Supplementary Material

Ms. entitled “MPA network design based on graph theory and emergent properties of larval dispersal”

By: Andres Ospina-Alvarez, Silvia de Juan, Josep Alós, Gotzon Basterretxea, Alexandre Alonso-Fernández, Guillermo Follana-Berná, Miquel Palmer, and Ignacio A. Catalán.

Table S1: Pelagic larval duration (mean and SD) in days and range of breeding season of some littoral species in the Mediterranean Sea and inhabiting the Balearic Islands. Adapted from Macpherson and Raventós (2006)\(^1\). The last row includes the PLD and range of months used in the Lagrangian transport simulations by Basterretxea et al. (2012)\(^2\).

| Common name         | Scientific name           | mean PLD | SD  | Breeding season         |
|---------------------|---------------------------|----------|-----|-------------------------|
| Cardinal fish       | Apogon imberbis           | 21.3     | 1.4 | July to September       |
| Adriatic blenny     | Lipophrys adriaticus      | 23.0     | 1.7 | April to August         |
| Mystery blenny      | Parablennius incognitus   | 23.8     | 1.6 | February to July        |
| Bucchich's goby     | Gobius bucchichi          | 19.2     | 1.0 | April to June           |
| Goldsinny wrasse    | Ctenolabrus rupestris     | 20.9     | 2.0 | January to July         |
| Brown meagre        | Sciaena umbra             | 22.5     | 0.7 | March to August         |
| Dusky grouper       | Epinephelus marginatus    | 24.6     | 1.3 | July to September       |
| Comber              | Serranus cabrilla         | 24.3     | 1.8 | April to July           |
| Brown comber        | Serranus hepatus          | 18.0     | 0.9 | March to August         |
| Annular seabream    | Diplodus annularis        | 18.3     | 1.4 | May to June             |
| Zebra seabream      | Diplodus cervinus         | 18.3     | 1.5 | January to April        |
| Straightnose pipefish| Nerophis ophidion        | 21.5     | 0.7 | May to August           |
| Tub gurnard         | Chelidonichthys lucerna   | 19.1     | 1.2 | October to April        |
| Red-black triplefin | Tripterygion tripteronotum| 18.4     | 2.8 | April to August         |
| Lagrangian transport simu. | NA                  | 21.0     | NA  | March to August         |

(1) Basterretxea, G., Jordi, A., Catalán, I.A., Sabatés, A., 2012. Model-based assessment of local-scale fish larval connectivity in a network of marine protected areas. Fish. Oceanogr. 21, 291–306. doi:10.1111/j.1365-2419.2012.00625.x

(2) Macpherson, E., Raventós, N., 2006. Relationship between pelagic larval duration and geographic distribution in Mediterranean littoral fishes. Mar. Ecol. Prog. Ser. 327, 257–265.
Table S2. Index or centrality measure, normalized* value and sorted nodes for the potential larval connectivity network. Local Retention (LR), Relative Local Retention (RLR), Self-Recruitment (SR), Strength (STR), Out-Strength (OST), In-Strength (IST), Closeness (CLO), Betweenness (BET), Eigenvector centrality (EIV), Hub score (HUB), Authority score (AUT) and Page Rank (PAR).

* The normalization was performed using the following formula: (x - min) / (max - min).

| Category | Cent. Mea. | Norm. value | Sorted nodes | Cent. Mea. | Norm. value | Sorted nodes | Cent. Mea. | Norm. value | Sorted nodes | Cent. Mea. | Norm. value | Sorted nodes | Cent. Mea. | Norm. value | Sorted nodes |
|----------|------------|-------------|--------------|------------|-------------|--------------|------------|-------------|--------------|------------|-------------|--------------|------------|-------------|--------------|
| Highest  | 0.044      | 1.000       | 6            | 57.000     | 1.000       | 6            | 1.000      | 1.000       | 11           | 1.000      | 1.000       | 11           | 1.000      | 1.000       | 11           |
|          | 0.043      | 0.985       | 7            | 55.000     | 0.965       | 7            | 0.878      | 0.850       | 9            | 0.972      | 0.968       | 10           | 0.770      | 0.729       | 2            |
|          | 0.040      | 0.875       | 5            | 35.000     | 0.614       | 8            | 0.742      | 0.683       | 4            | 0.912      | 0.902       | 9            | 0.763      | 0.722       | 3            |
|          | 0.031      | 0.536       | 2            | 28.000     | 0.491       | 5            | 0.735      | 0.675       | 1            | 0.904      | 0.894       | 12           | 0.444      | 0.346       | 5            |
|          | 0.030      | 0.508       | 8            | 27.000     | 0.474       | 10           | 0.727      | 0.666       | 12           | 0.569      | 0.521       | 8            | 0.419      | 0.316       | 4            |
|          | 0.029      | 0.474       | 1            | 24.000     | 0.421       | 9            | 0.701      | 0.634       | 11           | 0.498      | 0.442       | 3            | 0.362      | 0.250       | 9            |
|          | 0.028      | 0.423       | 9            | 16.000     | 0.281       | 4            | 0.656      | 0.579       | 10           | 0.471      | 0.412       | 4            | 0.291      | 0.166       | 8            |
|          | 0.026      | 0.341       | 4            | 12.000     | 0.211       | 2            | 0.605      | 0.516       | 2            | 0.207      | 0.119       | 7            | 0.223      | 0.087       | 12           |
|          | 0.023      | 0.235       | 3            | 2.000      | 0.035       | 3            | 0.601      | 0.511       | 8            | 0.125      | 0.027       | 2            | 0.163      | 0.016       | 7            |
|          | 0.018      | 0.062       | 10           | 1.000      | 0.018       | 11           | 0.353      | 0.207       | 5            | 0.120      | 0.022       | 6            | 0.162      | 0.015       | 11           |
|          | 0.018      | 0.041       | 12           | 1.000      | 0.018       | 1            | 0.268      | 0.104       | 7            | 0.108      | 0.009       | 1            | 0.156      | 0.008       | 10           |
|          | 0.017      | 0.000       | 11           | 0.000      | 0.000       | 12           | 0.184      | 0.000       | 6            | 0.100      | 0.000       | 5            | 0.150      | 0.000       | 6            |

| Category | LR        | RLR       | SR        | STR       | OST       | IST       |
|----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Highest  | 0.082     | 1.000     | 0.032     | 0.082     | 0.082     | 0.082     |
|          | 0.077     | 0.918     | 0.082     | 0.082     | 0.082     | 0.082     |
|          | 0.063     | 0.700     | 0.082     | 0.082     | 0.082     | 0.082     |
|          | 0.059     | 0.625     | 0.082     | 0.082     | 0.082     | 0.082     |
|          | 0.054     | 0.549     | 0.082     | 0.082     | 0.082     | 0.082     |
|          | 0.047     | 0.434     | 0.082     | 0.082     | 0.082     | 0.082     |
|          | 0.036     | 0.272     | 0.082     | 0.082     | 0.082     | 0.082     |
|          | 0.033     | 0.223     | 0.082     | 0.082     | 0.082     | 0.082     |
|          | 0.032     | 0.207     | 0.082     | 0.082     | 0.082     | 0.082     |
|          | 0.023     | 0.066     | 0.082     | 0.082     | 0.082     | 0.082     |
|          | 0.021     | 0.037     | 0.082     | 0.082     | 0.082     | 0.082     |
|          | 0.019     | 0.000     | 0.082     | 0.082     | 0.082     | 0.082     |

| Category | CLO       | BET       | EIV       | HUB       | AUT       | PAR       |
|----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Highest  | 0.063     | 1.000     | 0.082     | 1.000     | 1.000     | 1.000     |
|          | 0.063     | 0.918     | 0.082     | 1.000     | 1.000     | 1.000     |
|          | 0.063     | 0.700     | 0.082     | 1.000     | 1.000     | 1.000     |
|          | 0.063     | 0.590     | 0.082     | 1.000     | 1.000     | 1.000     |
|          | 0.063     | 0.434     | 0.082     | 1.000     | 1.000     | 1.000     |
|          | 0.063     | 0.272     | 0.082     | 1.000     | 1.000     | 1.000     |
|          | 0.063     | 0.223     | 0.082     | 1.000     | 1.000     | 1.000     |
|          | 0.063     | 0.207     | 0.082     | 1.000     | 1.000     | 1.000     |
|          | 0.063     | 0.066     | 0.082     | 1.000     | 1.000     | 1.000     |
|          | 0.063     | 0.037     | 0.082     | 1.000     | 1.000     | 1.000     |
|          | 0.063     | 0.000     | 0.082     | 1.000     | 1.000     | 1.000     |
Table S3. Index or centrality measure, normalized* value and sorted nodes for the realised larval connectivity network. Local Retention (LR), Relative Local Retention (RLR), Self-Recruitment (SR), Strength (STR), Out-Strength (OST), In-Strength (IST), Closeness (CLO), Betweenness (BET), Eigenvector centrality (EIV), Hub score (HUB), Authority score (AUT) and Page Rank (PAR).

* The normalization was performed using the following formula: (x - min) / (max - min).

| Category | LR | RLR | SR | STR | OST | IST |
|----------|----|-----|----|-----|-----|-----|
|          | Index value | Norm. value | Sorted nodes | Sorted nodes | Sorted nodes | Sorted nodes | Sorted nodes |
| Highest  | 0.191 | 1.000 | 4   | 0.825 | 1.000 | 3   | 0.7513 | 1.000 | 4   | 0.497 | 1.000 | 4   | 0.244 | 1.000 | 4   | 0.254 | 1.000 | 4   |
| High     | 0.063 | 0.323 | 10  | 0.713 | 0.806 | 11  | 0.6645 | 0.873 | 5   | 0.211 | 0.399 | 5   | 0.121 | 0.491 | 3   | 0.095 | 0.325 | 10  |
| Medium   | 0.051 | 0.261 | 8   | 0.668 | 0.729 | 10  | 0.6622 | 0.870 | 10  | 0.188 | 0.351 | 10  | 0.100 | 0.404 | 8   | 0.078 | 0.256 | 8   |
| Low      | 0.019 | 0.091 | 11  | 0.448 | 0.347 | 1   | 0.5261 | 0.670 | 8   | 0.179 | 0.331 | 8   | 0.094 | 0.376 | 10  | 0.073 | 0.234 | 12  |
| Lowest   | 0.002 | 0.000 | 1   | 0.248 | 0.000 | 5   | 0.068  | 0.000 | 6   | 0.022 | 0.000 | 1   | 0.003 | 0.000 | 1   | 0.018 | 0.000 | 1   |

| Category | CLO | BET | EIV | HUB | AUT | PAR |
|----------|-----|-----|-----|-----|-----|-----|
|          | Cent. Mea. | Norm. value | Sorted nodes | Cent. Mea. | Sorted nodes | Cent. Mea. | Sorted nodes | Cent. Mea. | Sorted nodes | Cent. Mea. | Sorted nodes | Cent. Mea. | Sorted nodes | Cent. Mea. | Sorted nodes |
| Highest  | 0.055 | 1.000 | 5   | 57.000 | 1.000 | 5   | 1.000 | 1.000 | 1   | 1.000 | 1.000 | 1   | 1.000 | 1.000 | 1   | 0.139 | 1.000 | 1   |
| High     | 0.040 | 0.680 | 4   | 44.000 | 0.772 | 7   | 0.747 | 0.661 | 11  | 0.809 | 0.805 | 11  | 0.773 | 0.684 | 8   | 0.130 | 0.905 | 9   |
| Medium   | 0.033 | 0.550 | 3   | 32.000 | 0.561 | 4   | 0.665 | 0.551 | 9   | 0.257 | 0.240 | 3   | 0.687 | 0.564 | 1   | 0.109 | 0.707 | 2   |
| Low      | 0.028 | 0.436 | 7   | 20.000 | 0.351 | 2   | 0.431 | 0.237 | 8   | 0.248 | 0.231 | 9   | 0.618 | 0.468 | 5   | 0.092 | 0.545 | 8   |
| Lowest   | 0.018 | 0.244 | 10  | 0.000 | 0.000 | 9   | 0.325 | 0.096 | 6   | 0.120 | 0.100 | 4   | 0.435 | 0.213 | 4   | 0.064 | 0.272 | 11  |

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Table S4. Index or centrality measure, normalized* value and sorted nodes for the larval connectivity network scenario. Local Retention (LR), Relative Local Retention (RLR), Self-Recruitment (SR), Strength (STR), Out-Strength (OST), In-Strength (IST), Closeness (CLO), Betweenness (BET), Eigenvector centrality (EIV), Hub score (HUB), Authority score (AUT) and Page Rank (PAR).

* The normalization was performed using the following formula: (x - min) / (max - min).

| Category | CLO   | BET   | EIV   | HUB   | AUT   | IST   |
|----------|-------|-------|-------|-------|-------|-------|
|          | Cent. Mea. | Norm. value | Sorted nodes | Cent. Mea. | Norm. value | Sorted nodes | Cent. Mea. | Norm. value | Sorted nodes | Cent. Mea. | Norm. value | Sorted nodes | Cent. Mea. | Norm. value | Sorted nodes | Cent. Mea. | Norm. value | Sorted nodes |
| Highest  | 0.051 | 1.000 | 7     | 66.000 | 1.000 | 1     | 1.000 | 1.000 | 1     | 1.000 | 1.000 | 1     | 1.000 | 1.000 | 1     | 9     | 0.139 | 1.000 | 1     |
| High     | 0.049 | 0.955 | 5     | 56.000 | 0.848 | 5     | 0.737 | 0.682 | 9     | 0.993 | 0.991 | 11    | 0.756 | 0.737 | 8     | 0.130 | 0.905 | 9     |
|          | 0.041 | 0.800 | 8     | 48.000 | 0.727 | 4     | 0.407 | 0.282 | 8     | 0.066 | 0.065 | 9     | 0.518 | 0.482 | 12    | 0.109 | 0.707 | 2     |
| Medium   | 0.038 | 0.699 | 4     | 36.000 | 0.545 | 3     | 0.361 | 0.226 | 11    | 0.046 | 0.044 | 6     | 0.387 | 0.341 | 7     | 0.102 | 0.635 | 3     |
|          | 0.034 | 0.650 | 3     | 27.000 | 0.409 | 10    | 0.318 | 0.174 | 12    | 0.035 | 0.032 | 4     | 0.382 | 0.335 | 10    | 0.092 | 0.545 | 8     |
| Lowest   | 0.030 | 0.579 | 2     | 20.000 | 0.303 | 2     | 0.239 | 0.078 | 10    | 0.025 | 0.023 | 2     | 0.331 | 0.282 | 11    | 0.085 | 0.479 | 12    |
|          | 0.018 | 0.335 | 9     | 17.000 | 0.258 | 8     | 0.212 | 0.046 | 5     | 0.022 | 0.019 | 12    | 0.300 | 0.248 | 5     | 0.069 | 0.323 | 5     |
|          | 0.017 | 0.315 | 10    | 0.000 | 0.000 | 9     | 0.211 | 0.045 | 3     | 0.021 | 0.018 | 3     | 0.207 | 0.148 | 6     | 0.064 | 0.272 | 11    |
|          | 0.015 | 0.278 | 12    | 0.000 | 0.000 | 12    | 0.204 | 0.036 | 7     | 0.017 | 0.015 | 10    | 0.182 | 0.121 | 4     | 0.063 | 0.262 | 10    |
|          | 0.014 | 0.245 | 6     | 0.000 | 0.000 | 6     | 0.184 | 0.011 | 2     | 0.008 | 0.006 | 8     | 0.155 | 0.092 | 3     | 0.062 | 0.256 | 4     |
|          | 0.011 | 0.194 | 11    | 0.000 | 0.000 | 11    | 0.183 | 0.011 | 6     | 0.005 | 0.003 | 5     | 0.088 | 0.020 | 2     | 0.049 | 0.130 | 7     |

**Lowest**

| **Category** | **LR** | **RLR** | **SR** | **STR** | **OST** | **IST** |
|--------------|--------|---------|--------|---------|---------|---------|
| **Index value** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Norm. value** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Sorted nodes** | 1     | 1     | 1     | 1     | 1     | 1     |

**Highest**

| **Category** | **Index value** | **Norm. value** | **Sorted nodes** | **Index value** | **Norm. value** | **Sorted nodes** | **Index value** | **Norm. value** | **Sorted nodes** | **Index value** | **Norm. value** | **Sorted nodes** | **Index value** | **Norm. value** | **Sorted nodes** | **Index value** | **Norm. value** | **Sorted nodes** |
|--------------|-----------------|-----------------|------------------|-----------------|-----------------|------------------|-----------------|-----------------|------------------|-----------------|-----------------|------------------|-----------------|-----------------|------------------|-----------------|-----------------|------------------|
| **Highest**  | 0.257 | 1.000 | 3     | 0.825  | 1.000 | 3     | 0.8464 | 1.000 | 3     | 0.616  | 1.000 | 3     | 0.312  | 1.000 | 3     | 0.304  | 1.000 | 3     |
| **Norm. value** | 0.136 | 0.527 | 4     | 0.782  | 0.926 | 4     | 0.6669 | 0.783 | 12    | 0.377  | 0.602 | 4     | 0.174  | 0.555 | 4     | 0.204  | 0.652 | 4     |
| **Sorted nodes** | 0.045 | 0.172 | 10    | 0.668  | 0.729 | 10    | 0.6327 | 0.741 | 10    | 0.158  | 0.237 | 5     | 0.110  | 0.350 | 5     | 0.071  | 0.193 | 6     |
| **Lowest**   | 0.036 | 0.140 | 8     | 0.634  | 0.670 | 12    | 0.6159 | 0.721 | 7     | 0.137  | 0.203 | 10    | 0.072  | 0.227 | 8     | 0.071  | 0.193 | 10    |
| **Medium**   | 0.036 | 0.139 | 12    | 0.506  | 0.448 | 8     | 0.5806 | 0.678 | 8     | 0.134  | 0.197 | 8     | 0.067  | 0.212 | 10    | 0.062  | 0.164 | 8     |
| **Low**      | 0.027 | 0.105 | 5     | 0.494  | 0.427 | 9     | 0.5672 | 0.662 | 5     | 0.111  | 0.159 | 12    | 0.057  | 0.180 | 12    | 0.054  | 0.135 | 12    |
| **Lowest**   | 0.005 | 0.019 | 9     | 0.368  | 0.208 | 7     | 0.2012 | 0.218 | 9     | 0.056  | 0.068 | 11    | 0.010  | 0.031 | 9     | 0.034  | 0.067 | 2     |
| **Lowest**   | 0.003 | 0.011 | 6     | 0.287  | 0.068 | 2     | 0.0462 | 0.031 | 6     | 0.035  | 0.033 | 9     | 0.008  | 0.024 | 6     | 0.025  | 0.036 | 9     |
| **Lowest**   | 0.000 | 0.000 | 1     | 0.248  | 0.000 | 5     | 0.0209 | 0.000 | 1     | 0.016  | 0.000 | 1     | 0.001  | 0.000 | 1     | 0.015  | 0.000 | 1     |
Figure S1: Four hypothetical graph networks of five nodes representing connected sites. Upper left panel shows a simple non-directed and unweighted graph network. Upper right panel shows a geodesic non-directed and weighted graph network, the number of nodes is the same, but now each node has assigned a geographical position. The importance of the nodes (weights) depends on the sum of all distances to other nodes. The strength of the linkages, showed as edges, depends on distance between node pairs. Lower left panel represents a hydrodynamic directed and weighted graph network, the geographical position of nodes is as in the geodesic network. The nodes and edges weights depend on the probability of connection determined by ocean currents. The directionality of ocean currents implies directionality in the linkages. This graph corresponds to a potential connectivity network. The lower right panel shows a bio-physical directed and weighted graph network. Here, the ocean currents exert influence on directionality and weighting of nodes and edges, but biological and ecological conditions determine the resulting importance of each node and linkage in the network. This graph corresponds to a realised larval connectivity network.
Figure S2: Graphs for the a) potential and b) realised larval connectivity networks. The nodes are symbolising Marine Protected Areas (MPAs) and Open Access Areas (OAAs) as in Fig. 1. The larval export and recruitment are showed as the normalised Out-Strength (yellow) and In-Strength (blue), respectively. When exportation is higher than recruitment the node represents a source site. When recruitment is higher than exportation the node represents a sink site. The strength of the connection is showed as coloured edges between node pairs.

Figure S3: Page Rank for the potential, realised and scenario larval connectivity networks. Node size and colour symbolise Page Rank and edge width and colour symbolise normalised edge strength. Note that Page Rank for the nodes show no difference between the different networks, suggesting that this measure of centrality is only of limited use in the study of larval connectivity.
Text S1. Individual Based Model for Total Egg production Method

The hydrodynamic directed network corresponds to a graphical representation of a potential larval connectivity matrix (see main document). In contrast, a realized larval transport directed network corresponds to a graphical representation of a realized larval connectivity matrix. We calculated the realized larval connectivity matrix weighting the potential larval connectivity matrix (probability of connection due to hydrodynamics) with the spatial variability in the abundance of eggs produced and released, derived from available reproductive output information for the painted comber Serranus scriba (Alonso-Fernández et al., 2011; Alos et al., 2013; 2014). To estimate the total number of eggs released every week in each of the nodes we developed a daily egg production probabilistic Individual Based Model (egg-IBM). The egg-IBM was based on a simulation model of the total number of eggs released considering the empirical number of individuals (abundance) and the size structure of each node, and the reproductive parameters estimated in two Bayesian models using empirical data: a spawning probability model (model 1) and the number of eggs released by each spawning individual in function of the Julian day and the size of the fish (total length, mm) (model 2).

In the first Bayesian Model (model 1), we estimated the parameters of a logistic regression model of being mature or not against the Julian date and fish size using a data-set published in Alonso-Fernández et al. (2011). Accordantly, 753 individuals of S. scriba were sampled in different locations of Mallorca island over the years 2006 and 2007, their gonads dissected and their maturity stage (spawning vs. non-spawning) histologically assessed (Alonso-Fernández et al., 2011). The parameters of the regression model were estimated using a Bayesian approach considering flat and uninformative priors. Interestingly, the single effect of size was significant (the Bayesian Credibility Interval-BCI didn’t overlap zero) suggesting the larger the individual, the longer the spawning season. The posterior distributions of the model parameters were further used to predict the probability of a simulated individual being in spawning stage or not.

In the second Bayesian model (model 2), we estimated the parameters of an exponential model fitting the number of eggs released by an individual every day (S. scriba is a daily batch spawner, Alos et al., 2013) in function of their fish size and the spatial location of the node. Thus, the batch fecundity (number of hydrated eggs) of 129 individuals sampled across the 12 nodes of the network in May 2007 was estimated. Alos et al. (2014) have shown that S. scriba displays significant differences in reproductive investment of isolated sub-populations on small spatial scales in the study area. Therefore, in order to achieve a more realistic realized larval connectivity matrix for a MPA-OAA mixed network, we have estimated the spatially structured egg production of S. scriba for all nodes considered in our matrix: nodes for the National Park of Cabrera (n=19), Palma Bay (n=27) and the rest (n=83) were aggregated. The parameters of the three spatial regression models were estimated using a Bayesian approach considering the same flat and uninformative prior structure. The posterior distributions of the model parameters were further used to predict the number of eggs released by an individual with a given fish size.