

<sup>1</sup> Ecological Network assembly: how the regional meta web influence  
<sup>2</sup> local food webs

<sup>3</sup> Abstract

<sup>4</sup> The idea that ecological networks are built in a sequence of colonization events is not new but has been  
<sup>5</sup> applied mostly to competitive interactions. Similar processes act in trophic networks, i.e. food webs: a  
<sup>6</sup> regional pool of species act as the source from which species colonize local areas, called the metaweb. Local  
<sup>7</sup> food webs are realizations of metawebs that result from assembly processes influenced by migration, habitat  
<sup>8</sup> filtering, stochastic factors, and dynamical constraints imposed by food-web structure. We analyse how the  
<sup>9</sup> structure of a metaweb influence local food webs with different spatial scales, using an assembly model, a  
<sup>10</sup> random model and properties at three levels: emergent global properties that take into account the whole  
<sup>11</sup> network e.g. modularity, sub-structural properties that consider several nodes e.g. motifs, and properties  
<sup>12</sup> related to one node e.g. topological roles. Three independent data-sets were included: the marine Antarctic  
<sup>13</sup> metaweb (34.8 million Km<sup>2</sup>), the Weddell Sea (3.5 million Km<sup>2</sup>) and Potter Cove (6.8 Km<sup>2</sup>) food webs.  
<sup>14</sup> Looking at the global properties, the metaweb presents a structure very different from the random model,  
<sup>15</sup> while the local food webs follow the same pattern and are very similar to the assembly model. The assembly  
<sup>16</sup> model only takes into account migration, local extinction and secondary extinctions. For sub-structural  
<sup>17</sup> properties the metaweb and the local food webs also showed the same pattern against the random model,  
<sup>18</sup> but we found differences compared to the assembly model that did not increase the local stability of food  
<sup>19</sup> webs. Topological roles also showed differences between the metaweb and local food webs that were explained  
<sup>20</sup> by the assembly model. We found that a great portion of the structure of the food webs is determined by  
<sup>21</sup> evolutionary processes that act on large temporal and spatial scales. On the contrary, dynamical processes  
<sup>22</sup> that favour stability have a small influence, but habitat filtering or dispersal limitations seem to be important  
<sup>23</sup> factors that determine food web structure.

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<sup>30</sup> **Introduction**

<sup>31</sup> The characterization of ecological systems as networks of interacting elements has a long history (Paine 1966,  
<sup>32</sup> May 1972, Cohen and Newman 1985). Much of this work has been devoted to investigate network structure  
<sup>33</sup> and its effects on dynamics and stability (Thebault and Fontaine 2010). In recent years a renewed emphasis  
<sup>34</sup> on structural stability (Rohr et al. 2014, Grilli et al. 2017) and new developments in random matrix theory  
<sup>35</sup> has greatly expanded our capability to analyse ecological networks (Allesina et al. 2015). However, the  
<sup>36</sup> analyses of the effects of ecological dynamical processes on food web structure are not so well developed.  
<sup>37</sup> One such dynamic process is community assembly: how species from a regional pool colonize a site and  
<sup>38</sup> build local interactions (Carstensen et al. 2013). Regional species pools are shaped by evolutionary and  
<sup>39</sup> biogeographical processes that imply large spatial and temporal scales (Carstensen et al. 2013, Kortsch et al.  
<sup>40</sup> 2018). More specifically, the assembly of local communities is influenced by dispersal, environmental filters,  
<sup>41</sup> biotic interactions and stochastic events (HilleRisLambers et al. 2012). These processes have been studied  
<sup>42</sup> by means of metacommunity theory (Leibold et al. 2017), where different spatial assemblages are connected  
<sup>43</sup> through species dispersal.

<sup>44</sup> Metacommunity theory provides a framework for assessing the roles of local- and regional-scale dynamics  
<sup>45</sup> (Leibold et al. 2004, Baiser et al. 2013). This approach has been applied mostly to competitive interactions,  
<sup>46</sup> whereas trophic interactions have received less attention (Baiser et al. 2016). Recently, there has been an  
<sup>47</sup> increase in food web assembly studies, integrating them with island biogeography (Gravel et al. 2011) and  
<sup>48</sup> with metacommunity (Pillai et al. 2011, Liao et al. 2016). These were mainly focused on complexity-stability  
<sup>49</sup> effects (Mougi and Kondoh 2016). Previous attempts to study the food web assembly process have used  
<sup>50</sup> motifs as building blocks of local communities (Baiser et al. 2016). Motifs are sub-structures in networks  
<sup>51</sup> composed of species and links whose frequency deviates from the expected in a random network (Milo et al.  
<sup>52</sup> 2002). By comparing motif representation at different spatial scales—from local to regional—the process of  
<sup>53</sup> assembly of interactions may be revealed (Baiser et al. 2016), e.g. if the same processes structure the food  
<sup>54</sup> web across scales, motif representation should be the same. Besides, as local food webs should have tighter  
<sup>55</sup> links and stronger interaction rates, other structural properties should change as scale changes (Coll et al.  
<sup>56</sup> 2011).

<sup>57</sup> The objective of the present study is to analyse the process of food web assembly addressing how multilevel  
<sup>58</sup> network properties change across different spatial scales. For this we considered: the Antarctic metaweb,  
<sup>59</sup> representing an area of 34.8 million Km<sup>2</sup>, and build from a dietary database (Raymond et al. 2011); the  
<sup>60</sup> Weddell Sea food web that represents 3.5 million Km<sup>2</sup> (Jacob et al. 2011); and the Potter Cove network

61 that represents 6.8 Km<sup>2</sup>, (Marina et al. 2018a).

62 There are several approaches to characterize the structure of ecological networks: emergent or global prop-  
63 erties that focus on averages over the entire network (e.g. modularity or connectance), and more local  
64 properties that focus on how one or several species are related to the whole. Global properties related to  
65 resilience and stability are fundamental to understand the response of ecological networks to global threats  
66 like climate change and biological invasions. One of these properties is the small-world pattern, associated  
67 with rapid responses to disturbances and resistance to secondary extinctions (Montoya and Solé 2002). The  
68 small-world pattern is related to two global properties: the average of the shortest distance between all  
69 species, called the characteristic path length, and the clustering coefficient, the probability that two species  
70 linked to the same species are linked. Then, small-world patterns imply a high level of clustering and a short  
71 average path length compared to random networks (Watts and Strogatz 1998). This pattern comes from  
72 the general network theory, beyond ecological networks, and has been recently applied to marine food webs  
73 (Gray et al. 2016, Navia et al. 2016, Bornatowski et al. 2017, Marina et al. 2018b).

74 Since the early studies of May (1972) stating that larger and more connected ecosystems will be unstable,  
75 there has been a search for factors that would stabilize food webs (García-Callejas et al. 2018); one of the  
76 potential properties is trophic coherence (Johnson et al. 2014). Trophic coherence is based on the distances  
77 between the trophic positions of species and measures how well species fall into discrete trophic levels. Then,  
78 more coherence implies a more hierarchical food-web structure , which is directly correlated with linear  
79 stability (Johnson et al. 2014). The advantage of coherence as an index of stability is that it does not make  
80 any assumptions about interaction strengths. A property related to coherence is the mean trophic level,  
81 which historically has been used as an ecosystem health indicator (Pauly et al. 1998), predicting that food  
82 webs with higher trophic levels are less stable (Borrelli and Ginzburg 2014).

83 Food webs have structurally complex and highly non-random patterns that contain internal functional units  
84 or sub-modules (Grilli et al. 2016). These are groups of prey and predators that interact more strongly with  
85 each other than with species belonging to other modules. These modules (also called compartments) act  
86 as a buffer to the propagation of perturbations throughout the network, increasing its persistence (Stouffer  
87 and Bascompte 2011). It is interesting to mention that small-world patterns and modularity act in opposite  
88 directions. Whereas the small-world structure favours the spread of perturbations through its rapid dissipa-  
89 tion (Gray et al. 2016), the presence of a high degree of modularity prevents the dispersal of perturbations  
90 (Krause et al. 2003, Stouffer and Bascompte 2011). The detection of these modules is an intermediate  
91 approach between the global and local analyses.

92 Species may participate in different ways with respect to modularity, depending on how many trophic links  
93 they have within their own module and/or between modules (Guimerà and Nunes Amaral 2005, Kortsch et  
94 al. 2015). This participation with respect to modularity is called a species' topological role. Theoretical and  
95 empirical results suggest these roles are related to species traits, such as wide niche breadth, environmental  
96 tolerance, apex position in local communities and high motility (Rezende et al. 2009, Guimerà et al. 2010,  
97 Borthagaray et al. 2014, Kortsch et al. 2015). This is a local property at an individual species level.

98 If we consider a subset of linked species inside the food web this forms a sub-network, when the abundance of  
99 one of these sub-networks deviates significantly from a null model network, this is called a motif (Milo et al.  
100 2002). Besides this definition, in the ecological literature motif has been used as a synonym of sub-network.  
101 We analyse here the three-species sub-networks that have been most studied theoretically and empirically  
102 in food webs (Prill et al. 2005, Stouffer et al. 2007, Baiser et al. 2016). Specifically, we focused on four of  
103 the thirteen possible three-species sub-networks: apparent competition, exploitative competition, tri-trophic  
104 chain, and omnivory (Figure 1).

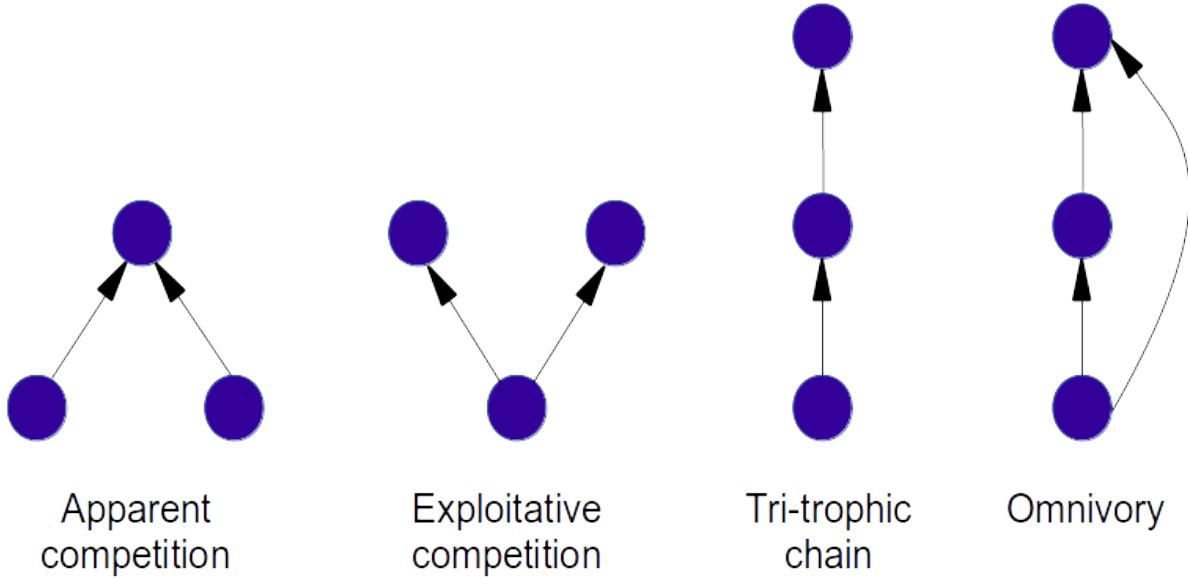


Figure 1: The four three-species sub-networks analysed: apparent competition, exploitative competition, tri-trophic chain, and omnivory. These four sub-networks have been explored both theoretically and empirically in ecological networks and are the most common sub-networks found in food webs

105 The frequency of motifs at different spatial scales (i.e over-represented, under-represented, or random) may  
106 reveal aspects about the process behind the assembly of interactions (Baiser et al. 2016). If the same processes  
107 structure the food web across scales, motif representation should be the same. Ecological interactions occur  
108 at the local scale so differences may show the importance of local interactions in the assembly of the food web.

109 During the assembly process those motif structures that are less dynamically stable tend to disappear from  
110 the food web (Borrelli 2015), this has been called non-adaptative systemic selection (Borrelli et al. 2015).  
111 The process is non-adaptative because the selection process is not adapting the system to local conditions  
112 (Borrelli et al. 2015).

113 In this study, we analyze food web assembly from a metaweb to local networks with different spatial scales.  
114 To our knowledge, combining modularity, trophic coherence and motifs at different spatial scales has not  
115 been applied in food web studies up to now. First we compared the networks—including the metaweb—  
116 against a random network model (i.e. absence of ecological mechanisms), and a metaweb assembly model  
117 (i.e. representing an assembly process). We hypothesize that network properties will change from the metaweb  
118 to a local scale at which interactions are realized. We particularly expect global properties related to resilience  
119 and stability to be close to the random null model at the metaweb scale and significantly different at the  
120 local scale; a greater frequency of stable motifs in the local food webs; as well as a change in the frequency  
121 of topological roles since habitat filtering or dispersal limitation act at the local food web scale. These last  
122 two changes also should be reflected as differences from the metaweb assembly model.

## 123 Methods

124 The three datasets used in this study encompass a wide range of spatial scales and were collected inde-  
125 pendently. The Southern Ocean database compiled by Raymond et al. (2011) was used to construct the  
126 Antarctic metaweb selecting only species located at latitudes higher than 60°S. Raymond et al. (2011)  
127 compiled information from direct sampling methods of dietary assessment, including gut, scat, and bolus  
128 content analysis, stomach flushing, and observed feeding. We considered that the metaweb is the regional  
129 pool of species defined by the biogeographic Antarctic region. Next we analysed two local food webs: the  
130 Weddell Sea food web dataset includes species situated between 74°S and 78°S with a West-East extension  
131 of approximately 450 km, and comprises all information about trophic interactions available for the zone  
132 since 1983 (Jacob et al. 2011). The Potter Cove dataset comes from a 4 km long and 2.5 km wide Antarctic  
133 fjord located at 62°14'S, 58°40'W, South Shetland Islands (Marina et al. 2018a). These food web datasets  
134 comprise benthic and pelagic habitats of the Antarctic ecosystem, few aggregated low-trophic level groups  
135 (e.g. detritus, diatoms, phytoplankton, zooplankton) and a high resolution of the macroalgae community  
136 (i.e. 24 biological species of red, brown and green macroalgae). The macroalgae community is responsible  
137 for the majority of the primary production and supports a large fraction of secondary production in Antarc-  
138 tic fjords (Quartino and Boraso de Zaixso 2008, Valdivia et al. (2015)). Higher trophic levels comprise:

139 invertebrate (e.g. ascidians, sponges, isopods, amphipods, bivalves, gastropods, cephalopods, echinoderms)  
140 and vertebrate predator groups (e.g. demersal and pelagic fishes, penguins, seals and whales). For more  
141 information about these datasets we refer to the original publications. To make datasets compatible, we first  
142 checked taxonomic names for synonyms, and second, we added species (either prey or predator) with their  
143 interactions to the metaweb when the local food webs contain a greater taxonomic resolution. When the  
144 metaweb contained more detailed records, only for predators we added them to the local food webs checking  
145 for its geographic range. We removed cannibalistic (self-links) and double arrows (i.d. A eats B and B eats  
146 A).

## 147 Analysis

148 We analysed the structure of the networks using properties that focus on different levels: emergent global  
149 properties that take into account the whole network, sub-structural properties that consider several nodes,  
150 and properties related to one node. To describe food webs as networks each species is represented as a node  
151 or vertex and the trophic interactions are represented as edges or links between de nodes. These links are  
152 directed, from the prey to the predator, as the flow of energy and matter. Two nodes are neighbours if they  
153 are connected by an edge and the degree  $k_i$  of node  $i$  is the number of neighbours it has. The food web  
154 can be represented by an adjacency matrix  $A = (a_{ij})$  where  $a_{ij} = 1$  if species  $j$  predaes species  $i$ , else is 0.  
155 Then  $k_i^{in} = \sum_j a_{ji}$  is the number of preys of species  $i$  or its in-degree, and  $k_i^{out} = \sum_j a_{ij}$  is the number of  
156 predators of  $i$  or its out-degree. The total number of edges is  $E = \sum_{ij} a_{ij}$ .

## 157 Null models

158 We considered two null models, the Erdős-Rényi random graph (Erdős and Rényi 1959), and the metaweb  
159 assembly model. An Erdős-Rényi network is constructed fixing the number of edges and nodes and assigning  
160 at random the  $m$  edges to the  $n$  nodes with equal probability (Erdős and Rényi 1959, Baiser et al. 2016).  
161 We restricted the random model eliminating double arrows and cannibalistic links. To calculate trophic level  
162 and the coherence parameter (see below) we further restricted to random webs with at least one basal node,  
163 to make these calculations possible. Since the random model represents the absence of any network assembly  
164 mechanism, the comparison against it does not guarantee information on this aspect.  
165 In order to consider network assembly mechanisms we designed a dynamic metaweb assembly model. In this  
166 model species migrate from the metaweb to a local web with a uniform probability  $c$ , and become extinct from  
167 the local web with probability  $e$ ; a reminiscence of the theory of island biogeography (MacArthur and Wilson

168 1967, Gravel et al. 2011), but with the addition of network structure. Species migrate with their potential  
169 network links from the metaweb, then in the local web species can only survive if at least one of its preys is  
170 present, or if it is a basal species. When a species goes extinct locally it may produce secondary extinctions;  
171 we check that the local predators maintain at least one prey if not they become extinct independent of the  
172 probability  $e$ . We simulated this model in time and it eventually reaches an equilibrium that depends on the  
173 migration and extinction probabilities but also on the structure of the metaweb. The ratio of immigration  
174 vs. extinction  $\alpha = c/e$  is hypothesized to be inversely related to the distance to the mainland (MacArthur  
175 and Wilson 1967), and as extinction  $e$  should be inversely proportional to population size (Hanski 1999), the  
176 ratio  $\alpha$  is also hypothesized to be related to the local area.

177 For the random model we simulated networks with the same number of nodes  $n$  and edges  $m$  as the empirical  
178 networks; for the metaweb model we fitted the parameters  $g$  and  $e$  to obtain networks with  $n$  and  $m$  close  
179 to the empirical networks. This implies that  $\alpha$  should reflect the differences in areas of the two local food  
180 webs. For details of the fitting and simulations see Appendix.

### 181 Small-world topology

182 The first global emergent property we used is the small-world pattern, which examines the average of the  
183 shortest distance between nodes and the clustering coefficient of the network (Watts and Strogatz 1998). We  
184 first calculated the characteristic path length that is the shortest path between any two nodes. Then  $L$  is  
185 the mean value of the shortest path length across all pairs of nodes. The clustering coefficient of node  $i$  was  
186 defined as

$$c_i = \frac{2E_i}{k_i(k_i - 1)}$$

187 where  $E_i$  is the number of edges between the neighbours of  $i$ . The clustering coefficient of the network is  
188 the average of  $c_i$  over all nodes. The original definition of small-world networks is conceptual (Watts and  
189 Strogatz 1998), a network  $G$  is small-world when it has a similar mean shortest path length but greater  
190 clustering than an Erdös-Rényi random network with the same number of nodes  $n$  and edges  $m$ . For the  
191 quantitative version of the small-world pattern we followed Humphries and Gurney (2008); we need to define:

$$\gamma_g = \frac{C_g}{C_{null}}$$

192 and

$$\lambda_g = \frac{L_g}{L_{null}}$$

193 where  $C_g$  and  $L_g$  are the clustering coefficient and the mean shortest path length of the network of interest  
 194  $G$ ;  $C_g$  and  $C_{null}$  are the same quantities for the corresponding null model. Thus, the quantitative small-  
 195 world-ness is defined as:

$$S = \frac{\gamma_g}{\lambda_g}$$

196 and to determine if  $S$  is statistically significant Monte Carlo methods are used. We built 1000 null model  
 197 networks with the same number of nodes  $n$  and edges  $m$  than the empirical network; then we calculated  $S$   
 198 for each random network and the lower and higher 99% quantiles of the  $S$  distribution are called  $ql, qh$ :

$$CI = \frac{qh - ql}{2}$$

199 the upper 99% confidence limit is then  $CL^{0.01} = 1 + CI$ . Thus, if a network has  $S > CL^{0.01}$  it is considered  
 200 a small-world network (Humphries and Gurney 2008). We also calculated the small-world-ness and the CI  
 201 using the metaweb assembly model as a null model.

## 202 Coherence

203 The second global property is called trophic coherence (Johnson et al. 2014), and is related to stability in  
 204 the sense that small perturbations could get amplified or vanished, which is called local linear stability (May  
 205 1972, Rohr et al. 2014). We first needed to estimate the trophic level of a node  $i$ , defined as the average  
 206 trophic level of its preys plus 1. That is:

$$tp_i = 1 + \frac{1}{k_i^{in}} \sum_j a_{ij} tp_j$$

207 where  $k_i^{in} = \sum_j a_{ji}$  is the number of preys of species  $i$ , basal species that do not have preys (then  $k_i^{in} = 0$ )  
 208 are assigned a  $tp = 1$ . Then the trophic difference associated to each edge is defined as  $x_{ij} = tp_i - tp_j$ .  
 209 The distribution of trophic differences,  $p(x)$ , has a mean  $E^{-1} \sum_{ij} a_{ij} x_{ij} = 1$  by definition. Then the trophic  
 210 coherence is measured by:

$$q = \sqrt{\frac{1}{E} \sum_{ij} a_{ij} x_{ij}^2 - 1}$$

that is the standard deviation of the distribution of all trophic distances. A food web is more coherent when  $q$  is closer to zero, thus the maximal coherence is achieved when  $q = 0$ , and corresponds to a layered network in which every node has an integer trophic level (Johnson et al. 2014, Johnson and Jones 2017). To compare coherence and trophic level we generated 1000 null model networks with at least one basal species and the same number of species and links—or approximately the same—than the network of interest. Then we calculated the 99% confidence interval using the 0.5% and 99.5% quantiles of the distribution of  $q$ ; we also calculated the confidence interval for the mean trophic level  $tp$ . We calculated the z-scores as:

$$z_i = \frac{q_{obs} - q_{null}}{\sigma_{qnull}}$$

where  $q_{obs}$  is the observed coherence,  $q_{null}$  is the mean coherence from the null model networks and  $\sigma_{qnull}$  is the standard deviation. The same formula is used for  $tp$ . The z-score thus measures the significance of deviations of the real network from the null hypothesis. If the distribution of the quantity ( $q$ ,  $tp$ ) under the null model is normal, a z-score greater than 2 is evidence than the observed quantity is significantly greater than its random counterpart, and a z-score less than 2 means that the quantity is significantly lower. If the distribution under the null model is skewed this is not necessarily true and thus we must rely on confidence intervals.

## Modularity

An intermediate level property (i.e. between the whole network and the individual species) is modularity. It measures how strongly sub-groups of species interact between them compared with the strength of interaction with other sub-groups (Newman and Girvan 2004). These sub-groups are called compartments, and in order to find the best partition we used a stochastic algorithm based on simulated annealing (Reichardt and Bornholdt 2006). Simulated annealing allows to maximize modularity without getting trapped in local maxima configurations (Guimerà and Nunes Amaral 2005). The index of modularity was defined as:

$$M = \sum_s \left( \frac{I_s}{E} - \left( \frac{d_s}{2E} \right)^2 \right)$$

where  $s$  is the number of modules or compartments,  $I_s$  is the number of links between species in the module

233  $s$ ,  $d_s$  is the sum of degrees for all species in module  $s$  and  $E$  is the total number of links for the network. To  
234 assess the significance of our networks we calculate the 99% confidence intervals and z-scores based on 1000  
235 null model networks as previously described.

## 236 Motifs

237 We considered four of the thirteen possible three-species sub-networks: apparent competition, exploitative  
238 competition, tri-trophic chain, and omnivory (Figure 1). These are the only motifs present in all networks  
239 analysed here. We compared the frequency of these motifs to 1000 null model networks using the 99%  
240 confidence interval and the z-score as previously described. To determine if the proportions of motifs change  
241 across networks we use the Pearson's Chi-squared test with simulated p-value based on 10000 Monte Carlo  
242 replicates.

## 243 Topological roles

244 As a local property that reflect the ecological role of each species we determined topological roles using the  
245 method of functional cartography (Guimerà and Nunes Amaral 2005), which is based on module membership  
246 (See modularity). The roles are characterized by two parameters: the standardized within-module degree  
247  $dz$  and the among-module connectivity participation coefficient  $PC$ . The within-module degree is a z-score  
248 that measures how well a species is connected to other species within its own module:

$$dz_i = \frac{k_{is} - \bar{k}_s}{\sigma_{ks}}$$

249 where  $k_{is}$  is the number of links of species  $i$  within its own module  $s$ ,  $\bar{k}_s$  and  $\sigma_{ks}$  are the average and standard  
250 deviation of  $k_{is}$  over all species in  $s$ . The participation coefficient  $PC$  estimates the distribution of the links  
251 of species  $i$  among modules; thus it can be defined as:

$$PC_i = 1 - \sum_s \frac{k_{is}}{k_i}$$

252 where  $k_i$  is the degree of species  $i$  (i.e. the number of links),  $k_{is}$  is the number of links of species  $i$  to  
253 species in module  $s$ . Due to the stochastic nature of the module detection algorithm we made repeated  
254 runs of the algorithm until there were no statistical differences between the distributions of  $PC_i$  and  $dz_i$  in  
255 successive repetitions; to test such statistical difference we used the k-sample Anderson-Darling test (Scholz  
256 and Stephens 1987). Then we calculated the mean and 95% confidence interval of  $dz$  and  $PC$ .

257 To determine each species' role the  $dz - PC$  parameter space was divided into four areas, modified from  
258 Guimerà and Nunes Amaral (2005), using the same scheme as Kortsch et al. (2015). Two thresholds were  
259 used to define the species' roles:  $PC = 0.625$  and  $dz = 2.5$ . If a species had at least 60% of links within  
260 its own module then  $PC < 0.625$ , and if it also had  $dz \geq 2.5$ , thus it was classified as a module hub. This  
261 parameter space defines species with relatively high number of links, the majority within its own module.  
262 If a species had  $PC < 0.625$  and  $dz < 2.5$ , then it was called a peripheral or specialist; this refers to a  
263 species with relatively few links, mostly within its module. Species that had  $PC \geq 0.625$  and  $dz < 2.5$  were  
264 considered module connectors, since they have relatively few links, mostly between modules. Finally, if a  
265 species had  $PC \geq 0.625$  and  $dz \geq 2.5$ , then it was classified as a super-generalist or hub-connector, because  
266 it has high between- and within-module connectivity. To test if the proportion of species' roles changed  
267 between networks we performed a Pearson's Chi-squared test with simulated p-value based on 10000 Monte  
268 Carlo replicates. Also, we tested if these proportions changed for one realization of the metaweb assembly  
269 model fitted for both local networks (i.e. Weddell Sea and Potter Cove food webs).

270 With the aim of giving an integrated visualization of the sub-structural and local properties of the food webs,  
271 we combined in a single plot information about compartments and the topological roles with the trophic  
272 level for each species.

273 All analyses and simulations were made in R version 3.4.3 (R Core Team 2017), using the igraph package  
274 version 1.1.2 (Csardi and Nepusz 2006) for motifs and topological roles analyses, and NetIndices (Kones et  
275 al. 2009) for trophic level calculations. Source code and data is available at <https://github.com/lstaravia/MetawebsAssembly>.

## 277 Results

### 278 Global network properties

279 The number of trophic species (size), links and connectance (Table 1), were in concordance with values found  
280 for marine food webs (Marina et al. 2018b). Based on the random null model, all networks presented the  
281 small-world topology as their small-world-ness index was larger than the 99% confidence interval (Table 1 &  
282 S1). However, we did not find differences between the local food webs and the assembly model (Table 1 &  
283 S2). Regarding trophic coherence, all networks presented negative random z-scores and significantly smaller  
284  $q$  values (Table 1 & S1). thus they are more locally stable as they are more coherent. Using the metaweb  
285 assembly model, the Weddell Sea food web showed negative z-scores lower than 2, and Potter Cove food web  
286 exhibited no significant differences (Table 1 & S2). Mean trophic level results were similar among networks

287 and significantly lower than the random null model (Table 1 & S1), though were not significantly different  
 288 when compared to the metaweb model trophic levels . Modularity values for the empirical food webs were  
 289 greater than the random model, but not significantly higher in the Potter Cove web. No differences were  
 290 found when compared to the metaweb assembly model (Table 1). Overall, networks differed from the random  
 291 null model though presented similarities with the metaweb assembly model.

Table 1: Network global properties across scales. The *Metaweb* represents the marine predator-prey relationships of Antarctica, the *Weddell Sea* and *Potter Cove* are the local food webs. Z-scores were calculated against 1000 null model networks (random or metaweb assembly models). Quantities marked with '\*' are significant at 1% level. A negative z-score means that the quantity is smaller than the expectation from null model simulations; a positive z-score means that is greater.

Network	Potter Cove	Weddell Sea	Metaweb
Size	91	437	859
Links	309	1908	9003
Area (Km <sup>2</sup> )	6.8	3.5e6	34.8e6
Connectance	0.037	0.010	0.012
PathLength	1.81	2.20	2.57
Clustering	0.10	0.048	0.22
Small-World-ness random	*2.75	*4.69	*10.87
Small-World-ness Assembly	0.42	0.21	
Coherence	0.53	0.45	0.70
Coherence random z-score	*-0.54	*-2.08	*-3.54
Coherence assembly z-score	-0.20	*-3.41	
Mean Trophic level	2.13	1.98	1.91
Trophic level random z-score	*-0.27	*-0.86	*-1.60
Trophic level assembly	1.29	1.09	
z-score			
Modularity	0.37	0.48	0.45
Modularity random z-score	0.89	*18.97	*85.75
Modularity assembly z-score	-0.38	0.41	

## 292 Sub-structural properties (motifs)

293 The representation of three-species sub-networks with respect to the random model showed similar patterns  
 294 in all networks (Figure 2A). While exploitative competition, apparent competition, and omnivory were over-  
 295 represented, tri-trophic chains were under-represented; all these patterns were significant (Table S3). We  
 296 found that motifs proportions for the three examined spatial scales were different (Chi-squared = 12612, p-  
 297 value < 9.9e-05). this means that local and regional networks are not a random sample of the metaweb. With  
 298 respect to the metaweb assembly model only some of them were significant (Table S4): tri-trophic chains  
 299 and omnivory were under-represented for Weddell Sea, and apparent competition was over-represented for

300 Potter Cove (Figure 2B). Contrary to our expectations Potter Cove was more similar to the metaweb than  
 301 Weddell Sea food web.

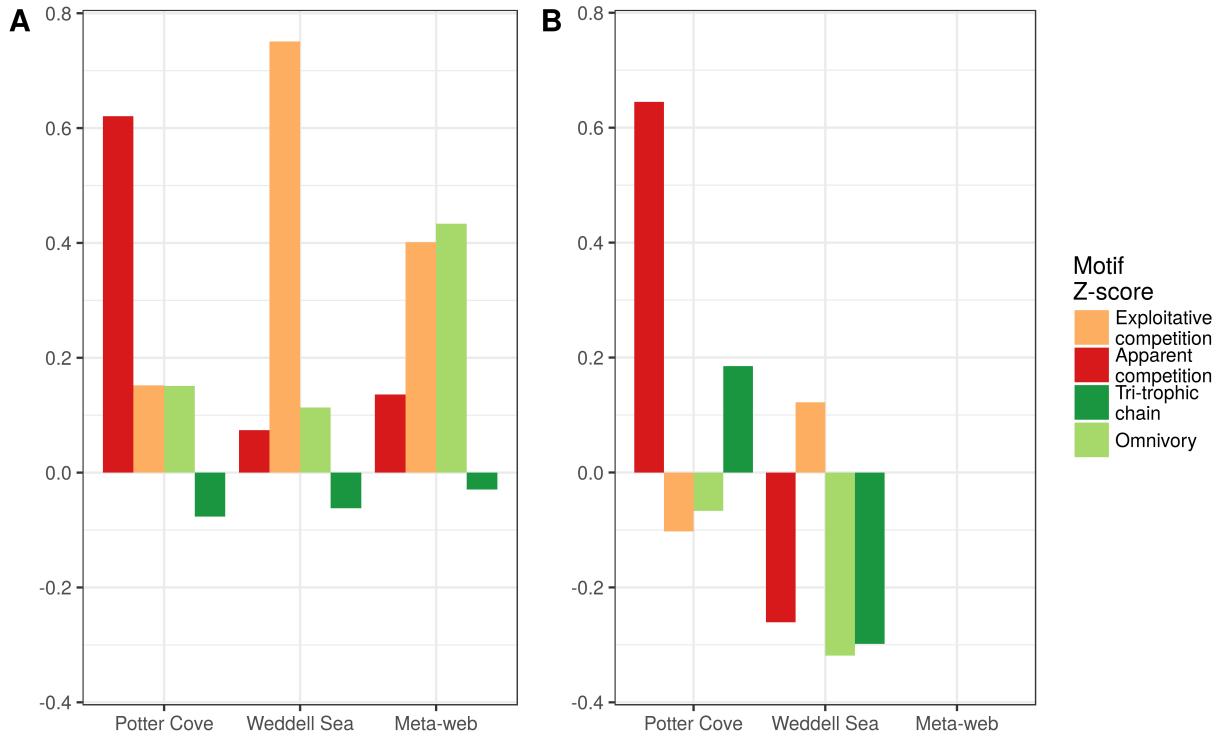


Figure 2: Network motifs z-scores across scales. Motifs are three-node sub-networks counted on each of the networks.: the *Metaweb* represents the marine predator-prey relationships of Antarctica (34.8 million Km<sup>2</sup>); the *Weddell Sea* (3.5 million Km<sup>2</sup>) and *Potter Cove* (6.8 Km<sup>2</sup>) are local food webs. A. Z-scores estimated with the random null model. B. Z-scores estimated with the metaweb assembly model. Z-scores were normalized by the square root of the sum of the squared z-scores for that food web.

### 302 Node-level properties (Topological roles)

303 The proportion of species displaying the four topological roles was different among food webs (Chi-squared  
 304 = 79.31, p-value = 9.9e-05). A higher presence of module connectors (few links, mostly between modules)  
 305 was observed in Weddell Sea, while a lack of module hubs (high number of links inside its module) was found  
 306 in Potter Cove (Figure 3 A), which can be related to its low modularity value (Table 1). The proportions  
 307 obtained with the metaweb assembly model were not different from the food webs (Chi-squared = 5.95,  
 308 p-value = 0.41)(Figura 3 B).

309 The plot of topological roles combined with trophic levels and modularity revealed important details of the  
 310 food webs (Figure 4): the metaweb has densely connected compartments but some of them have few low-  
 311 connected species (module connectors or module specialists). Additionally, we observed in the Weddell Sea

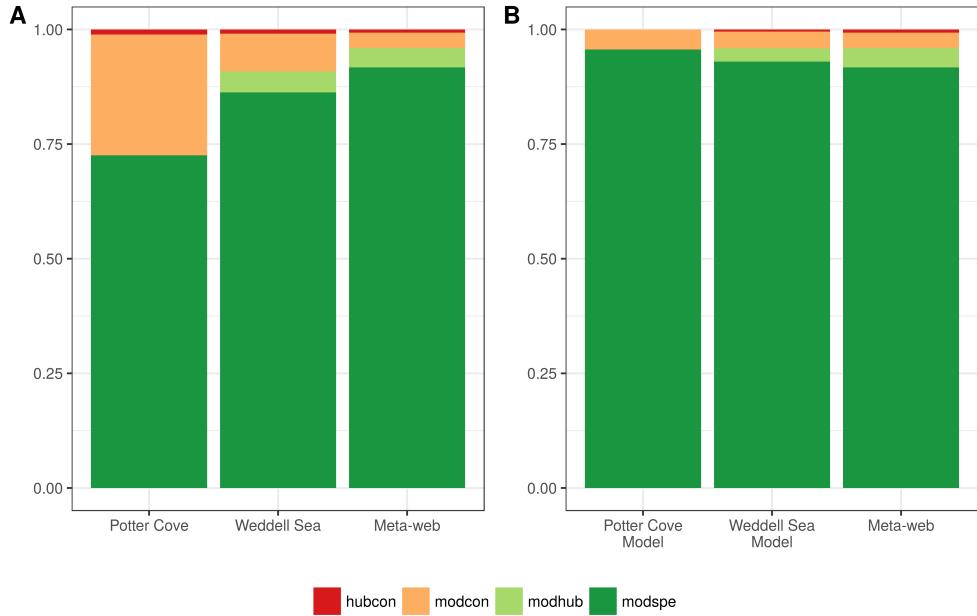


Figure 3: Proportion of topological roles across scales., the *Metaweb* represents the marine predator-prey relationships of Antarctica (34.8 million Km<sup>2</sup>); the *Weddell Sea* (3.5 million Km<sup>2</sup>) and *Potter Cove* (6.8 Km<sup>2</sup>) are local food webs. The topological roles are: *Hub connectors*, high number of between-module links; *Module connectors*, low number of links mostly between modules; *Module hubs*, high number of links within its module; *Module specialists*, low number of links within its module. A. Observed proportions for each food web; significant differences were found between them (Chi-squared = 79.31, p-value = 9.9e-05). B. Proportions for local networks obtained from the metaweb assembly model; no differences were found (Chi-squared = 5.95, p-value = 0.41)

312 food web hub connectors with a basal trophic level (Table S5). These are aggregated nodes that represent  
313 generic preys, e.g. fish or zooplankton, they only have incoming links or predators and they cannot have  
314 outgoing links or preys because they comprise several species. Different fish species are present in the  
315 Weddell Sea food web with detailed information about preys and predators, but for some predators there is  
316 insufficient knowledge of its preys and aggregated nodes must be added. Thus the existence of these basal  
317 hub connectors is a spurious result of aggregating prey species. The other non-aggregated hub connectors  
318 are highly mobile species with an intermediate trophic level like krill (Table S5). The variation of maximum  
319 trophic levels is evidenced in Figure 4, where both Potter Cove and Metaweb networks had similar values  
320 and Weddell Sea food web exhibited a lower maximum trophic level.

## 321 Discussion

322 We expected the metaweb structure to reflect the evolutionary constraints of the species interactions, and  
323 the local networks to be influenced and determined by the assembly processes and the local environment.

324 Our results showed that the structure of the metaweb does not change significantly in many properties as  
325 the spatial scale changes. We did not find a clear pattern in the properties expected to be maximized by  
326 dynamical assembly and local stability, but we found clear differences in the properties influenced by habitat  
327 filtering and dispersal limitation. As a consequence, food webs would be mainly shaped by evolutionary  
328 forces and local environment drivers and less constrained by dynamical assembly processes.

329 Global level network properties showed a similar pattern across scales; most of them were significantly  
330 different from the random null model but not from the assembly model. Modularity for Potter Cove food  
331 web was the only property that is similar to the random model. Studies suggest that modularity enhances  
332 local stability (Stouffer and Bascompte 2011), even though stability strongly depends on the interaction  
333 strength configuration (Grilli et al. 2016) and on the existence of external perturbations (Gilarranz et al.  
334 2017). We did not find modularity is greater than the metaweb assembly model, the existence of a modular  
335 structure could be related to different habitats—in marine environments could be benthic and pelagic (Zhao  
336 et al. 2017). Thus we observed that the modular structure is present in the metaweb and not produced  
337 by a maximization of local stability. Dynamical stability is expected to be maximized at the local level but  
338 we only found that Weddell Sea food web exhibited a greater trophic coherence than the assembly model.

339 Thus, although this evidence is not conclusive with regard to the importance of dynamical processes in the  
340 assembly of food webs, the structure of the local food webs examined here seem to be a consequence of the  
341 metaweb structure.

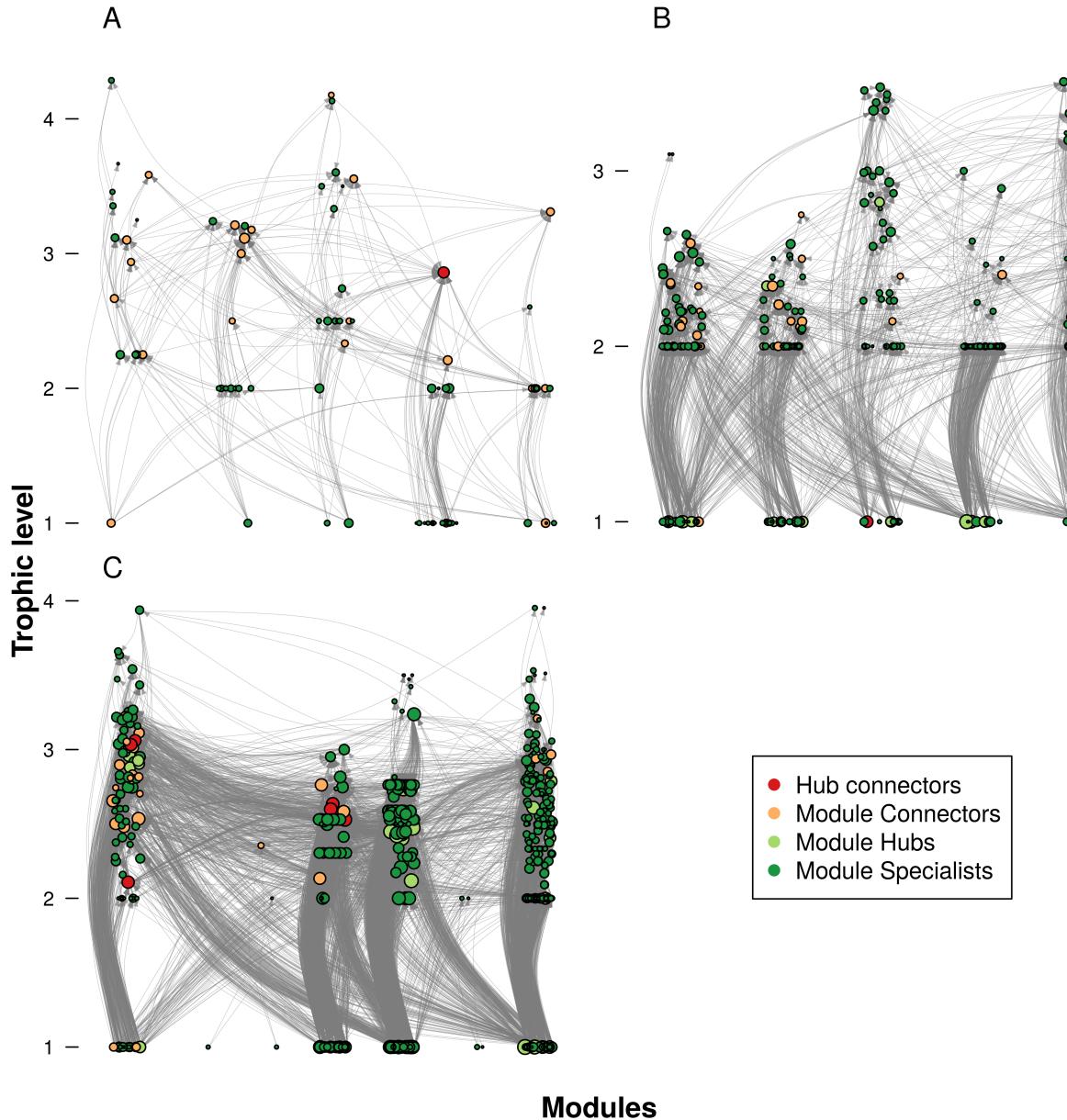


Figure 4: Plot of topological roles combined with trophic levels and modularity for each food web. The topological roles are: *Hub connectors* have a high number of between module links, *Module connectors* have a low number of links mostly between modules, *Module hubs* have a high number of links inside its module. *Module specialists* have a low number of links inside its module. Size of the nodes is proportional to the log of the species degree.

342 All networks have a significant value of small-world-ness compared with the random model but the local food  
343 webs are not different from the assembly model. In general, food webs do not show the small-world topology  
344 (Dunne et al. 2002, Marina et al. 2018b), which suggests that the small-world property is inherited from  
345 the metaweb and is less influenced by the greater percentage of realized interactions. If small-world-ness was  
346 determinant for an increased resilience and robustness to secondary extinctions (Bornatowski et al. 2017),  
347 local food webs should reflect significantly higher values than those obtained from the metaweb assembly  
348 models.

349 Motifs also have the same representation patterns against the random model. Local food webs should have  
350 motif patterns that increase its persistence. The expected pattern, based in dynamical models, is an over-  
351 representation of omnivory and tri-trophic chains and an under-representation of apparent and exploitative  
352 competition (Stouffer and Bascompte 2010). Other studies showed that tri-trophic chains, exploitative and  
353 apparent competition should be displayed more frequently (Borrelli 2015), but this was based on the stability  
354 of isolated three-species sub-networks and the assumption that during the assembly process these 3 species  
355 sub-networks were selected because of their intrinsic stability (Borrelli et al. 2015). The fact that tri-trophic  
356 (or n-trophic) interactions cannot account fully for the properties of the food webs (Cohen et al. 2009) make  
357 the results based on isolated modules less convincing. Our results showed an over-representation of omnivory,  
358 exploitative competition and apparent competition, this configuration is not the most stable one based on  
359 either criteria. A first hypothetical explanation is that the structure observed in the metaweb is maintained  
360 in local food webs. Despite the fact that almost all motifs were not different from the assembly model,  
361 neither tri-trophic chains and omnivory (lower in Weddell Sea) nor apparent competition (higher in Potter  
362 Cove) followed the pattern expected from theoretical studies. Thus, the assembly process is not random,  
363 there are differences in the frequencies of motifs as the scale change, but the selection of motifs due to its  
364 dynamical stability is not the main driver. This implies that other dynamical processes that influence the  
365 presence or absence of species like habitat filtering or dispersal limitation are acting and probably modifying  
366 motif frequencies in empirical food webs. This kind of structures that are a sub-product of process that  
367 happen at a different level have been called spandrels of assembly (Solé and Valverde 2006).

368 As expected all the networks have a short mean trophic level (Williams et al. 2002, Borrelli and Ginzburg  
369 2014) compared with the random model. Different hypothesis were posed to explain this pattern: the low  
370 efficiency of energy transfer between trophic levels, predator size, predator behaviour, and consumer diversity  
371 (Young et al. 2013). These have contradictory support, reviewed by Ward and McCann (2017). Recently, it  
372 has been proposed that maximum trophic level could be related to productivity and ecosystem size depending  
373 on the context but related to energy fluxes that promote omnivory (Ward and McCann 2017). A different

374 mechanism based on dynamic stability of the whole web was proposed: food webs with shorter trophic levels  
375 (between 2 and 4) that have more omnivore chains are more likely to be stable, which increase the probability  
376 of being observed in nature [Borrelli2014]. We found that mean trophic level of the local food webs was not  
377 different from the assembly model, and omnivory was under-represented. This combination suggests that  
378 the trophic level could also be a spandrel of assembly, inherited from the metaweb structure.

379 Topological roles are useful to detect the existence of functional roles of species, like super-generalists (or  
380 hub connectors). These roles may change as the scale changes. A simple explanation is that modules also  
381 change. It was demonstrated in Arctic and Caribbean marine food webs that modules are usually associated  
382 with habitats (Rezende et al. 2009, Kortsch et al. 2015). For example, the Antarctic cod (*Notothenia*  
383 *coriiceps*) is a super-generalist for Potter Cove, and a module hub—a species with most of their links within  
384 its module—for the metaweb. This means that the same species can have different influences on the food  
385 web depending on the type or extension of the habitat considered. Although the metaweb assembly model  
386 showed no change in the frequency of topological roles, we found a change in topological roles with the scale.  
387 That means that in smaller areas there will be a smaller amount of different habitats, thus habitat filtering  
388 should be an important factor and will change the frequency of species that represent a particular topological  
389 role.

390 The spatial scales involved in our study do not represent a continuity; the metaweb and regional web have  
391 a 10 to 1 ratio but the local web is  $10^6$  smaller, besides that most of the global network properties and the  
392 motif structure showed no changes relative to the null model. Thus, we found evidence that local processes  
393 that limit species from the metaweb to local scales are influencing the assembly process but the structure of  
394 the food web originated through an emergent process from evolutionary or co-evolutionary forces seems to  
395 be more important. This could guide us to find a unified theory of ecological interactions that could describe  
396 the diversity of patterns observed in the natural world.

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