New insights into the Weddell Sea ecosystem applying a network approach

Tomás I. Marina[1,*], Leonardo A. Saravia[1,*], and Susanne Kortsch[2]

[1]Centro Austral de Investigaciones Científicas (CADIC-CONICET), Ushuaia, Argentina
[2]University of Helsinki, Helsinki, Finland
[*]These authors contributed equally to this work.

Correspondence: Tomás I. Marina (tomasimarina@gmail.com) and Leonardo A. Saravia (arysar@gmail.com)

Abstract. The abstract goes here. It can also be on *multiple lines*.

1 Introduction

Introduction text goes here.

The objective of this work was twofold: 1) estimate the strength for each interaction in the Weddell Sea food web, and 2) determine key trophic species considering weighted and unweighted properties and the influence on the stability of the network.

2 Methodology

2.1 Study area

The high Antarctic Weddell Sea shelf is situated between 74 and 78ºS with a length of approximately 450 km (Figure 1). Water depth varies from 200 to 500 m. Shallower areas are covered by continental ice, which forms the coastline along the eastern and southern part of the Weddell Sea. The shelf area contains a complex three-dimensional habitat with large biomass, intermediate to high diversity in comparison to benthic boreal communities and a spatially patchy distribution of organisms (Dayton, 1990; Teixidó et al., 2002).

2.2 Weddell Sea food web dataset

We obtained the dataset of the Weddell Sea food web from the GlobAL daTabasE of traits and food Web Architecture (GATEWAy, version 1.0) of the German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig (Brose, 2018). This open access database is a list of predator-prey interactions that contains several highly-resolved food webs, including biological data about the consumer and resource species involved in each trophic interaction (i.e. mean mass). Furthermore, it incorporates information on the interaction itself, such as the dimensionality.

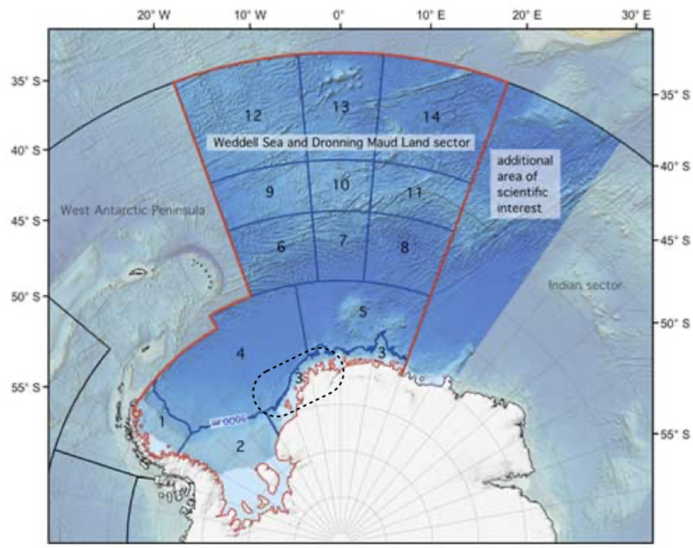

Figure 1. Map of the Weddell Sea and Dronning Maud Land sector highlighting the high Antarctic shelf as a dashed-line contour. Modified from www.soos.aq.

This marine food web compiles all the food web data available for the high Antarctic Weddell Sea collected since 1983, and is one of the most highly-resolved marine food webs documented to date. It's noteworthy that it is a summary network that ignores seasonal changes (Jacob et al., 2011).

2.3 Dataset analyses

We analysed the food web of the Weddell Sea by: a) estimating the strength of each interaction; b) studying the properties of the species in a network approach; and c) comparing the stability of the food web after performing extinction simulations.

2.3.1 Interaction strength estimation and distribution

To estimate the strength of each interaction in the food web, we followed the methodology proposed by Pawar et al. (2012). The minimum data requirements are: body mass of the consumer (predator) and resource (prey), and the interaction dimensionality classified as 2 or 3 dimensions. GATEWAy v.1.0 does provide information on the mean mass for consumers and resources (except for 'detritus' and 'sediment') for every interaction, but lacks the dimensionality for 924 interactions. To solve this issue, we used the information about movement type for consumer and resource. Then, we classified the interaction as 2D when both consumer and resource move in 2D (e.g., both are sessile or walking) or if a consumer moves in 3D and a resource in 2D (e.g., swimming consumer and sessile/walking resource). The interaction was classified as 3D when both consumer and resource move in 3D (e.g., both swimming) or if the consumer moves in 2D and resource in 3D (e.g., sessile/walking consumer, swimming resource) (Pawar et al., 2012).

The main equation we used for estimating the interaction strength IS is:

$$IS = \alpha x_R \frac{m_R}{m_C} \tag{1}$$

where α is the search rate, x_R is the density of the resource, and m_R and m_C are the body mass of the resource and the consumer, respectively (Pawar et al., 2012).

We obtained estimations for the resource density and the search rate from the scaling relationships with the resource and the consumer mass, respectively (Pawar et al. (2012)). The coefficients of such relationships, determined by ordinary least squares regression, vary with the interaction dimensionality. On one hand, resource density scales with resource mass as a power-law with exponents $p = -0.79 \pm 0.09$ in 2D and $p = -0.86 \pm 0.06$ in 3D. Since mean mass for resources 'detritus' and 'sediment' were not available in GATEWAy v.1.0, we calculated it considering the scaling relationship with consumer mass, also different in 2D and 3D (for details see equation S9 and figures 2c-d of Supplementary Information in Pawar et al. (2012)). On the other hand, search rate scales with consumer mass as a power-law with exponents $p = 0.68 \pm 0.12$ in 2D and $p = 1.05 \pm 0.08$ in 3D.

Finally, we fit the distribution of the interaction strengths of the food web considering six candidate models (Uniform, Normal, Exponential, Power-law, log-Normal and Gamma) using maximum likelihood (**?**), and selected the model performance by computing the Akaike Information Criterion (**?**).

2.3.2 Species properties

In order to individually characterize the species of the food web, we considered weighted and unweighted properties (Figure 2). The former is based on the estimation of the interaction strength described in the previous section. The latter is related to properties commonly used in qualitative (presence/absence of interaction) food web studies (Martinez, 1991; Dunne et al., 2002; Borrelli and Ginzburg, 2014).

As weighted property we took into account the mean interaction strength, meaning the average strength of all interactions. After exploring the distribution of the interaction strength among the species of the food web, we decided to apply the k-means clustering method, which aims to partition the species into k groups such that the sum of squares from points to the assigned cluster centres is minimized (**?**).

As unweighted properties we used: a) degree or the total number of trophic interactions, taking into account in- and out-interactions (role as predator and prey, respectively); b) trophic level or the position in the food web relative to primary producers/detritus; and c) trophic similarity or the trophic overlap between species based on shared and unique resources and consumers.

Formulas used to obtain the mentioned species properties are described in Appendix A1.

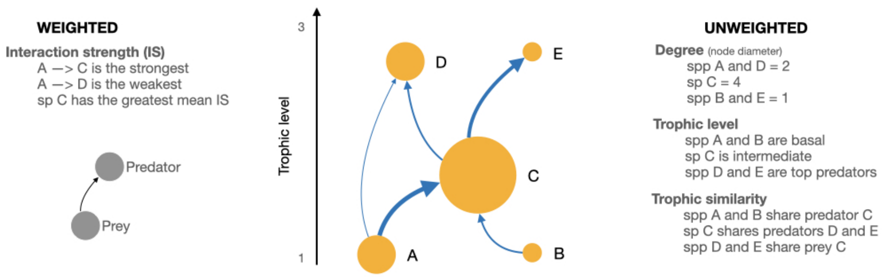

Figure 2. Scheme of a network showing the weighted and unweighted properties we used to characterize the species of the Weddell Sea food web.

2.3.3 Stability and extinction simulations

Finally, we run extinction simulations and estimated its impact on the stability of the network. For this, we calculated a stability index called Quasi-Sign Stability (QSS), which is the proportion of stable networks using randomized Jacobians and keeping the predator-prey sign structure fixed (Allesina and Pascual, 2008). With the aim of analysing the effect of each species on the food web's stability, we deleted one species at a time, so the network size was reduced by one. After each species extinction, we calculated the QSS for the food web minus one species (size = 489) and compared it with the QSS for the whole network (size = 490); we performed 1000 simulations for each species. Then we statistically analysed such difference with an Anderson-Darling test (Scholz and Stephens, 1987). The formula for the QSS is described in Appendix A2.

All analyses were performed in R software, mainly using packages igraph (Csardi and Nepusz, 2005), cheddar (Hudson et al., 2013), and multiweb (Saravia, 2019). The source code and data are available at https://github.com/EcoComplex/WeddellSea.

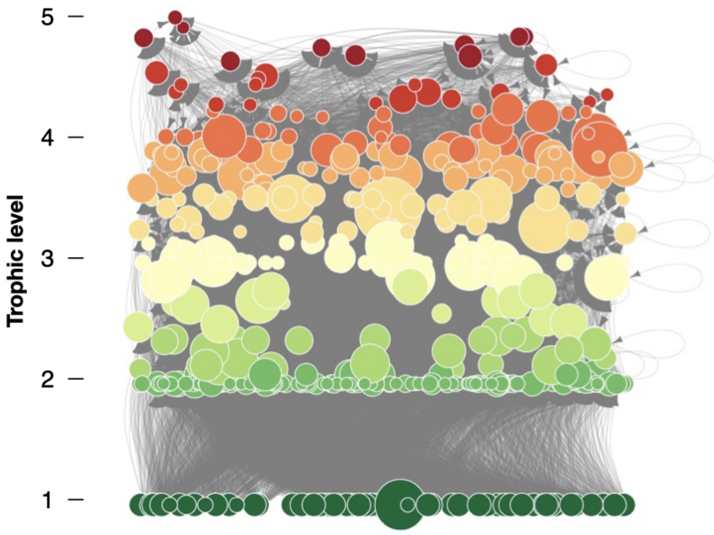

Figure 3. Graphic representation of the Weddell Sea food web. Species (nodes) are arranged verticaly and colored by trophic level. The diameter of the node indicates the total number of interactions. Predator-prey interactions are represented by the arrows, from the prey to the predator.

3 Results

3.1 Interaction strength

In this work we have estimated the interaction strength for the most highly-resolved marine food web to date, which comprises 490 species and 16041 predator-prey interactions (Figure 3).

The distribution of the interaction strength best fit to a log-Normal model, which indicates that there is a prevalent skew towards weaker interactions (Figure 4, Table 1). Regarding the distribution of the mean interaction strength among the species of the food web, the clustering method shows that species can be classified in two groups: ‘High’ and ‘Low’ interaction strength.

3.2 Species properties and stability

Clustering in 2 groups: high and low IS Linear regressions btw IS (weighted) and unweighted prop. Biplots btw QSS difference and weighted and unweighted prop.

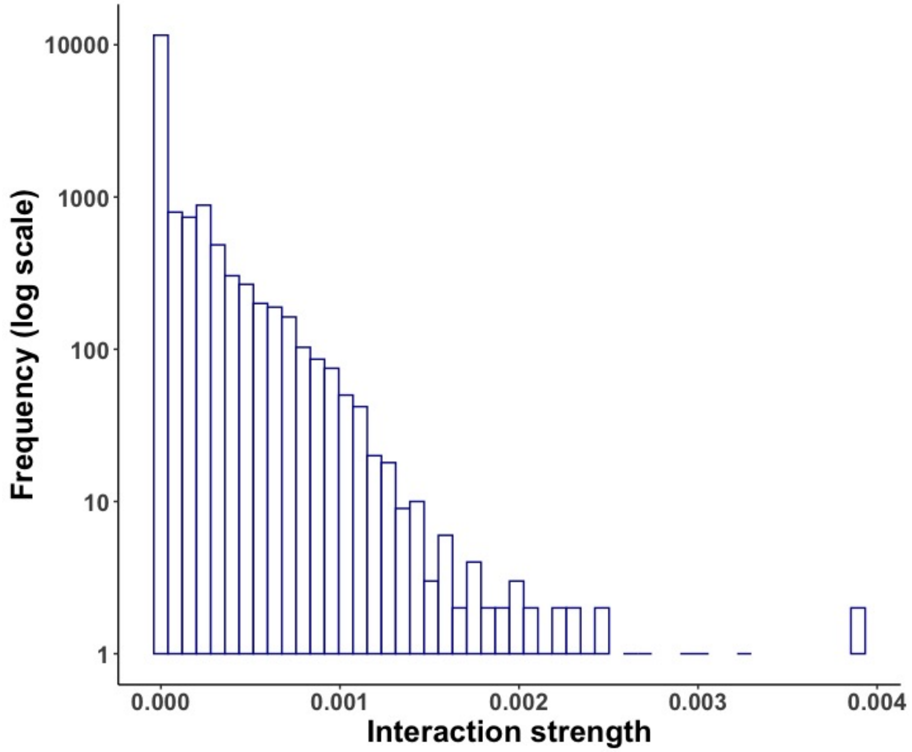

Figure 4. Frequency distribution of interaction strengths for the Weddell Sea food web (n = 490).

Table 1. Model comparison (AIC) for the distribution of interaction strengths of the Weddell Sea food web.

Model	df	AIC	deltaAIC
log-Normal	2	-356579	0
Gamma	2	-352575	4004
Power-law	2	-347646	8933
Exponential	1	-262852	93726
Normal	2	-222785	133793
Uniform	2	-178001	178578

4 Discussion

"Low functional redundancy at key trophic levels makes these ecosystems (polar pelagic) particularly sensitive to change". (**?**)

5 Examples from the official template

5.1 FIGURES

When figures and tables are placed at the end of the MS (article in one-column style), please add

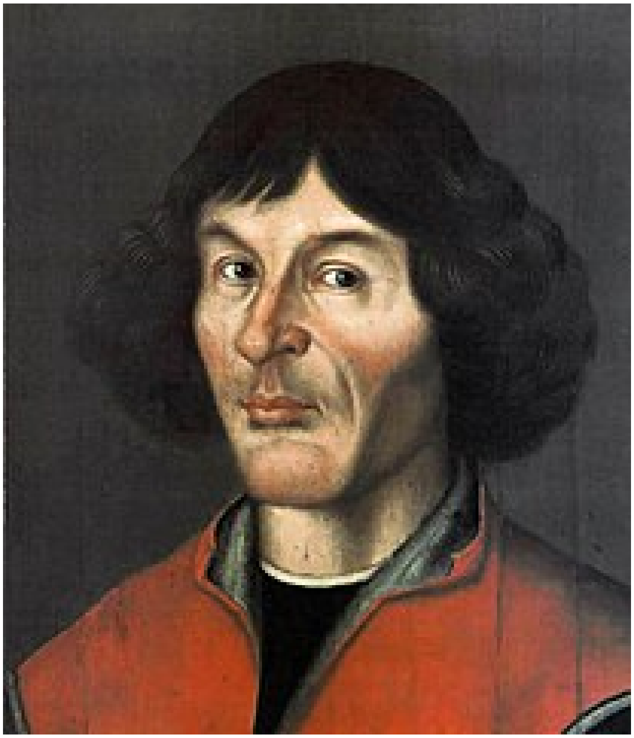

Figure 5. one column figure

Table 2. TEXT

a	b	c
1	2	3

Table Footnotes

between bibliography and first table and/or figure as well as between each table and/or figure.

5.1.1 ONE-COLUMN FIGURES

5.1.2 TWO-COLUMN FIGURES

5.2 TABLES

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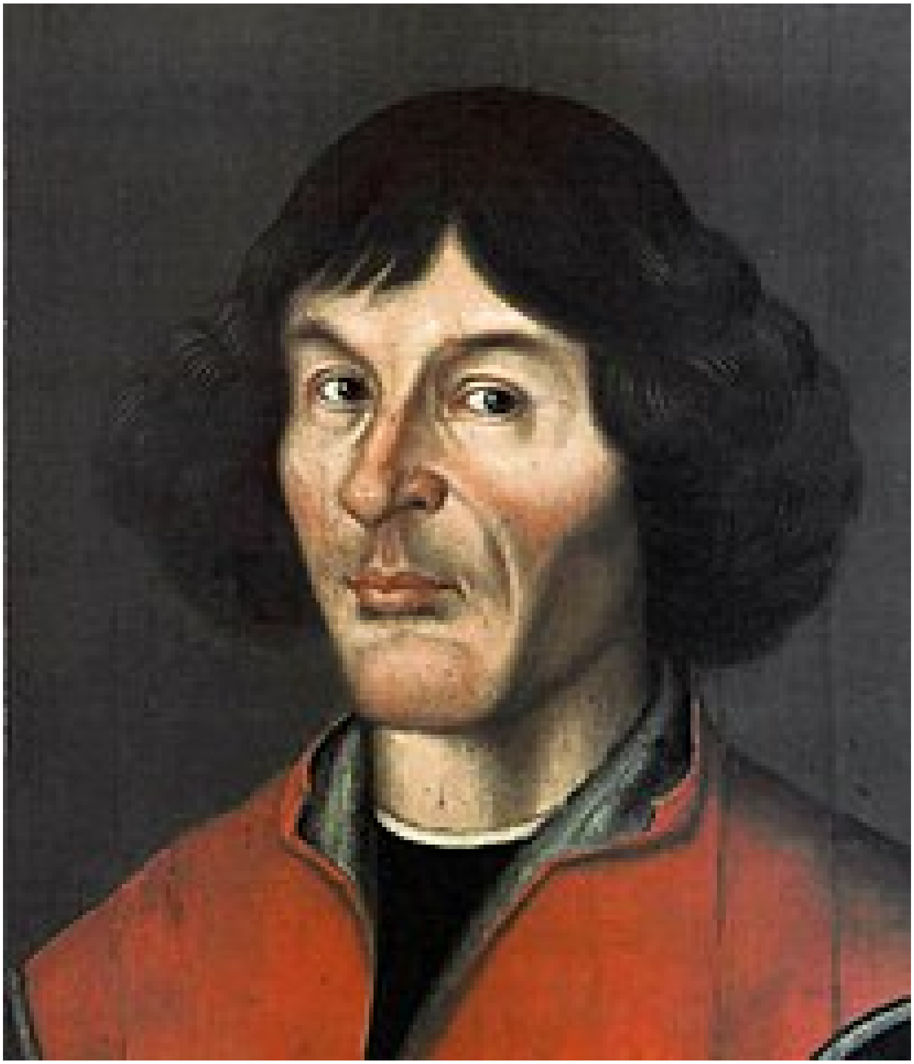

Figure 6. two column figure

Table 3. TEXT

a	b	c
1	2	3

Table footnotes

5.2.1 ONE-COLUMN TABLE

5.2.2 TWO-COLUMN TABLE

5.3 MATHEMATICAL EXPRESSIONS

All papers typeset by Copernicus Publications follow the math typesetting regulations given by the IUPAC Green Book (IUPAC: Quantities, Units and Symbols in Physical Chemistry, 2nd Edn., Blackwell Science, available at: http://old.iupac.org/publications/books/gbook/green_book_2ed.pdf, 1993).

Physical quantities/variables are typeset in italic font (t for time, T for Temperature)

Indices which are not defined are typeset in italic font (x, y, z, a, b, c)

Items/objects which are defined are typeset in roman font (Car A, Car B)

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Abbreviations from 2 letters are typeset in roman font (RH, LAI)

Vectors are identified in bold italic font using $\boldsymbol{x}$

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Multiplication signs are typeset using the LaTeX commands `\times` (for vector products, grids, and exponential notations) or `\cdot`

The character * should not be applied as mutliplication sign

5.4 EQUATIONS

5.4.1 Single-row equation

Unnumbered equations (i.e. using `$$` and getting inline preview in RStudio) are not supported by Copernicus.

$$1 \times 1 \cdot 1 = 42 \tag{2}$$

$$A = \pi r^2 \tag{3}$$

$$x = \frac{2b \pm \sqrt{b^2 - 4ac}}{2c}. \tag{4}$$

5.4.2 Multiline equation

$$3 + 5 = 8 \tag{5}$$
$$3 + 5 = 8 \tag{6}$$
$$3 + 5 = 8 \tag{7}$$

5.5 MATRICES

$$\begin{matrix} x & y & z \\ x & y & z \\ x & y & z \end{matrix}$$

5.6 ALGORITHM/PROGRAMMING CODE

If you want to use algorithms, you need to make sure yourself that the LaTeXpackages `algorithms` and `algorithmicx` are installed so that `algorithm.sty` respectively `algorithmic.sty` can be loaded by the Copernicus template. Both need to be available through your preferred LaTeX distribution. With TinyTeX (or TeX Live), you can do so by running `tinytex::tlmgr_install(c("algorithms", "algorithmicx"))`

```
## tlmgr update --all --self

## tlmgr install algorithms algorithmicx
```

Copernicus staff will no accept any additional packages from your LaTeX source code, so please stick to these two acceptable packages. They are needed to use the example below

Algorithm 1 Algorithm Caption

$i \leftarrow 10$
if $i \geq 5$ **then**
  $i \leftarrow i - 1$
else
  if $i \leq 3$ **then**
    $i \leftarrow i + 2$
  end if
end if

5.7 CHEMICAL FORMULAS AND REACTIONS

For formulas embedded in the text, please use `\chem{}`, e.g. $\mathrm{A \rightarrow B}$.

The reaction environment creates labels including the letter R, i.e. (R1), (R2), etc.

- `\rightarrow` should be used for normal (one-way) chemical reactions
- `\rightleftharpoons` should be used for equilibria
- `\leftrightarrow` should be used for resonance structures

$$A \rightarrow B \tag{R1}$$

$$Coper \rightleftharpoons nicus \tag{R2}$$

$$Publi \leftrightarrow cations \tag{R3}$$

5.8 PHYSICAL UNITS

Please use `\unit{}` (allows to save the math/`$` environment) and apply the exponential notation, for example $3.14\,\mathrm{km\,h^{-1}}$ (using LaTeX mode: `\( 3.14\,\unit{...} \)`) or $0.872\,\mathrm{m\,s^{-1}}$ (using only `\unit{0.872\,m\,s^{-1}}`).

6 Conclusions

The conclusion goes here.

Appendix A: Figures and tables in appendices

A1 Option 1

If you sorted all figures and tables into the sections of the text, please also sort the appendix figures and appendix tables into the respective appendix sections. They will be correctly named automatically.

A2 Option 2

If you put all figures after the reference list, please insert appendix tables and figures after the normal tables and figures.

`\appendixfigures` needs to be added in front of appendix figures `\appendixtables` needs to be added in front of appendix tables

Please add `\clearpage` between each table and/or figure. Further guidelines on figures and tables can be found below. Regarding figures and tables in appendices, the following two options are possible depending on your general handling of figures and tables in the manuscript environment: To rename them correctly to A1, A2, etc., please add the following commands in front of them:

. TIM and LAS: Conceptualization (lead); Data curation (lead); Formal analysis (lead); Methodology (lead); Coding (lead); Writing – original draft (lead); Writing – review and editing (lead). SK: Conceptualization (lead); Formal analysis (supporting); Methodology (supporting); Coding (supporting); Writing – original draft (supporting); Writing – review and editing (supporting).

. The authors declare no competing interests.

. Thanks to the rticles contributors!

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