

1 On the sensitivity of food webs to multiple
2 disturbances

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³² Checklist

- ³³ Proposal letter Ecology Letters - Ideas and Perspectives
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- ³⁹ Keywords
- ⁴⁰ Abstract
- ⁴¹ Introduction
- ⁴² Of food webs and multiple disturbances (concept)
- ⁴³ Simulations
- ⁴⁴ Sensitivity
- ⁴⁵ Amplification
- ⁴⁶ Food web sensitivity & amplification
- ⁴⁷ Conclusions
- ⁴⁸ Acknowledgements
- ⁴⁹ References
- ⁵⁰ Figure 1 - Concept
- ⁵¹ Figure 2 - Sensitivity
- ⁵² Figure 3 - Amplification
- ⁵³ Figure 4 - Food web scores table
- ⁵⁴ Figure 5 - Topological ~ Realised scores
- ⁵⁵ Figure 6 - Scores ~ Trophic level & degree
- ⁵⁶ Table S1 - Systems of equations
- ⁵⁷ Article formatting

58 Plan

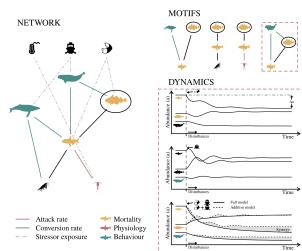
59 • Abstract

60 • Introduction

- 61 – Global changes and disturbances propagation through food webs
- 62 – Uncertainty associated with multiple disturbances
- 63 – Limits of *in situ* and experimental approaches to study multiple disturbances
- 64 – Limited insights from null model testing
- 65 – Shift towards ecological modelling to better understand mechanisms
- 66 – Insights on the effects of disturbances on ecological communities from theoretical
- 67 – ecology
- 68 – Theoretical focus on single disturbances, coexistence and extinctions

69 • Objectives

- 70 – Investigate the role of species and their interactions in mediating the effects of
- 71 – multiple disturbances on food webs.
- 72 – Questions of particular significance to management:
 - 73 1) should interactions be considered in impact assessments?
 - 74 2) can the effects of stressors be evaluated separately or should they be consid-
 - 75 ered in combination?
 - 76 3) which species are most sensitive to disturbances based on their trophic posi-
 - 77 tion?
- 78 • Of food webs and multiple disturbances
 - 79 – Whole food webs & disturbances (pathways of effects)
 - 80 – Motifs to understand how topology (species position and interaction type) influ-
 - 81 – ences the observed effects of disturbances
 - 82 – Dynamics of motifs
 - 83 * Trophic sensitivity and define weak entry points and biotic/trophic sinks
 - 84 * Trophic amplification and define biotic/trophic buffers and biotic/trophic
 - 85 multipliers

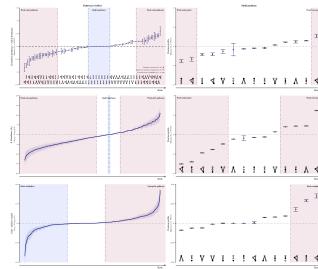


86 • Simulating multiple disturbances

- 87 – Method for simulations:
- 88 * Exhaustive investigation of how topology affects species abundance at
- 89 * equilibrium to univariate and multivariate pathways of effects

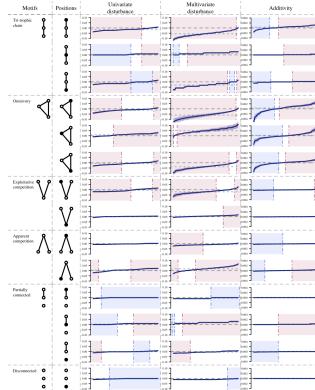
90 • **Topology and sensitivity**

- 91 – Method: Comparison between initial and disturbed abundance: trophic sensitiv-
- 92 ity
- 93 – Amplitude of effects is highly variable, and much higher for multivariate pathways
- 94 of effects
- 95 – Importance of considering species interactions
- 96 * Univariate pathways of effects simulations clearly show that interactions in-
- 97 fluence the amplitude of the effects of disturbances
- 98 * Complex interactions = greater variability
- 99 * Control motifs (disconnected &)
- 100 – Species position and interaction type leads to varying sensitivity
- 101 * Control motifs largely unaffected
- 102 * Complex interactions more sensitive (i.e. tri-trophic food chain and omnivory)
- 103 * Competitive interactions (Competitive and apparent competition)
- 104 * Basal resources and top predators generally more sensitive



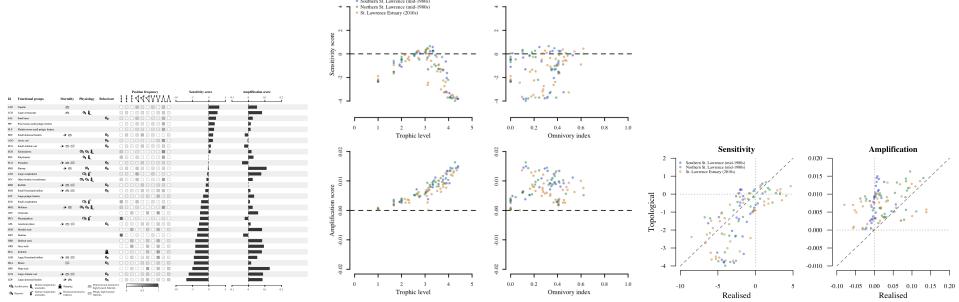
105 • **Topology and amplification**

- 106 – Method: Comparison between full models considering all pathways of effects si-
- 107 multaneously and additive models considering the sum of the effects of univariate
- 108 pathways of effect to identify antagonistic, additive and synergistic pathways of
- 109 effect: trophic amplification
- 110 – Frequency and variability of non-additive effects more important for omnivory
- 111 and tri-trophic chain.
- 112 – Predator release for resources or meso-predators (positive effects)
- 113 – Limited non-additive effects for control motifs



114 • Complex food webs

- 115 – Method: Topological and realised sensitivity and amplification scores; expert
116 opinion on effects of drivers on mortality, physiology and behaviour.
- 117 – Empirical food web: Northern Gulf of St. Lawrence, prior to the groundfish stock
118 collapse in the 1990s
- 119 – Topological vs realised scores
 - 120 * Interpret biplots
- 121 – Trophic level
 - 122 * Realised sensitivity non-linear with trophic level. Lower and higher trophic
123 levels have low sensitivity scores, while intermediate trophic levels have null
124 or positive sensitivity scores
 - 125 * Realised Amplification looks like a sinusoid, with antagonism at low trophic
126 levels which increases to synergism towards intermediate trophic levels. It
127 then drops to antagonisms again at intermediate trophic levels and then in-
128 creases again towards synergisms for higher trophic levels.
- 129 – Food web:
 - 130 * Few biotic sinks, more negative weak entry points
 - 131 * Very few biotic buffers, many biotic multipliers
 - 132 * A species does not have to be impacted directly to have large trophic sensitiv-
133 ity and amplification scores (*e.g.* seals and seabirds), and direct disturbances
134 do not necessarily result in sensitivity or amplification.
 - 135 * Groundfish collapse: decrease in groundfish species and increase in inverte-
136 brates, crustaceans and shrimp (economical shift ensued with fisheries now
137 focused on those species)
 - 138 · Groundfish species are negative weak entry points and biotic multipliers
 - 139 · Large crustaceans positive weak entry point and biotic multiplier
 - 140 · Shrimp biotic sink
 - 141 · Check up on capelin populations post stock collapse



142 • Conclusions

- 143 – Complex interactions = more sensitive and non-additive effects
- 144 – Meso-predator in complex interactions or resources in apparent competition =
- 145 predator release
- 146 – Competitive interactions = less sensitive and more antagonism
- 147 – Mecanistic understanding
- 148 – Probabilities
- 149 – Management

150 **To do:**

- 151 Proposal for Ecology Letters Ideas and Perspectives
152 Check and adjust for unique pathways of effect (exploitative and apparent competition).
153
- 154 – They are all unique when you consider the position of the species, except for the disconnected motif.
- 155
- 156 Think on the best way to establish position profile. At the moment what is used is
157 the mean of individual pathways of effect per position, and I feel we could do better.
158 ***Perhaps with maximal positional scores.***
- 159 Integrate (Hodgson *et al.* 2019) in the introduction
- 160 Figure out how to evaluate species motifs position as a probability rather than a
161 frequency. This could make use of empirical diet % available in Ecopath models. ->
162 This will be discussed in this paper, and developed in the subsequent spatial paper
- 163 Figure out methodology to evaluate species profile through two indices: sensitivity score
164 and amplification score. These could be used to adjust Halpern's equation later on.
- 165 Cheung, W.W.L., Sarmiento, J.L., Dunne, J., Frolicher, T.L., Lam, V.W.Y., Palomares,
166 M.L.D., Watson, R., and Pauly, D. 2013. Shrinking of fishes exacerbates
167 impacts of global ocean changes on marine ecosystems. Nature Climate Change 3:
168 254-258.
- 169 Uniformiser les indices dans les équations de l'article
- 170 Modify the score for species using realised pathways of effects. I thought that this was
171 done, but since we are not using probabilities, I'm not sure what I should be doing
172 anymore with this. Ideally I would still use a probability and have a general function,
173 but we might still want to keep this for the 4th chapter of the thesis. -> in 4th chapter.
- 174 Verify all codes so that the proper equations are used
- 175 Update thresholds used
- 176 Give proper credit to icons and images used
- 177 Sensitivity and amplification ~ in- and out-degree
- 178 Figure ex. biotic multiplier ~ position
- 179 Evaluate realised score potential (maximum) for each position. Not all pathways could
180 be realised simultaneously, since when a multivariate pathway of effect exists, all of
181 its constituent pathways cannot exist anymore. We could therefore come up with a
182 maximal sensitivity and amplification score. We could then check the maximal possible
183 score for a species and see whether we are close to it or not. Since there can only be a
184 single realised pathway between 3 species, the maximum score would be the pathway
185 of effect with the highest sensitivity and the one with the higher amplification score.
- 186 Check whether the unsensitivity of resources in competitive exploitation is due to the
187 competitive parameters added to the models to get to equilibrium

188 **Proposal letter**

¹⁸⁹ **Cover letter and novelty statement**

¹⁹⁰ **Letter**

¹⁹¹ **Documents joined**

¹⁹² **Reviewers**

¹⁹³ **Proposed reviewers:**

- ¹⁹⁴ • Reviewer 1
¹⁹⁵ • Reviewer 2
¹⁹⁶ • Reviewer 3

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¹⁹⁹ **Conflict of interest statement**

²⁰⁰ The authors declare that the submitted work was carried out in the absence of any personal,
²⁰¹ professional or financial relationships that could potentially be construed as a conflict of
²⁰² interest.

203 **1 Abstract**

204 Global changes are resulting in increasingly intricate environmental stress exposure regimes.
205 These can in turn induce complex and unpredictable environmental effects permeating entire
206 ecological communities by way of species interactions.
207 The role of species and their interactions in mediating the effects of multiple disturbances
208 on food webs is however still understudied. Experimental and *in situ* approaches provide
209 limited insight, while theoretical approaches have yet to fully tackle the issue.
210 Using Lotka-Volterra equilibria models of the 4 most common 3-species motifs in empirical
211 food webs, we show that trophic position and interaction type influence the sensitivity to
212 and the amplification of the effects of multiple disturbances.
213 We then show that how species are embedded in complex food webs and the types of dis-
214 turbances they are exposed to dictates their sensitivity to multiple sources of stress.
215 Our results illustrate the importance of explicitly considering species interactions to properly
216 capture the effects of multiple stressors and safeguard ecological communities against global
217 changes.

218 **2 Introduction**

219 • **Global changes, multiple stressors and food webs**

- 220 – Global changes are resulting in increasingly intricate environmental stress expo-
221 sure regimes (Halpern *et al.* 2015; Côté *et al.* 2016; Bowler *et al.* 2019). These can
222 in turn induce complex and unpredictable environmental effects that propagate
223 through entire ecological communities by way of species interactions (Bascompte
224 2009; Montoya *et al.* 2009).

225 • **Uncertainty associated with mutliple stressors**

- 226 – Largest uncertainty in predicting environmental effects is the potential for com-
227 plex driver interactions (Darling & Côté 2008; Côté *et al.* 2016).
228 – Stressors can combine non-additively and result in effects that are greater (*i.e.*
229 synergistic) or lower (*i.e.* antagonistic) than the sum of individual effects (Crain
230 *et al.* 2008; Darling & Côté 2008; Côté *et al.* 2016)
231 – Net effects of multiple stressors can be additive (*i.e.* joint effect equal to the sum
232 of individual effects), synergistic (joint effect superior to the sum of individual
233 effects), antagonistic (joint effect inferior to the sum of individual effects) or dom-
234 inant (joint effect equal to an individual effect) (e.g. Crain *et al.* 2008; Darling &
235 Côté 2008; Côté *et al.* 2016).
236 – This is of particular significance for management, because we have mostly been
237 operating under the assumption that stressors are mostly additive and thus can
238 be managed independently.
239 – Maybe cite (Hodgson *et al.* 2019) (cite it for certain in the article).
240 – most research on driver effects in marine environments remains overwhelmingly
241 focused on single driver assessments (O'Brien *et al.* 2019).

242 • **Limits of *in situ* and experimental approaches to study multiple distur-
243 bances**

- 244 – The number of stressors and of their potential interactions limits the insights we
245 can glean into the effects of multiple disturbances *in situ* and in experimental
246 settings such as mesocosm (Côté *et al.* 2016).
247 – In food webs, this is compounded by the myriad of possible interactions
248 – between species

249 • **Limited insights from null model testing**

- 250 – The knowledge we do have has mostly been gleaned from null model testing
251 providing little insights into ecological mecanisms underlying non-additive stressor
252 effects (De Laender 2018).

253 • **Shift towards ecological modelling to better understand mecanisms**

- 254 – (De Laender 2018; Schäfer & Piggott 2018; Thompson *et al.* 2018a)

255 • **Some insights on the effects of disturbances on ecological communities from
256 theoretical ecology**

- 257 – Importance of interactions and web complexity
258 – Indirect effects [Wootton (1993); Yodzis (2000); Wootton (2002); Montoya *et al.*
259 (2009); ogorman2009]; see intro séminaire 1
260 – Different types of interactions will lead to different overall effects (???).

261 * Different sensitivity for species involved in different types of interactions (seg-
262 way to motifs)

- 263 – How direct and indirect effects combine to affect food web sensitivity to distur-
264 bances

265 • **Theoretical has thus far mostly been concerned mostly with single distur-
266 bances and resistance of communities to extinctions**

- 267 – Little insights into how different pathways of effect influences food webs, let alone
268 pathways of multiple effects.

- 269 – Little on the role of species and their interactions in propagating or buffering
270 against disturbances

271 • **State the objective**

- 272 – Here, we investigate the role of species in mediating the effects of multiple dis-
273 turbances on food webs. In doing so, we seek to answer questions of particular
274 significance to management: 1) should species interactions be considered in im-
275 pact assessments, 2) should the effects of stressors be evaluated separately or in
276 combination, and 3) which species are most sensitive to disturbances?

277 **3 Of food webs and multiple disturbances**

278 **4 Others**

279 • **How we do this**

- 280 – To do so, we focus on how trophic position and interaction types affect species
281 sensitivity to disturbances and the likelihood of species acting as buffer against
282 or amplifiers of the effects of multiple disturbances.

283 • **Transition to motifs**

- 284 – ...?

285 • **Motif description and use**

- 286 – A food web can be decomposed into a set of smaller n -species subgraphs called
287 motifs (Milo *et al.* 2004; Stouffer *et al.* 2007). For example, there are 13 distinct
288 3-species motifs composed of 30 unique positions (Stouffer *et al.* 2007, 2012).
289 Motifs are the backbone of food webs and their study has unearthed valuable
290 insights on community dynamics such as [...].

- 291 – Their type and frequency has been linked to food web stability and persistence
 292 (???)
 293 – Like many disturbance studies in theoretical ecology, however, these have focused
 294 less on the dynamics of population abundances and more on the resistance of food
 295 webs to extinctions.
 296 – Motifs have been used to investigate the persistence of food web to species ex-
 297 tinctions (Stouffer & Bascompte 2010) and the benefit associated to each species
 298 in food web persistence (Stouffer *et al.* 2012).
 299 – *The ecological role of a species in a network is a direct rest if its interactions with*
 300 *other species (Luczkovich 2003; Olesen 2007; Allesina 2009) (in Stouffer 2012)*
 301 – *The number and types of motifs that make up a food web are known to directly*
 302 *affect the web’s stability and persistence (Neutel 2002; Kondoh 2008; Allesina*
 303 *2008; García-Domingo 2008; Stouffer 2010; in Stouffer 2012)*

304 • **Our focus**

- 305 – Here we focus on the most abundant types of interactions: omnivory, tri-trophic
 306 food chain, exploitative competition and apparent competition (Camacho *et al.*
 307 2007; Stouffer & Bascompte 2010)
 308 – Two additional motifs, *i.e.* partially connected and disconnected were also consid-
 309 ered in order to evaluate whether interactions in food webs are truly more likely
 310 to be characterized by non-linear effects.
 311 – To study the effects of multiple stressors in a trophic context, we rather focus on
 312 the resulting disturbances following different pathways of effect rather than on
 313 the disturbances themselves. This means that we will not investigate the effects
 314 of multiple stressors applied to a single species in the food web. This precludes us
 315 from investigating the sensitivity of species to each individual stressor. Rather,
 316 we investigate the effects of disturbances to multiple species simultaneously. But
 317 see Thompson *et al.* (2018b) and Thompson *et al.* (2018a) for a description of
 318 a modelling approach incorporating multiple sources of stress in a food web
 319 model.
 320 – We are interested in pathways that affect the trophic dynamic of food webs, *i.e.*
 321 those that target population growth (*i.e.* birth and death rates) and the rates at
 322 which species interact (*i.e.* attack and conversion rates).

323 • **Pathways of effect**

- 324 – Studying the effects of multiple disturbances means that we will be focusing on
 325 disturbances affecting multiple species, referred to as pathways of multiple effects
 326 ($D_{i,j}$, $D_{i,k}$, $D_{j,k}$, and $D_{i,j,k}$).
 327 – In a food web context, we will define linear and non-linear effect as a function of
 328 whether these pathways of multiple effects result in additive ($D_{i,j} = D_i + D_j$),
 329 synergistic ($D_{i,j} \gg D_i + D_j$), antagonistic ($D_{i,j} \ll D_i + D_j$) or dominant
 330 ($D_{i,j} = D_i \vee D_j$) effects.

331 • **Terminology for types of pathways and position profile**

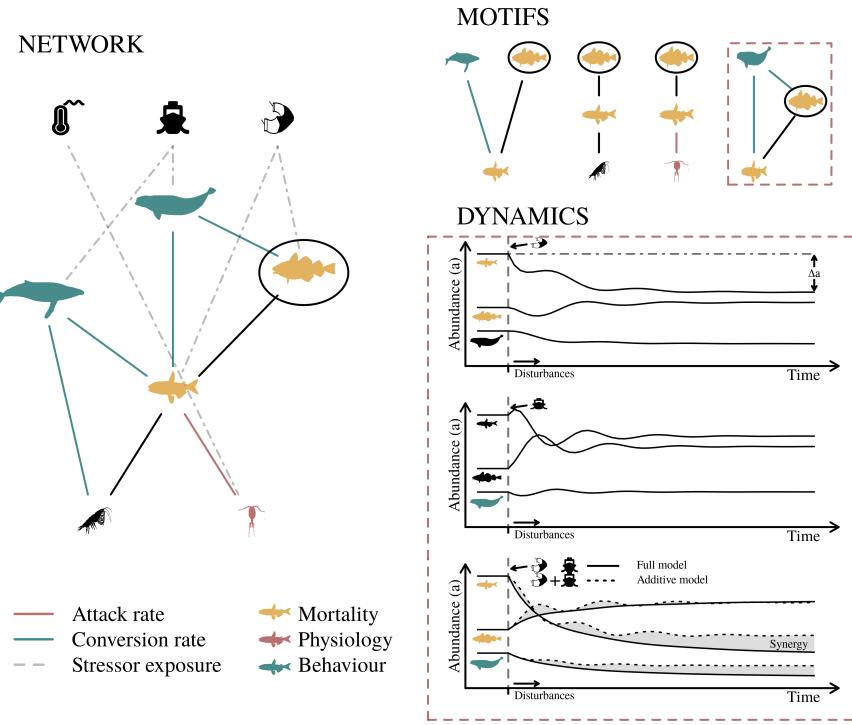


Figure 2: Conceptualize the effects of multiple disturbances on food webs

- 332 – Species can occupy different roles in these pathways of multiple effects. Inves-
- 333 tigating species profile (e.g.* Stouffer *et al.* 2012) could thus inform us on the
- 334 role played by individual species in buffering against or amplifying the effects of
- 335 multiple disturbances.
- 336 – We define 4 key roles in species propagating or buffering against multiple distur-
- 337 bances:

³³⁸ **5 Methodology**

³³⁹ **5.1 Models**

³⁴⁰ The dynamics of the four most abundant 3-species motifs (*i.e.* tri-trophic food chain, om-
³⁴¹ nivory, exploitative and apparent competition) in empirical food webs (Stouffer & Bascompte
³⁴² 2010) were modeled using Lotka-Volterra equation systems (Table S1). Two additional motifs
³⁴³ were included to serve as controls to test the importance of considering species interactions
³⁴⁴ when evaluating environmental effects, *i.e.* a partially connected motif with a disconnected
³⁴⁵ species and a predator-prey interaction, and a fully disconnected motif with three indepen-
³⁴⁶ dent species.

³⁴⁷ Resources were modeled using logistic growth equations of the form $\frac{dX_i}{dt} = X_i(r_i - \alpha_{ii}X_i -$
³⁴⁸ $\sum \alpha_{ij}X_j)$, where X are species, i is the resource, j are the consumers, r_i is the intrinsic
³⁴⁹ resource growth rate, α_{ii} is the density-dependent effect of the resource on itself and α_{ij} is
³⁵⁰ the rate at which consumer j affects resource i , *i.e.* the attack rate.

³⁵¹ Consumers were modeled using a Type I functional response of the form $\frac{dX_j}{dt} = X_j(-m_j +$
³⁵² $\sum e_{ij}\alpha_{ij}X_i - \alpha_{jk}X_k)$, where m is the mortality rate and e is the rate at which resource biomass
³⁵³ is transformed into consumer biomass, *i.e.* the conversion rate, and is a scaling parameter
³⁵⁴ of the attack rate which cannot exceed 1.

³⁵⁵ Models were solved at equilibrium to study the effects of disturbances on persistent motif dy-
³⁵⁶ namics. As no equilibrium exists for the exploitative competition motif with Lotka-Volterra
³⁵⁷ models of the selected forms, competitive parameters of the form $\alpha_{jj}\alpha_{jk}X_jX_k - \alpha_{jj}X_j^2$ were
³⁵⁸ included in the consumer models to constrain their growth.

³⁵⁹ **5.2 Disturbances**

³⁶⁰ For each motif, a 1% change in initial equilibria equations parameter values was applied
³⁶¹ to simulate negative disturbances through all possible unique pathways of univariate and
³⁶² multivariate effects. Parameters selected to simulate disturbances were those related to
³⁶³ population growth (r and m) and interaction rates (e and α_{ij}), as their effects on population
³⁶⁴ dynamics can readily be attributed to environmental pressure effects. For example, cod
³⁶⁵ mortality will increase through fishing activities, whale attack rates on krill will be altered
³⁶⁶ by behavioural changes induced by marine traffic, and conversion rates of copepods by capelin
³⁶⁷ will be reduced through physiological effects of temperature anomalies on copepods.

³⁶⁸ Initial parameter values for intrinsic growth (r) and resource density-dependence (α_{ii}) were
³⁶⁹ fixed to 1 and 0.001, respectively, to bound all resource solutions. Competitive parameters
³⁷⁰ for the exploitative competition motif were also fixed at 0.001 since those parameters were
³⁷¹ not to be investigated in our analyses. Conversion rates (e) were fixed to 0.5. Finally, a
³⁷² total of 100 sets of mortality (m) and attack rates (α_{ij}) were evaluated using a simulated
³⁷³ annealing algorithm optimizing for consumer abundance.

³⁷⁴ **5.3 Trophic sensitivity**

³⁷⁵ For each 13 unique motif positions considered and all unique pathways of effects, the variation
³⁷⁶ in abundance between the 100 sets of initial conditions and disturbed conditions was used
³⁷⁷ as a proxy of trophic sensitivity ($s_{i,j}$) to disturbances:

$$s_{i,j} = \frac{a_{i,j} - a_i}{a_i}$$

³⁷⁸ where i is a motif position, j is a unique pathway of effect, a_i is the initial abundance at
³⁷⁹ position i , and $a_{i,j}$ is the abundance at position i after the simulation of the pathway of effect
³⁸⁰ j . Sensitivity scores are bounded negatively to -1, as abundances cannot fall below 0. The
³⁸¹ sensitivity score used for a single pathway of effect ($S_{i,j}$) is the mean of the 100 simulation
³⁸² using all initial conditions:

$$S_{i,j} = \frac{1}{n} \sum_{l=1}^n s_{i,j}$$

³⁸³ We define *weak entry pathways* and *sink pathways* as those pathways whose effect on the
³⁸⁴ abundance of a motif position exceeds 1% ($S_{i,j} < -1\%$ or $S_{i,j} > 1\%$) and is null (*i.e.*
³⁸⁵ $S_{i,j} = 0$), respectively (2).

³⁸⁶ A score of position sensitivity (S_i) was evaluated using the mean of the set of all possible
³⁸⁷ pathways of effect (K^i) for a give position i :

$$S_i = \frac{1}{|K^i|} \sum_{j \in K^i} S_{i,j}$$

³⁸⁸ We define *weak entry points* and *biotic sinks* as positions whose sensitivity score is signifi-
³⁸⁹ cantly different than 1% ($S_i < -1\%$ or $S_i > 1\%$) and is null ($S_i = 0$), respectively.

³⁹⁰ **5.4 Trophic amplification**

³⁹¹ To evaluate whether the effects of disturbances should be investigated in combination, a
³⁹² score of trophic amplification was evaluated to

³⁹³ A score of trophic amplification ($A_{i,j}$) was measured to evaluate the potential of pathways
³⁹⁴ of effects to result in non-additive effects:

$$A_{i,j} = S_{i,K_j} - \sum_{k_j \in K_j} S_{i,j}$$

³⁹⁵ where K_j is a multivariate pathway of effect j and k_j are unitary pathways of effect compo-
³⁹⁶ nition j . The amplification score evaluates the deviance of a multivariate pathway of effect
³⁹⁷ and the sum of the univariate effects composing the pathway of effect, *i.e.* the additive

³⁹⁸ model. Thus, a value of 0 identifies a null of additive effect, a value below 0 identifies an
³⁹⁹ antagonistic effect, and a value over 0 identifies synergistic effects.

⁴⁰⁰ We define *antagonistic pathways* and *synergistic pathways* as those pathways whose effect on
⁴⁰¹ the abundance of a motif position is significantly different than the additive model, while
⁴⁰² *additive pathways* are those pathways whose effect is not significantly different than the
⁴⁰³ additive model (2).

⁴⁰⁴ A score of position amplification (A_i) was evaluated using the mean of the set of all possible
⁴⁰⁵ pathways of effect (K^i) for a give position i :

$$A_i = \frac{1}{|K^i|} \sum_{j \in K^i} A_{i,j}$$

⁴⁰⁶ We define *biotic buffers* and *biotic multipliers* as positions whose amplification score is sig-
⁴⁰⁷ nificantly different than 0, while *biotic invariants* are positions whose amplification score is
⁴⁰⁸ not significantly different than 0 (2).

⁴⁰⁹ 5.5 Species sensitivity and amplification

⁴¹⁰ We define two sets of scores at the species level. The first requires no information on realised
⁴¹¹ pathways of effect and provides a general evaluation of a species sensitivity and amplification
⁴¹² potential based on the frequency of times it occupies a position in a food web:

$$S_m = \sum_i f_{mi} S_i$$

$$A_m = \sum_i f_{mi} A_i$$

⁴¹³ where S_m and A_m are the sensitivity and amplification scores of species m , respectively, f_{mi}
⁴¹⁴ is the frequency at which species m occupies position i in a food web, and S_i and A_i are the
⁴¹⁵ sensitivity amplification scores at position i , respectively.

⁴¹⁶ The second set of scores at the species level uses a list of realised pathways of effect:

$$S_m = \sum_{j \in K^{i*}}^{position} S_{i,j}$$

$$A_m = \sum_{j \in K^{i*}}^{position} A_{i,j}$$

⁴¹⁷ where S_m and A_m are the sensitivity and amplification scores of species m , respectively, j
⁴¹⁸ are pathways of effect, K^{i*} is the set of realised pathways of effects for position i , and $S_{i,j}$
⁴¹⁹ and $A_{i,j}$ are the sensitivity and amplification scores for pathway of effect j on position i

⁴²⁰ **5.6 Empirical food webs**

⁴²¹ We used empirical food web data from the Estuary and Gulf of St. Lawrence, in eastern
⁴²² Canada, to evaluate the sensitivity and amplification scores of its constituent species. The
⁴²³ food webs come from different regions of the St. Lawrence and different time periods, and
⁴²⁴ contain different yet overlapping functional groups. The Northern (???) and Southern (???)
⁴²⁵ St. Lawrence food webs were for the mid-1980s, prior to the groundfish stock collapses of
⁴²⁶ the early 1990s, and contain the same functional groups. The Estuary food web, mean-
⁴²⁷ while, contains more functional groups and represents the beginning of the 2010s (???). See
⁴²⁸ supplementary materials for a description of the food webs used for this analysis.

6 Results

6.1 Disturbances

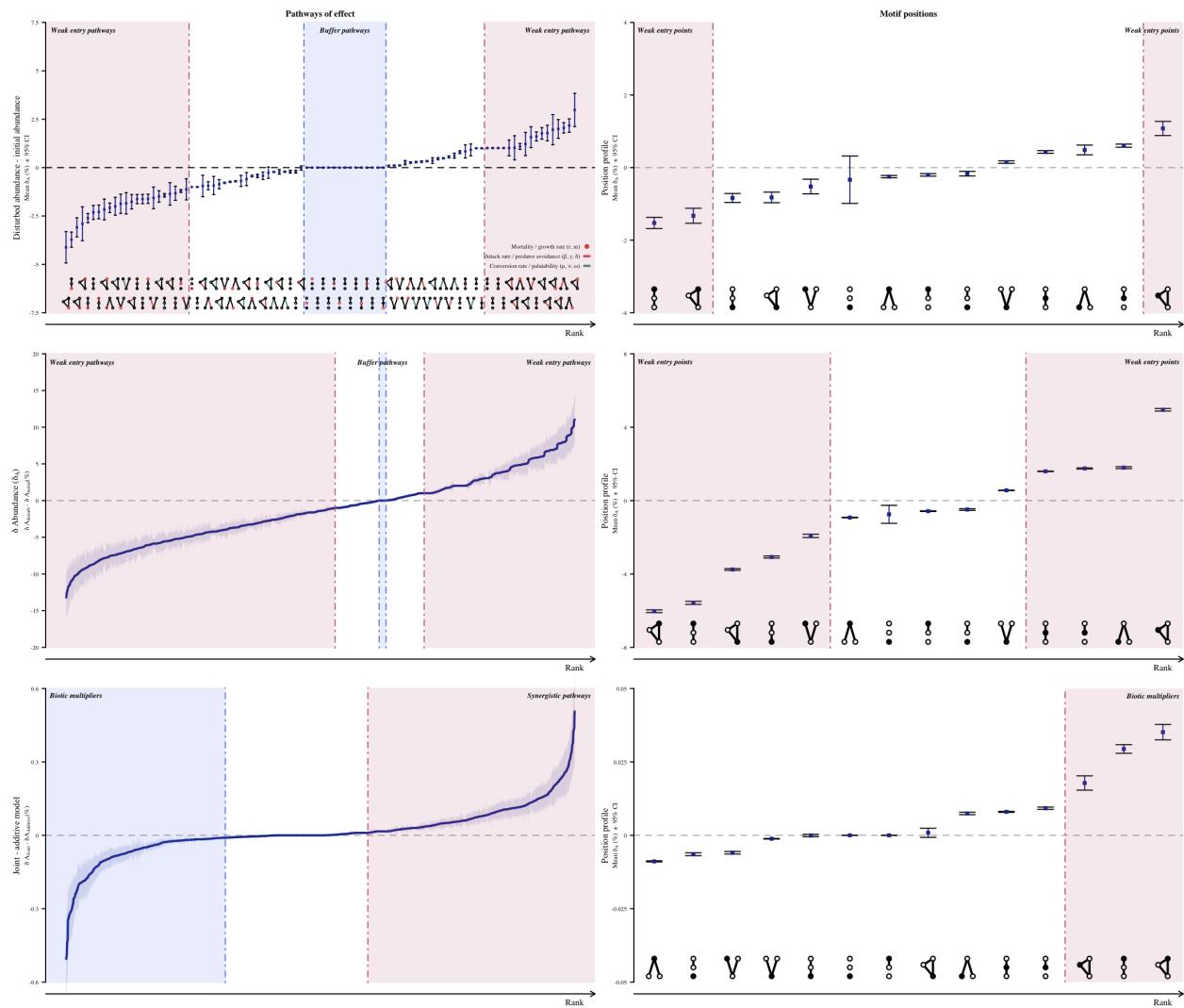


Figure 3: Disturbances. Line 1: Univariate disturbances; Line 2: Multivariate disturbances; Line 3: Joint - additive disturbances

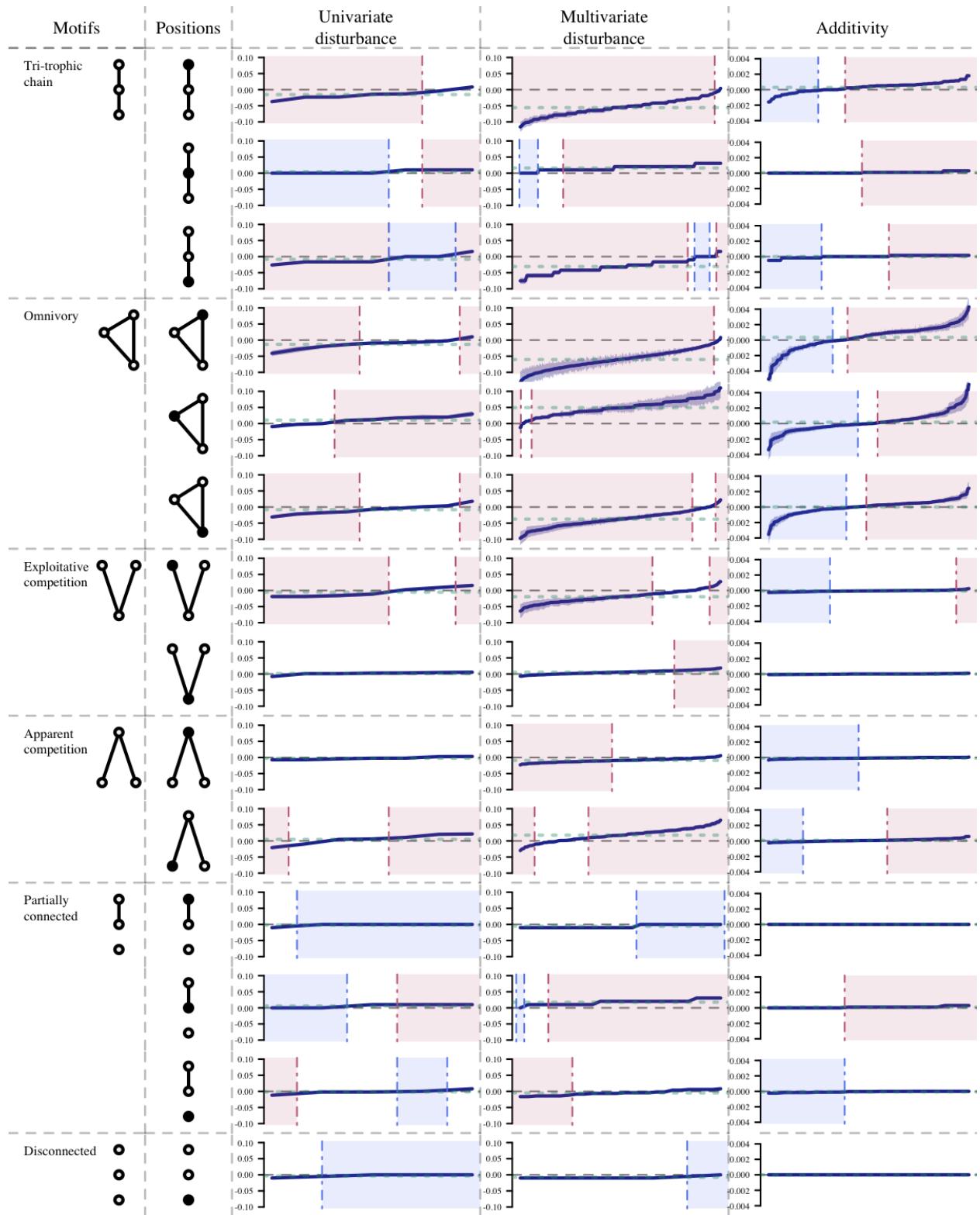


Figure 4: Morif positions and disturbances

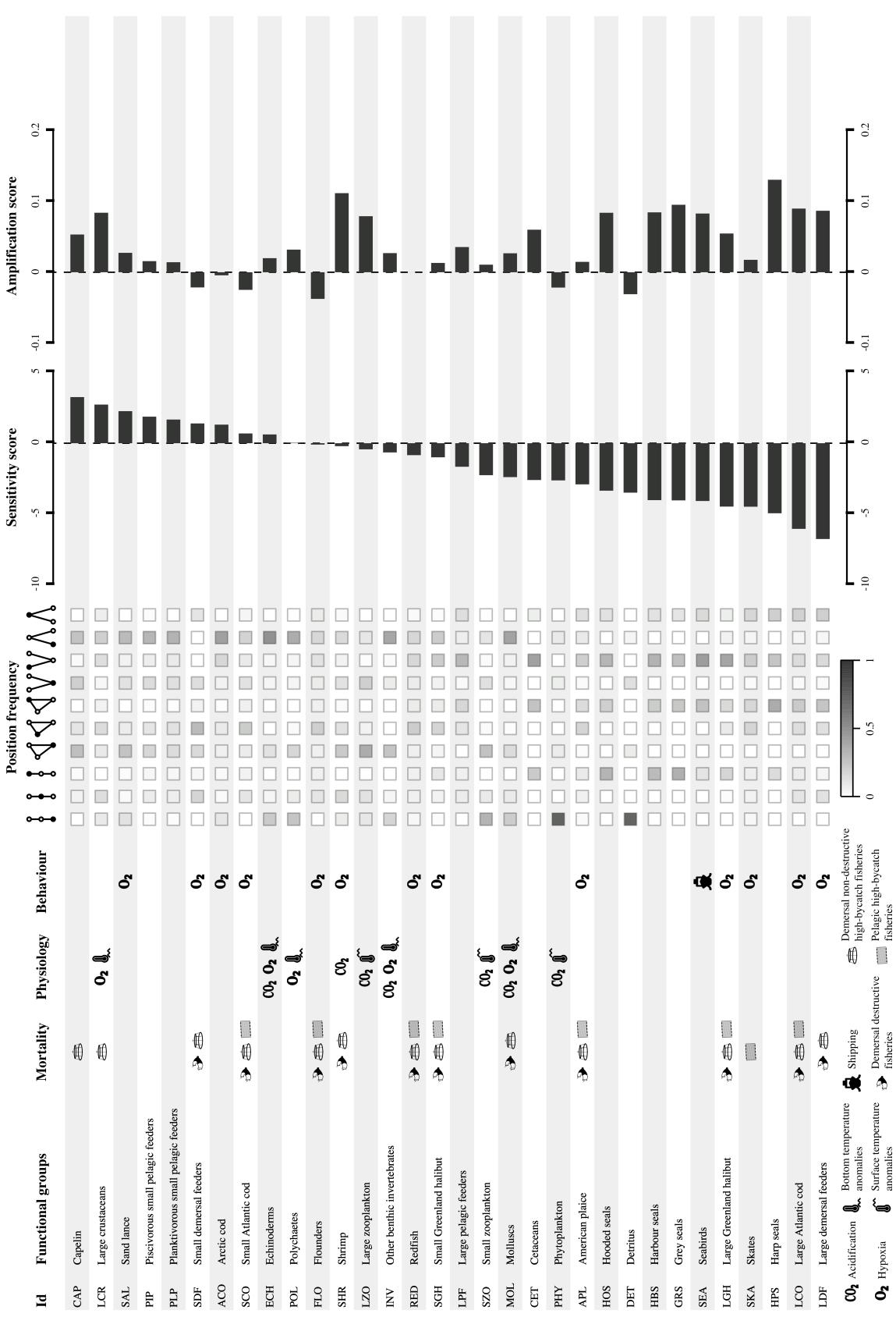


Figure 5: Species scores for the St. Lawrence

431 7 Supplementary Figures

432 7.1 Simulation figures

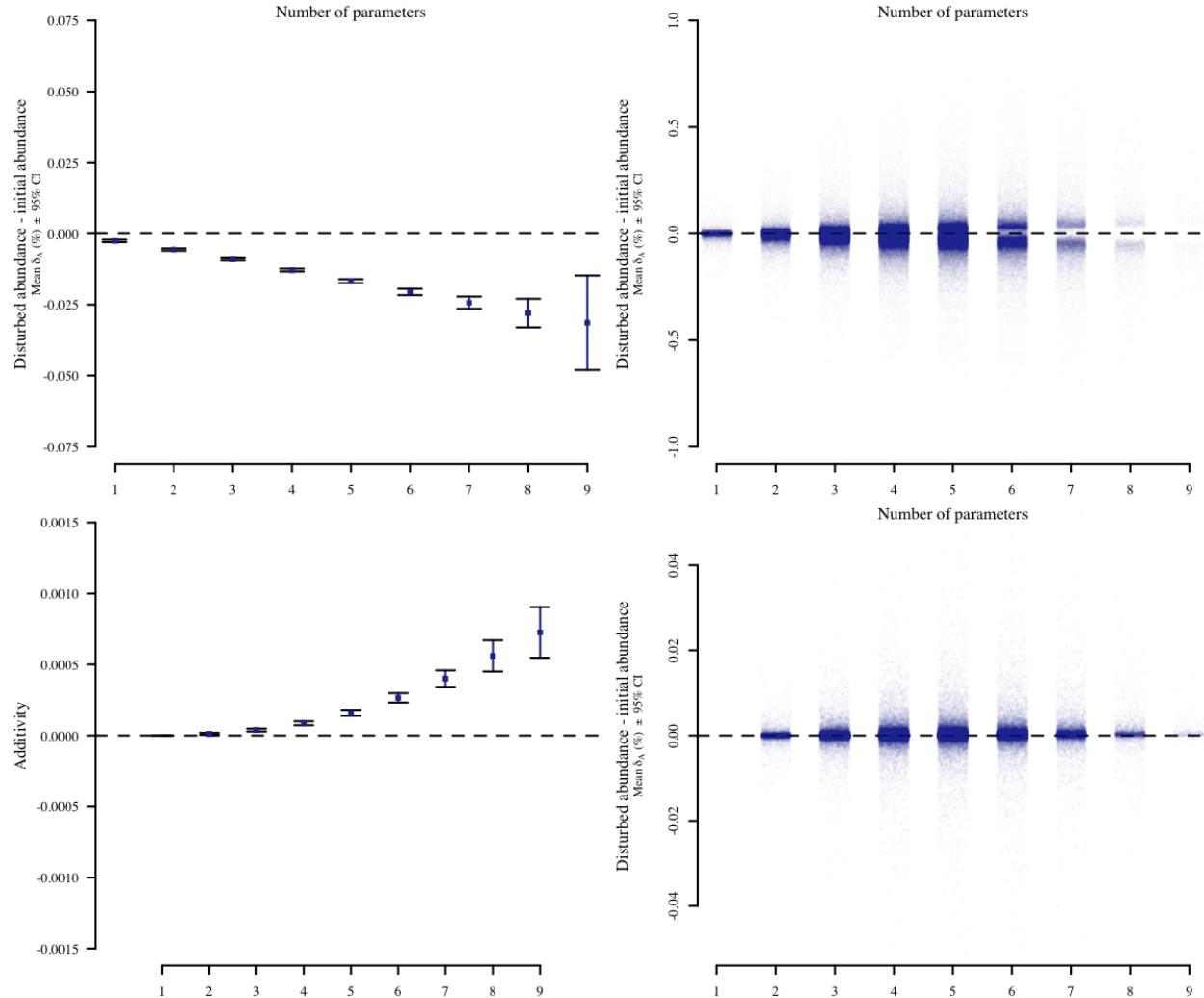


Figure 6: Mean delta abundance and difference between joint and additive models as a function of the number of parameters

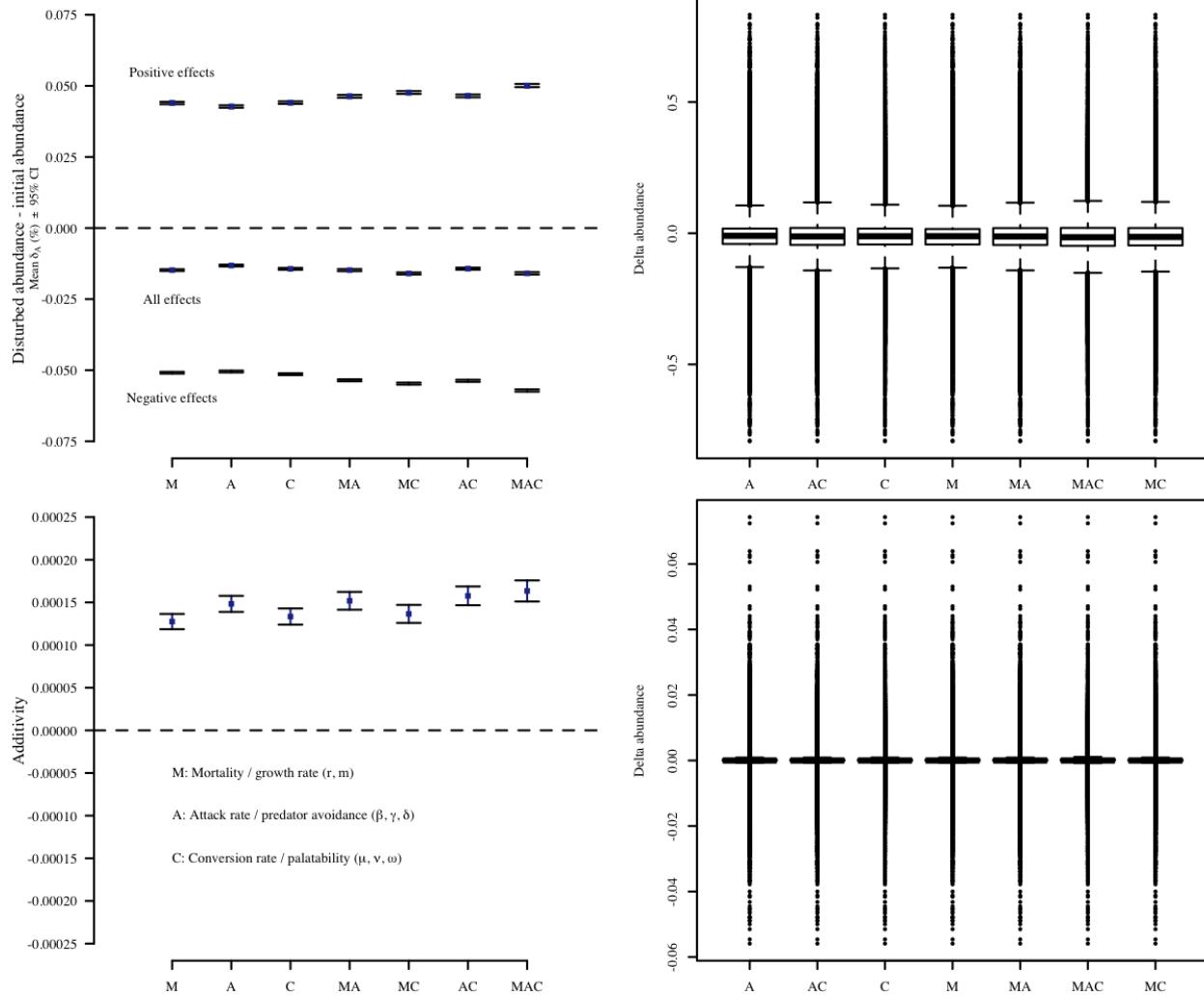


Figure 7: Mean delta abundance and difference between joint and additive models as a function of the types of parameters, i.e. growth/mortality rates, attack rates and conversion rates

433 7.2 Species position frequency

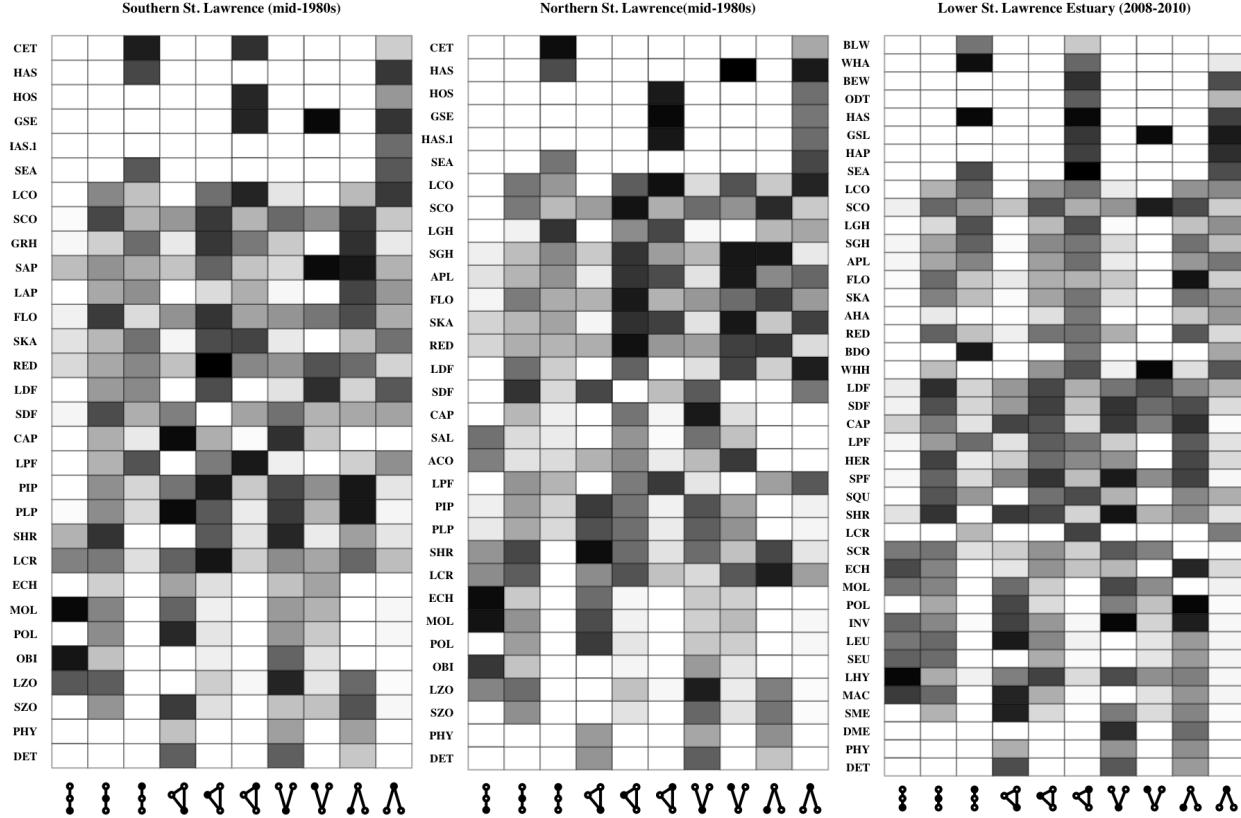


Figure 8: Frequency in which each species of three empirical food webs are found in each motif position.

434 7.3 Food web sensitivity and amplification scores

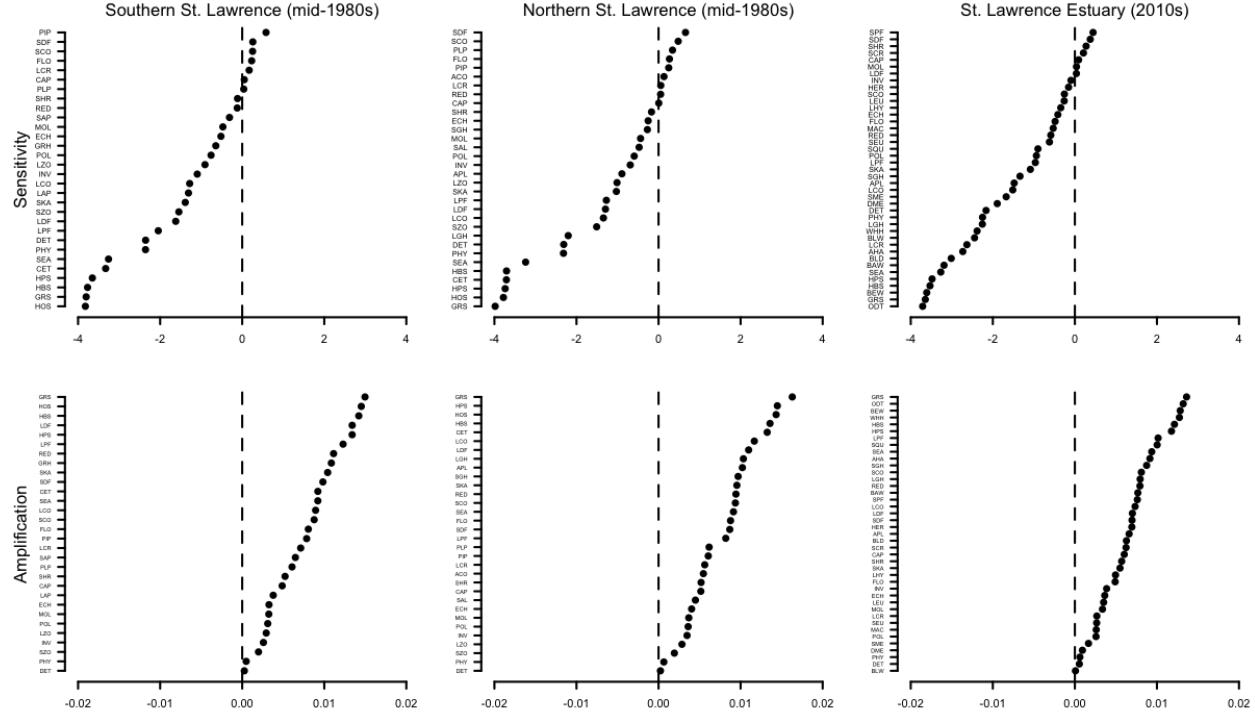


Figure 9: Sensitivity scores for species in the food webs of the southern St. Lawrence, northern St. Lawrence, and the estuary of St. Lawrence

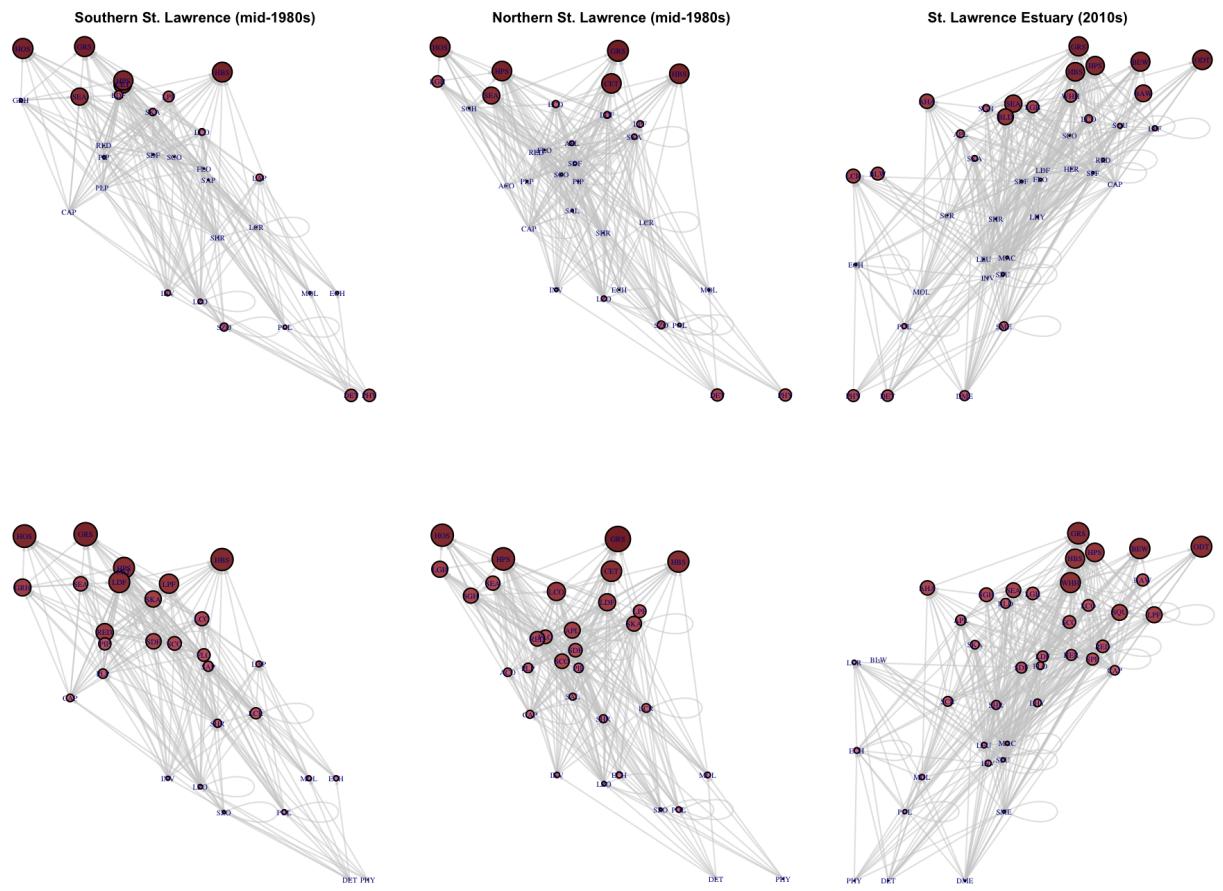


Figure 10: Sensitivity scores for species in the food webs of the southern St. Lawrence, northern St. Lawrence, and the estuary of St. Lawrence

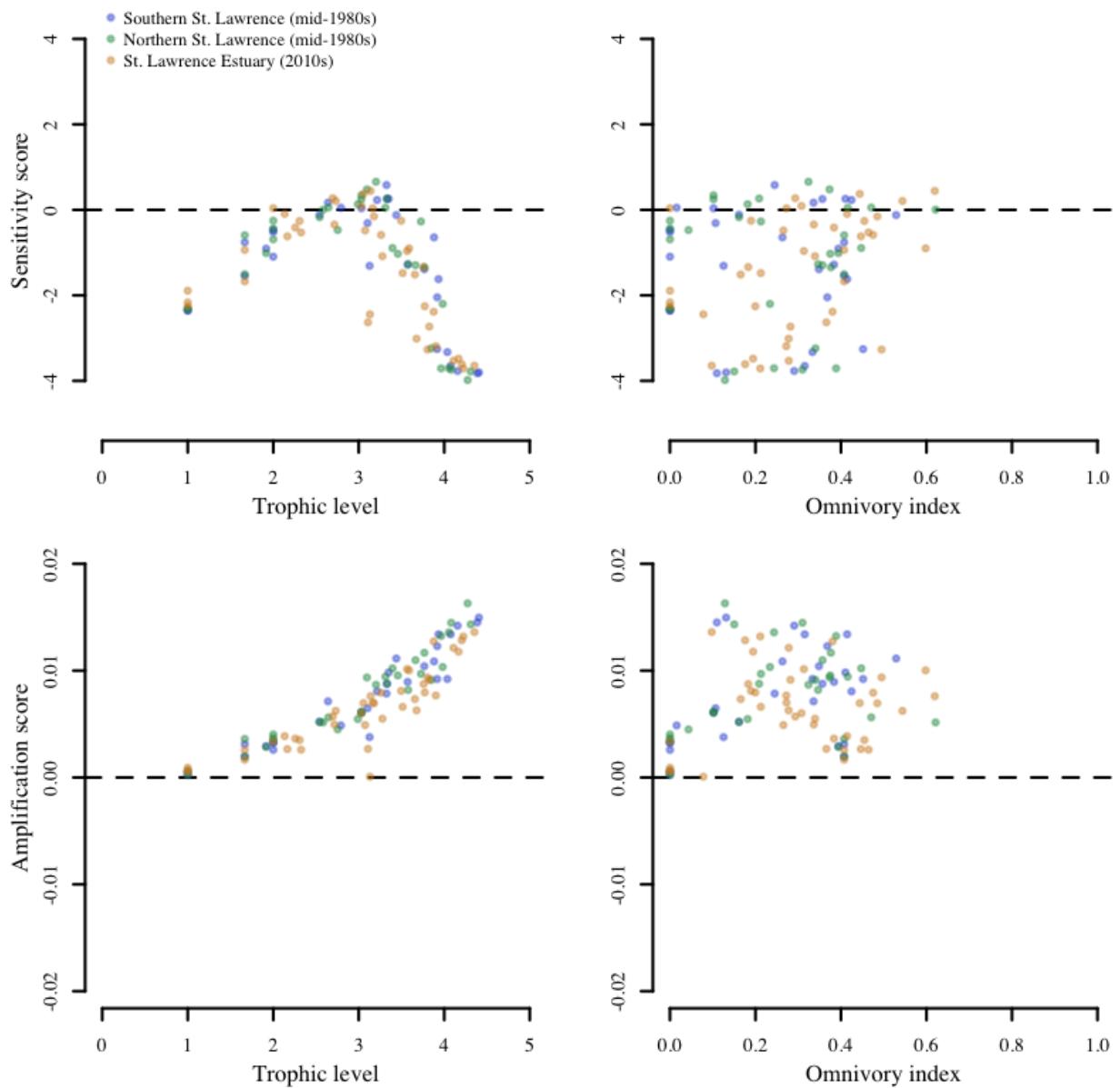


Figure 11: Sensitivity scores as a function of trophic level and omnivory index

7.4 Realised food web sensitivity and amplification scores

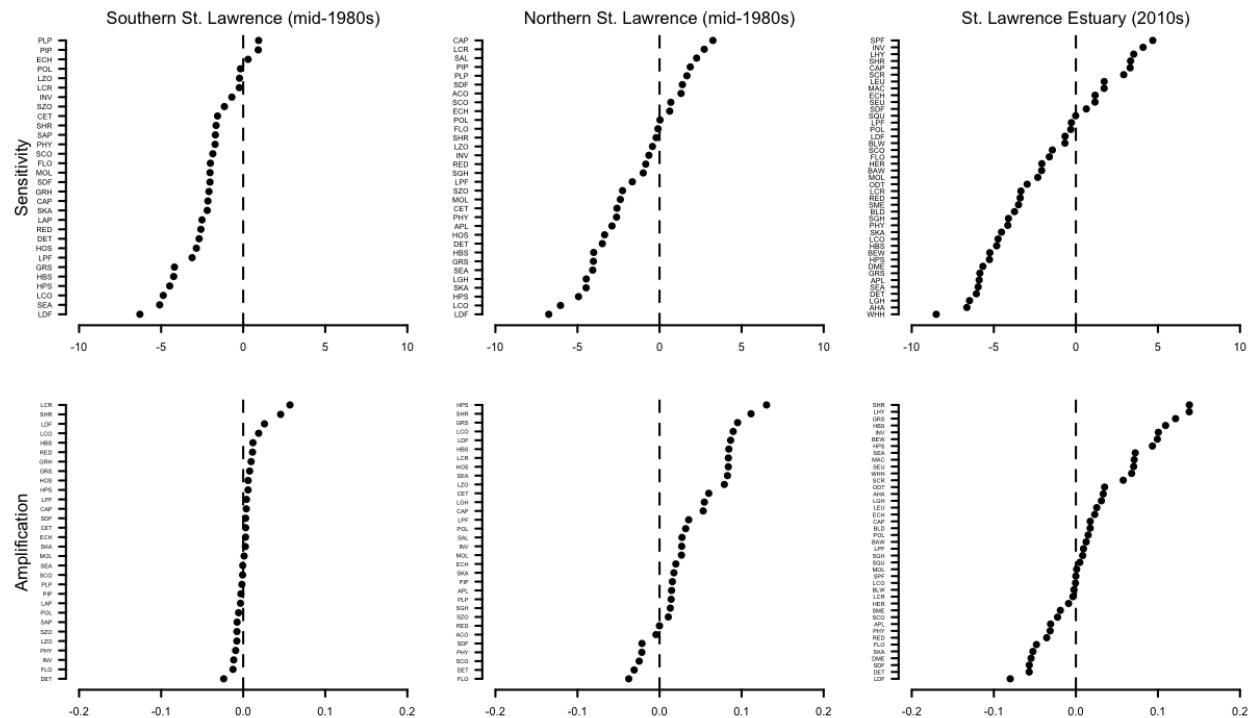


Figure 12: Impact scores for species in the food webs of the southern St. Lawrence, northern St. Lawrence, and the estuary of St. Lawrence

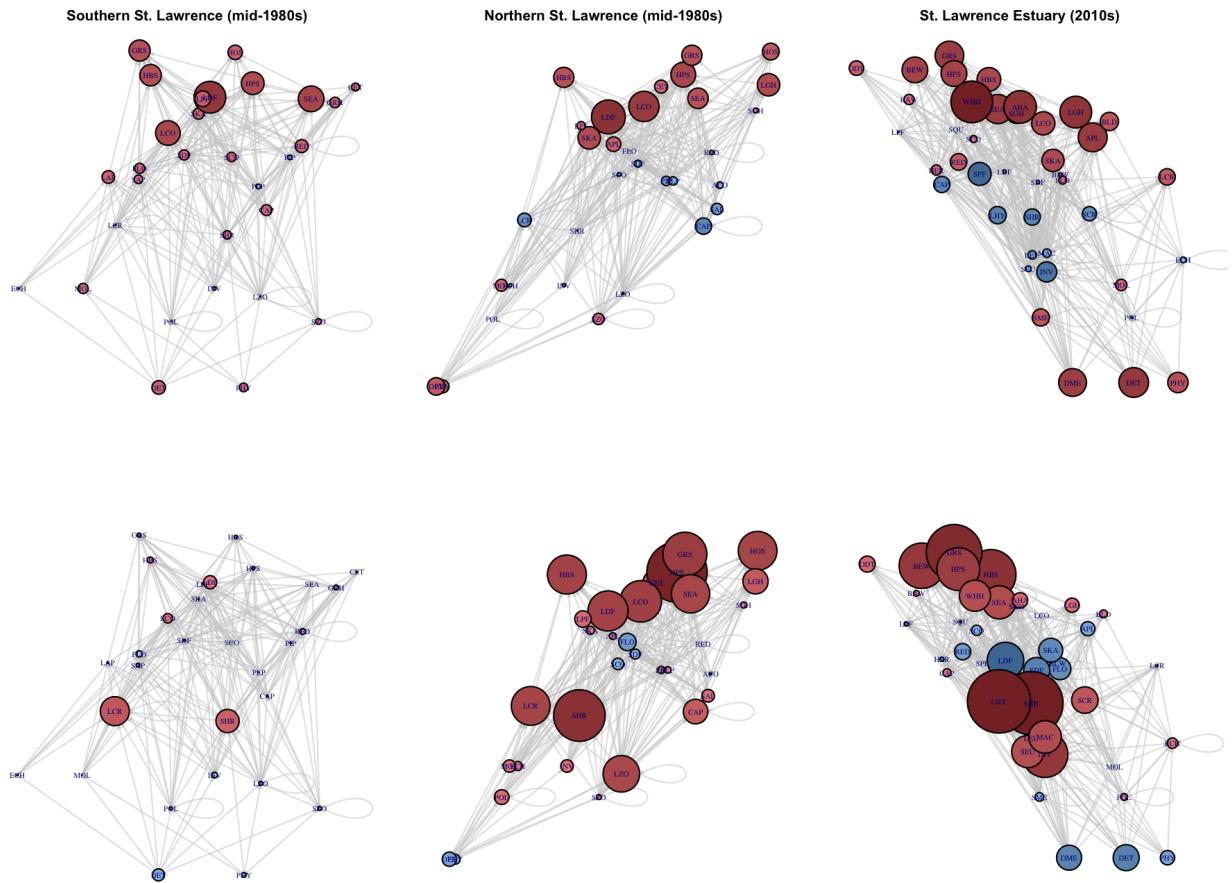


Figure 13: Sensitivity scores for species in the food webs of the southern St. Lawrence, northern St. Lawrence, and the estuary of St. Lawrence

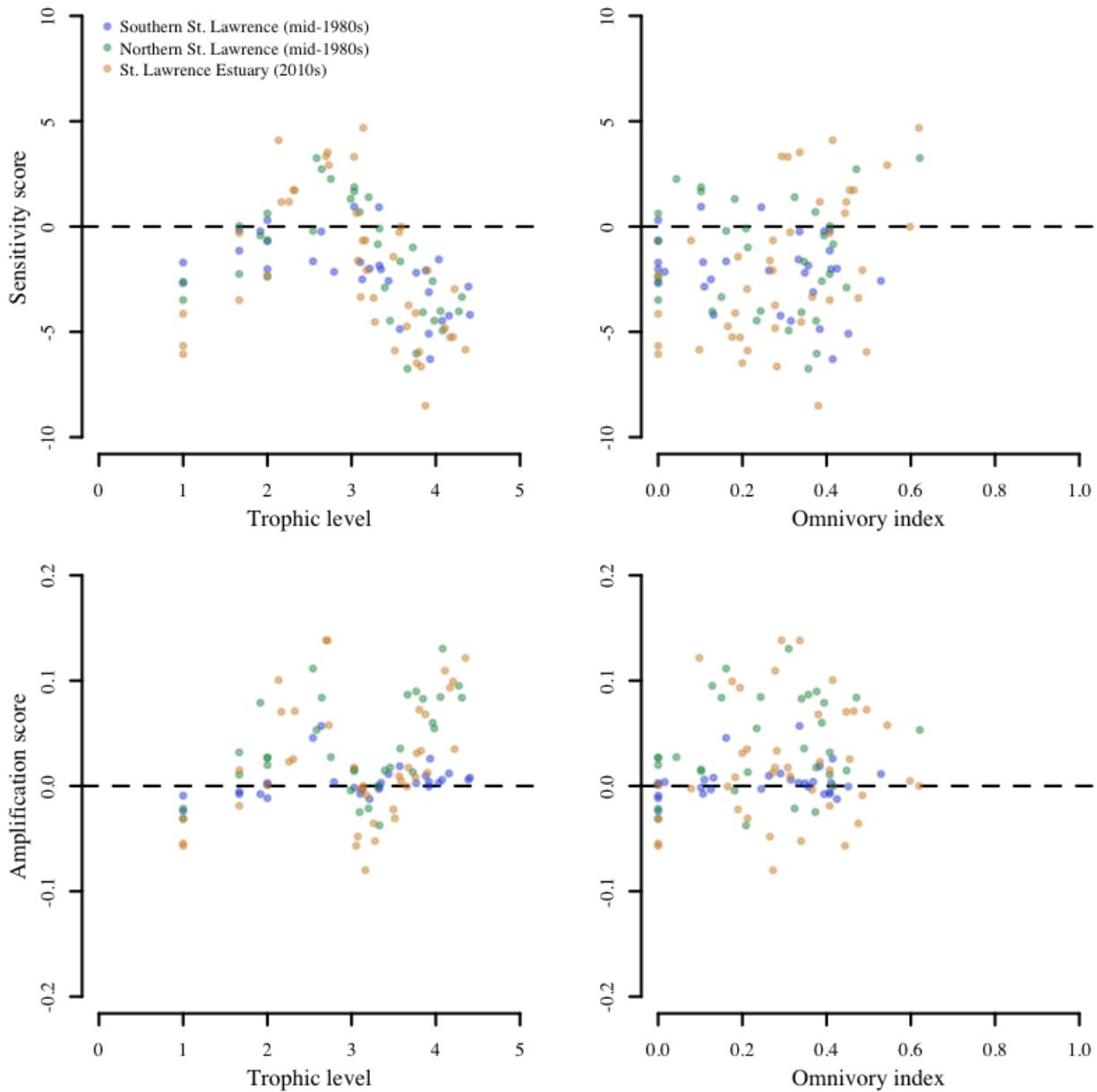


Figure 14: Impact scores as a function of trophic level and omnivory index

436 8 Supplementary Material

437 8.1 Models

Motifs	Equation systems	Initial parameters values
Tri-trophic food chain	$\frac{dX_i}{dt} = X_i(r_i - \alpha_{ii}X_i - \alpha_{ij}X_j)$ $\frac{dX_j}{dt} = X_j(e_{ij}\alpha_{ij}X_i - \alpha_{jk}X_k - m_j)$ $\frac{dX_k}{dt} = X_k(e_{jk}\alpha_{jk}X_j - m_k)$	$r_i = 1$ $\alpha_{ii} = 0.001$ $\alpha_{ij}, \alpha_{jk} \in [0.0001, 0.01]$ $e_{ij}, e_{jk} = 0.5$ $m_j, m_k \in [0.01, 0.5]$
Omnivory	$\frac{dX_i}{dt} = X_i(r_i - \alpha_{ii} - \alpha_{ij}X_j - \alpha_{ik}X_k)$ $\frac{dX_j}{dt} = X_j(e_{ij}\alpha_{ij}X_i - \alpha_{jk}X_k - m_j)$ $\frac{dX_k}{dt} = X_k(e_{ik}\alpha_{ik}X_i + e_{jk}\alpha_{jk}X_j - m_k)$	$r_i = 1$ $\alpha_{ii} = 0.001$ $\alpha_{ij}, \alpha_{ik}, \alpha_{jk} \in [0.0001, 0.01]$ $e_{ij}, e_{ik}, e_{jk} = 0.5$ $m_j, m_k \in [0.01, 0.5]$
Exploitative competition	$\frac{dX_i}{dt} = X_i(r_i - \alpha_{ii} - \alpha_{ij}X_j - \alpha_{ik}X_k)$ $\frac{dX_j}{dt} = X_j(e_{ij}\alpha_{ij}X_i - \alpha_{jj}\alpha_{jk}X_k - \alpha_{jj}X_j - m_j)$ $\frac{dX_k}{dt} = X_k(e_{ik}\alpha_{ik}X_i - \alpha_{kk}\alpha_{kj}X_j - \alpha_{kk}X_k - m_k)$	$r_i = 1$ $\alpha_{ii}, \alpha_{jj}, \alpha_{kk}, \alpha_{jk}, \alpha_{kj} = 0.001$ $\alpha_{ij}, \alpha_{ik}, \in [0.0001, 0.01]$ $e_{ij}, e_{ik} = 0.5$ $m_j, m_k \in [0.01, 0.5]$
Apparent competition	$\frac{dX_i}{dt} = X_i(r_i - \alpha_{ii}X_i - \alpha_{ik}X_k)$ $\frac{dX_j}{dt} = X_j(r_j - \alpha_{jj}X_j - \alpha_{jk}X_k)$ $\frac{dX_k}{dt} = X_k(e_{ik}\alpha_{ik}X_i + e_{jk}\alpha_{jk}X_j - m_k)$	$r_i, r_j = 1$ $\alpha_{ii}, \alpha_{jj} = 0.001$ $\alpha_{ik}, \alpha_{jk} \in [0.0001, 0.01]$ $e_{ik}, e_{jk} = 0.5$ $m_k \in [0.01, 0.5]$
Partially disconnected	$\frac{dX_i}{dt} = X_i(r_i - \alpha_{ii}X_i - \alpha_{ik}X_k)$ $\frac{dX_j}{dt} = X_j(r_j - \alpha_{jj}X_j)$ $\frac{dX_k}{dt} = X_k(e_{ik}\alpha_{ik}X_i - m_k)$	$r_i, r_j = 1$ $\alpha_{ii}, \alpha_{jj} = 0.001$ $\alpha_{ik} \in [0.0001, 0.01]$ $e_{ik} = 0.5$ $m_k \in [0.01, 0.5]$
Disconnected	$\frac{dX_i}{dt} = X_i(r_i - \alpha_{ii}X_i)$ $\frac{dX_j}{dt} = X_j(r_j - \alpha_{jj}X_j)$ $\frac{dX_k}{dt} = X_k(r_k - \alpha_{kk}X_k)$	$r_i, r_j, r_k = 1$ $\alpha_{ii}, \alpha_{jj}, \alpha_{kk} = 0.001$

Table 1: Systems of Lotka-Volterra equations used to model the effect of multiple disturbances

438 **9 Next points**

- 439 • Non-linear effects in motifs
440 • Species contribution to non-linear effects
441 • Species profiles (frequency of times occupying roles that contribute to non-linear effects;
442 see Stouffer *et al.* (2012))
443 • Graphs to present these results
444 • Methods

445 **10 Notes - to explore**

- 446 • With synergies, one should expect higher rates of community collapse, i.e. loss of
447 species to extinction, because the effects increase more rapidly. Maybe look at Stouffer
448 to better dissect their result on community persistence as a function of motifs. Perhaps
449 they also explain which are the motif positions that tend to go extinct more rapidly?

450 **11 Interesting points**

- 451 • Effect limit (Schäfer & Piggott 2018): maximum effect size for a response (*e.g.* 100%
452 mortality, zero growth or reproduction)

453 **12 Literature to cite - or at least look at!**

- 454 • Adams (2005)
455 • Brown *et al.* (2013)
456 • Brown *et al.* (2014)
457 • Christensen *et al.* (2006)
458 • Crain *et al.* (2008)
459 • Darling *et al.* (2013)
460 • Folt *et al.* (1999)
461 • Galic *et al.* (2018) *
462 • Jackson *et al.* (2016)
463 • Kath *et al.* (2018)
464 • Lange *et al.* (2018)
465 • Piggott *et al.* (2015)
466 • Schäfer & Piggott (2018) *
467 • Segner *et al.* (2014)
468 • Thompson *et al.* (2018a)
469 • Thompson *et al.* (2018b)
470 • Vinebrooke *et al.* (2004)

471 **13 References**

472 **14 Ecology Letters formatting and submission**

473 **14.1 Latex files**

474 **Instructions:** *Ecology Letters does not have a standard LaTex style file. Manuscripts sub-*
475 *mitted using LaTeX should be accompanied by a PDF version of the paper. Upon final accep-*
476 *tance for publication, authors will be requested to send their LaTeX source files accompanied*
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478 *the manuscript preparation.*

479 **14.2 Formatting**

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 - 492 – Footnotes to tables hsould be identified by the symbols * † ‡ § ¶ (in that order)
 - 493 – and placed at the bottom of the table.
 - 494 – No vertical rules should be used
- 495 • Figures
 - 496 – Cited consecutively in the text
 - 497 – Numbered with Arabic numerals
 - 498 – Grouped together at the end od the paper or in a separate file
 - 499 – Titles and typed double-spaced on a separate sheet
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 - 503 – separately as pixel-based graphics at 600 dpi at the required print size, and they
 - 504 – should be saved in TIFF (not jpg) format or embedded as such in Word.

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- 515 – Text boxes may be used for standalone definitions, equations, necessary explana-
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524 nal. Text boxes should be cited consecutively using Arabic numerals (e.g., Box
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547 are supported, but if submitting in this format authors should also provide an
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642 and amplification score data?

643 Adams, S.M. (2005). Assessing cause and effect of multiple stressors on marine systems.
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