Effects of macroalgae loss in an Antarctic marine food web: applying extinction thresholds to food web studies

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Antarctica is seriously affected by climate change, particularly at the Western Antarctic Peninsula (WAP) where a rapid regional warming is observed. Potter Cove is a WAP fjord at Shetland Islands that constitutes a biodiversity hotspot where over the last years, Potter Cove annual air temperatures averages increased by 0.66°C, coastal glaciers declined, and suspended particulate matter increased due to ice melting. Macroalgae are the main energy source for all consumers and detritivores of Potter Cove. Some effects of climate change favor pioneer macroalgae species that exploit new ice-free areas and can also decline rates of photosynthesis and intensify competition between species due to the increase of suspended particulate matter. In this study, we evaluated possible consequences of climate change at Potter Cove food web by simulating the extinction of macroalgae and detritus using a topological approach with thresholds of extinction. Thresholds represent the minimum number of incoming links necessary for species' survival. When we simulated the extinctions of macroalgae species at random, a threshold of extinction beyond 50 % was necessary to obtain a significant number of secondary extinctions, while with a 75 % threshold a real collapse of the food web occurred. Our results indicate that Potter Cove food web is relative robust to macroalgae extinction. This is dramatically different from what has been found in other food webs, where the reduction of 10 % in prey intake caused a disproportionate increase of secondary extinctions. Robustness of the Potter Cove food web was mediated by omnivory and redundancy, which had an important relevance in this food web. When we eliminated larger-biomass species more secondary extinctions occurred, a similar response was observed when more connected species were deleted, yet there was no correlation between species of larger-biomass and high-degree. This similarity could be explained because both criteria involved key species that produced an emerging effect on the food web. In this way, large-biomass

and high-degree species could be acting as source for species with few trophic interactions or low redundancy. Based on this work, we expect Potter Cove food web to be robust to changes in macroalgae species caused by climate change until a high threshold of stress is reached, and then negative effects are expected to spread through the entire food web leading to its collapse.

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18 **Abstract**

19 Antarctica is seriously affected by climate change, particularly at the Western Antarctic
20 Peninsula (WAP) where a rapid regional warming is observed. Potter Cove is a WAP fjord at
21 Shetland Islands that constitutes a biodiversity hotspot where over the last years, Potter Cove
22 annual air temperatures averages increased by 0.66°C, coastal glaciers declined, and suspended
23 particulate matter increased due to ice melting. Macroalgae are the main energy source for all
24 consumers and detritivores of Potter Cove. Some effects of climate change favor pioneer
25 macroalgae species that exploit new ice-free areas and can also decline rates of photosynthesis
26 and intensify competition between species due to the increase of suspended particulate matter. In
27 this study, we evaluated possible consequences of climate change at Potter Cove food web by
28 simulating the extinction of macroalgae and detritus using a topological approach with thresholds
29 of extinction. Thresholds represent the minimum number of incoming links necessary for
30 species' survival. When we simulated the extinctions of macroalgae species at random, a
31 threshold of extinction beyond 50 % was necessary to obtain a significant number of secondary
32 extinctions, while with a 75 % threshold a real collapse of the food web occurred. Our results
33 indicate that Potter Cove food web is relatively robust to macroalgae extinction. This is
34 dramatically different from what has been found in other food webs, where the reduction of 10 %
35 in prey intake caused a disproportionate increase of secondary extinctions. Robustness of the
36 Potter Cove food web was mediated by omnivory and redundancy, which had an important
37 relevance in this food web. When we eliminated larger-biomass species more secondary
38 extinctions occurred, a similar response was observed when more connected species were
39 deleted, yet there was no correlation between species of larger-biomass and high-degree. This
40 similarity could be explained because both criteria involved key species that produced an
41 emerging effect on the food web. In this way, large-biomass and high-degree species could be
42 acting as source for species with few trophic interactions or low redundancy. Based on this work,
43 we expect Potter Cove food web to be robust to changes in macroalgae species caused by climate
44 change until a high threshold of stress is reached, and then negative effects are expected to
45 spread through the entire food web leading to its collapse.

46 **Introduction**

47 Western Antarctic Peninsula (WAP) is the region of Antarctica most affected by climate change,
48 with a regional warming rate that doubles what is observed in other Antarctic regions
49 (McClintock, Ducklow & Fraser, 2008; Turner et al., 2009; Bromwich et al., 2013; Nicolas &
50 Bromwich, 2014). One particular example of environmental changes in WAP was observed at
51 Potter Cove (Fig. 1), a hotspot of biodiversity, where over the last years the average winter air
52 temperatures increased by 0.66°C, coastal glaciers declined and suspended particulate matter
53 increased due to ice melting (Schloss et al., 2012; Bers et al., 2013; Ducklow et al., 2013;
54 Quartino et al., 2013; Grange & Smith, 2013; Lagger et al., 2017). These changes produce a
55 variety of effects on the organisms of the cove; pioneer macroalgae species are favored by the
56 increase of rocky bottom areas due to glaciers retreat (Quartino et al., 2013), whereas increased

57 suspended particulate matter affects rates of photosynthesis and intensity of competition between
58 species (Quartino et al., 2013; Deregibus et al., 2016). Moreover, a long-term succession study
59 showed that sites with higher levels of stress and disturbance caused by glacial influence
60 presented lower number of macroalgal taxa and a tendency to decrease diversity over time
61 (Campana et al., 2018). In recent years, environmental changes have triggered modifications at
62 the benthic community of Potter Cove (Pasotti et al., 2015; Sahade et al., 2015). The community
63 structure changed from an assemblage dominated by filter feeders squirts to a mixed assemblage,
64 and this alteration can be explained by organism sensitivity to increased sedimentation (Sahade
65 et al., 2015). A descriptive analysis of the Potter Cove food web has suggested fragility to
66 species loss and susceptibility to propagation of trophic cascade effects based on topology
67 parameters as connectance (*C*) or link density (*LD*) (Marina et al., 2018). However, alternative
68 food sources could contribute to food web robustness (Marina et al., 2018).

69 About forty species of macroalgae have been reported at Potter Cove (Quartino & Boraso de
70 Zaixso, 2008a), a significant fraction of the approximately 130 registered for Antarctica as a
71 whole. In Potter Cove, macroalgae constitute a direct pathway of energy and matter into
72 organisms that feed on them, and also indirectly, through species that feed on macroalgae
73 detritus (Quartino, Boraso de Zaixso & Momo 2008b). Macroalgae are not only important as
74 primary producers that supply significant amounts of fixed carbon to marine ecosystems, but as
75 substrates for organisms that inevitably provide a large fraction of the secondary production to
76 the benthos (Gómez et al., 2009). Considering this, we can reaffirm the words of Neushul (1965)
77 that macroalgae are the energetic base of Potter Cove food webs.

78 Since the macroalgal community plays a fundamental role in Potter Cove food web, it might
79 affect ecosystem dynamics and stability through propagation of direct and indirect effects.
80 Changes in species abundance or presence can indeed alter the whole community structure (e.g.
81 Dulvy et al., 2000; Jackson et al., 2001; Ellison et al., 2005; Sorte et al., 2017). Moreover, the
82 loss of species can lead to a cascade of secondary extinctions that propagate through the
83 community (Ebenman, Law & Borrvall 2004; Sanders, Sutter & Veen, 2013; Donohue et al.,
84 2017; Witman, Smith & Novak, 2017). Food webs are considered an excellent tool to explore
85 possible effects of global change and biodiversity loss on communities and ecosystems, since
86 trophic interactions are crucial for the survival of both resource and consumer species (Ings et
87 al., 2009; Bascompte, 2009; Hastings, McCann & de Ruiter, 2016). The vulnerability of food
88 webs to adverse effects can be estimated from the topology of the network (de Santana et al.,
89 2013). Several authors have studied the effects of species extinctions in food webs (Sóle &
90 Montoya, 2001; Dunne, Williams & Martinez, 2002; Memmott, Waser & Price, 2004; Allesina
91 et al., 2006; Curtsdotter et al., 2011; Eklöf, Tang & Allesina, 2013; Bellingeri et al., 2013).
92 Borvall et al. (2000) studied the effect of omnivory and redundancy in model food webs, and
93 found that both lessen the risk of cascading extinctions following primary loss of species.
94 Additionally, Montoya & Solé (2002) demonstrated that food webs are vulnerable to the
95 elimination of the most connected species. Moreover, it has been observed that extinctions and
96 invasions can alter costal marine food webs by reshaping trophic level relationship (Byrnes,

97   Reynolds & Stachowicz, 2007). In this sense, it is not trivial to study the behavior of food webs
98   to local species extinctions since it can be a suitable proxy of community response to alterations.

99   Although much is known about macroalgae species and the environmental changes that Potter
100 Cove is facing, there is a lack of information of how local extinctions of macroalgae species
101 might impact on other species of the Cove and on the community as a whole. In this work we
102 study the robustness of Potter Cove food web by simulating primary loss of macroalgae species
103 using a topological approach. We hypothesized that the loss of these species from Potter Cove
104 food web will generate a cascade of secondary extinctions that will lead the food web to collapse
105 by a bottom-up mechanism. The aim of this study was to explore the robustness of Potter Cove
106 food web to local extinctions of macroalgae species as possible consequences from ongoing
107 climate change.

108 **Materials and methods**

109 *Study site*

110 Potter cove is a WAP fjord of 4 km long and 2.5 km wide, on the southern coast of 25 de
111 Mayo/King George Island (62°14′S, 58°40′W), the largest of the South Shetlands Archipelago
112 (Fig. 1). It is adjacent to Maxwell Bay, which connects to the Bransfield Strait. Water circulation
113 in Potter Cove is strongly influenced by the general circulation of Maxwell Bay (Roese &
114 Drabble, 1998). The fjord is divided into an outer and an inner Cove which differ in bottom
115 characteristics (Klöser et al., 1994; Klöser, Quartino & Wiencke, 1996). The outer Cove consists
116 of hard substrate of solid rocks and big boulders, whereas the inner part is dominated by soft
117 sediments with high presence of muddy substrate. The rocky shores of the outer Cove are
118 colonized by a large biomass of macroalgae (Klöser et al., 1996; Quartino et al., 2005), while the
119 inner Cove has one of the highest concentrations of benthic filter feeders found in Antarctic
120 coastal areas representing a hotspot of biodiversity (Sahade et al., 1998; Tatián et al., 1998;
121 Tatián et al., 2004; Grange & Smith, 2013).

122 *Food web dataset*

123 We based our analysis on the food web presented by Marina et al. (2018). Potter Cove food web
124 includes 91 trophic species comprising algae, amphipods, isopods, sponge, gastropods, bivalves,
125 echinoderms, fishes, among others, and compromising 308 trophic interactions, with a mean
126 trophic level of 2.1 (±0.9) and a maximum trophic level of 4.27 (Fig. 2). It is important to note
127 that, within the 91 trophic species, 24 correspond to macroalgae species and 2 to detritus sources,
128 fresh and aged detritus. This food web model was constructed based primarily upon studies
129 within the framework of international research cooperation between Argentina and Germany
130 initiated in 1994 (Wiencke et al., 1998; Wiencke et al., 2008). Further details on the construction
131 and properties of the network can be found in Marina et al. (2018).

132 *Common-enemy graph*

133 The analysis of secondary graphs is a useful tool for the study of food webs. Any food web can
134 be associated with two non-directed graphs: the niche overlap graph and the common-enemy or
135 resource graph. The former is constructed by linking consumers that share at least one prey in
136 common, and the latter is constructed by linking prey that share at least one consumer in
137 common (Bersier, 2007). Common-enemy graphs provide a representation of indirect
138 interactions within species of the food web. One of these possible indirect interactions is
139 apparent competition, where an increase in prey abundance produces a decrease in another prey
140 of a shared predator, not by direct competition but through an increase in the abundance of this
141 shared predator (Holt & Lawton, 1994). Additionally, the common-enemy graph is useful to
142 know the number of predators that each species share and to compare this number with the
143 degree obtained from the original food web. If a positive correlation exists; we expect a low
144 number of secondary extinctions because more connected species also share a large number of
145 predators. Also, common-enemy graphs represent an approximation to the complexity of the
146 food web because they describe the map of indirect interactions that remain between preys. Such
147 interactions may trigger cascading effects that involve positive and negative impacts on the
148 abundance of prey populations (Holt & Lawton, 1994). The common-enemy graph for Potter
149 Cove food web was obtained by multiplying the original predation matrix (or adjacency matrix
150 as it is classically known in food web literature) by its transpose, considering only those nodes
151 that represent basal species (i.e. species without preys).

152 *Extinctions by topological approach*

153 The method used in this study is based on the topological approach of secondary extinctions
154 (Albert, Jeong & Barabasi, 2000) with the incorporation of extinctions thresholds (Schleuning et
155 al., 2016; Bellingeri & Bodini, 2013). The topological approach focuses exclusively on the
156 presence or absence of consumer-resource relationships, taking into account only the qualitative
157 network structure (i.e. its topology). In this manner, secondary extinctions occur when one
158 consumer species lose all of its prey species (Solé & Montoya, 2001). This approach has the
159 advantage of requiring only the network structure as input, simplifying its application to large
160 complex networks. However, it has its limitations due to the fact that species are lost secondarily
161 only if all of its preys are removed. It is also assumed that all species have the same baseline
162 probability of extinctions, whereas in natural systems some species are more vulnerable than
163 others (Eklöf, Tang & Allesina, 2013). One possibility to reduce such limitations is incorporate
164 thresholds of extinctions that allow to model secondary extinctions of species which have not
165 necessarily lost all of their preys. Schleuning et al. (2016) applied this approach to mutualistic
166 networks, while Bellingeri & Bodini (2013) did it in food webs. Bellingeri & Bodini (2013)
167 define threshold (v) as the minimum level of energy necessary for species' survival. After each
168 node removal, the fraction of original incoming energy $e(i)$ is calculated for each species, and the
169 species i is secondarily lost if this fraction is equal or less than the threshold (i.e. $e(i) \leq v$). For
170 example, a value of $v = 0.25$ means that species i goes extinct if $e(i)$ is equal or less than 25 %,
171 when the 75 % of the inflow is lost. In the classical topological approach, v is implicitly assumed

172 to be equal to 0, and a species goes extinct when its energy inflow is null (Bellingeri & Bodini,
173 2013). Since Potter Cove food web lacks energy flows information, it is necessary to assume that
174 all preys contribute equally to its predator diets and redefine v concept as the fraction of
175 incoming links $l(i)$ from original ones that species i needs to survive after a primary loss (i.e.
176 species i is considered secondary loss when $l(i) \leq v$). We performed diversity loss simulations of
177 macroalgae species (and detritus) of Potter Cove food web. Simulations consisted in removal of
178 target species from the predation matrix by deleting row and columns (primary extinction).
179 Following each primary extinction, we looked for secondary extinctions in a recursive manner as
180 follows. We computed an intermediate predation matrix where each $l(i)$ was calculated and
181 compared to the set extinction threshold. If $l(i)$ was equal or less that v, species i was removed
182 from the intermediate predation matrix, thus leading to a secondary extinction, and a new
183 intermediate matrix was computed. This procedure was repeated until no $l(i)$ was less than v and
184 a final predation matrix was obtained. Then the final predation matrix was characterized by
185 computing the number of species (S), the number of trophic interactions or links (L) and
186 connectance ($C=L/S^2$), (Pimm, 2002; Cohen, 1989), and was used as an input for a new primary
187 loss simulation. This procedure was repeated until all macroalgae species were removed (an
188 explicit example is presented in Supplementary Material: Fig. S1). Since the extinction
189 procedure is carried out until all secondary extinctions are recorded, all the remaining species in
190 the food web are connected to at least one basal species (i.e. they had at least one path that
191 connected them to a basal producer). It is important to note that there are other basal species in
192 Potter Cove food web different from macroalgae species. Therefore a non-null final predation
193 matrix is possible given that there are species that depend on other sources (e.g. phytoplankton).

194 Macroalgae species were removed from the predation matrix according to different removal
195 sequences established by the degree of each macroalgae (total number of trophic interactions per
196 node) and total biomass in Potter Cove. Four sequences of extinctions were used: random order,
197 degree in ascending and descending order, and biomass order in ascending order. The sequences
198 established by the species' degree depended only on the food web structure, and in consequence
199 all macroalgae species could be eliminated following these sequences. According to Solé &
200 Montoya (2001), we expected that descending order sequence presented the more abrupt
201 changes, and eliminations in random order set an intermediate situation between ascending and
202 descending order. Thus, the upper and lower limits in which the parameters of the network could
203 vary are established by descending and ascending order. We decided to eliminate macroalgae
204 from lower values of biomass to higher values (i.e. in ascending order of biomass) since
205 extinction risk is typically high for rare species, because small populations are more vulnerable
206 to environmental and demographic stochasticity than larger ones (Lawton, 1994; McKinney,
207 1997). In this way, we eliminated 20 macroalgae species based on biomass data obtained by
208 Quartino & Boraso de Zaixso (2008a). Extinction simulations were performed varying v (0 %, 25
209 %, 50 % and 75 %), and 100 repetitions were randomly performed for the sequences: random,
210 ascending and descending degree orders. As a consequence, we had four different responses per
211 topological parameter (L vs primary extinctions, C vs primary extinctions and secondary

212   extinctions vs primary extinctions). After the loss of all macroalgae species, we simulated the
213   removal of the two detritus sources (fresh and aged) given that macroalgae species are the main
214   source of these types of detritus in Potter Cove ecosystem (Quartino, Boraso de Zaixso & Momo,
215   2008b). We tested whether there was a correlation between large-biomass and high-degree
216   macroalgae species by computing the Pearson´s correlation coefficient. The impact of secondary
217   extinctions in the food web, was assessed considering the percentage of species loss by
218   secondary extinction with respect to maximum number of possible extinctions (i.e all non-basal
219   species) which corresponded to 61 species. The v complement (100 % - v) indicates the
220   percentage of prey that a predator has to lose to go extinct. We compared the v complement with
221   the percentage of secondary extinctions in order to assess the effect of macroalgae loss in the
222   whole food web. A percentage of secondary extinction greater than the v complement indicates a
223   collapse of the food web produced by the instability of the network and not because of individual
224   effects.

Testing Thresholds

226   To test the importance of v in secondary extinctions, we simulated the primary loss of a given
227   quantity of macroalgae species choosing at random the identity of them. We varied v from 5 to
228   95 % by 5 %, and recorded the number of secondary extinctions for each v value. These
229   simulations were performed increasing the number of macroalgae primary losses: 3, 5, 10, 15
230   and 20 species. We obtained mean and confidence interval values for the five quantities
231   analyzed. Then, we plotted secondary extinctions vs v.

232   The GNU R software (R Core Team, 2017, version 3.4.2) was used for food web simulations and
233   matrix computations, and Visone (Brandes & Wagner, 2004, version 2.9.2) was used to plot
234   Potter Cove food web and the common-enemy graph.

Results

Common-enemy graph

237   The common-enemy graph of basal species from Potter Cove food web had all species connected
238   with a high density of 9.53 interactions per node (Fig. 2). It compromised 30 species consisting
239   of: 24 macroalgae species, 2 sources of diatoms (i.e. benthic and epiphytic), one node
240   representing phytoplankton and 3 non-living nodes corresponding to fresh, aged detritus and
241   necromass. Among all the links of the graph (286 indirect interactions), most of them (222) were
242   between macroalgae species. However, fresh detritus and benthic diatoms shared the maximum
243   number of common predators (11). There was a high correlation between the degree of each
244   macroalgae species obtained from the original food web and the number of shared predators
245   calculated from the common-enemy graph (Pearson´s correlation coefficient 0.87).

Extinctions by topological approach

247   As the number of primary extinctions increased, L of the remaining food web decreased
248   irrespectively of v (Fig. 3). Removal in a descending order, from highest to lowest degree,
249   showed a fast loss of L at the beginning; while the removal in ascending order showed a slow
250   loss of L. Random order resulted in an intermediate position between ascending and descending
251   degree sequences. Elimination of macroalgae species based on biomass order displayed a
252   response very similar to the response of the removal in ascending degree order at first, and then it
253   behaved as the random extinctions sequence with a similarity that increased with v. There was a
254   low correlation between macroalgae biomass and degree (Pearson´s correlation coefficient 0.27),
255   which means macroalgae of high biomass did not necessarily have a high degree in Potter Cove
256   food web. When we compared the responses at different v, we found that an increase in v led to
257   an increase in the number of lost interactions (L_{min} values of 211, 197, 129, and 30 for v of 0, 25,
258   50, and 75 %, respectively).

259   The response of C to extinctions differed from L response pattern (Fig. 4). At low v (0 % and 25
260   %), C increased with primary extinctions. Regarding this, removal in descending order led to a
261   slow increment of C. On the other hand, the loss of low connected species was associated with a
262   high slope in the curve, meaning that the elimination of species by ascending degree led to a
263   rapid increase of C. Random removal depicted an intermediate situation between ascending and
264   descending degree sequences. Elimination based on biomass order displayed a similar response
265   to that of removal in ascending order. An increase in C is directly associated to the way it is
266   computed, as possible interactions (S^2) increased faster than real interactions (L). At high v (50 %
267   and 75 %), C increased for all sequences but showed fluctuations.

268   We observed a general trend of increase of secondary extinctions with the number of primary
269   losses (Fig. 5), and also with v (6.5, 9.8, 29.5, and 70.5 % of secondary extinctions with v of 0,
270   25, 50, and 75 %, respectively). This increase of secondary extinctions is expected because
271   species lose a greater number of preys as the number of incoming links decrease, which leads $l(i)$
272   to be less than v. Among the elimination sequences, we observed that elimination in descending
273   degree reached maximum number of secondary extinctions in less number of steps than the
274   others sequences and the elimination in ascending degree was the last sequence to reach it.
275   Biomass and random sequences exhibited an intermediate response between the ascending and
276   descending degree order, overlapping in several points.

277   *Testing thresholds*

278   While increasing v value, the number of secondary extinctions increased independently of the
279   number of primary extinctions. In all cases, there was an inflection point in v value that triggered
280   a great number of secondary extinctions. Such inflection point appeared at a lower v value as the
281   number of primary loss increased. It is worth noting that, for all cases, this trigger was generated
282   at a v value greater than 50 % (Fig. 6).

283   **Discussion**

284   We found that Potter Cove food web is relatively stable to macroalgae loss. A significant number
285   of secondary extinctions were obtained beyond a 50 % threshold (v). Indeed, to observe a real

286   collapse where the percentage of secondary extinctions is greater than v complement, a v of 75 %
287   was needed. A v of 75 % means predators cannot survive if they have less than 75 % of their
288   original prey set, a very extreme and unreal condition. Bellingeri & Bodini (2013) showed that
289   reducing only 10 % of prey intake, a disproportionate growth of secondary extinctions emerged.
290   Allesina, Bodini & Bondavalli (2006) also found a similar result imposing link thresholds equal
291   to 15 %. Our results do not support the hypothesis that the elimination of macroalgae species
292   from Potter Cove food web will generate a cascade of secondary extinctions, and thus suggests
293   that Potter Cove food web could be more robust than similar ecological networks (Allesina,
294   Bodini & Bondavalli, 2006; Bellinger & Bodini, 2013). We found that macroalgae of high
295   degree were positively correlated with those that shared more predators, which indicates that
296   these macroalgae species are functionally redundant (i.e. species with equivalent trophic
297   interactions). Functional redundancy has important consequences in potential cascade
298   extinctions, since it increases food web resistance by means of availability of alternative preys
299   (Borrvall et al., 2000). Functional redundancy and omnivory explain why a high v has to be
300   reached to observe a high number of secondary extinctions. Functional redundancy and
301   omnivory could be the result of a long evolution time and extreme conditions of the studied
302   ecosystem where the preferred strategy is to be a generalist (i.e. species with many feeding
303   links). Redundancy appears to be the rule in many food webs, with stabilizing effects (Lawton &
304   Brown, 1994; Borrvall et al., 2000; Worm & Duffy, 2003; Thompson et al., 2007; Sanders et al.,
305   2018).

306   The common-enemy graph has a high density value of interactions per node. Similar values were
307   obtained in studies of rocky intertidal ecosystems in Patagonia (Fueyo Sanchez, 2013). The
308   presence of subnets in common-enemy graphs is usually associated with the identification of
309   habitat structures (Holt & Lawton, 1994). The common-enemy graph for Potter Cove food web
310   exhibited no subnets, consistent with the marine nature of this food web (Marina et al., 2018).
311   Given the high density of the common predators network, it is very difficult to predict indirect
312   relationships between species, as each interaction involves positive and negative effects between
313   species abundances (Holt & Lawton, 1994). The high density of this graph also suggests the
314   presence of high redundancy in the food web.

315   Montoya & Solé (2002) have shown that the elimination of the most connected species causes
316   the greatest number of secondary extinctions. As expected, removing the most connected
317   macroalgae from Potter Cove food web produced a fast secondary species loss, and the same
318   happened for the number of links (L). Connectance (C) increased with extinction for all deletion
319   sequences, which is explained by the number of possible interactions (S^2) decreasing faster than
320   the number of real interactions (L). However, the number of secondary extinctions remained low
321   even when v was quite high (75 %). Analyses of potential secondary extinctions showed that
322   marine food webs appear to be robust to the loss of the most connected species as well as random
323   species (Dunne, Williams & Martinez, 2004). It is important to note that the elimination of
324   species in biomass order generated a similar general response in L, C and secondary extinctions

325   than the loss of the most connected macroalgae species, especially at the first removals and when
326   v was increased. Nevertheless, there was no correlation between large-biomass and high-degree
327   species. This similarity response could be explained because both criteria involved key species
328   that produced an emerging effect on the food web. This means that large-biomass and high-
329   degree species are acting as source for species with few trophic interactions or low redundancy,
330   and this in turn produces a great number of secondary extinctions.

331   Even though the number of secondary extinctions was low, a clear impact on the emergent
332   properties of the network such as L and C was observed when macroalgae species were lost.
333   These changes could have a significant impact on the fragility and resilience of Potter Cove food
334   web altering the dynamics of the system. Dynamical analyses of the response of communities to
335   species loss usually predict a higher number of secondary extinctions than topological ones
336   (Eklöf & Ebenman, 2006). The main difference between topological and dynamical approaches
337   is that the topological analyses cannot detect indirect effects, as top-down extinctions caused by
338   the loss of a top predator, while dynamical analyses can detect this type of indirect effects
339   (Ebenman & Jonsson, 2005). In this way, the topological approach underestimates the actual
340   number of secondary extinctions, and in consequence overestimates food web robustness.
341   However, the topological approach enables the analysis of more complex food webs, since it
342   only requires knowledge of network structure (Eklöf, Tang & Allesina, 2013). Dynamical
343   analyses have also found that the effect of interaction strengths has important consequences on
344   food web stability (Allesina, Bodini & Bondavalli, 2006; Bellingeri & Bodini 2013).
345   Furthermore, we have to consider that this food web includes all recorded trophic interactions,
346   though trophic interactions do not always occur simultaneously in time and space. We cannot
347   ignore the additional potentially confounding effects of seasonality and spatial sampling (Ings et
348   al., 2009). In fact, the network represents an ideal niche space and dynamic stability depends
349   more on how interactions materialized in time and space. Some nodes are clearly pulsatile, such
350   as the massive influx of Krill (Aguirre, 2015), which it is difficult to reflect in a static description
351   of the network topology. The consideration of all these factors might increase the fragility of
352   Potter Cove food web. By reducing the number of possible interactions, predators cannot switch
353   to alternative preys, depending solely on preys that are present and available. For these reasons,
354   future studies considering the effect of time and space, massive pulses of certain species and the
355   strength of each interaction are required to satisfactory predict the impacts of climate change on
356   the currently threatened Antarctic marine ecosystem of Potter Cove.

Conclusions

358   We found that Potter Cove food web was relatively robust to local extinctions of macroalgae
359   species under a topological approach considering extinction thresholds (v). We could attribute
360   this robustness to the effects of omnivory and functional redundancy (Borrvall et al., 2000). This
361   robustness becomes clear in the high link density of the common-enemy graph. Therefore, we
362   expect Potter Cove food web to be moderately affected by the changes in macroalgae species
363   caused by climate change until a high threshold of stress is reached, and then negative effects are

364 expected to spread through the entire food web leading it to collapse. In this manner, our results
365 suggest that, despite the apparent robustness of Potter Cove food web, structural changes in the
366 community might not be detected until most of the macroalgae species are affected.

367 **Acknowledgments**

368 We thank Kevin Sánchez and Florencia Ríos for suggestions on language aspects, which helped
369 us to improve the manuscript. We also thank the editor and the two reviewers for their valuable
370 comments which helped us improving the quality and clearness of this paper.

371 **Figure Texts**

372 **Figure 1**. Map of Potter Cove at 25 de Mayo/King George Island where scientific research
373 station Base Carlini is highlighted (Map data: ©2018 Google Earth, DigitalGlobe). 25 de
374 Mayo/King George Island is the largest island of the South Shetland Islands, lying 120 km
375 Western Antarctic Peninsula (WAP).

376 **Figure 2.** A: common-enemy graph of Potter Cove food web, nodes represent basal species and
377 links indirect interactions (shared predators). Node and link widths are proportional to number of
378 shared predators. B: Potter Cove food web, vertical position indicates trophic level and node
379 widths are proportional to total degree (in and out) (Marina et al., 2018). Node colors represent
380 functional groups.

381 **Figure 3.** Remaining links (L) vs primary extinctions, when macroalgae species and detritus
382 were removed. L was recorded after primary and secondary extinctions have taken place. Each
383 box corresponds to a different threshold (v) (A: 0 %, B: 25 %, C: 50 % and D: 75 %).
384 Macroalgae loss was done following different sequences of extinctions: red, ascending degree
385 (mean and standard deviation); blue, descending degree (mean and standard deviation); violet,
386 random degree (mean and standard deviation) and green, biomass (ascending order).

387 **Figure 4.** Connectance (C) vs primary extinctions, when macroalgae species and detritus were
388 removed. C was computed after primary and secondary extinctions have taken place. Each box
389 corresponds to a different threshold (v) (A: 0 %, B: 25 %, C: 50 % and D: 75 %). Macroalgae
390 loss was done following different sequences of extinctions: red, ascending degree (mean and
391 standard deviation); blue, descending degree (mean and standard deviation); violet, random
392 degree (mean and standard deviation) and green, biomass (ascending order).

393 **Figure 5.** Secondary extinctions vs primary extinctions, when macroalgae species and detritus
394 were removed. Each box corresponds to a different threshold (v) (A: 0 %, B: 25 %, C: 50 % and
395 D: 75 %). Macroalgae loss was done following different sequences of extinctions: red, ascending
396 degree (mean and standard deviation); blue, descending degree (mean and standard deviation);
397 violet, random degree (mean and standard deviation) and green, biomass (ascending order).

398   **Figure 6.** Secondary extinctions with threshold (v) variations (from 5 % to 95 % by 5 %) when
399   macroalgae are primary lost (blue: three, brown: five, green: ten, red: fifteen, pink: twenty).
400   Points are means of secondary extinctions when x number of primary extinctions took place at a
401   particular v (by random simulations). Shaded area represents confidence interval of the series.

402   **Figure S1.** Scheme of the methodology used to detect secondary extinctions after the removal of
403   a particular species (primary loss). In this example, the extinction threshold (v) was 0.75 and H2,
404   P1 and P2 species were secondarily extinct when their fraction of incoming links $l(i)$ was lower
405   than v after the removal of species A3. A1, A2 and A3 represent algae species, H1 and H2
406   herbivores, and P1 and P2 predators.

407   **REFERENCE**

408   Aguirre G. (2015). Ecología del mesozooplancton marino en ambientes costeros de altas
409   latitudes: Canal Beagle (extremo sur de Sudamérica) y Caleta Potter (Isla 25 de Mayo,
410   Antártida). D. Phil. Thesis, University of Buenos Aires.

411   Albert, R, Jeong, H & Barabasi, AL. (2000) Error and attack tolerance of complex networks.
412   *Nature*, 406:378–382.

413   Allesina, S, Bodini, A, & Bondavalli, C. (2006). Secondary extinctions in ecological networks:
414   bottlenecks unveiled. *Ecological Modelling*, 194(1-3): 150-161.

415   Bascompte, J. (2009). Disentangling the web of life. *Science*, 325(5939): 416-419.

416   Bellingeri, M, & Bodini, A. (2013). Threshold extinction in food webs. *Theoretical ecology*,
417   6(2): 143-152.

418   Bers, AV, Momo, F, Schloss, IR, & Abele, D. (2013). Analysis of trends and sudden changes in
419   long-term environmental data from King George Island (Antarctica): relationships between
420   global climatic oscillations and local system response. *Climatic change*, 116(3-4): 789-803.

421   Bersier, LF. (2007). A history of the study of ecological networks. In: Kepes F. ed. Biological
422   Networks. Complex systems and inter-disciplinary science Series, World Scientific, Singapour,
423   3(11): 365-421.

424   Borrvall, C, Ebenman, B, Jonsson, T, & Jonsson, T. (2000). Biodiversity lessens the risk of
425   cascading extinction in model food webs. *Ecology Letters*, 3(2): 131-136.

426   Brandes, U, & Wagner, D. (2004). Visone - Analysis and Visualization of Social Networks. In
427   Michael Jünger and Petra Mutzel (Eds.): Graph Drawing Software, pp. 321-340. © Springer-
428   Verlag.

429 Bromwich, DH, Nicolas, JP, Monaghan, AJ, Lazzara, MA, Keller, LM, Weidner, GA, & Wilson,
430 AB. (2013). Central West Antarctica among the most rapidly warming regions on Earth. *Nature*
431 *Geoscience*, 6(2): 139-145.

432 Byrnes, JE, Reynolds, PL, & Stachowicz, JJ. (2007). Invasions and extinctions reshape coastal
433 marine food webs. *PloS one*, 2(3): e295.

434 Campana, GL, Zacher, K, Deregibus, D, Momo, FR, Wiencke, C, & Quartino, ML. (2018).
435 Succession of Antarctic benthic algae (Potter Cove, South Shetland Islands): structural patterns
436 and glacial impact over a four-year period. *Polar Biology*, 41(2): 377-396.

437 Curtsdotter, A, Binzer, A, Brose, U, de Castro, F, Ebenman, B, Eklöf, A, Riede JO, Thierry A &
438 Rall, BC. (2011). Robustness to secondary extinctions: comparing trait-based sequential
439 deletions in static and dynamic food webs. *Basic and Applied Ecology*, 12(7): 571-580.

440 Deregibus, D, Quartino, ML, Campana, GL, Momo, FR, Wiencke, C, & Zacher, K (2016).
441 Photosynthetic light requirements and vertical distribution of macroalgae in newly ice-free areas
442 in Potter Cove, South Shetland Islands, Antarctica. *Polar Biology*, 39(1): 153-166.

443 de Santana, CN, Rozenfeld, AF, Marquet, PA, & Duarte, CM. (2013). Topological properties of
444 polar food webs. *Marine ecology progress series*, 474: 15-26.

445 Donohue, I, Petchey, OL, Kéfi, S, Génin, A, Jackson, AL, Yang, Q, & O'Connor, NE. (2017).
446 Loss of predator species, not intermediate consumers, triggers rapid and dramatic extinction
447 cascades. *Global Change Biology*, 23(8): 2962-2972.

448 Ducklow, HW, Fraser, WR, Meredith, MP, Stammerjohn, SE, Doney, SC, Martinson, DG &
449 Amsler, CD. (2013). West Antarctic Peninsula: an ice-dependent coastal marine ecosystem in
450 transition. *Oceanography*, 26(3): 190-203

451 Dunne, JA, Williams, RJ, & Martinez, ND. (2002). Food-web structure and network theory: the
452 role of connectance and size. *Proceedings of the National Academy of Sciences*, 99(20): 12917-
453 12922.

454 Dunne, JA, Williams, RJ, & Martinez, ND. (2004). Network structure and robustness of marine
455 food webs. *Marine Ecology Progress Series*, 273: 291-302.

456 Dulvy, NK, Metcalfe, JD, Glanville, J, Pawson, MG, & Reynolds, JD. (2000). Fishery stability,
457 local extinctions, and shifts in community structure in skates. *Conservation Biology*, 14(1): 283-
458 293.

459 Ebenman, B, Law, R & Borrvall, C. (2004). Community viability analysis: the response of
460 ecological communities to species loss. *Ecology*, 85(9): 2591–2600.

461 Eklöf, A, & Ebenman, BO. (2006). Species loss and secondary extinctions in simple and
462 complex model communities. *Journal of animal ecology*, 75(1): 239-246.

463 Eklöf, A, Tang, S, & Allesina, S. (2013). Secondary extinctions in food webs: a Bayesian
464 network approach. *Methods in Ecology and Evolution*, 4(8): 760-770.

465 Ellison, AM, Bank, MS, Clinton, BD, Colburn, EA, Elliott, K, Ford, CR, Foster, DR, Kloeppel,
466 BD, Knoepp, JD, Lovett GM, Mohan, J, Orwing, DA, Rodenhouse NL, Sobczak, WV, Stinson,
467 KA, Stone, Swan, CM, Thompson, J, Von Holle, B, & Webster, JR. (2005). Loss of foundation
468 species: consequences for the structure and dynamics of forested ecosystems. *Frontiers in
469 Ecology and the Environment*, 3(9): 479-486.

470 Fueyo Sánchez, L. (2013). Estructura de redes tróficas y flujos de energía en comunidades
471 intermareales de la costa argentina. D. Phil. Thesis. National University of Mar del Plata.

472 Gómez, I, Wulff, A, Roleda, MY, Huovinen, P, Quartino, ML, Dunton, K & Wiencke, C. (2009)
473 Light and temperature demands of marine benthic microalgae and seaweeds in polar regions.
474 *Botanica Marina,* 52: 593–608. doi: 10.1515/BOT.2009.073

475 Grange, LJ, & Smith, CR. (2013). Megafaunal communities in rapidly warming fjords along the
476 West Antarctic Peninsula: hotspots of abundance and beta diversity. *PloS one*, 8(12): e77917.

477 Hastings, A, McCann, KS, & de Ruiter, PC. (2016). Introduction to the special issue: theory of
478 food webs. *Theoretical Ecology*, 9(1): 1-2.

479 Holt, RA, & Lawton, JH. (1994). The ecological consequences of shared natural enemies.
480 *Annual review of Ecology and Systematics*, 25(1): 495-520.

481 Ings, TC, Montoya, JM, Bascompte, J, Blüthgen, N, Brown, L, Dormann, CF & Lauridsen, RB.
482 (2009). Review: Ecological networks–beyond food webs. *Journal of Animal Ecology*, 78(1):
483 253-269.

484 Jackson, JB, Kirby, MX, Berger, WH, Bjorndal, KA, Botsford, LW, Bourque, BJ, Bradbury, RH,
485 Cooke, R, Erlandson, J, Estes, JA, Hughes, TP, Kidwell, S, Lange, CB, Lenihan, HS, Pandolfi,
486 JH, Peterson, CH, Steneck, RS, Tegner, MJ, & Hughes, TP. (2001). Historical overfishing and
487 the recent collapse of coastal ecosystems. *Science*, 293(5530): 629-637.

488 Klöser, H, Mercuri, G, Laturnus, F, Quartino, ML, & Wiencke, C. (1994). On the competitive
489 balance of macroalgae at Potter Cove (King George Island, South Shetlands). *Polar Biology*,
490 14(1): 11-16.

491 Klöser, H, Quartino, ML, & Wiencke, C. (1996). Distribution of macroalgae and macroalgal
492 communities in gradients of physical conditions in Potter Cove, King George Island, Antarctica.
493 *Hydrobiologia*, 333(1): 1-17.

494   Lagger, C, Nime, M, Torre, L, Servetto, N, Tatián, M, & Sahade, R. (2017). Climate change,
495   glacier retreat and a new ice-free island offer new insights on Antarctic benthic responses.
496   Ecography, 41(4): 579-591.

497   Lawton, JH. (1994). Population dynamic principles. *Phil. Trans. R. Soc. Lond. B*, 344(1307): 61-
498   68.

499   Lawton, JH, & Brown, VK. (1994). Redundancy in ecosystems. *In Biodiversity and ecosystem*
500   *function* (pp. 255-270). Springer, Berlin, Heidelberg.

501   Marina, T, Salinas, V, Cordone, G, Campana, G, Moreira, ME, Deregibus, D, Torre, L, Sahade,
502   R, Tatián, M, Barrera Oro, E, De Troch, M, Doyle, S, Quartino, ML, Saravia, L, & Momo, F.
503   (2018). The food web of Potter Cove (Antarctica): complexity, structure and function *Estuarine,*
504   *Coastal and Shelf Science,* 200: 141-151. doi:10.1016/j.ecss.2017.10.015.

505   McClintock, J, Ducklow, H, & Fraser, W. (2008). Ecological Responses to Climate Change on
506   the Antarctic Peninsula: The Peninsula is an icy world that's warming faster than anywhere else
507   on Earth, threatening a rich but delicate biological community. *American Scientist*, 96(4): 302-
508   310.

509   McKinney, ML. (1997). Extinction vulnerability and selectivity: combining ecological and
510   paleontological views. *Annual Review of Ecology and Systematics*, 28(1): 495-516.

511   Memmott, J, Waser, NM, & Price, MV. (2004). Tolerance of pollination networks to species
512   extinctions. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, 271:
513   2605–2611.

514   Montoya, JM, & Solé, RV. (2002). Small world patterns in food webs. *Journal of theoretical*
515   *biology,* 214(3): 405-412.

516   Neushul M. (1965) Diving observation of sub-tidal Antarctic marine vegetation. *Botanica*
517   *marina,* 8(2-4): 234–243.

518   Nicolas, JP, & Bromwich, DH. (2014). New reconstruction of Antarctic near-surface
519   temperatures: Multidecadal trends and reliability of global reanalyses. *Journal of Climate*,
520   27(21): 8070-8093.

521   Pasotti, F, Manini, E, Giovannelli, D, Wölfl, AC, Monien, D, Verleyen, E, Braeckman, U,
522   Abele, D & Vanreusel, A. (2015). Antarctic shallow water benthos in an area of recent rapid
523   glacier retreat. *Marine Ecology,* 36(3): 716-733.

524   Quartino, ML, Zaixso, HE, & Boraso de Zaixso, AL. (2005). Biological and environmental
525   characterization of marine macroalgal assemblages in Potter Cove, South Shetland Islands,
526   Antarctica. *Botanica Marina*, 48(3): 187-197.

527 Quartino, ML, & De Zaixso, AB. (2008a). Summer macroalgal biomass in Potter Cove, South
528 Shetland Islands, Antarctica: its production and flux to the ecosystem. *Polar Biology*, 31(3): 281-
529 294.

530 Quartino, ML, Boraso de Zaixso A, Momo, FR. (2008b) Macroalgal production and the energy
531 cycle of Potter Cove.   In: Wiencke, C, Ferreyra, GA., Abele, D,Marenssi, S. (Eds.), The
532 Antarctic ecosystem of Potter cove, King-George Island (Isla 25 de Mayo). Alfred-Wegener
533 Institut (AWI), Bremerhaven, pp. 68-74.

534 Quartino, ML, Deregibus, D, Campana, GL, Latorre, GEJ, & Momo, FR. (2013). Evidence of
535 macroalgal colonization on newly ice-free areas following glacial retreat in Potter Cove (South
536 Shetland Islands), Antarctica. PloS one, 8(3): e58223.

537 R Core Team (2017). R: A language and environment for statistical computing. R Foundation for
538 Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

539 Roese, M, & Drabble, M. (1998). Wind-driven circulation in Potter Cove. *Berichte zur*
540 *polarforschung*, 299: 40-46.

541 Sahade, R, Lagger, C, Torre, L, Momo, F, Monien, P, Schloss, I, Barnes, D, Servetto, N,
542 Tarantelli, S, Tatián, M, Zamboni, N & Abele, D. (2015). Climate change and glacier retreat
543 drive shifts in an Antarctic benthic ecosystem. *Science Advances*, 1(10): e1500050.

544 Sahade, R, Tatián, M, Kowalke, J, Kühne, S, & Esnal, GB. (1998). Benthic faunal associations
545 on soft substrates at Potter Cove, King George Island, Antarctica. *Polar Biology*, 19(2): 85-91.

546 Sanders, D, Sutter, L, & Veen, FJ. (2013). The loss of indirect interactions leads to cascading
547 extinctions of carnivores. *Ecology letters*, 16(5): 664-669.

548 Sanders, D, Kehoe, R, Thebault, E, & Van Veen, FJF. (2018). Trophic redundancy reduces
549 vulnerability to extinction cascades. *Proceedings of the National Academy of Sciences*, 115(10):
550 2419-2424.

551 Schleuning, M, Fründ, J, Schweiger, O, Welk, E, Albrecht, J, Albrecht, M, Böhning-Gaese, KD,
552 Dehling, M, Dormann, CF, Exeler, N, Farwig, N, Harpke, A, Hickler, T, Kratochwil, A,
553 Kuhlmann, M, Kühn, I, Michez, D, Mudri-Stojnić, S, Plein, M, Rasmont, P, Schwabe, A,
554 Settele, J, Vujić, A, Weiner, CN, Wiemers, M & Hof C. (2016). Ecological networks are more
555 sensitive to plant than to animal extinction under climate change. *Nature Communications*, 7:
556 13965.

557 Schloss, IR, Abele, D, Moreau, S, Demers, S, Bers, AV, González, O, & Ferreyra, GA. (2012).
558 Response of phytoplankton dynamics to 19 year (1991–2009) climate trends in Potter Cove
559 (Antarctica). Journal of marine Systems, 92(1): 53–66. doi:10.1016/j.jmarsys.2011.10.006

560 Sorte, CJ, Davidson, VE, Franklin, MC, Benes, KM, Doellman, MM, Etter, RJ, Hanningan, RE,
561 Lubchenco J & Menge, BA. (2017). Long-term declines in an intertidal foundation species
562 parallel shifts in community composition. *Global change biology*, 23(1): 341-352.

563 Sole, RV, & Montoya, M. (2001). Complexity and fragility in ecological networks. *Proceedings*
564 *of the Royal Society of London B: Biological Sciences*, 268(1480): 2039-2045.

565 Tatián, M, Sahade, RJ, Doucet, ME, & Esnal, GB. (1998). Ascidians (Tunicata, Ascidiacea) of
566 Potter Cove, South Shetland Islands, Antarctica. *Antarctic science*, 10(2): 147-152.

567 Tatian, M, Sahade, R, & Esnal, GB. (2004). Diet components in the food of Antarctic ascidians
568 living at low levels of primary production. *Antarctic Science*, 16(02): 123-128.

569 Thompson, RM, Hemberg, M, Starzomski, BM, & Shurin, JB. (2007). Trophic levels and trophic
570 tangles: the prevalence of omnivory in real food webs. *Ecology*, 88(3): 612-617.

571 Turner, J, Bindschadler, R, Convey, P, Di Prisco, G, Fahrbach, E, Gutt, J, Hodgson, DA,
572 Mayewski, PA, & Summerhayes, C. (2009). Eds., Antarctic Climate Change and the
573 Environment (Scientific Committee on Antarctic Research, Scott Polar Research Institute,
574 Cambridge).

575 Wiencke, C, Ferreyra, G, Arntz, W, & Rinaldi, C. (1998). The Potter Cove coastal ecosystem,
576 Antarctica. *Berichte zur Polarforschung*, 299: 1-106.

577 Wiencke, C, Ferreyra, GA, Abele, D, & Marenssi, S. (2008). The Antarctic ecosystem of Potter
578 cove, King-George Island (Isla 25 de Mayo): Synopsis of research performed 1999-2006 at the
579 Dallmann Laboratory and Jubany Station. *Berichte zur Polar-und Meeresforschung* (Reports on
580 Polar and Marine Research), 571.

581 Witman, JD, Smith, F, & Novak, M. (2017). Experimental demonstration of a trophic cascade in
582 the Galápagos rocky subtidal: Effects of consumer identity and behavior. *PloS one*, 12(4):
583 e0175705.

584 Worm, B, & Duffy, JE. (2003). Biodiversity, productivity and stability in real food webs. *Trends*
585 *in Ecology & Evolution*, 18(12): 628-632.

Figure 1

Map of Potter Cove at 25 de Mayo/King George Island

Map of Potter Cove at 25 de Mayo/King George Island where scientific research station Base Carlini is highlighted (Map data: ©2018 Google Earth, DigitalGlobe). 25 de Mayo/King George Island is the largest island of the South Shetland Islands, lying 120 km Western Antarctic Peninsula (WAP).
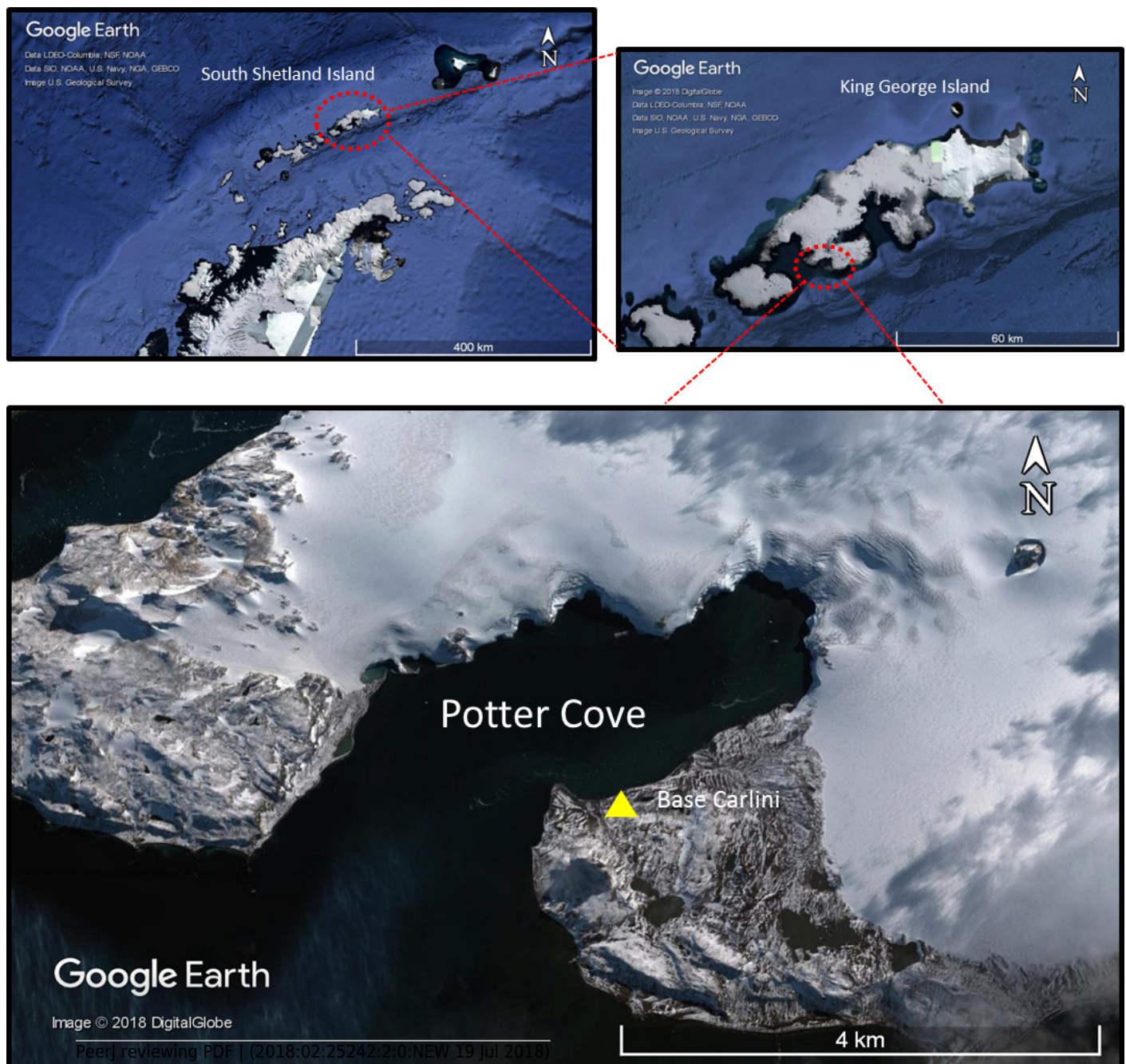
Figure 2

Common-enemy graph and Potter Cove food web

A: common-enemy graph of Potter Cove food web, nodes represent basal species and links indirect interactions (shared predators). Node and link widths are proportional to number of shared predators. B: Potter Cove food web, vertical position indicates trophic level and node widths are proportional to total degree (in and out) (Marina et al., 2018). Node colors represent functional groups.
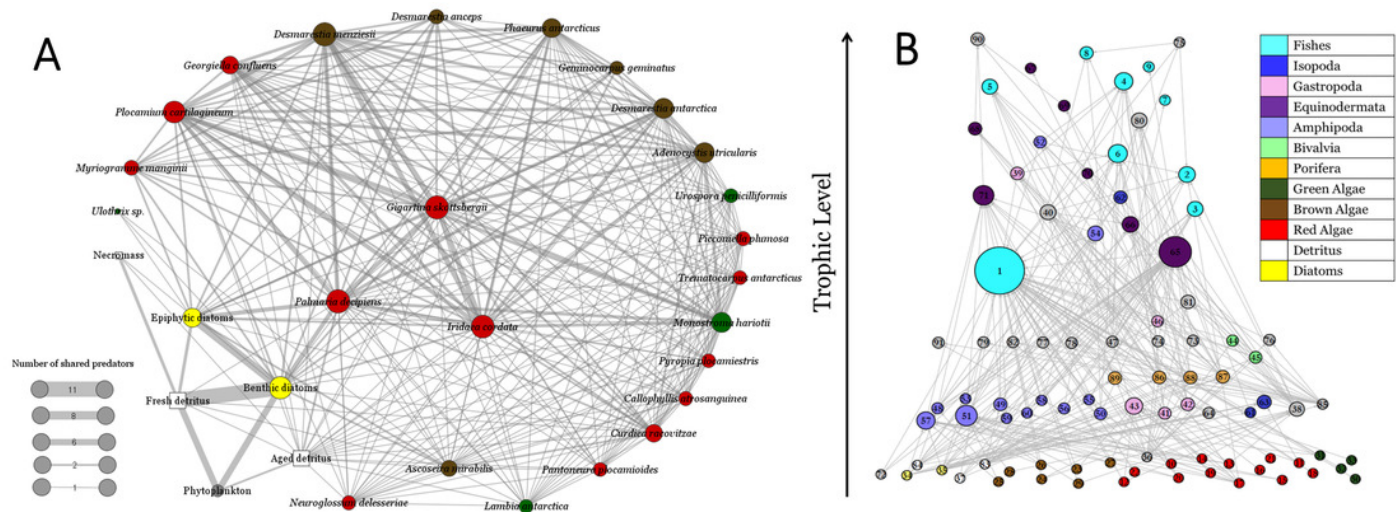
Figure 3

Links response to simulation of species loss

Remaining links (*L*) vs primary extinctions, when macroalgae species and detritus were removed. *L* was recorded after primary and secondary extinctions have taken place. Each box corresponds to a different threshold (*v*) (A: 0 %, B: 25 %, C: 50 % and D: 75 %). Macroalgae loss was done following different sequences of extinctions: red, ascending degree (mean and standard deviation); blue, descending degree (mean and standard deviation); violet, random degree (mean and standard deviation) and green, biomass (ascending order).
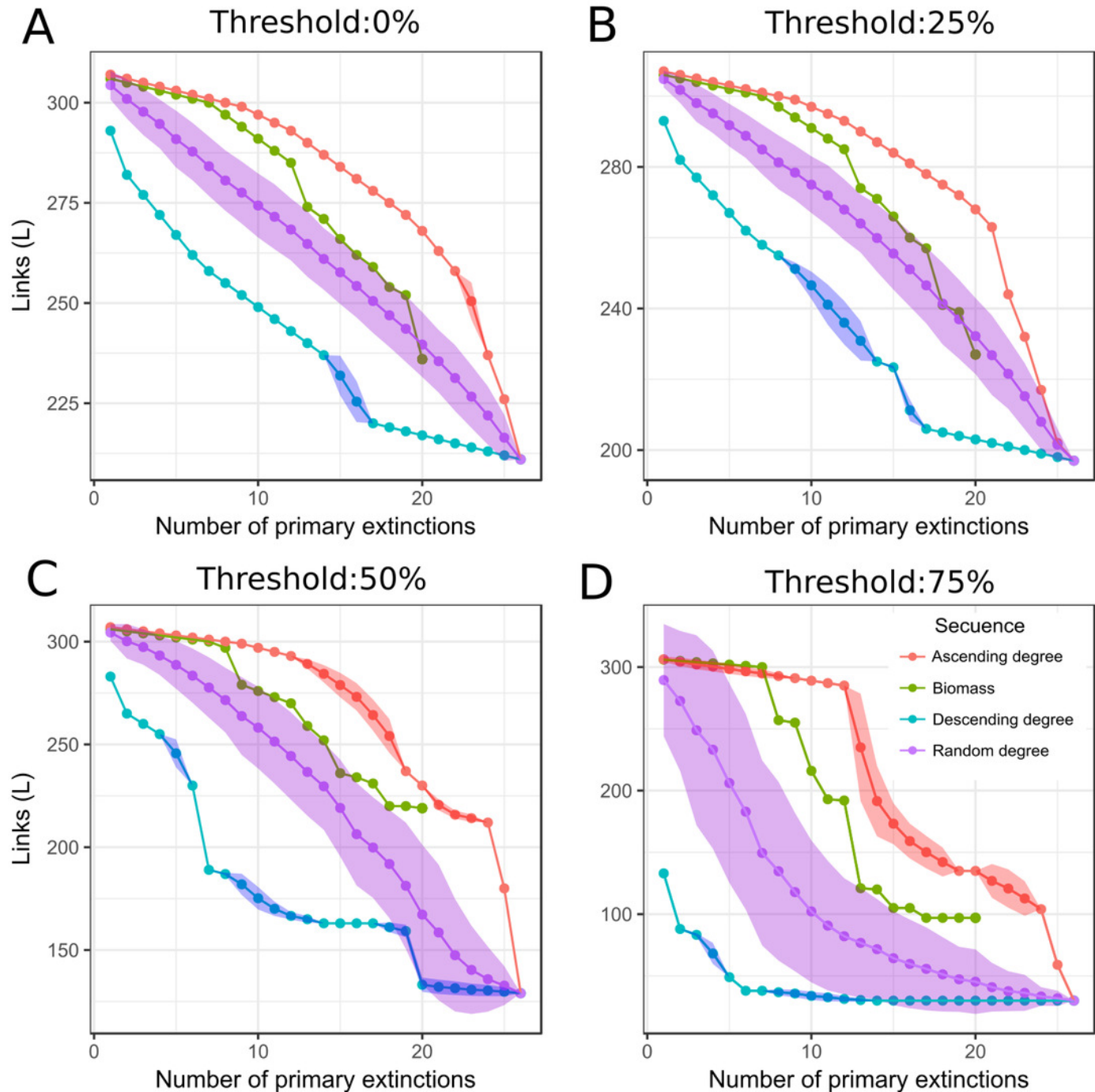
Figure 4

Connectance response to simulation of species loss

Connectance (C) vs primary extinctions, when macroalgae species and detritus were removed. C was computed after primary and secondary extinctions have taken place. Each box corresponds to a different threshold (v) (A: 0 %, B: 25 %, C: 50 % and D: 75 %). Macroalgae loss was done following different sequences of extinctions: red, ascending degree (mean and standard deviation); blue, descending degree (mean and standard deviation); violet, random degree (mean and standard deviation) and green, biomass (ascending order).
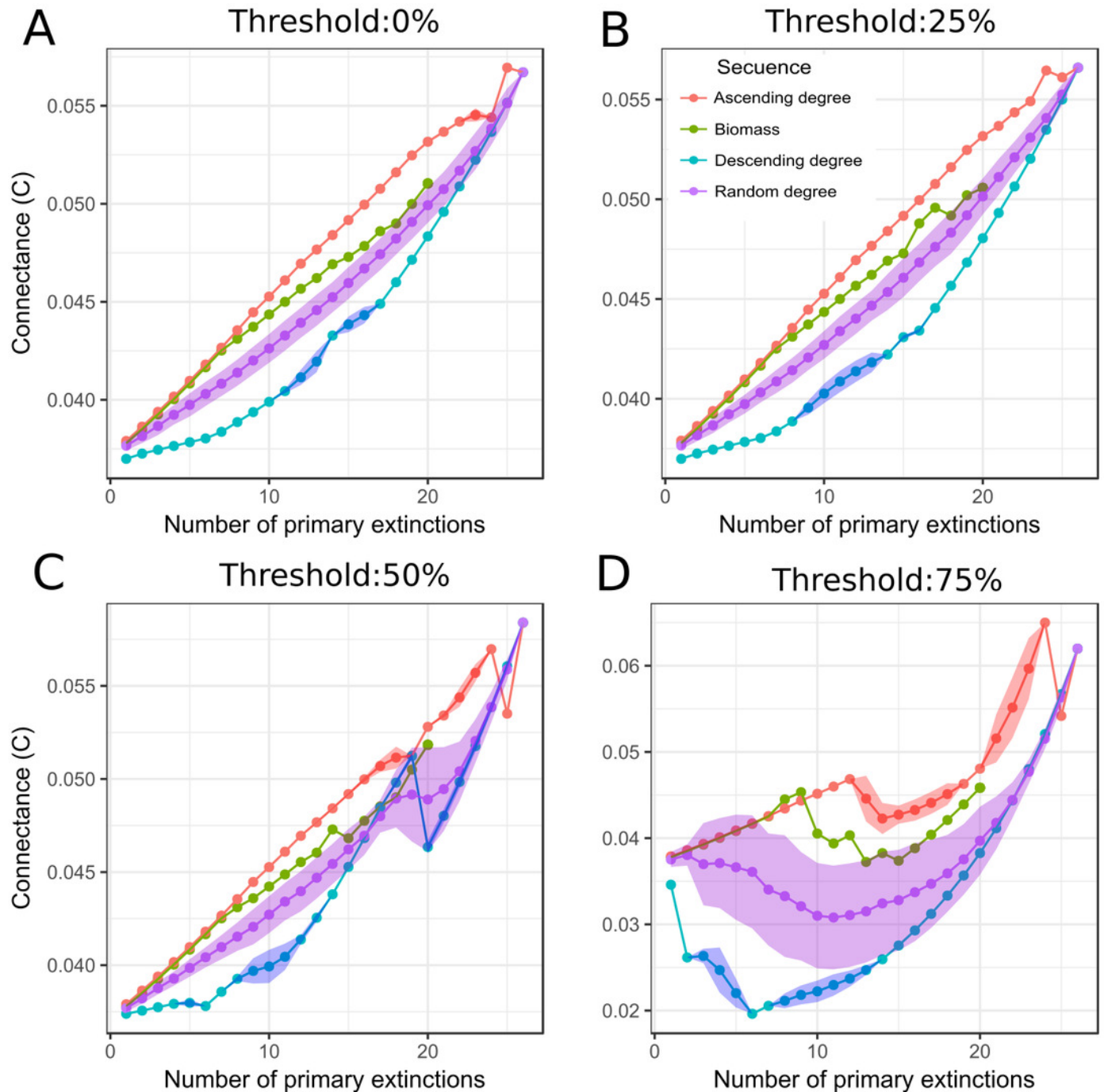
Figure 5

Secondary extinctions response to simulation of species loss

Secondary extinctions vs primary extinctions, when macroalgae species and detritus were removed. Each box corresponds to a different threshold (*v*) (A: 0 %, B: 25 %, C: 50 % and D: 75 %). Macroalgae loss was done following different sequences of extinctions: red, ascending degree (mean and standard deviation); blue, descending degree (mean and standard deviation); violet, random degree (mean and standard deviation) and green, biomass (ascending order).
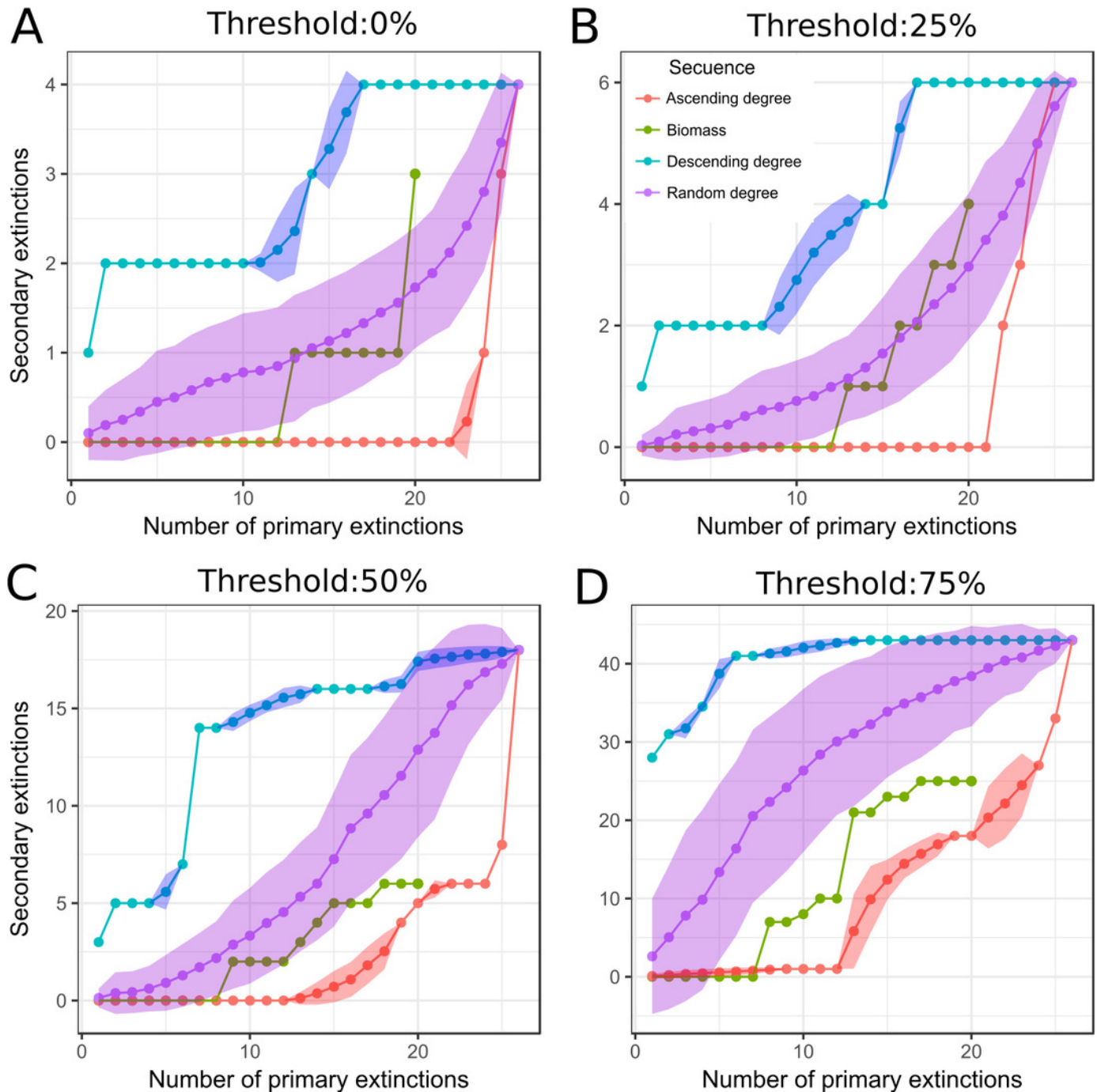
Figure 6

Effect of threshold in secondary extinctions

Secondary extinctions with threshold (*v*) variations (from 5 % to 95 % by 5 %) when macroalgae are primary lost (blue: three, brown: five, green: ten, red: fifteen, pink: twenty). Points are means of secondary extinctions when *x* number of primary extinctions took place at a particular *v* (by random simulations). Shaded area represents confidence interval of the series.