the Channel MPA network was computed for each release time for all species and resulting values were analyzed in relation to the season of the particles release (Figure 12).

Despite the drift duration, which has a large effect on the retention rate within the MPA network, the season of release does not have an impact on a larger or lesser retention of particles. Similarly, the vertical position of particles release (surface, whole water column or sea bottom) does not seem to affect the number of particles retained in the Channel MPA network (Figure 12).

For long-drifting larval stages, retention within the network declines to about 10%, which also means that 90% of the particles released in the Channel MPAs are exported towards non-protected areas. For the bulk of species, drift duration is between 20 to 40 days, resulting in a percentage of larvae retained in the Channel MPA network varying from 15% to 45%.

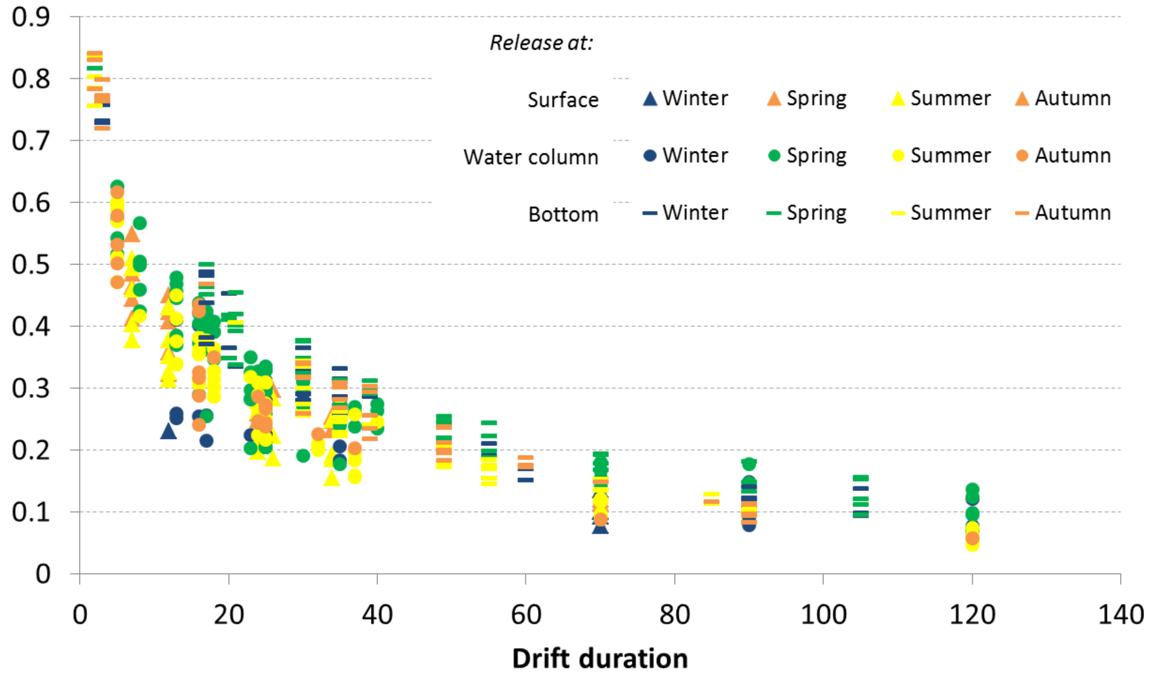


Figure 12: Percentage of particles coming from the MPA network that are retained in the MPA network (not necessarily in the same MPA) at the end of the simulation according to the drift duration. Color represents season of spawning (red: summer; orange: autumn, blue: winter, green: spring).

3.2.3 Integrative view of the results

In order to synthesize the results, a global connectivity matrix was computed using the average of the 53 species connectivity matrices presented above. Figure 13 shows the average number of particles moving from one MPA to another relatively to the number of released particles. Except for a small number of areas with high retention rates, this matrix shows small values of connectivity among MPAs in the Channel. Due to the existence of very poorly dispersing species, the average percentage of particles moving from one area to another is very low outside the diagonal region of the matrix.

When considering the number of links between an MPA and the rest of the network (grey histograms on Figure 13), some “sink” and “source” areas can be characterized. For instance, due to the eastward residual current in the Channel the western French MPAs (areas 1-4, from Parc marin d’Iroise to Ouessant-Molène and Abers-côtes des Légendes) export larvae to more than 20 areas but receive larvae from less than 5 areas: these zones appear as source MPAs. Note that area 5 (Anse Goulven – dunes de Keremma) does not receive or export particles in the model; due to its very coastal location, and despite an *a priori* selection of MPAs suitable regarding our model constraints, this area was not well represented in the model and should not be considered for interpretation of results. In term of number of links with other MPAs, the French areas seem to have a greater “source” role than English MPAs, as illustrated by the smaller number of MPAs receiving particles issued from English areas. On the contrary, cross-border distinction concerning the “sink” role cannot be made as French and English MPAs receive particles from approximately the same number of MPAs. Finally, particular areas, such as the offshore MPA 39 (Wight - Barfleur Reef), appear to be of importance as sink and source regions, as they receive particles for a high number of MPAs and their particles are exported towards a high number of MPAs.

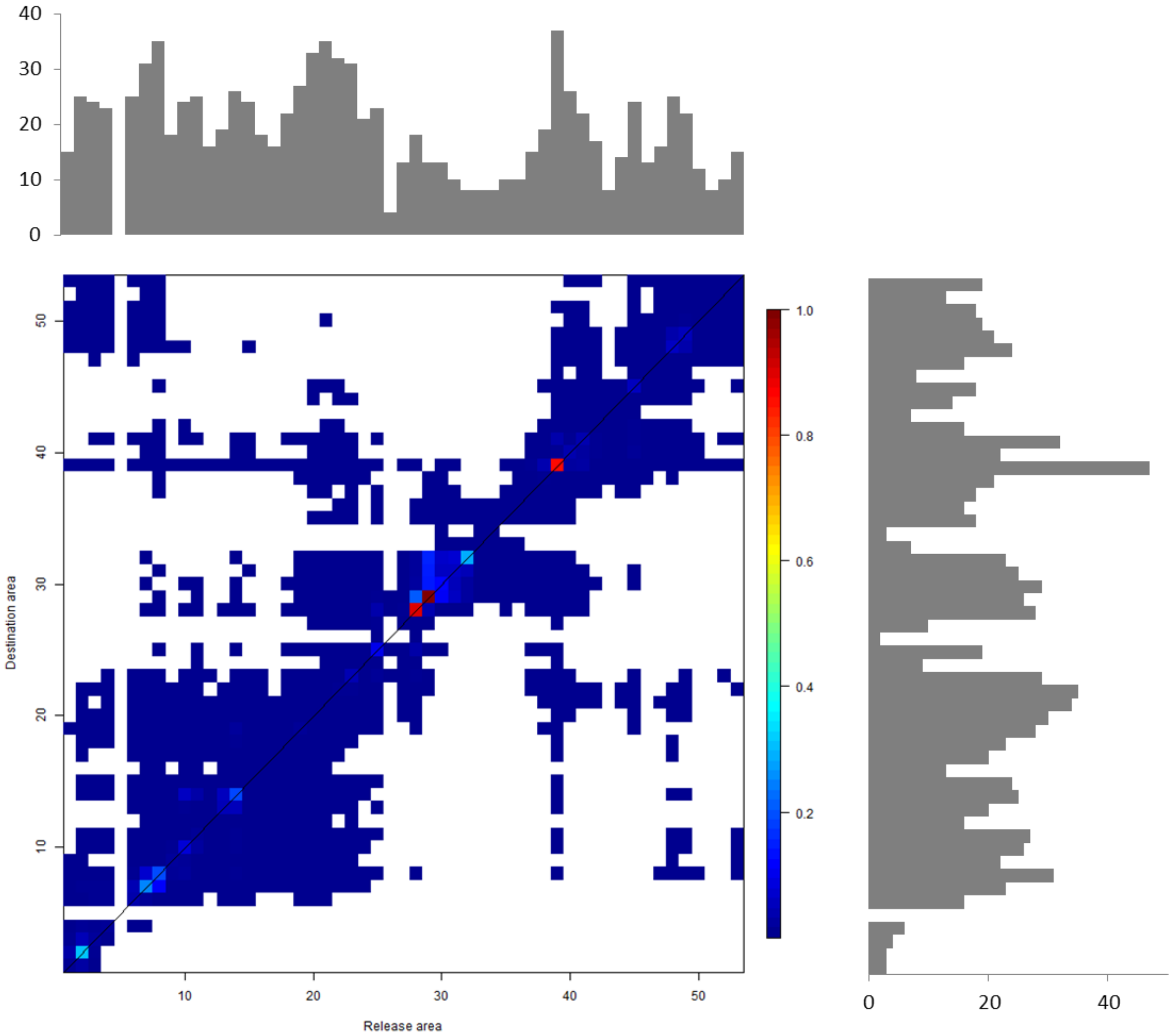


Figure 13: Total connectivity matrix, integrated for the 53 species groups over their spawning period. The color indicates the proportion of the particles released in zone i (on the x-axis), that arrived in zone k (on the y-axis) at the end of the simulation. Grey histograms indicate the number of connected MPAs that receive particles from a particular MPA (top histogram) or the number of connected MPAs from which particles arriving in a particular MPA are coming from (histogram on the right)

Providing a complementary vision to the previous density of particles exchanges, Figure 14 shows the number of connectivity links among MPAs observed among the 53 species for which dispersal was simulated. The synthetic view of Figure 14 highlights the overall high connectivity of the MPA network at the local scale (between nearby MPAs). Some high connectivity hotspots between sub-groups of MPAs may also be highlighted. Thus, areas 9 (Baie de Saint Brieuc) to 21 (la Hague) corresponding to the “golfe normand-breton” are highly connected compared to the rest of the MPA network. Similarly, areas 29 to 36, which correspond to the MPAs of the Dover Strait, are highly connected regarding larval dispersal. Areas 47 to 53 are also linked with a relatively high exchange of particles between these MPAs on the western English coast. In general, highly connected MPAs are very close and located in the same ecological entity.

Figure 14 can also provide insights on key MPAs for exchange of organisms between French and English areas. For instance, offshore area 39 of Wight - Barfleur Reef is essential for cross-border connectivity as particles for the majority of MPAs can arrive in this zone and conversely, particles from this zone can reach most of the other MPAs within the network. To a lesser extent, other areas also participate in such exchanges: particles from areas 48-49 (Skerries Bank and surrounds and Start Point to Plymouth Sound and Eddystone) can cross the Channel towards MPAs of the "golfe normano-breton"; particles from areas 1 to 8 (Parc Marin d'Iroise to Trégor-Goëlo) can travel to areas 48 to 53 (Skerries Bank and surrounds to Start Point to Plymouth Sound and Eddystone).

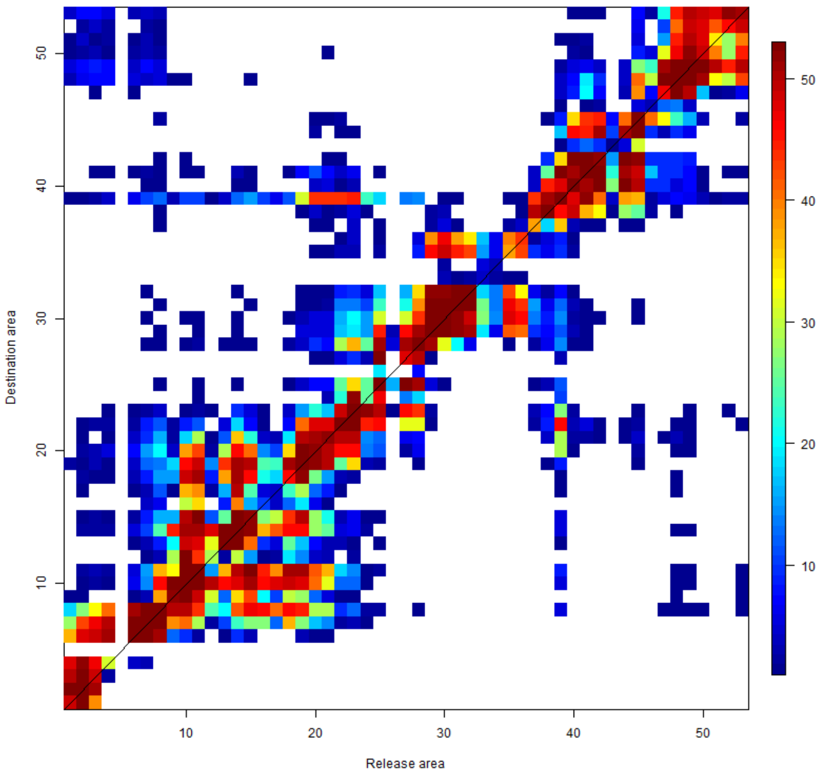


Figure 14: Frequency of connections between MPAs. The color indicates the number of species group for which a connection between two MPAs has been observed (whatever the intensity of the connection)

3.3 The detailed approach: sole study case

3.3.1 MPA network

Figure 15 details the estimated probability of survival of the eggs spawned in the whole model domain, averaged over all the simulated years. This is, per egg spawned, the probability to survive and successfully settle in a nursery (any nursery in the model domain). Please note that these probabilities are per egg; they are independent from the number of eggs spawned at each point.

According to our model, sole appears to maximize its success in larval transport when spawning along the coasts, in particular in the "Golfe Normand Breton" (GNB), in the Bay of Seine, along the French coast from Dieppe to Boulogne sur Mer, and along the English coast in the Bay of Hastings, the Bay of Brighton, around the Isle of Wight.

The nurseries located in the Celtic Sea and the Iroise Sea are not included in this model which partly explains why the probability of larvae survival (PLS) are lower in the western Channel as an important proportion of the eggs spawned there are transported westwards. From the map in Figure 15, potentially relevant MPAs in terms of the protection of sole spawning grounds can be inferred: the "domaine public maritime": Chausey, the "zones d'importance communautaire" (Natura 2000 and DHFF): "Cap d'Erquy – Cap Fréhel", "Baie de Seine Orientale", and "Littoral Seino-marin", and finally the "parc naturel marin": Estuaires Picards et Côte d'Opale.

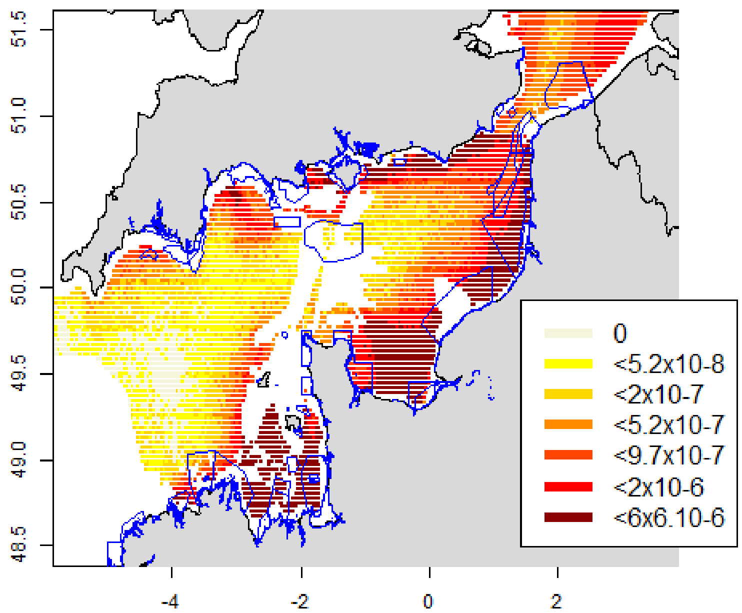


Figure 15: Probability of larvae survival map: for each point in the grid, the colour represents the mean probability, averaged over all simulated years, of successful settlement in a nursery (in the Channel or the southern bight of the North Sea) for a particle released from this point. The darker the area, the higher the probability, with beige representing a probability of 0. The MPAs are represented in blue.

The results presented below only focus on the eggs spawned within the MPAs, as detailed in the methods section.

Figure 16 details the proportion -of the total amount of eggs spawned in the English Channel- spawned in the different MPAs under consideration (i.e. MPA larger than 100 km2 and deeper than 20m). These proportions depend on the surface area of the MPA as well as on the absolute distribution of the spawning, which varies from year to year (see the methods section, p12).

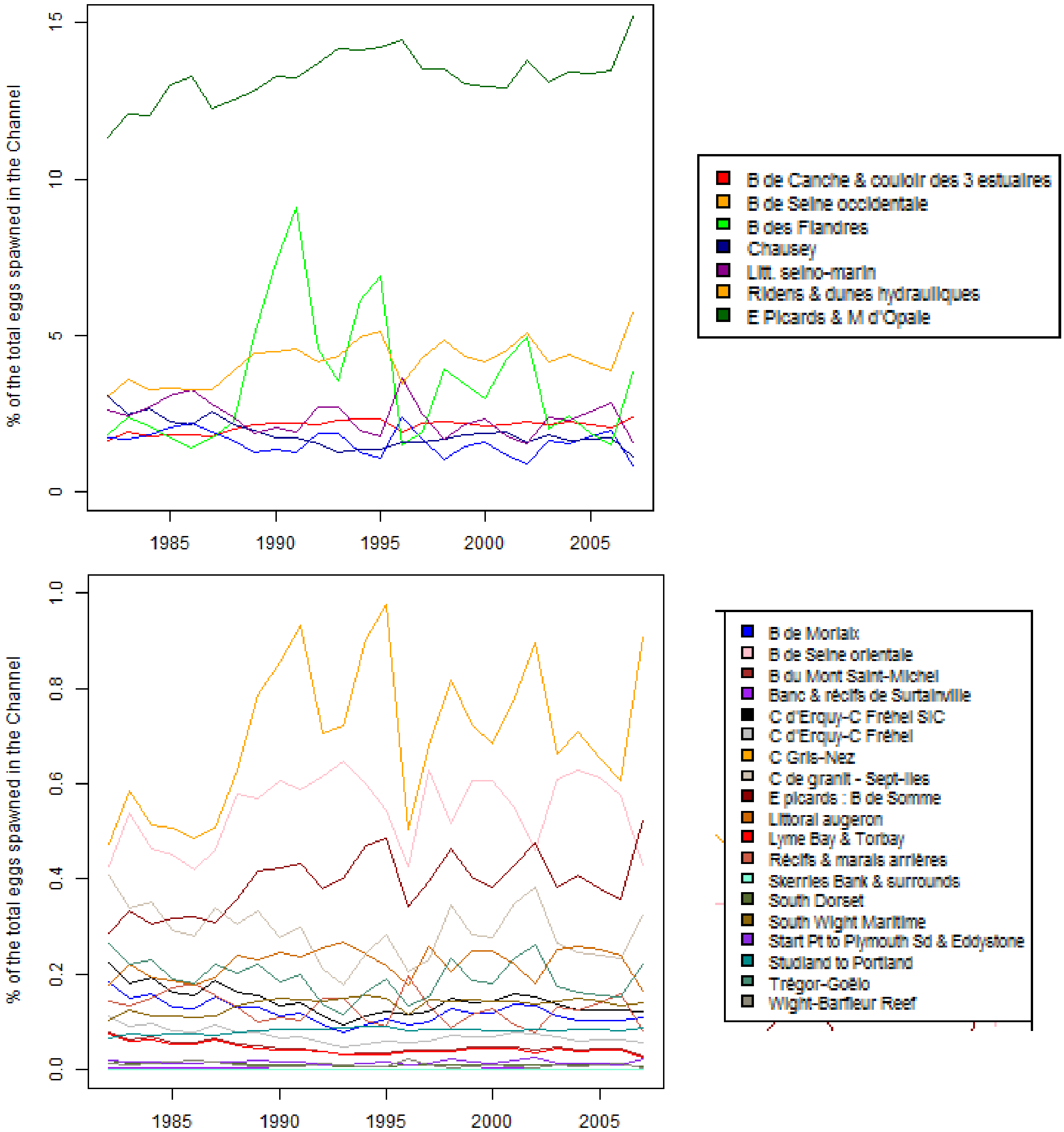


Figure 16: Proportion of the total amount of eggs spawned in the English Channel spawned within each MPA (highest proportions on the top, lowest on the bottom).

3.3.2 Connectivity between MPAs and nurseries

We investigated the connectivity among the MPAs (Figure 17- spawning grounds) and the nurseries (Figure 18) in two ways. First, for each MPA we computed the distribution of successfully settled larvae (originating from this MPA) in the different nurseries for all the simulated years (Figure 19).

Most of the MPAs have quite a limited range of action in terms of the nurseries reached by the larvae. However, the MPAs located off the French coast in the Eastern Channel, exports larvae to up to 7 different nursery grounds. This is also the case for the “Récifs and marais arrières” MPA, off the Cotentin.Depending on the timing of the spawning and the distribution of the spawning population, spawning does not occur every year in certain MPAs (e.g. Surtainville).

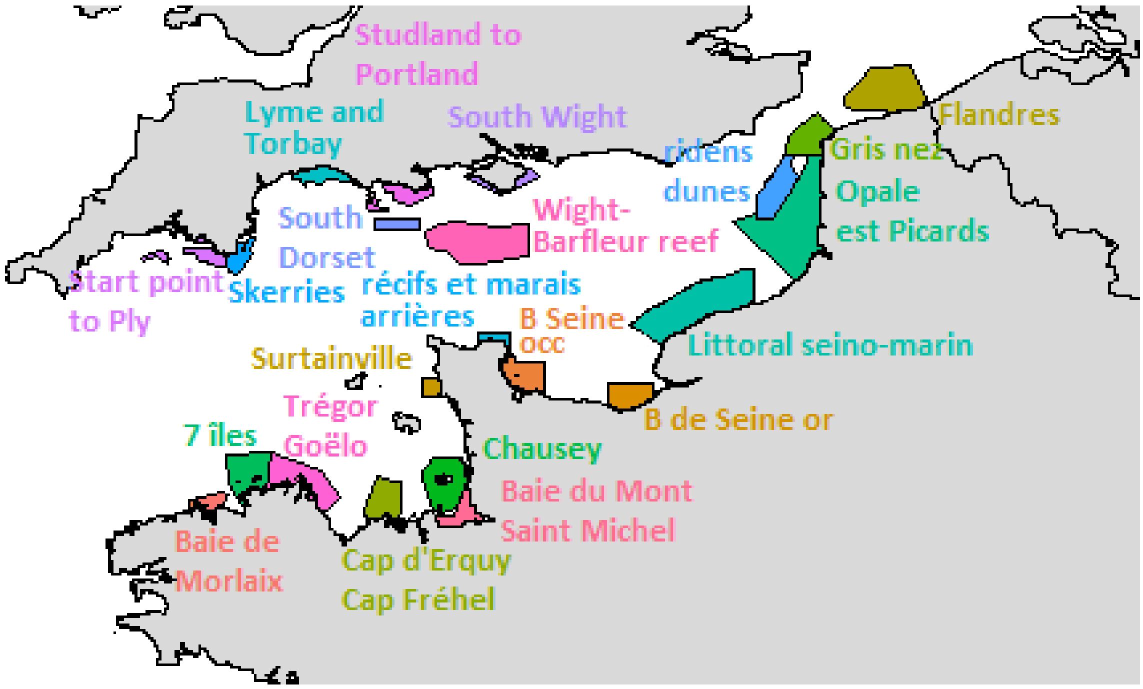


Figure 17: Marine Protected Areas relevant to this study (i.e., larger than 100 km², and within the sole spawning grounds such as defined in the model).

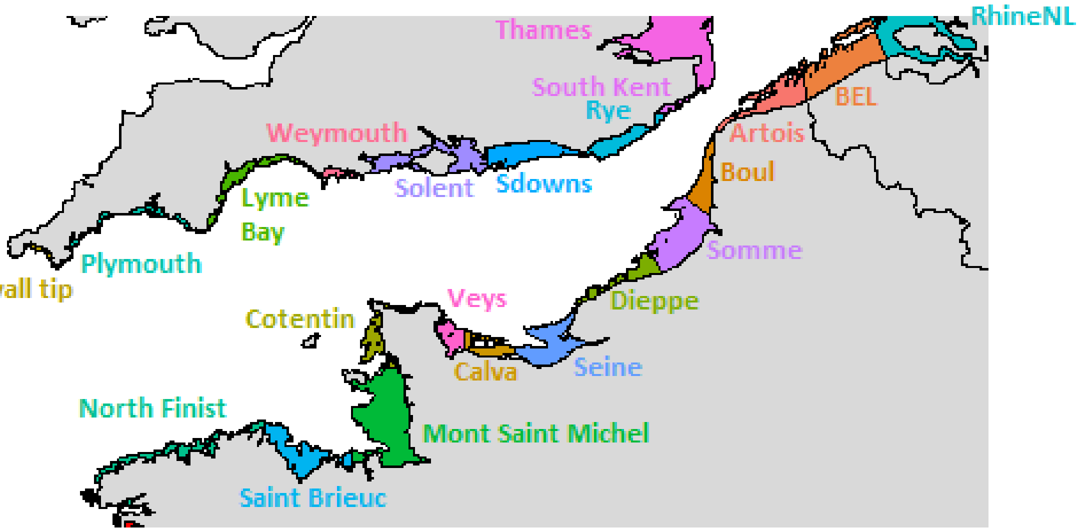


Figure 18: Sole nurseries considered in the model

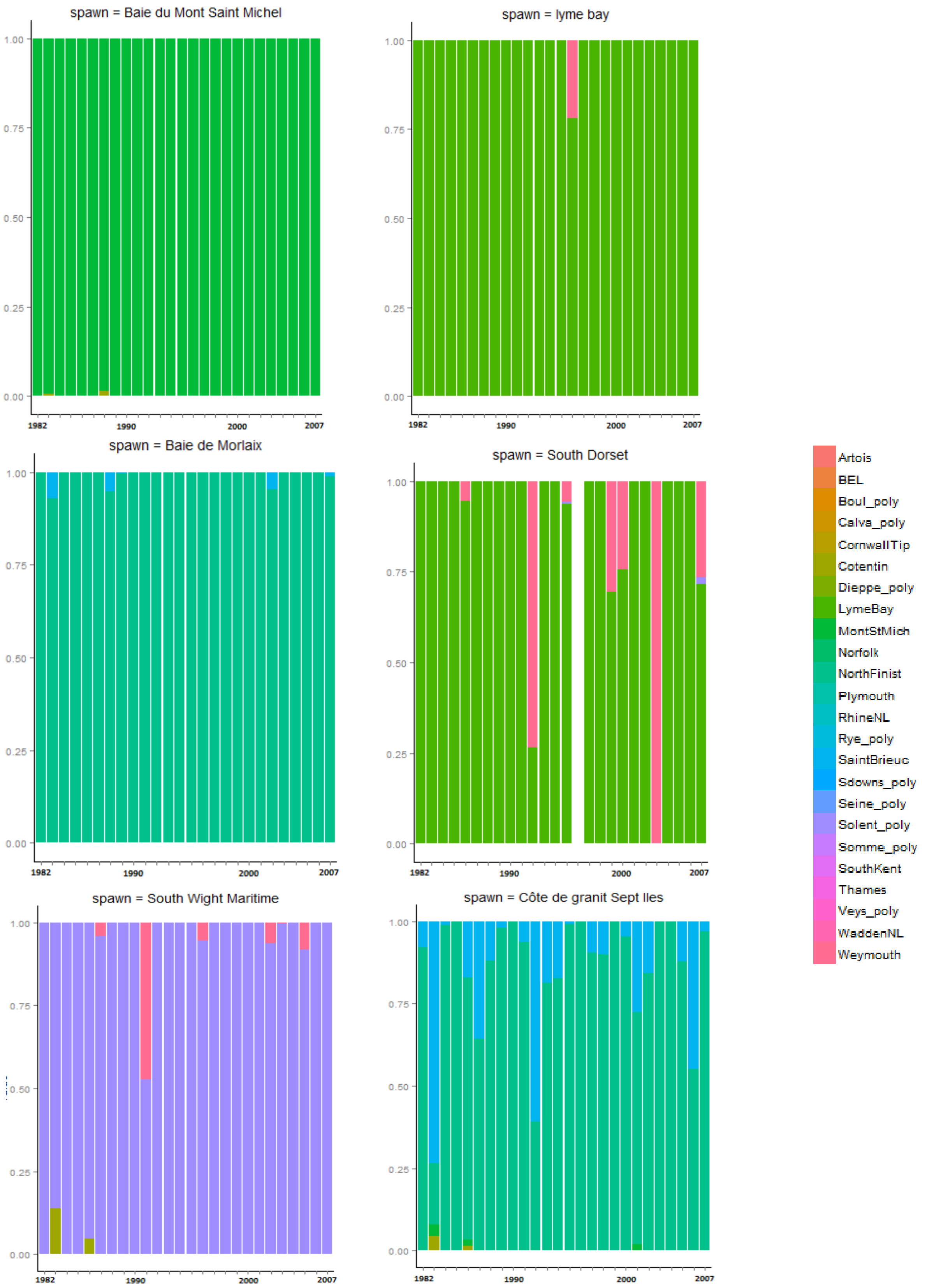


Figure 19: Proportion of the larvae spawned in a given MPA arriving in each nursery, with years from 1982 to 2006 on the x-axis, and the proportion of the total amount of successfully settled larvae on the y-axis.

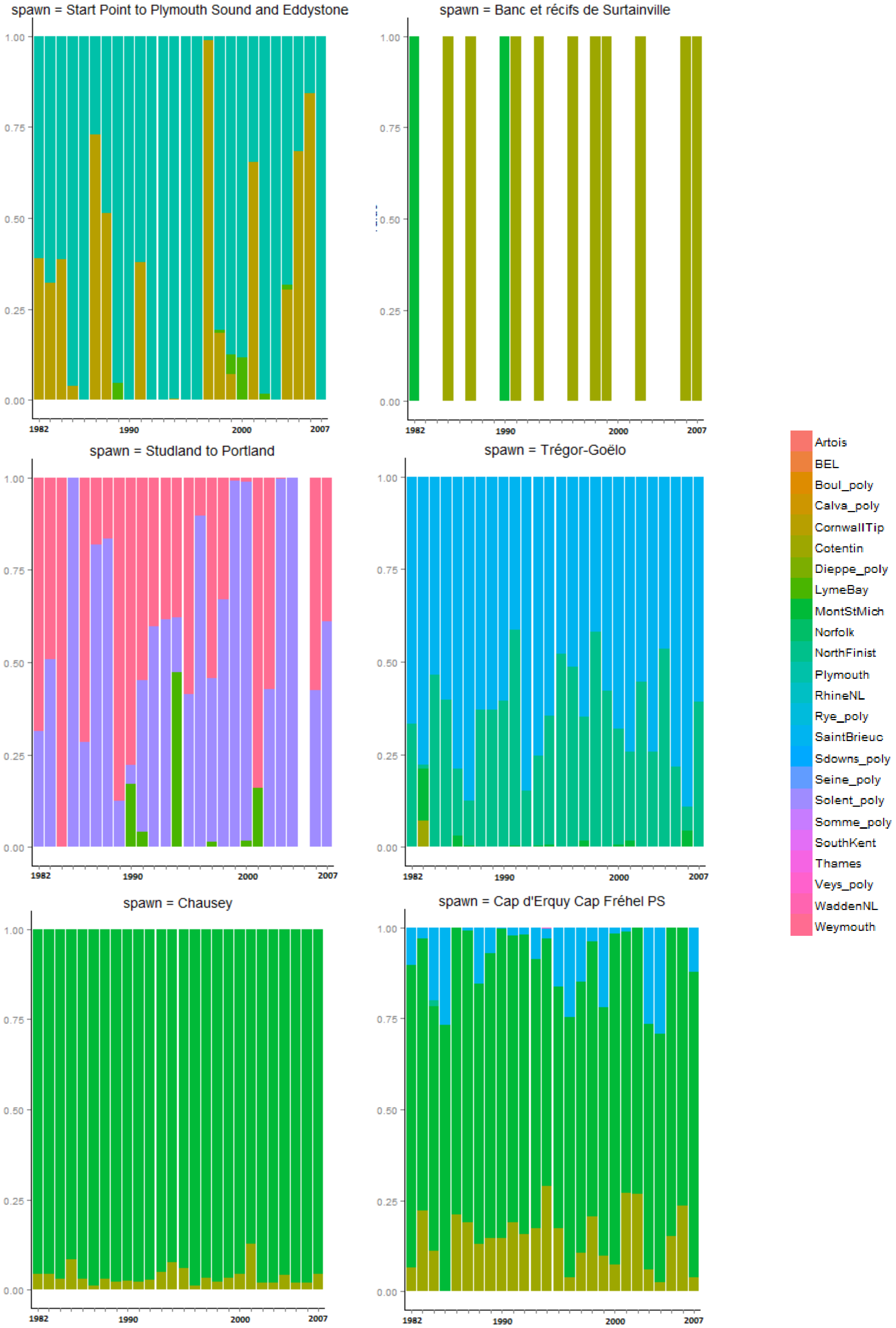


Figure 19 cont.

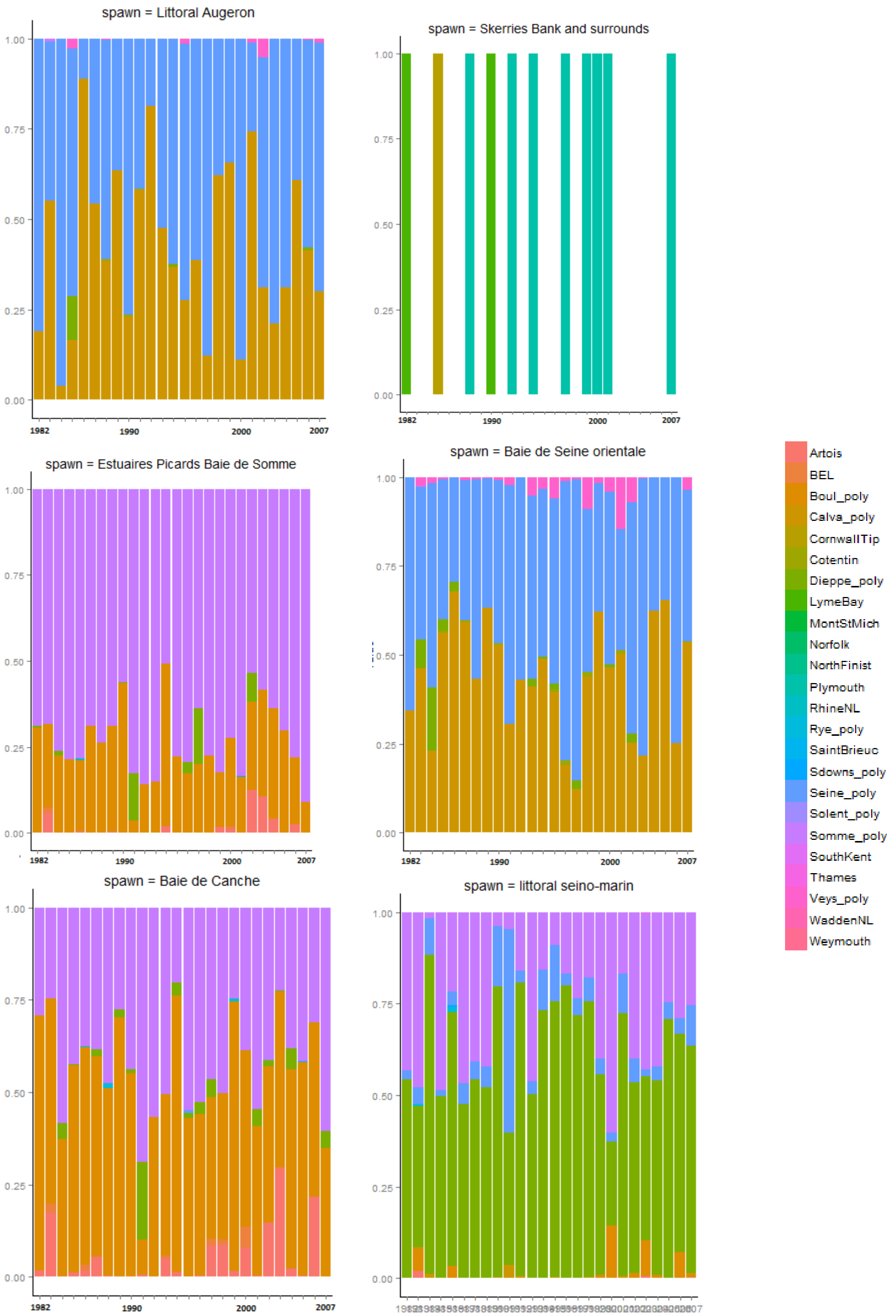


Figure 19 cont.

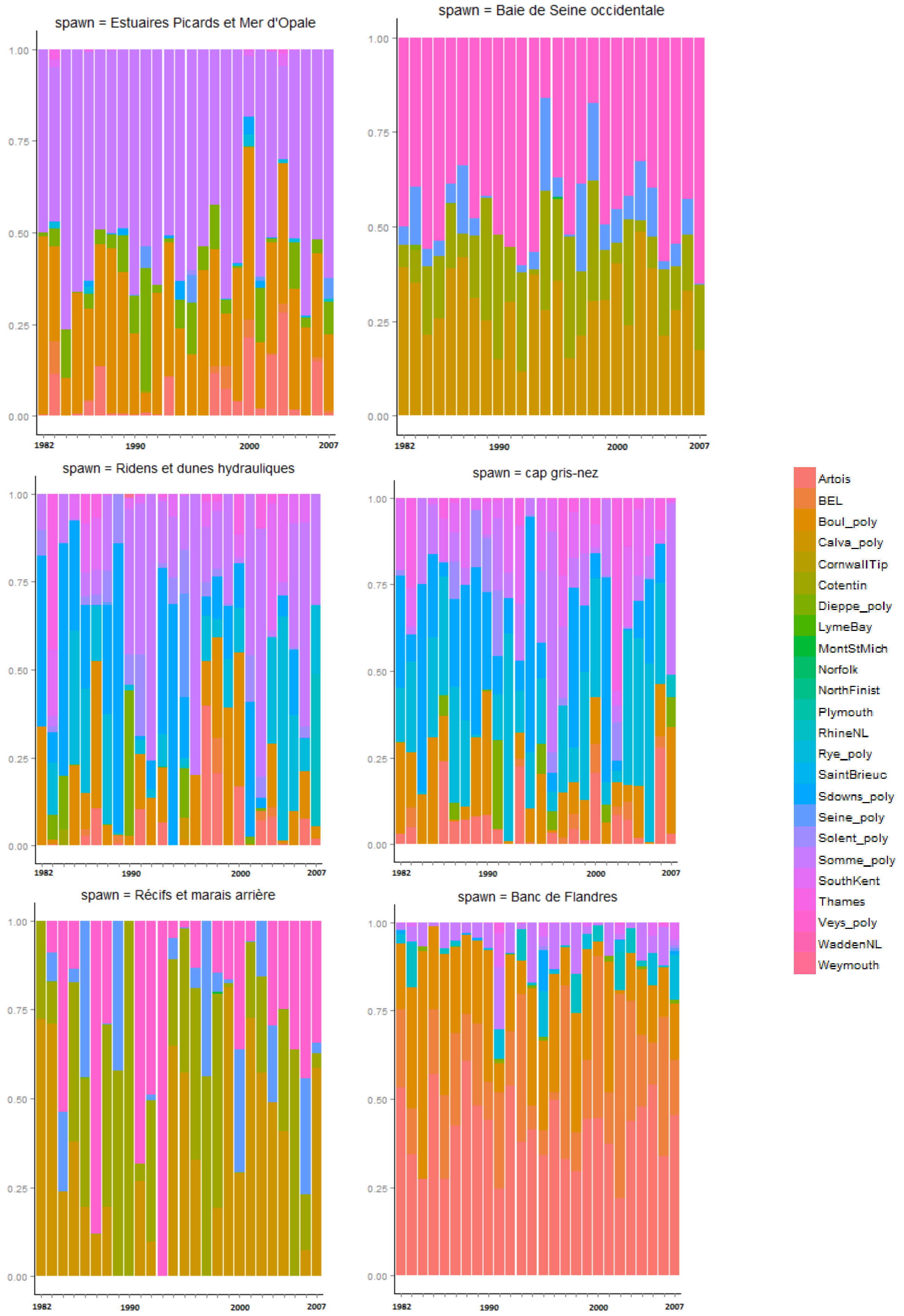


Figure 19 cont.

Secondly, for each nursery we computed the distribution of larvae coming from the different MPAs (i.e. the proportions sum up to 1 as the larvae coming from non-MPA spawning grounds were not considered,Figure 20).

Some nursery grounds are supplied almost exclusively from MPAs enclosed within their boundaries. This is the case of the Cornwall tip, Plymouth and the Mont Saint-Michel indicating self-recruitment. For most nurseries, the contributing MPAs are the same every year although their relative contribution may vary over time. This is not the case for Mont Saint-Michel which displays an extremely steady distribution, in agreement with the presence in this region of permanent gyres.

Some of the nurseries, however, are characterized by changes in their main contributing MPAs from year to year, e.g. RhineNL, Sdowns, Thames and Weymouth.

The nurseries along the eastern English coast, i.e. Sdowns, Rye, South Kent, and Thames are exclusively supplied by MPA located outside their boundaries as they do not include MPAs in which spawning occurs.

The Solent nursery receives larvae from the highest number of MPAs, i.e. 6: the South Wight Maritime MPA, but also the Studland to Portland, and the French “Banc des Flandres”, “Cap Gris-Nez”, “Estuaires picards et mer d’Opale”, and “Ridens et dunes hydrauliques”.

Some nurseries do not receive larvae from the MPAs every year, e.g. Cornwall tip or Rhine NL.

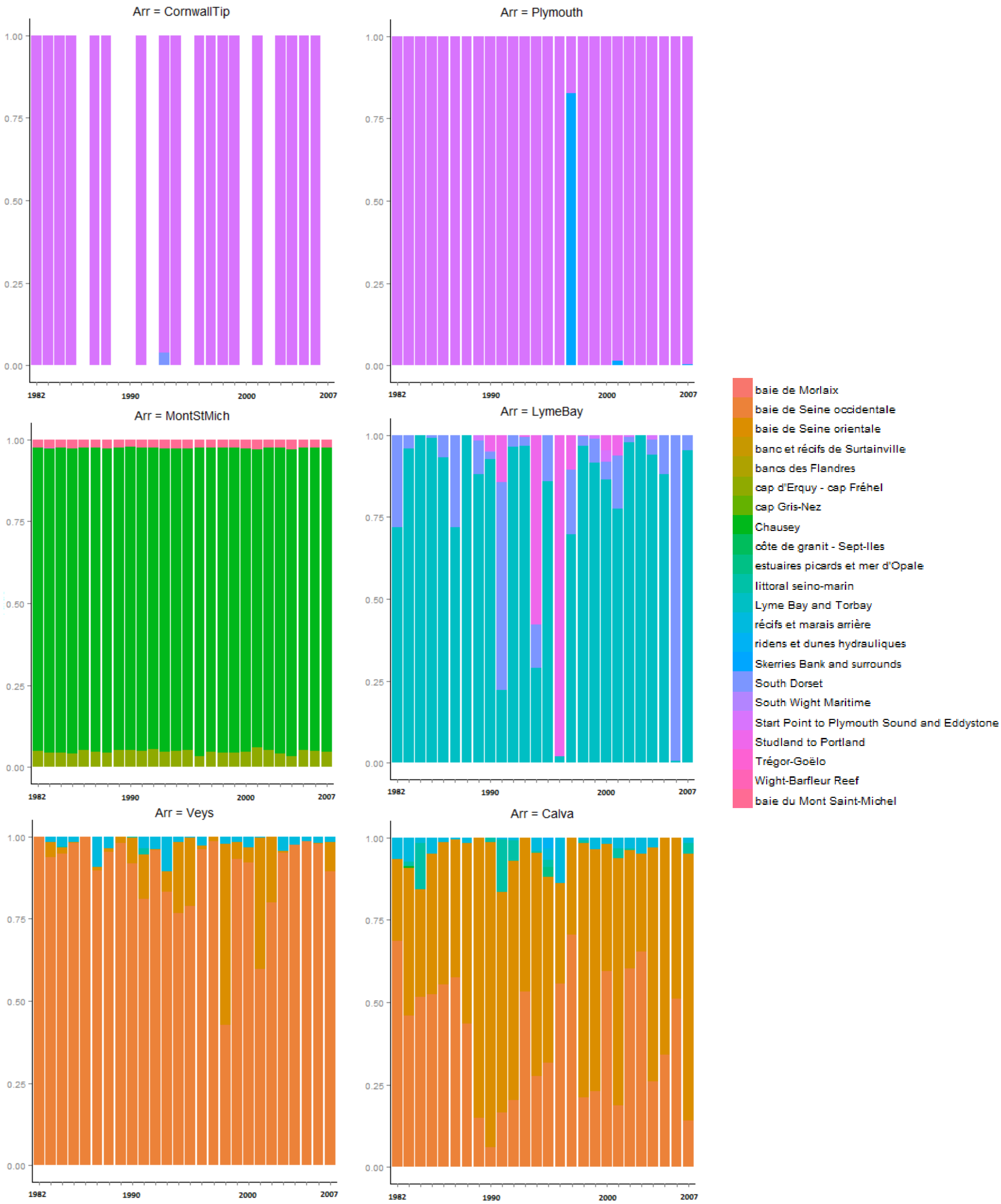


Figure 20: Proportion of larvae for a given nursery coming from all the MPAs.

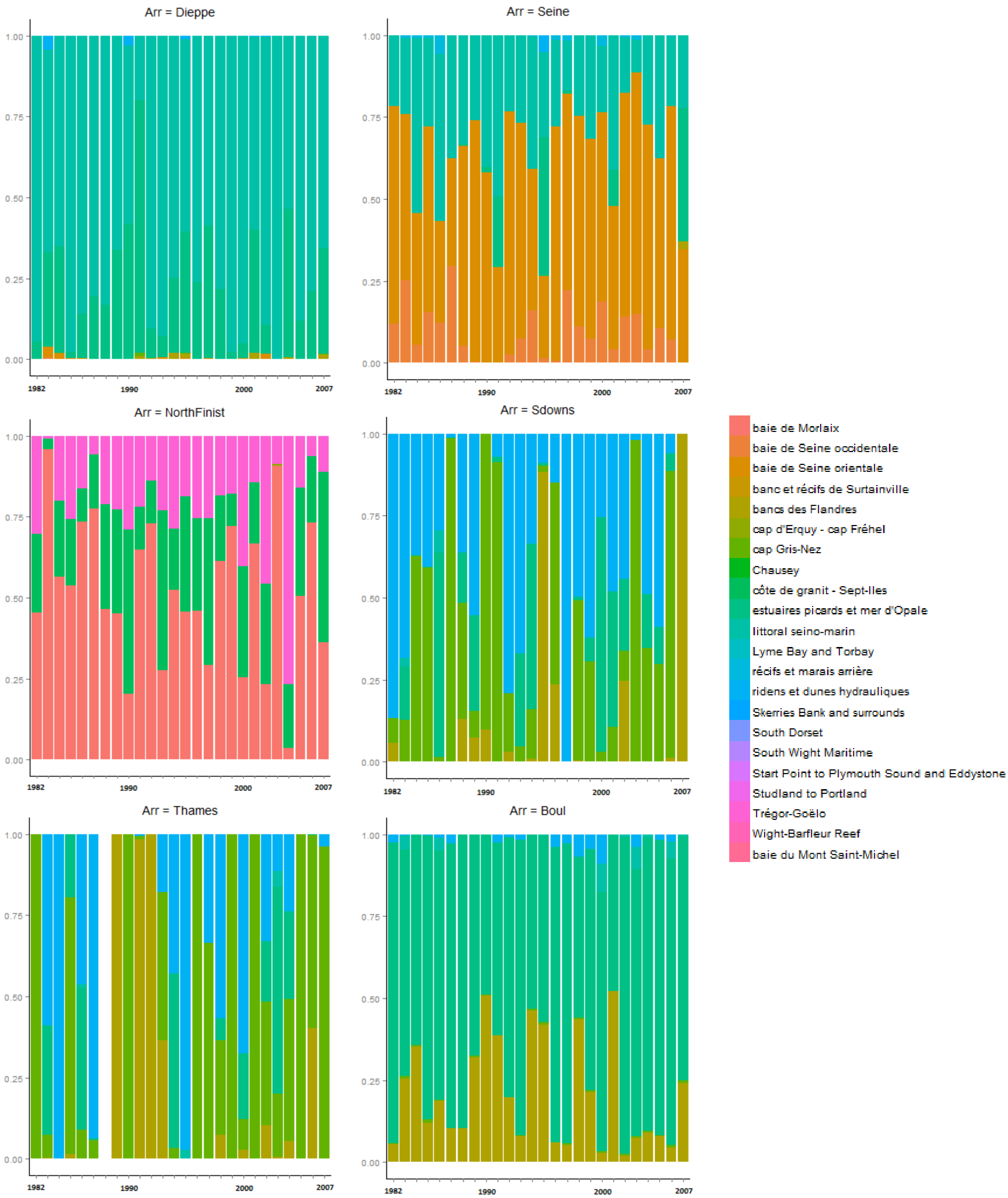


Figure 20 cont.

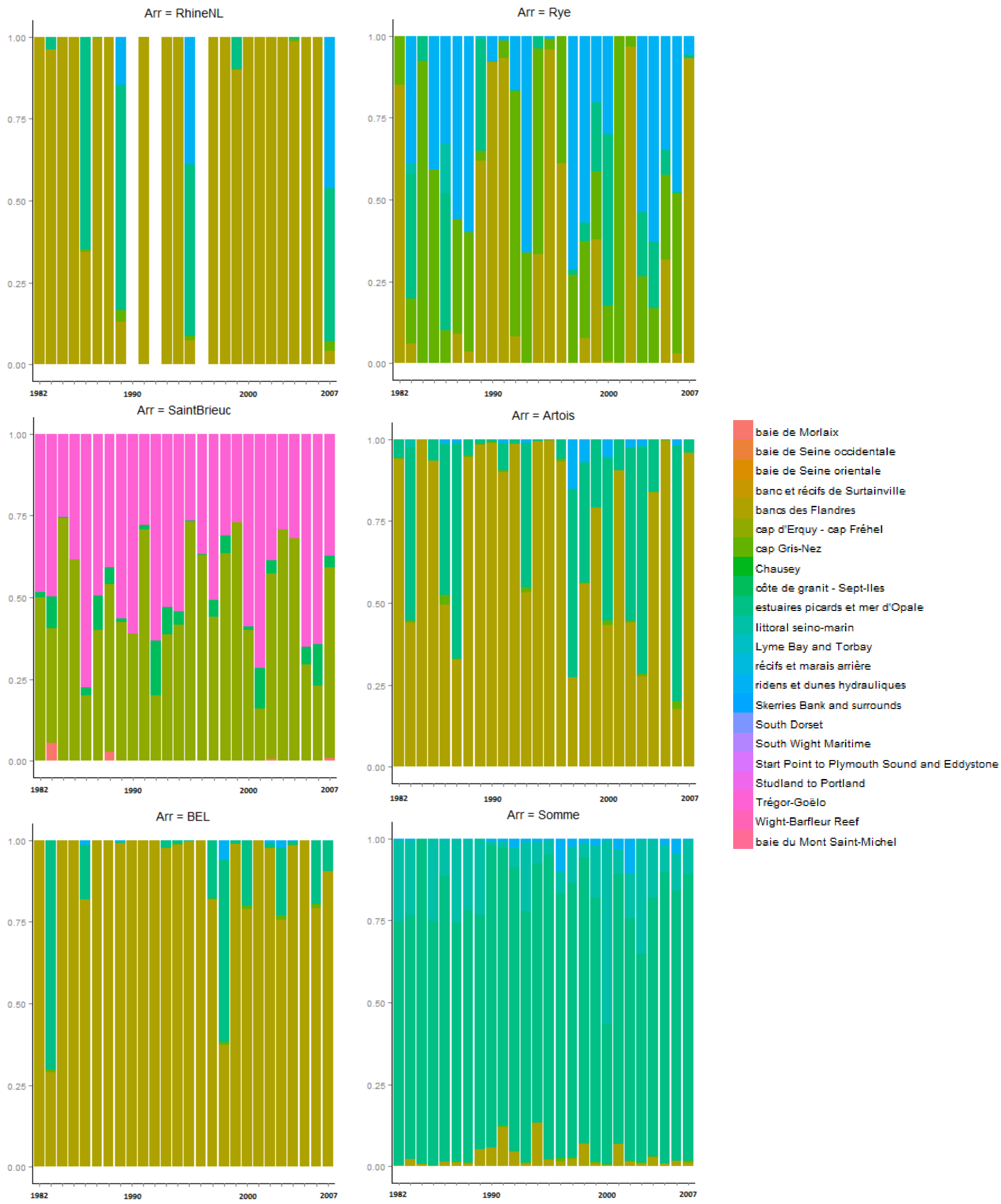


Figure 20 cont.

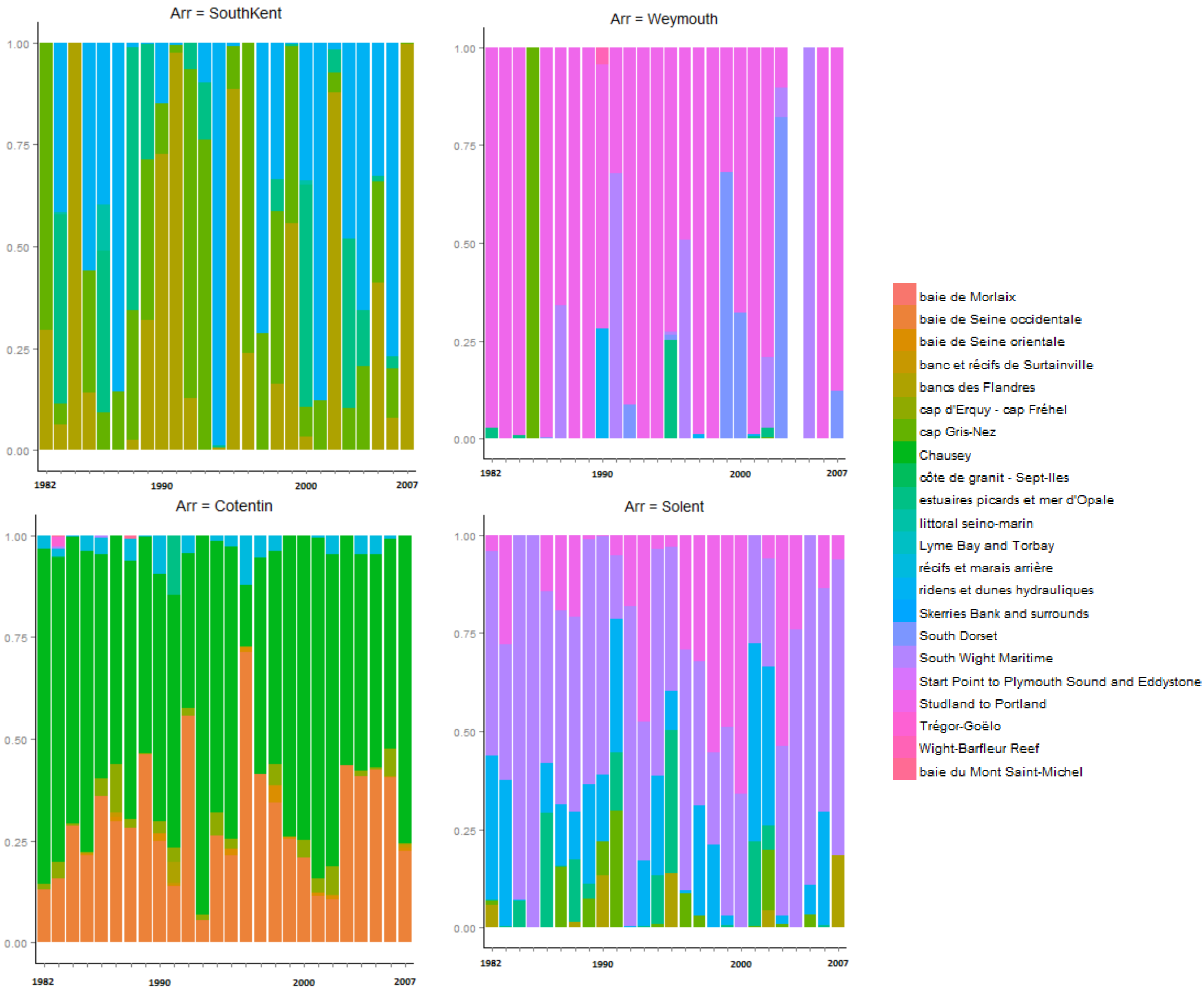


Figure 20 cont.

IV Discussion

The present study is part of the Work Package 1 dedicated to the analysis of the ecological coherence of the current network of MPAs in the English Channel. It focuses on the analysis of inter-MPA connectivity during the larval stage of meroplanktonic species (invertebrates and fish). Two complementary approaches have been used, both based on Lagrangian modeling of eggs and larval drift.

In the first approach -i.e. the generic approach- 158 species have been considered, and grouped into 53 groups according to their biological characteristics. Due to a lack of information, it was not feasible to integrate a real, observed distribution of spawning areas: for all the groups, eggs have been released in all MPAs and larval retention has been computed for all MPAs. As a consequence, the potential connectivity characterized here is probably over-estimated. In the model used, no larval behavior is implemented; eggs and larvae are modelled as passive particles. The retention of particles in suitable nursery areas might be underestimated as a result, and the overall connectivity modified as larvae are believed to use several processes including vertical migration to maintain themselves in suitable habitat (Runge et al. 2005; Leis 2007). Finally, due to simulation time constraints, this generic approach was limited to one year, and it was not possible to test the effect of interannual variability on the overall connectivity.

The second approach used here complemented the generic one, focusing on only one species, but using a more specific model, and covering 26 years. The spawning of the sole is represented fairly realistically in the sole model in terms of timing distribution and quantity, and the biology of the larvae is taken into account to some extent (influence of the temperature on growth and mortality, diel vertical migrations). However, neither predation on eggs and larvae nor the larvae feeding are considered. In addition, the model has not been validated through comparison of its results with real larvae distribution data.

For both approaches, the MPA network had to be simplified. Spatially first: some MPAs were too small or too much inshore (considering the scale of our models) and had not been considered; others (including MPAs of different status) were overlapping and have been merged into groups of MPA. Some of the analysis could simply not run with such complex spatial objects. Secondly, the variety of MPA status has not been considered, all MPAs were treated the same in our models. A lot of the MPAs in our selection do not have any management measures currently implemented anyway (for marine species and habitats), thus this study aims at providing insights for the optimisation of potential future management measures.

The initial objective of this study was to assess the planktonic connectivity of the Channel MPA network currently implemented. As a consequence, in the generic approach, only the connectivity between MPA was assessed (i.e. eggs were spawned within the MPA, and larval supply was estimated on MPAs only). In the case of the second approach, the model design prevented us to proceed in a similar fashion. (1) Spawning was distributed over the whole model domain. The probability of larvae survival was thus computed for the whole Channel, but for the rest of the study, only the eggs spawned in MPAs were considered, similarly to the first approach. (2) The larval supply had to be estimated at the scale of each nursery area as a whole (see section methods p 20).

Overall, the present study shows a strong larval connectivity between adjacent MPAs and generally decreasing connectivity with increasing distance. Our results confirm the results presented in the main PANACHE WP1 report (Foster et al. 2014) stating that there is relatively little connectivity among French and English MPAs. The particular position of the offshore MPA, Wight-Barfleur Reef, is critical in term of planktonic connectivity as it is the main link among MPAs of the two countries. MPAs located around the Dover strait also show some exchange of particles due to their geographical proximity and hydrodynamic conditions. It is worth noting that for species with long distance dispersal, a link from western French MPAs to western English MPAs may sometimes exist. However, in general, the eastward currents of the Channel (Sentchev et al. 2006) transport particles along a longitudinal axis to the North Sea, and may act as a natural barrier to particles, generally preventing exchanges on a North-South axis. In the current configuration of the Channel MPA network, i.e. with only one MPA offshore, this small cross-border exchange of particles may tend to promote a national management of MPAs rather than a cross-border management.

In the generic, multi-species approach, connectivity hotspots are identified, namely the “Golfe Normand-Breton”, Dover strait, and the Cornwall coast, where management should be undertaken with cooperation between the local managers. Indeed actions taken in a particular area may have repercussions in other zones, and reciprocally changes observed in a particular MPA might come from an implementation of a management measure in other zones. These clusters form highly connected groups of MPAs, and thus should be managed in a coherent integrative way. Others MPAs on the other hand show very small exchanges with the rest of the MPA network, e.g. the French MPA “littoral augeron” in the generic approach, or the “Baie du Mont Saint Michel” in the sole case study. These areas will not be able to benefit from adjacent areas, and thus specific conservation measures should be implemented in these “isolated” zones.

Our results suggest the following MPA as remarkable potential source areas of larvae: “Côte de granit rose - Sept îles”, “Trégor-Goëlo”, “anse de Vaudeville”, “Récif et landes de la Hague”, “Récifs et marais arrières”, and « Baie de Seine occidentale ». Knowing the potential source and sink MPAs is interesting for identifying key areas within the current network. Indeed, source MPAs should be managed carefully as eggs and larvae originated from such areas will spread to several zones, ensuring over-spilling of protected organisms offsprings.

At a larger level of aggregation, the overall retention rate of particles within the current Channel MPA network is about 15-45% for a majority of species, but ranges from 5% to 85%, according to dispersal duration. The Channel MPA network can thus be viewed as a fractionated source area providing particles to the non-protected zones of the Channel, which corresponds to one of the expected role of

MPA (Russ et al. 2004).

In the specific approach, we found that connectivity was extremely variable interannually, except in a few places, such as the “Baie du Mont Saint Michel”. In most cases, the links among MPAs and nurseries were the same every year but with varying strengths; but in some cases, connectivity links varied through time (e.g., Eastern English coast: Sdowns, Thames, Weymouth, and Kent). Extrapolating these results allows us to consider with high confidence the frequency of links between MPAs obtained from the generic approach, even from only one year of simulation, but suggest caution when analyzing the results concerning number of particles or percentages of retention. The results for sole showed, similar to those observed in the generic approach, low connectivity between the French and English coast, except in the region of the Dover strait, where the exchanges are quite significant (from the French coast to the English coast), and with the MPA in the North of France being a remarkable source of larvae. Furthermore, we also identified the Baie du Mont Saint-Michel and the Baie of Seine as being rather isolated self-recruiting nursery grounds (neither receiving larvae from outside MPAs nor exporting larvae to other regions). These results are associated with the sole spawning period and larval duration and can only be compared with the Sole case within the generic approach.

V Recommendations

Based on the outcomes of the assessment of planktonic connectivity of the Channel MPA network, the following recommendations are made with regard to improvements in the status of the Channel MPA network by considering connectivity links prior to management measures.

1. The overall retention rate of the network is mainly a function of the drift duration, rather than season and vertical layer of release. Larval connectivity of species not included here could then be approximated using only its drift duration.

2. Some MPAs (e.g. “littoral augeron”, “Baie du Mont Saint Michel”) are self recruiting: a protection of spawning adults may have a direct effect on the nursery function. Such areas appear vulnerable as they cannot benefit from protection of other zones.

3. Some MPAs are highly connected in clusters (“Golfe Normand-Breton”, Dover strait, and the Cornwall coast), and should be managed together.

4. Some MPAs are sink areas, i.e. potentially important nurseries, but the spawning grounds themselves need to be protected too if the enhancement of a particular species productivity is to become an additional objective of the MPAs.

5. French and English MPAs are poorly connected which tend to promote a national management of MPAs rather than a cross-border management. Depending on the actual distribution of species of interest, increasing cross-border exchange of larvae would require definition of new MPAs located offshore in areas where pelagic connectivity is prevented by too large distances.

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Appendix

Latin valid	spawning season	spawning behaviour (bottom, water column, surface)	Initial length Length at hatch length yolk-salc to feeding larvae	egg stage duration	larval stage duration	Dispersion time	information on egg density or larval behaviour	information on spawner distribution in the CHANNEL, possibly spawner habitat
DEMERSAL AND BENTHIC FISH								
Ammodytidae	december-january	all species lay demersal adhesive eggs which attach to sand-grains. Leave the sand in order to spawn.	y : 6mm metamorphose length= 45mm	2 to 4 months	90 days	90 days	larvae and post-larvae are pelagic during all stages of development.	shallower sand and fine gravel of the continental shelf from littoral to offshore habitat. Western english Channel and Channel Islands
Aspitrigla cuculus	April - august	female lay eggs which float at the surface. After hatching, larvae leave are pelagic before living at the bottom.		16 days	8 days	24 days	pelagic eggs and larvae	in the central Channel . Between north Cotentin and Uisle of Wight from february until June.
Buglossidium luteum	mai-August	eggs between the surface and 1m depth	0,69 - 0,94 mm 2 mm 3,5 mm	hatch at 2mm	metamorphosis begins at 7mm	24 days	pelagic larvae after hatching. Spawning event appearded in function of water temperature. There are 2 spawning events, separated from one month.	along the coast. Abundant between 5-20m depth. Found in the south coast of england (English Channel). Distibution not related to sediment type.
Callionymidae	April - august	spawning in 4 phases : courtship, pairing, ascension to the surface and release of pelagic eggs.	0,81 - 0,97 mm 2mm 4 - 5 mm	1 days	6 days	7 days	Larvae also pelagic.	in temperate and warm seas. Sandy and muddy substrate sometimes under stones. From the tidal zone down to 200m. Spawning areas seem to display shallow depth but stong bed shear stress with higher temperature.
Chelidonichthys gurnardus	february to august	eggs and larvae are pelagic. Eggs float in the water column.	1,16 - 1,63 mm 3,5 mm 4,7 mm	5 days	8 days	13 days	pelagic life	sandy mud bottom between 0 and 200m depth
Clupea harengus	end of november to february with a peak in december	benthic spawner, eggs attached to gravel, stones or vegetation	0,9 - 1,5mm 5 to 9 mm 8,2 mm	2-3 weeks (stay attached to the bottom)	60 days 40mm at metamorphosis	60 days	herring spawn near the bottom (5-20m) at the french side of the Channel from Fécamp to Dunkerque in gravelly, rocky bottoms. Eggs fall in the bottom and fixed to the substrate.	shallow waters (5-20m), gravely substrates, from Boulogne sur Mer to Fecamp
Dicentrarchus labrax	from mid-february to end of june (peak from mid-february to end of march in western channel)	eggs are pelagic. No density which permit to maintain on the plankton.	1,20 - 1,51 mm 3,5 mm 5 mm	5 days	30 days	35 days	hatching when the eggs mesure 3,5mm. Larvae stay 30 days in coastal area then, they go in estuary areas where juveniles spend among 3 years.	spawning areas first in the western english Channel and then in the eastern English Channel at the end of the season.
Echiichthys vipera	june - august	pelagic eggs spawned in the water column.	1,01 - 1,37 mm 3 mm 4,5 mm	9 days hatching at 3mm	7 days metamorphosis at 8.3mm	18 days	planctonic eggs and larvae	Common on clean sandy bottoms from the low water mark to the shallow sub-littoral down to 50 m. The species lives buried in the sand with only the head and back uncovered. The species is probably most active at night. Lives in very shallow depths to 150m, burried in the sand in daytime.
Engraulis encrasicolus	April - august	spawning near the surface (10-30m depth) having a temperature between 14 and 19°C	1,2 - 1,9 mm 3,5 mm 4mm	4 days	30 days	34 days	1 spawning event each 3-4 days between 22h and 2h, near the surface (<30m).	areas off the Seine estuary, east of the Isle of Wight, off the Normandy coast and south of the Dover Strait.
Gadus morhua	December - May	benthic spawner in a bottom between 50 and 200m	1,16 - 1,89 mm 3 mm 5 mm	12 days	5 months (pelagic larvae) before moving to the bottom	167 days	fast growth for alevin with a length of 20cm after the first year of life	bottom between 50 and 200m. 2 different zone for spawning and nutrition = seasonal migrations. Spawning region in North sea

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DEMERSAL AND BENTHIC FISH								
Limanda limanda	february to april	benthic spawner in a bottom between 20 and 40m	0,66 - 0,98 mm 3 mm 5mm	14 days	6 days metamorphosis in may-june at a length of 12-13mm	20 days	migration to the bottom after the metamorphosis. First year between 8-10m then they leave the coastal region.	coastal region (20-40m), Channel and south of the North sea. Spawning area seems to require fine to coarse sands. Spawning grounds are in the central eastern of the English Channel.
Lotidae	january - september	spawn pelagic eggs off the eastern Channel. Spawning on sediment types ranging from coarse sand to pebbles. Eggs fall in the bottom		4 weeks	3 months (with the first to weeks swimming to the surface)	120 days	pelagic eggs and larvae. Spawning site in fairly shallow waters (<5m depth) over sand or gravel bottom. Fertilized eggs will then drift until they settle into cracks and holes in the substrate.	spawning area appears to require shallow to intermediate depth, with higher temperature but lower salinities and chlorophylle a concentration than elsewhere.
Merlangius merlangus	march - june	water column at 20 to 150m depth	0,97 - 1,32 mm 3,2 - 3,5 mm 6,5 mm	10 days	20 days	30 days	eggs are pelagics. Larvae and juveniles often associated to jelly fish and do not become demersal until they reach 5 to 10cm. Juveniles concentrate in coastal waters. Fast growth (from 15 to 19cm at 1 year). Spwan in the continental shelf until 200m depth with an important concentration between 40 and 80m depth.	spawning at 20 to 150m. Spawning area are extended from the central part of the english Channel and along the French and British coast. Bentho-demersal species living on gravel or mud bottom between 10 and 200m found in marine and brackish temperate water.
Microstomus kitt	march - august	pelagic eggs float at the surface.	1,13 - 1,45 mm 4 mm 4,7 mm	8 days	4 days undergo metamorphosis when they reach 15-20mm. Fry then migrate to the bottom.	12 days	pelagic larvae drif with currents at the surface but migrate deeper in the water column during development	benthic species that lives on hard bottoms (rock shelf), gravels or shelly sand between 40 to 200m principally in temperate marine waters.
Mullus surmuletus	may - july	eggs are pelagic (in the water column)		8 days	32 days	40 days	absorbtion of the vitellus 4 days after eclosion then migration to the coastal region in autumn. Juveniles live on sand and shelly sand bottom below 10m depth.	pelagic fish living on pebbly, gravelly and sandy bottom on the continental shelf and on the continental slope between 10 and 300m depth. Found in marine water which temperature between 8 and 24°C
Platichthys flesus	february - june	pelagic eggs float at the water surface	0,82 - 1,13 mm 2 - 3 mm 4,5 mm	7 days	10 days undergo metamorphis reaching 15-20mm length.	17 days	at first pelagic eggs float at the water surface and then sink in deeper waters during development. Pelagic larvae that migrate to the bottom reaching 7-10mm.	in marine waters or estuary (brackish water). The spawning areas seem to require coarse sands, deep waters though protected from tidal currents, and relatively warm temperatures.
Pleuronectes platessa	december - march	surface	1,66 - 2,17 mm 5,5 - 7 mm 5,8 mm	30 days	40 days	70 days	eggs start to float at the surface before going deeper in the water column. Larvae are pelagic before metamorphosing.	spawning areas seem to be located in the central english Channel in relatively deep waters protected from strong tidal currents.
Sardina pilchardus	september - december	the spawning area seems to shift eastwards between march to august, with sardines coming back in the western Channel from September to November.	1,3 - 1,9 mm 3,5 mm 5,5 mm	4 days	12 days	16 days	The pelagic eggs float between 10 and 70 m in depth.	pelagic fish gregarious. large schools which are found near to the surface at night (between 15 and 40 m in depth) and deeper during the day (between 30 and 50 m in depth). High abundance in the Seine estuary and in the Bay of Veys

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DEMERSAL AND BENTHIC FISH								
Scomber scombrus	june - july	eggs float close to the surface. Pelagic eggs.	1,0 - 1,38 mm 3 mm 4 mm	6 days	20 days	26 days	The various larval and juvenile stages swim at depths between 0 and 30 m along the coast, until the autumn when they begin their migration towards offshore wintering areas.	gregarious pelagic fish found in substrates between 0 to 250 m, but mainly from the surface down to 40 m below. found in coastal waters: in estuaries, in the Dover Strait and in the southern North Sea.
Solea solea	February - june	pelagic eggs	0,95 - 1,58 mm 3 mm 4,3 mm	11 days	14 days	25 days	pelagic eggs and larvae. Benthic fry. Juneniles spend the first 2 or 3 years in coastal nurseries (bays and estuaries) where fast growth occurs before moving to deepers waters.	reproduction mainly in the coastal areas of the Dover Strait and in large bays (Somme, Seine , Solent, Mt St Michel, Start and Lyme Bay). Spawning starts when water temperure is higher than 7°C.
Spondyliosoma cantharus	april - september	eggs at the bottom in nest in fine gravel. In coastal water between 20 and 30m depth.		10 days	pelagic larvae 2 months before migrating to nurseries areas	70 days	benthic eggs, pelagic larvae before migrating in nurseries areas in shallow waters	bentho-pelagic species spawning in coastal waters. Gravelly bottom. this species seems to tolerate a range of depths but favours weak bed shear stress and fine to gravely sediment types that correspond to a range of coastal zones.
Sprattus sprattus	december - march	pelagic eggs and larvae	0,8 - 1,3 mm 3,5 mm 4,5 mm	5 days	20 days	25 days	Larvae were found almost everywhere except near the headlands of the Dover Strait and along the southern coast of Normandy.	Maximum preferred habitats were located in the center of the Dover Strait. This species does not follow the classical scheme of migration towards coastal nurseries as its larvae remains pelagic throughout their development.
Trachurus trachurus	May - september	Eggs only develop if temperature is warmer than 10°C.	0,81 - 1,04 mm 2,5 mm 3,5 mm	2,5 to 3 days (2,5mm length)	15 days	18 days	pelagic eggs and larvae	pelagic and gregarious fish. Lives in midwater or sandy substrates mostly between the surface and 200m depth. a very extensive favourable habitat. Low salinity and sandy sediments in the French coastal areas seemed to better suit these young individuals. reproduction in the easter english Channel
Trisopterus luscus	february - june	pelagic eggs	0,9 - 1,23 mm 3 mm 3,8 mm	12 days	13 days size of first metamorphosis = 18mm	25 days	After hatching, the larvae migrate to the bottom. Juveniles live near to the coast.	demersal and gregarious specie. mostly found on sandy (juveniles) or rocky substrates or around wrecks (adults), and from the surface near the coast to depths of 100-150 m. Juveniles also gather in estuaries.
Trisopterus minutus	february - may	external fertilisation. Eggs in the bottom and then pelagic larvae	0,95 - 1,03 mm 2,5 mm 4,5 mm	10 days	7 days size of first metamorphosis = 9,5mm	17 days	pelagic eggs and larvae	young individuals are found in shallow waters, often seen in and around wrecks, or in cracks or crevices of rocky substrates. Physiographic preferences = Open coast, Offshore seabed.
Zeus faber	June - august	no eggs observed in the English Channel. Demersal eggs	1,96 - 2,00 mm 4,3 mm 4,3 - 3,76 mm (due to change in morphology : shape)	17 days	8 days size of first metamorphose = 19mm	25 days	juveniles observed in the English Channel	

Latin valid	spawning season	spawning behaviour (bottom, water column, surface)	Initial length Length at hatch length yolk-salc to feeding larvae	egg stage duration	larval stage duration	Dispersion time	information on egg density or larval behaviour	information on spawner distribution in the CHANNEL, possibly spawner habitat
INVERTEBRATE GROUPS								
Aequipecten opercularis	june - october	spawn as adults i.e. at the bottom		5 days	30 days	35 days	external fertilization. Eggs probably demersal. After hatching, there is a short period of crawling before larvae attached themselves to the substrate and reach metamorphosis.	central part of the Channel. Gravel / shingle, Coarse clean sand, Fine clean sand, Muddy sand, Gravelley sand. Benthic adults. Down to 100m depth. Open coast, Offshore seabed, Strait / sound, Sealoch, Ria / Voe, Estuary, Enclosed coast / Embayment.
Alcyonium digitatum	december - february	spawn at the bottom (as adults).		7 days	10 days	17 days	external fertilization; embryos are neutrally buoyant and float freely. The embryos give rise to actively swimming lecithotrophic planulae which may have an extended pelagic life before they eventually settle (usually within one or two further days) and metamorphose to polyps .	Depth range = Low water (Springs) to 50 m. prefers areas of strong water movement resulting from wave turbulence or currents. Substratum preferences = Large to very large boulders, Small boulders, Bedrock, Artificial (e.g. metal/wood/concrete), Caves, Overhangs, Cobbles. Found in, Open coast and Offshore seabed.
Ascidia *Phallusia mammillata* *Pelonaia corrugata* *Aplidium* *Ascidiacea* *Styela clava* *Ciona intestinalis* *Molgula manhattensis* *Botryllus* *Ascidiella scabra* *Ascidia mentula* *Ascidia virginea* *Ascidiella* *Molgulidae* *Polyclinidae* *Botryllus schlosseri* *Ascidiella aspersa* *Pyuridae* *Dendrodoa grossularia*	may - october	eggs hatch at temperatures of 16 to 20ºC. The eggs are negatively buoyant and sink in still water. They are adhesive and stick to the substratum. The eggs are about 160 microns in diameter, yolky and red or green in colour. Long tapering outer follicle cells radiate from the surface of the eggs. Eggs may be released individually or in mucus strings. The mucus strings tangle with and readily adhere to nearby adults.		among 24h	larvae active for approximatively 12h	2 days	larvae are pelagic. they are negatively geotactic and exhibit high barokinesis. They rarely travel more than a few centimetres in sustained swimming activity; their movement is mainly vertical. Some dispersal is possible at the egg stage but most occurs during the short swimming larval stage and is, therefore, limited.	permanent attachment to hard substrates. Substratum preferences = Artificial (e.g. metal/wood/concrete), Bedrock, Large to very large boulders, Small boulders, Cobbles, Algae, Under boulders, Biogenic reef. Found in Open coast, Offshore seabed, Strait / sound, Sealoch, Ria / Voe, Estuary, Enclosed coast / Embayment.
Asterias rubens	february - april	reproductive location = water column		1-2 days	3 months	90 days	female produces small eggs that are released into the sea and fertilized externally to develop as planktotrophic larvae before they settle on seabed for metamorphosis	zones of fine sediments in the central Eastern English Channel and on coarser sediments near to the Dover Strait. Substratum preferences = Gravel / shingle, Coarse clean sand, Bedrock. Found in Open coast, Offshore seabed, Strait / sound, Enclosed coast / Embayment.

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Astropecten irregularis	may - june	reproductive location = water column		<1 day	30 days	30 days	The fertilization gives a said dipleurula larva, which joins the plankton. After a few weeks, the larva undergoes a metamorphosis. While the great majority of the larvas of Astérides pass by two additional, said embryonic stages bipinnaria then brachiolaria, the stars Astropecten have no brachiolaria phase, what is a primitive character of the group. The larva bipinnaria grave on the bottom and is directly transformed tiny one star-comb, which will not delay burying itself.	substratum preferences : Gravelley sand, Muddy sand, Fine clean sand, Coarse clean sand. Fin in Strait / sound, Offshore seabed, Open coast.
Cancer pagurus	mid-november to january	during all the incubation, the female lies in the sand, partly burried.		7 to 8 months	among 60 days but some studies record 40 days, or even up to 51-78 days including zoea stage IV	300 days	pelagic larvae. Development in function of temperautre	simulation in areas shallower than 12m depth. Simulated larvae were allowed to disperse for 21 days in April-May, at a constant depth of 0.5-3m.
Crangon *Crangon allmanni* *Crangon crangon*	march - december	eggs are carried by the female. (not floatting with plankton)		2-3 weeks at 20°C to more than 3 months at 6°C	49 days	49 days	only eggs developed between 6 and 21°C are viable. Larvae are pelagic. Larvae hatching at from summer eggs are smaller than those from winter eggs.	live on sandy, muddy areas in bays and estuaries. Abundant in estuary and intertidal marine waters. Lives between 0 and 50m depth. Inabits mainly soft bottom (sand, sandy-mud or muddy substrates) in estuarine and marine shallow area. Reproduction in deeper (10-20m depth) and more saline off shore marine water usually in sandy or muddy area.
Crepidula fornicata	february - september	Eggs are incubated in the female cavity paleal in capsule fixed at the substrate where the female lives.		3 to 4 weeks	30 days	30 days	pelagic larvae	fixed on a hard substrate or directly on other individuals.
Flustra foliacea	august - april.	spawn as adult i.e. at the bottom.		90 days	< 1 day	90 days	internal fertilization.	substratum preferences = Bedrock, Large to very large boulders, Mixed, Small boulders, Cobbles. Found in Open coast, Offshore seabed, Strait / sound, Sealoch, Ria / Voe. All wave exposure.
Homarus gammarus	July -> december	reproduction on the bottom as adults		7 to 10 months	30 days	30 days	5000 to 50000 eggs. At hatching 2/3 of the eggs have survived. Larvae released at night. The female need 2 or 3 weeks to release all of its offsprings.	rocky bottom. In the tidal zone down to 200min depth but rarely over 100m. East of the Isle of Wight and center of the Dover Strait.
Hyas *Hyas araneus* *Hyas coarctatus*	august - september	Spawn at the bottom.		75 days	85 days	85 days	hatching at the owest seasonal water temperature (less than 4 °C). A diapause occurs for a period of 16 weeks with seawater temperatures between 11 and 15 °C. The eggs of these species ceased to develop beyond the gastrula stage which was achieved	inabits rocky sandy and muddy bottoms from the intertidal region down to 555m depth.

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Hydrozoa	october - february	fertilized eggs fixe to a rudimentary polyp, the female blastostyle		2 to 20 days	3 days	3 days	pelagic larvae. Reproducting localisation = as adults. External fertilization.	substratum preferences : Bedrock, Large to very large boulders, Small boulders, Cobbles.
Obelia								
Hydractinia echinata								
Diphasia								
Diphasia attenuata								
Sertulariidae								
Hydrallmania falcata								
Abietinaria abietina								
Amphisbetia operculata								
Eudendrium								
Campanulariidae								
Kirchenpaueria pinnata								
Tubularia indivisa								
Tubularia								
Thuiaria thuja								
Tamarisca tamarisca								
Sertularia cupressina								
Sertularia								
Aglaophenia								
Halecium halecium								
Lytocarpia myriophyllum								
Nemertesia ramosa								
Nemertesia antennina								
Nemertesia								
Aglaophenia pluma								
Inachus	january-june					105 days		
Liocarcinus depurator	january - june	females produce 2 broods per year. Eggs develop beneath the abdomen of ovigerous female.		1 month	55 days	55 days	eggs on the female pleopods and then pelagic larvae.	coastal areas on muddy bottom. Distributed at depths around 100m.
Liocarcinus holsatus	April - august	at the bottom		30 days at	55 days	55 days	spawn as adults at the bottom	substratum preferences : Bedrock, Large to very large boulders, Gravel / shingle, Mixed. Found in Open coast, Offshore seabed, Strait / sound, Sealoch, Ria / Voe, Estuary, Enclosed coast / Embayment.
Macropodia	all year	at the bottom		48 days	30 days	30 days	larval development occured in open sea.	find on mixed substratum between 0 and 170m depth. In the sublittoral zone. muddy bottom on the continental shelf
Macropodia deflexa								
Macropodia linaresi								
Macropodia rostrata								
Macropodia tenuirostris								
Maja brachydactyla	March - june	eggs attached to pleopods develop under the female's abdomen.		2 to 3 months	3 weeks of pelagic life then after metamorphosis begins the benthic life.	21 days	3 consecutive broods between the consecutive cycle. After htching, eggs are release in the water column.	on rocks among algae. Also on soft bottoms. Found down to about 50m depth. Abundance high along the british coast (Selsey, Sorenham, Dungeness and Folkestone).

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Metridium senile	august - september	spawn in the water column		36 hours	30 days	32 days	eggs are fertilized internally or externally and hatch into free swimming planular larvae. fertilization occurs, the resulting zygotes develop into swimming planula larvae that can drift great distances before settling onto a suitable substrate and metamorphosing into juvenile anemones.	substratum preferences = Bedrock, Large to very large boulders, Biogenic reef Artificial (e.g. metal/wood/concrete), Caves, Overhangs. Biological zone = Sublittoral Fringe, Upper Infralittoral, Lower Infralittoral, Upper Circalittoral, Lower Circalittoral.
Necora puber	october - january and May -june	eggs stay on pleopods		50 days	39 days	39 days	eggs fixed on pleopods. pelagic larvae	hard substrate. Rocky and gravelly bottoms. relatively shallow water, ranging from the lower intertidal down to depths of approximately 20m. Spawning area are often located in sandy-muddy bottom off the coastal area. North-south gradient : in the high lattitude, spawning appears later.
opisthobranchia *Dendronotus frondosus* *Onchidoris muricata* *Acanthodoris pilosa* *Acteon tornatilis* *Doridoidea* *Tritonia hombergi* *Scaphander lignarius* *Aeolidia papillosa* *Pleurobranchus* *Armina loveni* *Nudibranchia* *Doris pseudoargus* *Onchidoris bilamellata* *Aplysia punctata* *Jorunna tomentosa* *Dorididae* *Geitodoris planata* *Gastropteron rubrum* *Philine aperta*	march - june	spawn periodically as long as food is available		13 days	10 days	23 days	pelagic larvae	live on rocky, sandy bottom, in brackish lagoons, soft bottoms and posidonia.
Ostrea edulis	june - october	female gametes are released in the paleal cavity where there is a fecundation with sperm. Then, eggs are release in the water column.		10 days	14 days	24 days	pelagic larvae before fixing on a hard substrate	eggs stay on the paleal cavity after the fecundation.
Pagurus bernhardus	december - march	crafs broods once or twice a year depending on their shells.		50 days	35 days	35 days	carry eggs on their pleopods between november and may.	
Pagurus prideaux	all year	pelagic larvae. Female keep eggs with her = benthic eggs.		8 weeks	30 days	30 days	gonochoric animals. Eggs, incubated on the female abdomen hatch and then larvae are pelagic.	substrate preferences : Muddy gravel, Coarse clean sand, Fine clean sand, Sandy mud, Mud, Gravelley sand, Muddy gravelly sand, Gravelly mud. Found in Open coast, Offshore seabed, Strait / sound, Sealoch, Estuary, Enclosed coast / Embayment.

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Pecten maximus	May - september	pelagic life permits the dispersion of scallops in function of currents.		3 to 7 days function of the water temperature	30 days pelagic life before fixing in a substrat.	37 days	eggs and larvae have a pelagic life. This pelagic life is for 3 to 5 weeks.	gravely, muddy-sandy and shelly bottoms. Sub-littoral up to 100m, mainly found between 10 to 50m depth. Bay of Veys off the Pays de Caux up to the central part of the esatern Channel. Spawning area correspond to the areas were adults live.
Psammechinus miliaris	April - september	external fertilisation reproductive location = water column.		30 days	40 days	70 days	Eggs are released into the water and the larvae that hatch out remain in the open sea for a month before settling on the shore.	hard bottom and gravels. From the intertidal zone down to 100m depth. Off the Pays de Caux, in the Dover Strait and in the Bay of Seine. Live in depth ranges extended to littoral zone exposed on boulders shores and low waters.
Sponges *Halichondria panicea* *Haliclona* *Pachymatisma johnstonia* *Hymedesmia* *Haliclona cinerea* *Axinella dissimilis* *Haliclona oculata* *Dysidea fragilis* *Mycale lingua* *Pachymatisma* *Stelligera stuposa* *Axinella* *Axinella infundibuliformis* *Adreus fascicularis* *Tethya aurantium* *Halichondria bowerbanki* *Suberites pagurorum* *Suberites ficus* *Polymastia* *Suberites* *Polymastia boletiformis* *Raspailia hispida* *Polymastia mamillaris* *Ciocalypta penicillus* *Raspailia* *Raspailia aculeata* *Raspailia pumila* *Raspailia ramosa* *Suberites domuncula* *Stelligera*	april - november	spawn in the water column. internal fertilization.		<2days	3 days	5 days	2 types of reproduction: sexual and asexual. With the sexual reproduction type, eggs hatch and then larvae are released, swim for a short time and fixed to the substrate	substratum preferences : Bedrock, Large to very large boulders. Found in Estuary, Strait / sound, Ria / Voe, Isolated saline water (Lagoon).

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Urticina *Urticina crassicornis* *Urticina eques*	april - june	spawn in water column, eternal fertilization		8 days	30 days	38 days	Development of the eggs will take place either in the surrounding ocean waters, or in the septal chambers of the animal. eggs develop into planula larvae which can be either planctonic larave. The planula larvae will typically develop in the open ocean, where they grow into juvenile anemones	offshore the coast until 400m. On bedrock, large to very large boulders, small boulders, crevices/fissures

PANACHE

Protected Area Network Across the Channel Ecosystem

PANACHE is a project in collaboration between France and Britain. It aims at a **better protection** of the Channel marine environment through the **networking** of existing marine protected areas.

The project's five objectives:

- **Assess** the existing marine protected areas network for its ecological coherence.
- **Mutualise** knowledge on monitoring techniques, share positive experiences.
- **Build** greater coherence and foster dialogue for a better management of marine protected areas.
- **Increase** general awareness of marine protected areas: build common ownership and stewardship, through engagement in joint citizen science programmes.
- **Develop** a public GIS database.

France and Great Britain are facing similar challenges to protect the marine biodiversity in their shared marine territory: PANACHE aims at providing **a common, coherent and efficient reaction**.

PANACHE est un projet franco-britannique, visant à une **meilleure protection** de l'environnement marin de la Manche par la **mise en réseau** des aires marines protégées existantes.

Les cinq objectifs du projet :

- **Étudier** la cohérence écologique du réseau des aires marines protégées.
- **Mutualiser** les acquis en matière de suivi de ces espaces, partager les expériences positives.
- **Consolider** la cohérence et encourager la concertation pour une meilleure gestion des aires marines protégées.
- **Accroître** la sensibilisation générale aux aires marines protégées : instaurer un sentiment d'appartenance et des attentes communes en développant des programmes de sciences participatives.
- **Instaurer** une base de données SIG publique.

France et Royaume-Uni sont confrontés à des défis analogues pour protéger la biodiversité marine de l'espace marin qu'ils partagent : PANACHE vise à apporter **une réponse commune, cohérente et efficace**.

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