

# Exploring the ocean multiverse with *Tara Oceans*

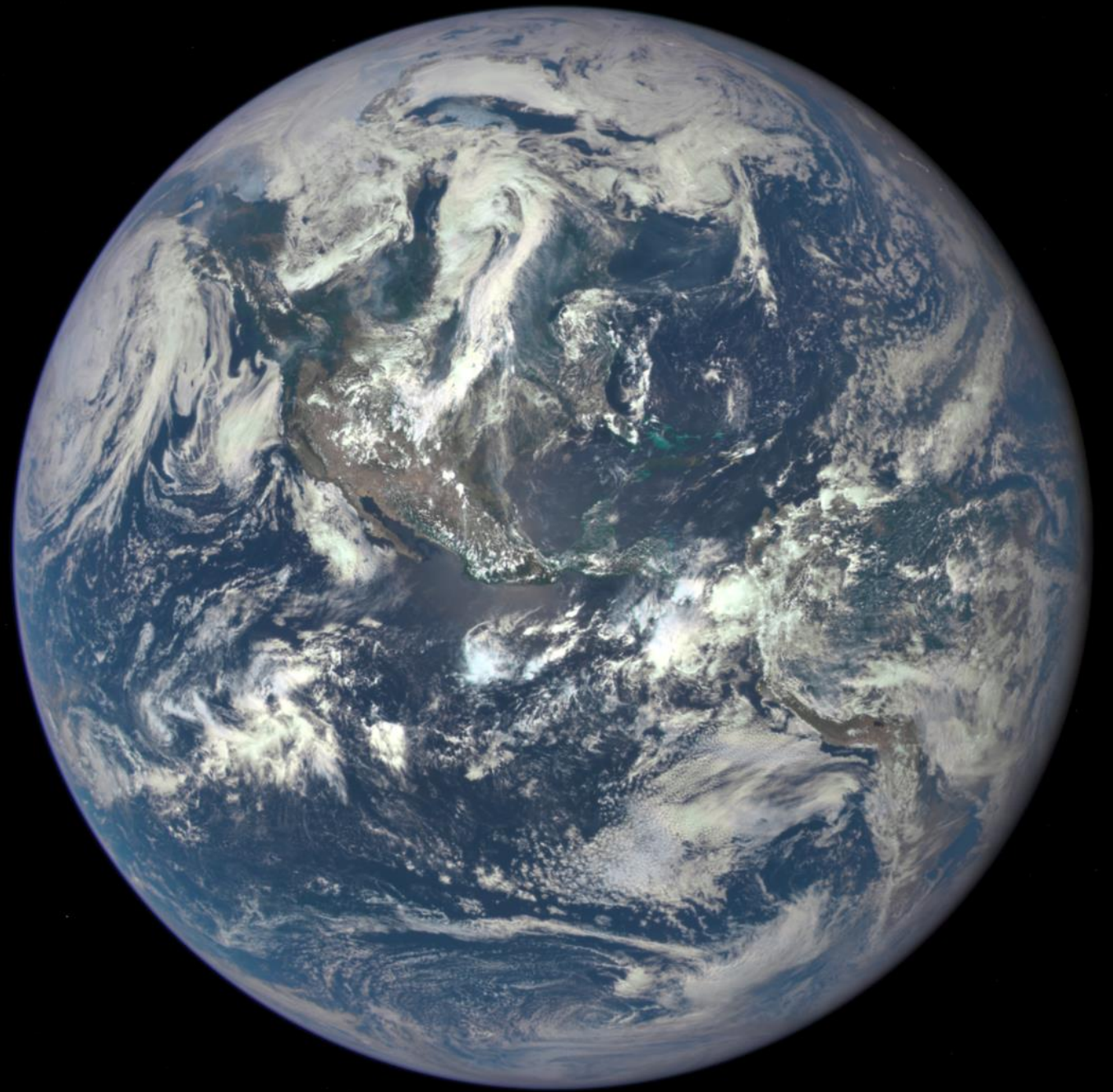
Chris Bowler  
CNRS

Institut de Biologie de l'École Normale Supérieure

Scientific Director of *Tara Oceans*



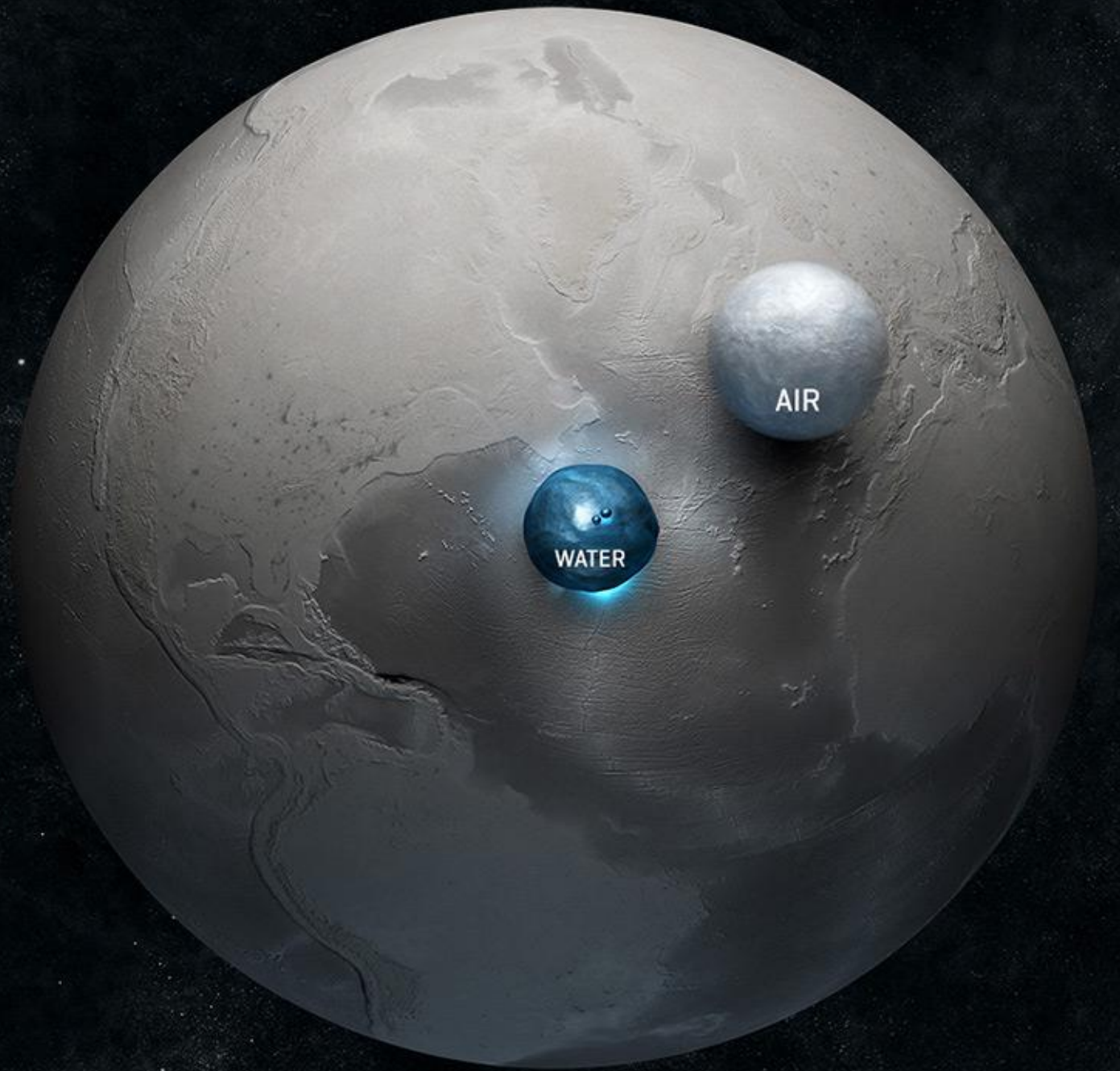
Although planet  
Earth looks  
mostly blue  
from space...





... water is  
relatively scarce.

Life appeared in,  
and is sustained  
by, the Ocean.





# The Ocean Our life support system

The Ocean covers 71% of our planet and is a Key player !

The Ocean captures 25%  
of human CO<sub>2</sub> emissions  
and 90% of the heat.

Ocean microbes perform 50%  
of photosynthesis on Earth.

The Ocean regulates the  
temperature on Earth.

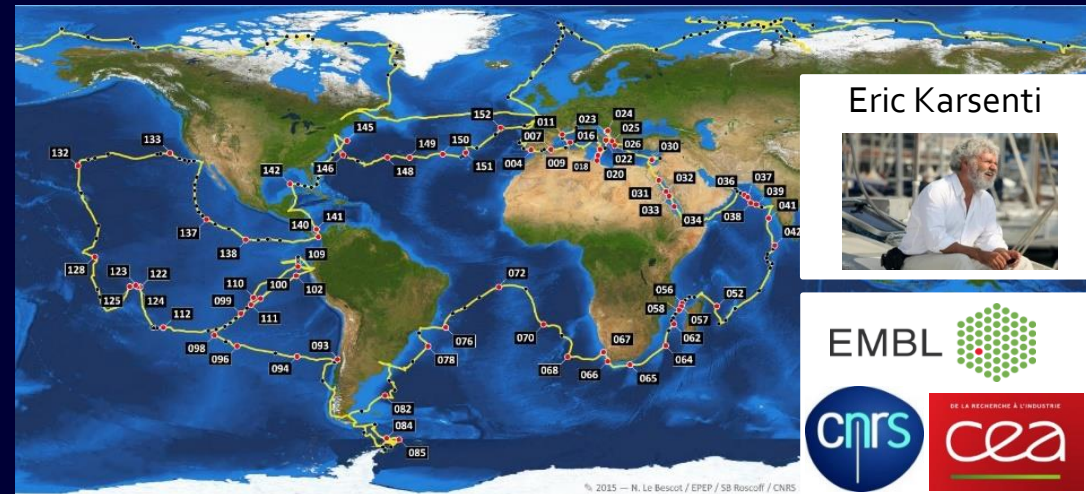
**... and yet it is still poorly known !**



# TARA OCEANS

A four year expedition

- To explore marine planktonic ecosystems and their sensitivity to climate change-induced modifications to the ocean
- To popularize science
- To educate
- To improve ocean governance



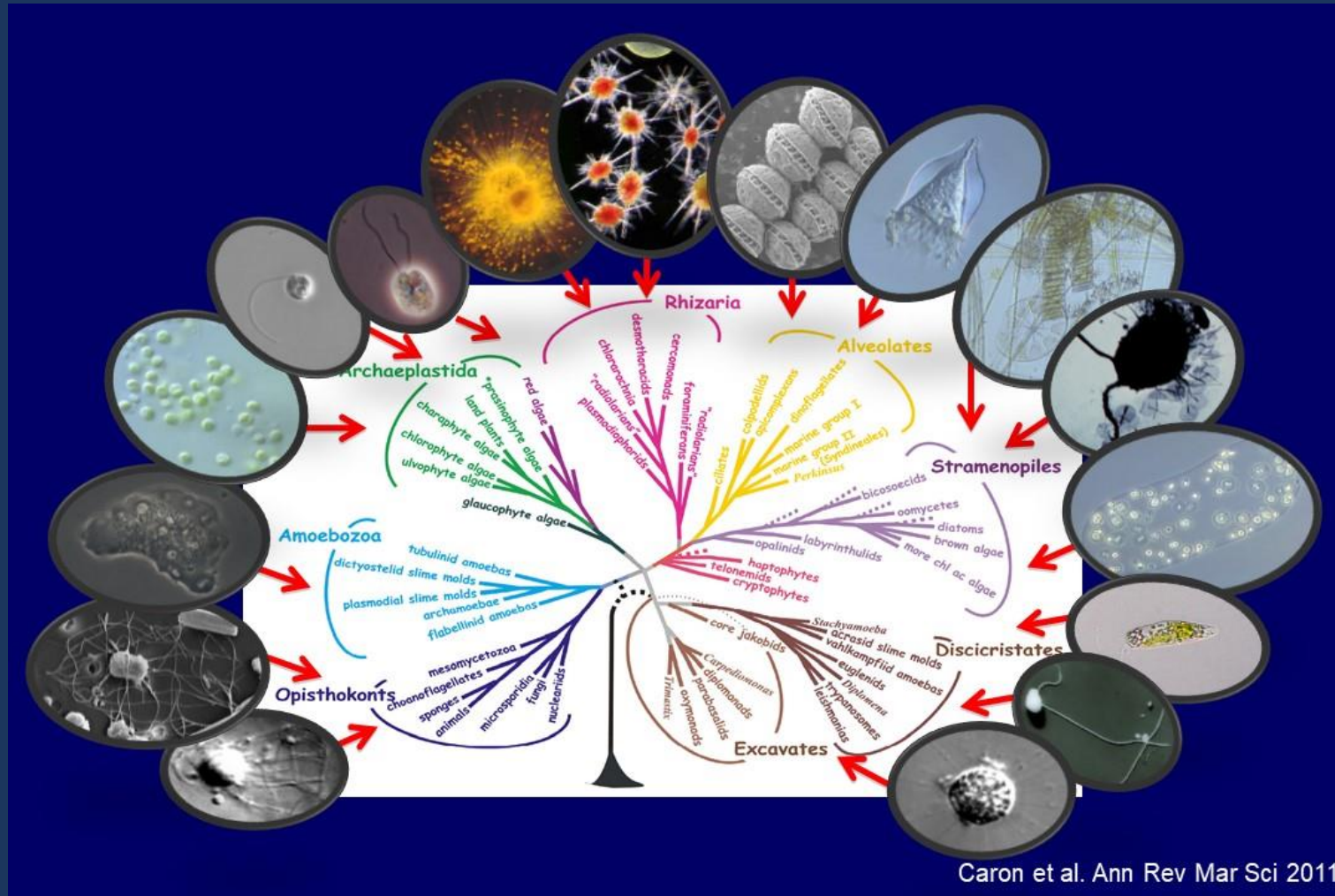




# Plankton are very small



# Marine micro-eukaryotes are found throughout the tree of life

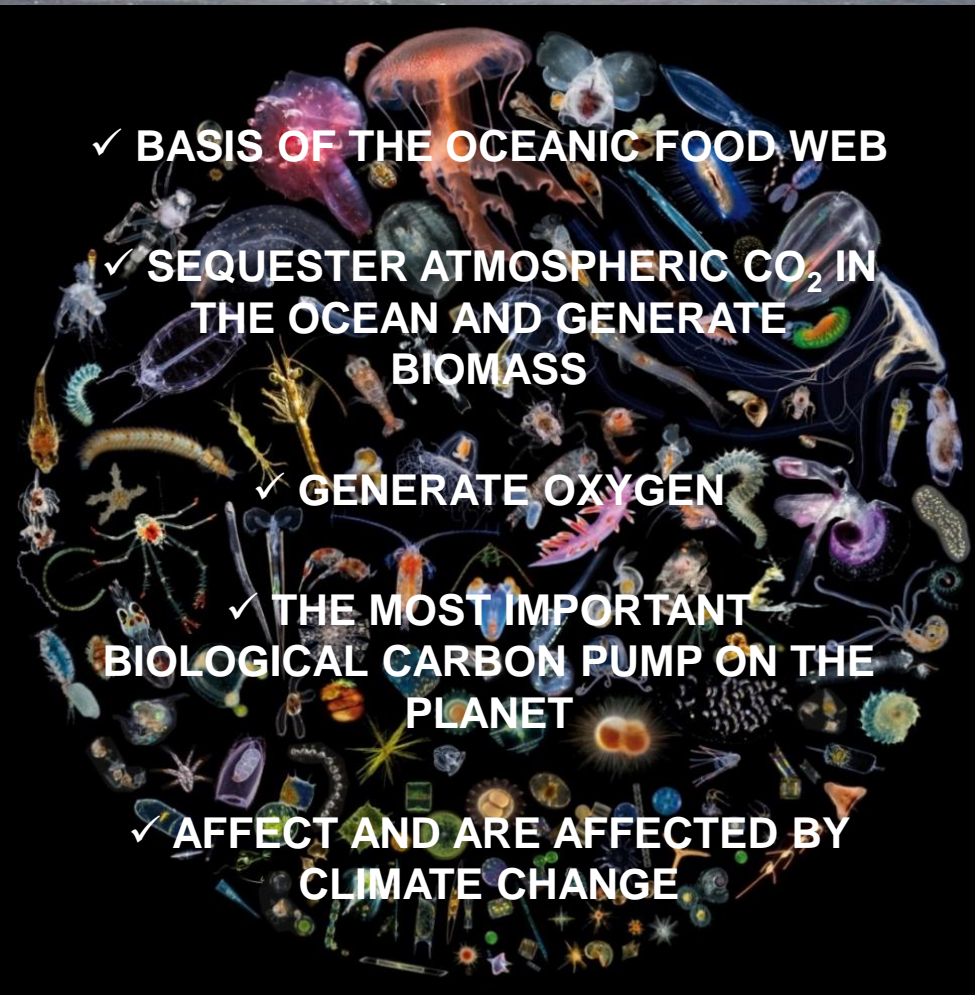


Caron et al. Ann Rev Mar Sci 2011



# The Plankton

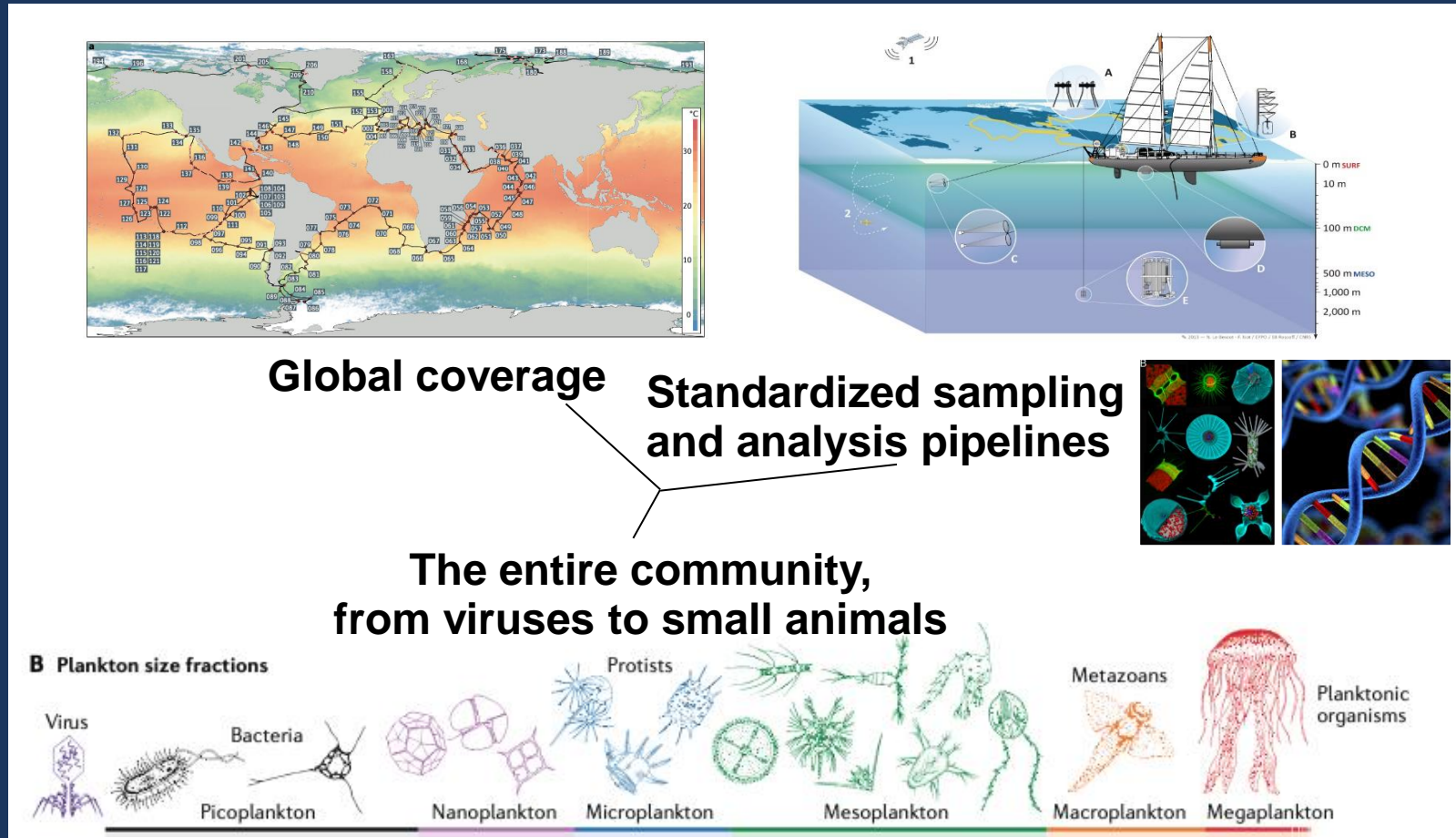
## THE INVISIBLE MULTITUDE

- 
- ✓ BASIS OF THE OCEANIC FOOD WEB
  - ✓ SEQUESTER ATMOSPHERIC CO<sub>2</sub> IN THE OCEAN AND GENERATE BIOMASS
  - ✓ GENERATE OXYGEN
  - ✓ THE MOST IMPORTANT BIOLOGICAL CARBON PUMP ON THE PLANET
  - ✓ AFFECT AND ARE AFFECTED BY CLIMATE CHANGE

>65% of the biomass in the ocean



# Tara Oceans: An eco-systems biology framework to understand a complex system at planetary scale



Who is there, what do they do, with whom, and why ?



OPEN ACCESS Freely available online PLOS ONE

Community Page

**A Holistic Approach to Marine Eco-Systems Biology**

Eric Kersanté<sup>1\*</sup>, Silvie G. Acinas<sup>2</sup>, Peer Bork<sup>3,4,5</sup>, Chris Bowler<sup>6,7</sup>, Colomán De Vargas<sup>8,9,10</sup>, Jeroen Raaij<sup>11,12</sup>, Matthew Sullivan<sup>13</sup>, Detlev Arendt<sup>14</sup>, Francesca Benzoni<sup>15</sup>, Jean-Michel Claverie<sup>16,17</sup>, Mick Follows<sup>18</sup>, Galby Gorsky<sup>19,20</sup>, Pascal Hingamp<sup>21</sup>, Daniele Iudicone<sup>22</sup>, Olivier Jallou<sup>23</sup>, Stefanie Kandel-Lewis<sup>24</sup>, Uros Krzic<sup>25</sup>, Fabrice Not<sup>26,27</sup>, Hiroyuki Ogata<sup>28,29</sup>, Stéphane Pesant<sup>30,31</sup>, Emmanuel Georges Reynaud<sup>32</sup>, Christian Sardet<sup>33,34</sup>, Michael E. Sieracki<sup>35</sup>, Sabrina Speich<sup>36,37</sup>, Didier Velayoudon<sup>38</sup>, Jean Weissenbach<sup>39</sup>, Patrick Wincker<sup>40</sup>, the Tara Oceans Consortium<sup>†</sup>



A smaller, faster, cheaper route to fusion energy p. 868  
 Sport, sex, and testosterone go to court p. 858  
 Making C-N bonds from nitro groups pp. 859 & 866

# Science

110  
22 MAY 2015  
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MAAAS

## A world of plankton

Marine biodiversity surveyed by the schooner Tara  
pp. 865 & 873

SPECIAL SECTION

## Tara Oceans studies plankton at PLANETARY SCALE

By B. Borer, C. Bowler, C. de Vargas, G. Gorsky, L. Kocum, P. Wincker

**T**he ocean is the largest ecosystem on Earth, and yet we know very little about it. This is particularly true for the plankton that inhabit the ocean. Although these organisms are at least as important for the Earth system as the rainforests and form the base of marine food webs, most plankton are invisible to the naked eye and thus are largely understudied. To study this invisible world, the multinational Tara Oceans consortium, with use of the 130-foot research schooner Tara, sampled microscopic plankton at 300 sites and depths up to 2000 m in 16 the equatorial regions during expeditions from 2008 through 2012 (1).

Access depends on collaboration between scientists and the Tara Expedition logistics team. The journey involved an arduous sea as well as negotiation through the shoals of legal and political regulations, funding uncertainties, threats from pirates, and unpredictable weather (2). At various times, journalists, artists, and teachers were also on board. Visitors included Ben Knapik (Secretary-General of the United Nations) and numerous scientists, including schoolchildren from the Pacific to Rio de Janeiro. Sampling, usually 60 hours per site, followed standardized protocols (3) to capture the morphological and genetic diversity of the entire plankton community from viruses to small zooplankton, covering a size range from 0.02 µm to a few millimeters. In concert with physical and chemical information, besides the sampling, a lab on board contained a range of culture treatments and microscopes to monitor the culture of the samples as they were being collected. The main focus was on the organisms with much upper tier of the ocean (above to 200 m), but the twilight zone below was also sampled, divided by cell size and in this, scientists sampled such as mesozooplankton, micronekton, upwelling, acidic waters, and anoxic zones. Frequently in the open ocean, in addition to being used for genetics and morphology, many samples were collected for other analyses, such as high-throughput microscopy imaging and flow cytometry. The samples and data collected on board were archived in a highly structured

way to enable extensive data mining and integration (see (4)). The five Research Articles in this issue of Science describe the same data, and analyze from Tara Oceans (based on a data freeze from 170 samples at 75 stations as of November 2013). De Vargas et al. used ribosomal RNA gene sequences to profile eukaryotic diversity in the photic zone. The taxonomic census shows that most biodiversity belongs to poorly known lineages of noncolonial heterotrophic single-celled protists. Sequences of used metagenomes to study viruses, prokaryotes, and picoplankton. They established a catalog with 100 million genes and identified temperature as the driver of phyletic microbial community composition. Bruner et al. by sequencing and electron microscopy found that viruses are diverse on a regional basis but less so on a global basis. The viral communities are genetically structured by oceanic currents and structured by local environmental conditions, between viruses, prokaryotes, and eukaryotes. Regional and global patterns reflect residence networks. Vilete et al. studied the dispersal of plankton in oceanic currents near around the southern tip of Africa, where the Agulhas ring is generated. Vertical mixing in the deep drives nitrogen cycling and selects for specific cyanobacteria. Borer et al. by sequencing and electron microscopy found that viruses are diverse on a regional basis but less so on a global basis. The viral communities are genetically structured by oceanic currents and structured by local environmental conditions, between viruses, prokaryotes, and eukaryotes. Regional and global patterns reflect residence networks. Vilete et al. studied the dispersal of plankton in oceanic currents near around the southern tip of Africa, where the Agulhas ring is generated. Vertical mixing in the deep drives nitrogen cycling and selects for specific cyanobacteria.

Tara Oceans combined ecology, system biology, and oceanography to study plankton in their environmental context. The project has generated resources such as an ocean microbial reference gene catalog, a census of plankton diversity covering viruses, prokaryotes, and eukaryotes, and methodology to explore interactions between them and their integration with environmental conditions. Although many more such analyses will follow, life in the ocean is slowly a little less murky than it was before.

REFERENCES  
 1. Kocum, G. *et al.* *Science* 345, 1102 (2014).  
 2. Borer, P. *et al.* *Science* 345, 1102 (2014).  
 3. Vilete, J. *et al.* *Science* 345, 1102 (2014).  
 4. Sunagawa, S. *et al.* *Science* 345, 1102 (2014).

110225 | www.sciencemag.org

SCIENCE | sciencemag.org | 22 MAY 2015 • VOL. 348 | ISSUE 6327 | 873

SPECIAL SECTION TARA OCEANS

### Eukaryotic plankton diversity in the sunlit ocean

C. de Vargas,\* S. Audic, N. Henry, J. Decelle, F. Mahé, R. Lagares, E. Lara, C. Berney, N. Le Besoult, I. Probert, M. Carmichael, J. Poulain, S. Romac, S. Collin, J.-M. Arriy, L. Bittner, S. Chaffron, M. Dunthorn, S. Engelen, O. Flegontova, L. Guidi, A. Horák, O. Jallou, G. Lima-Mendez, J. Lukeš, S. Malviya, R. Morard, M. Mouton, E. Scalco, R. Siano, F. Vincent, A. Zingone, C. Dimier, M. Picheral, S. Searson, S. Kandel-Lewis, Tara Oceans Coordinators, S. G. Acinas, P. Borer, C. Bowler, G. Gorsky, N. Grimsley, P. Hingamp, D. Iudicone, F. Not, H. Ogata, S. Pesant, J. Raes, M. E. Sieracki, S. Speich, L. Stemann, S. Sunagawa, J. Weissenbach, P. Wincker, E. Karsenti\*

Marine plankton support global biological and geochemical processes. Surveys of their biodiversity have hitherto been geographically restricted and have not accounted for the full range of plankton size. We assessed eukaryotic diversity from 334 size-fractionated photic-zone plankton communities collected across tropical and temperate oceans during the circumglobal Tara Oceans expedition. We analyzed 18S ribosomal DNA sequences across the intermediate plankton-size spectrum from the smallest unicellular eukaryotes (protists, >0.8 micrometers) to small animals of a few millimeters. Eukaryotic ribosomal diversity saturated at ~150,000 operational taxonomic units, about one-third of which could not be assigned to known eukaryotic groups. Diversity emerged at all taxonomic levels, both within the groups comprising the ~11,200 cataloged morphospecies of eukaryotic plankton and among twice as many other deep-branching lineages of unappreciated importance in plankton ecology studies. Most eukaryotic plankton biodiversity belonged to heterotrophic protist groups, particularly those known to be parasites or symbiotic hosts.

The list of author affiliations is available in the full article online. \*Corresponding author. E-mail: vargas@embl.de (S.G.); karsenti@embl.de (E.K.); jeren.raes@vib-kuleuven.be (J.R.); sachdev@cmic.ca (S.G.A.); bowler@embl.de (P.B.); olean.s.sunagawa@sci.azhpc.gov.au (S. Sunagawa); P. Wincker, E. Karsenti\*

### Structure and function of the global ocean microbiome

J. Sunagawa,\* T. P. Coello, S. Chaffron, J. R. Kultima, K. Labadie, J. Salazar, B. Djahanschiri, G. Zeller, D. R. Mendes, A. Alberti, M. Cornejo-Castillo, P. I. Costas, C. Cruaud, F. d'Ovidio, J. Engelen, I. Ferrera, J. M. Gasol, L. Guidi, F. Hildebrand, K. Kokoszka, C. Lepoivre, G. Lima-Mendez, J. Poulain, B. P. Poulos, M. Royo-Llonch, H. Sarmiento, S. Vieira-Silva, C. Dimier, M. Picheral, S. Searson, S. Kandel-Lewis, Tara Oceans Coordinators, C. Bowler, C. de Vargas, G. Gorsky, N. Grimsley, P. Hingamp, D. Iudicone, O. Jallou, F. Not, H. Ogata, S. Pesant, S. Speich, L. Stemann, M. B. Sullivan, J. Weissenbach, P. Wincker, E. Karsenti, J. Raes, S. G. Acinas, P. Borer\*

Microbes are dominant drivers of biogeochemical processes, yet drawing a global picture of functional diversity, microbial community structure, and their ecological determinants remains a grand challenge. We analyzed 72 terabases of metagenomic data from 243 Tara Oceans samples from 68 locations in pelagic and mesopelagic waters across the globe to

generate an ocean microbial reference gene catalog with >40 million nonredundant, mostly novel sequences from viruses, prokaryotes, and picoeukaryotes. Using 139 prokaryote-enriched samples, containing ~35,000 species, we show vertical stratification with epipelagic community composition mostly driven by temperature rather than other environmental factors or geography. We identify ocean microbial core functionality and reveal that >73% of its abundance is shared with the human gut microbiome despite the physicochemical differences between these two ecosystems.

The list of author affiliations is available in the full article online. \*Corresponding author. E-mail: sunagawa@embl.de (S.G.); karsenti@embl.de (E.K.); jeren.raes@vib-kuleuven.be (J.R.); sachdev@cmic.ca (S.G.A.); bowler@embl.de (P.B.); olean.s.sunagawa@sci.azhpc.gov.au (S. Sunagawa); P. Wincker, E. Karsenti\*

### Patterns and ecological drivers of ocean viral communities

J. R. Brum, J. C. Ignacio-Espinoza, S. Roux, G. Doucier, S. G. Acinas, A. Alberti, S. Chaffron, C. Cruaud, C. de Vargas, J. M. Gasol, G. Gorsky, A. C. Gregory, L. Guidi, P. Hingamp, D. Iudicone, F. Not, H. Ogata, S. Pesant, B. T. Poulos, S. M. Schwcnck, S. Speich, C. Dimier, S. Kandel-Lewis, M. Picheral, S. Searson, Tara Oceans Coordinators, P. Borer, C. Bowler, S. Sunagawa, P. Wincker, E. Karsenti, M. B. Sullivan\*

Viruses influence ecosystems by modulating microbial population size, diversity, metabolic outputs, and gene flow. Here, we use quantitative double-stranded DNA (dsDNA) viral-fraction metagenomes (viromes) and whole viral community morphological data sets from 43 Tara Oceans expedition samples to assess viral community patterns and structure in the upper ocean. Protein cluster cataloging defined pelagic upper-ocean viral community pan and core gene sets and suggested that this sequence space is well-sampled. Analyses of viral protein clusters, populations, and morphology revealed biogeographic patterns whereby viral communities were passively transported on oceanic currents and locally structured by environmental conditions that affect host community structure. Together, these investigations establish a global ocean dsDNA viromic data set with analyses supporting the seed-bank hypothesis to explain how oceanic viral communities maintain high local diversity.

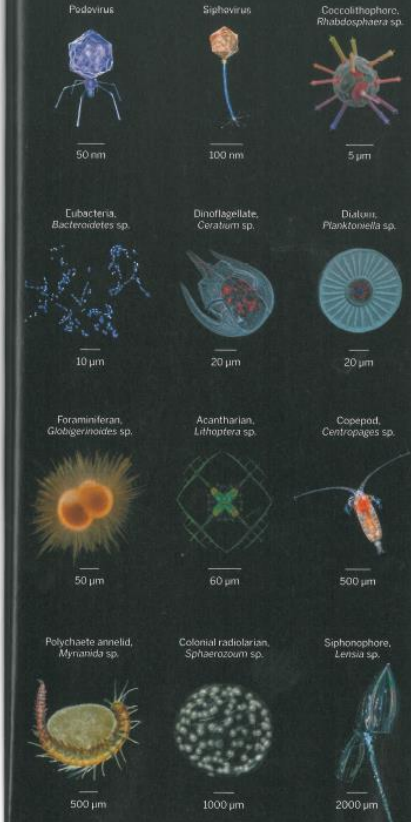
The list of author affiliations is available in the full article online. \*Corresponding author. E-mail: mbsullivan@gmail.com (M.B.S.); karsenti@embl.de (E.K.) Cite as Brum et al. *Science* 348, 12619 (2015).

### Determinants of community structure in the global plankton interactome

G. Lima-Mendez, K. Faust, N. Henry, J. Decelle, S. Collin, F. Carcello, S. Chaffron, J. C. Ignacio-Espinoza, S. Roux, F. Vincent, L. Bittner, Y. Dazul, J. Wang, S. Audic, L. Berline, G. Boukremel, A. M. Cabello, L. Coppola, F. M. Cornejo-Castillo, F. d'Ovidio, L. De Meester, I. Ferrera, M.-J. Garat-Delmas, L. Guidi, E. Lara, S. Pesant, M. Royo-Llonch, G. Salazar, P. Sánchez, M. Sebastian, C. Souffreau, C. Dimier, M. Picheral, S. Searson, S. Kandel-Lewis,

### Plankton diversity

Tara Oceans sampled the smallest in the planktonic world, including viruses, bacteria, protists, and zooplankton. These spectacular and plentiful organisms form the microscopic basis of marine food webs. Analysis of their genes and genomes provides the basis for research insights into identities and interactions.



EXISTS: (LEFT TO RIGHT) COCCOLITHOPHORE RABDOSPHAERA SP., BACTERIUM BACTEROIDES SP., DINOFLAGELLATE CERATIUM SP., FORAMINIFERAN GLOBOBULIMINA SP., ACANTHARION LITHOPTERA SP., COPEPOD CENTROPAGES SP., POLYCHAETE ANNELID MYRTILID SP., COLONIAL RADIOLARIAN SPHAEROZOU M SP., AND SIPHONOPHORE LENSIA SP.

Tara Oceans Coordinators, G. Gorsky, F. Not, H. Ogata, S. Speich, L. Stemann, J. Weissenbach, P. Wincker, S. G. Acinas, S. Sunagawa, P. Borer, M. B. Sullivan, E. Karsenti, C. Bowler, C. de Vargas, J. Raes\*

Species interaction networks are shaped by abiotic and biotic factors. Here, as part of the Tara Oceans project, we studied the photic zone interactome using environmental factors and organismal abundance profiles and found that environmental factors are incomplete predictors of community structure. We found associations across plankton functional types and phylogenetic groups to be nonrandomly distributed on the network and driven by both local and global patterns. We identified interactions among grazers, primary producers, viruses, and (mainly parasitic) symbionts and validated network-generated hypotheses using microscopy to confirm symbiotic relationships. We have thus provided a resource to support further research on ocean food webs and integrating biological components into ocean models.

The list of author affiliations is available in the full article online. \*Corresponding author. E-mail: jeren.raes@vib-kuleuven.be (J.R.); vargas@sb-roscoff.fr (C.V.); bowler@biologie.ens.fr (C.B.); karsenti@embl.de (E.K.) Cite as Lima-Mendez et al. *Science* 348, 12620 (2015).

### Environmental characteristics of Agulhas rings affect interocean plankton transport

E. Villar,\* G. K. Farrant, M. Follows, L. Garcez, S. Speich, S. Audic, L. Bittner, B. Blanke, J. R. Brum, C. Brunet, R. Casatta, A. Chase, J. R. Dolan, F. d'Ortenzio, J.-P. Gattuso, N. Grima, L. Guidi, C. N. Hill, O. Jahn, J.-L. Jamet, H. Le Goff, C. Lepoivre, S. Malviya, E. Pelletier, J.-B. Rognon, S. Roux, S. Santini, E. Scalco, S. M. Schwcnck, A. Tanaka, P. Testor, T. Santini, F. Vincent, A. Zingone, C. Dimier, M. Picheral, S. Searson, S. Kandel-Lewis, Tara Oceans Coordinators, S. G. Acinas, P. Borer, E. Boss, C. de Vargas, G. Gorsky, H. Ogata, S. Pesant, M. B. Sullivan, S. Sunagawa, P. Wincker, E. Karsenti, C. Bowler, F. Not, P. Hingamp, D. Iudicone\*

Agulhas rings provide the principal route for ocean waters to circulate from the Indo-Pacific to the Atlantic basin. Their influence on global ocean circulation is well known, but their role in plankton transport is largely unexplored. We show that, although the coarse taxonomic structure of plankton communities is continuous across the Agulhas choke point, South Atlantic plankton diversity is altered compared with Indian Ocean source populations. Modeling and in situ sampling of a young Agulhas ring indicate that strong vertical mixing drives complex nitrogen cycling, shaping community metabolism and biogeochemical signatures as the ring and associated plankton transit westward. The peculiar local environment inside Agulhas rings may provide a selective mechanism contributing to the limited dispersal of Indian Ocean plankton populations into the Atlantic.

The list of author affiliations is available in the full article online. \*Corresponding author. E-mail: villar@igs.cnr.fr (E.V.); not@sb-roscoff.fr (F.N.); hingamp@igs.cnr.fr (P.H.); iudicone@szn.it (D.I.); karsenti@embl.de (E.K.); bowler@biologie.ens.fr (C.B.) Cite as Villar et al. *Science* 348, 12614 (2015).

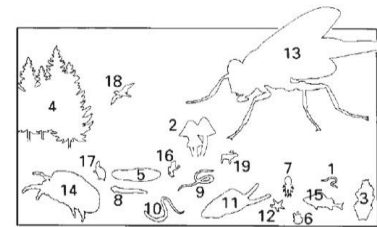
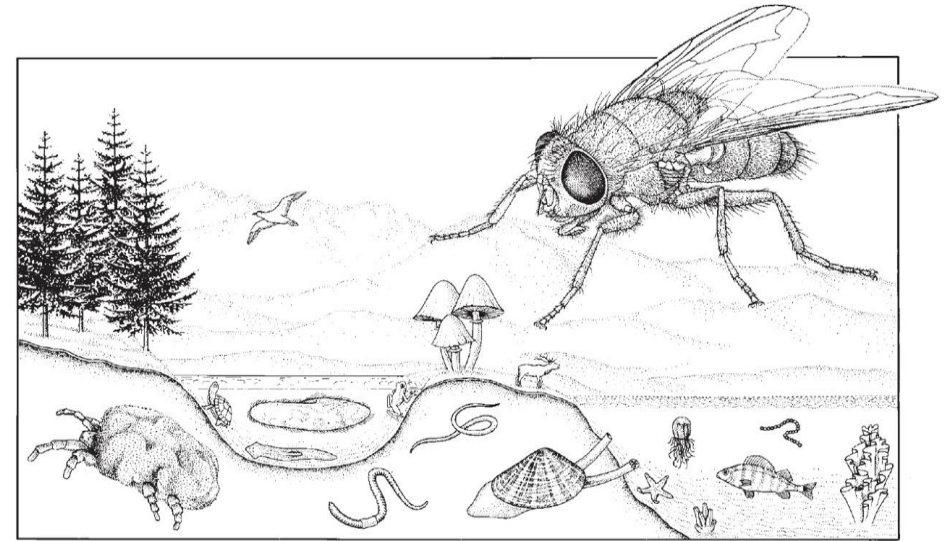
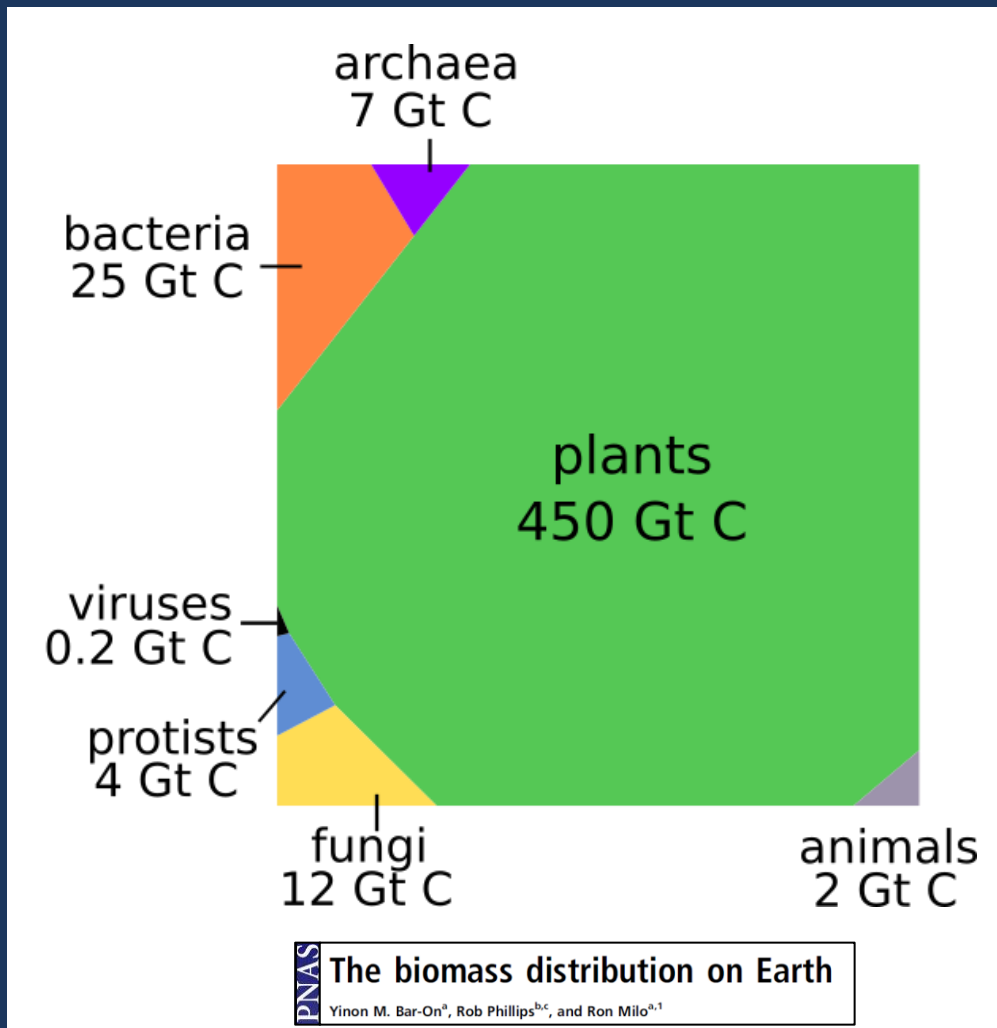
Read the full article at <http://dx.doi.org/10.1126/science.1261447>

# Some very basic questions

- ✓ Which plankton group is the most abundant ?
- ✓ Which plankton group is the most diverse ?



# Biomass and number of species in terrestrial ecosystems

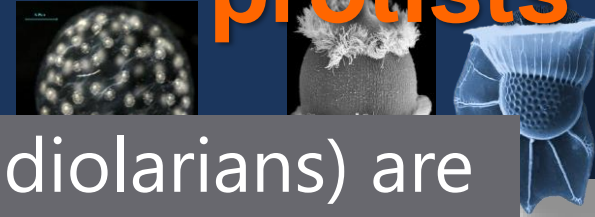
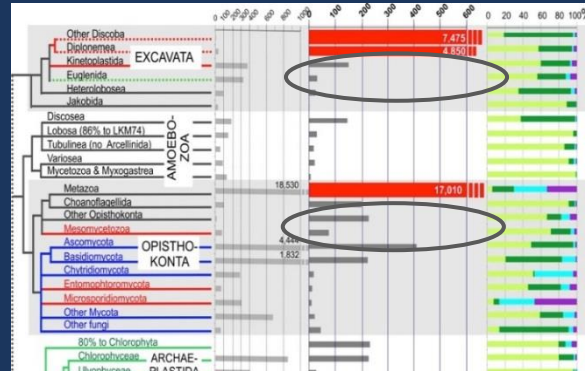


- 1 Prokaryotes
- 2 Fungi
- 3 Algae
- 4 Plantae (multicellular plants)
- 5 Protozoa
- 6 Porifera (sponges)
- 7 Cnidaria (jellyfish, corals, etc.)
- 8 Platyhelminthes (flatworms)
- 9 Nematoda (roundworms)
- 10 Annelida (earthworms, leeches, etc.)
- 11 Mollusca (snails, bivalves, octopus, etc.)
- 12 Echinodermata (starfish, sea urchins, etc.)
- 13 Insecta
- 14 Non-insect Arthropoda
- 15 Pisces (fish)
- 16 Amphibia (frogs, salamanders, etc.)
- 17 Reptilia (snakes, lizards, turtles)
- 18 Aves (birds)
- 19 Mammalia (mammals)

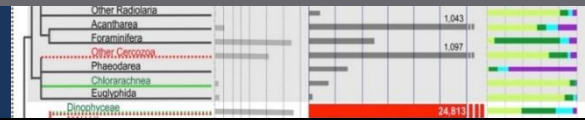
**Fig. 1.1** Speciescape, in which the size of individual organisms is approximately proportional to the number of described species in the higher taxon that it represents. (After Wheeler 1990.)

*The Insects: An Outline of Entomology*, P. J. Gullan, 5th edition, 2014

# A new world of marine protists



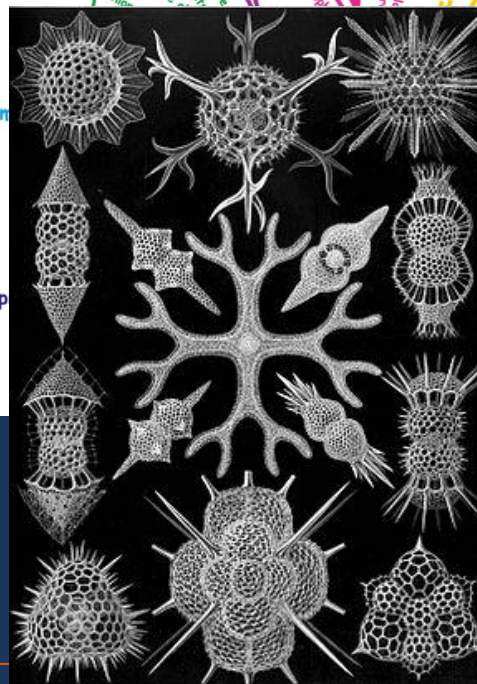
Collodaria and Phaeodaria (radiolarians) are unexpectedly abundant



**LETTER** doi:10.1038/nature17652

**In situ imaging reveals the biomass of giant protists in the global ocean**

Tristan Biard<sup>1,2</sup>, Lars Stemann<sup>2</sup>, Marc Picheral<sup>2</sup>, Nicolas Mayot<sup>2</sup>, Pieter Vandromme<sup>3</sup>, Helena Hauss<sup>3</sup>, Gabriel Gorsky<sup>2</sup>, Lionel Guidi<sup>2</sup>, Rainer Kiko<sup>3</sup> & Fabrice Not<sup>1</sup>

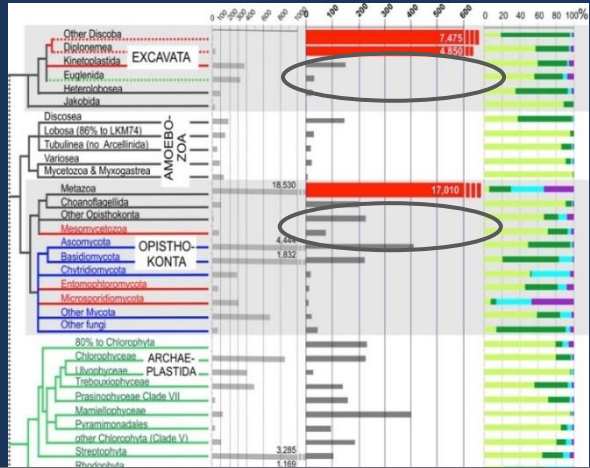


**ic plankton diversity in the an**

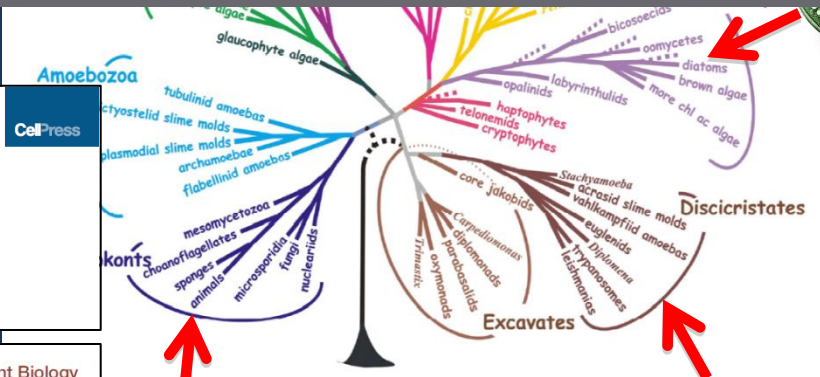
<sup>1,2,3</sup> Stéphane Audic, <sup>1,2,3</sup> Nicolas Henry, <sup>1,2,3</sup> Johan Decelle, <sup>1,2,3</sup> miro Logares, <sup>4</sup> Enrique Lara, <sup>5</sup> Cédric Berney, <sup>1,2</sup> Noan Le Besco, <sup>1,2</sup> x Carmichael, <sup>1,2,3</sup> Julie Poulain, <sup>6</sup> Sarah Romac, <sup>1,2</sup> an-Marc Aury, <sup>7</sup> Lucie Bittner, <sup>10,11,8,1,2</sup> Samuel Chaffron, <sup>12,13,14</sup> in Engelen, <sup>9</sup> Olga Flegontova, <sup>15,16</sup> Lionel Guidi, <sup>17,18</sup> Aleš Horák, <sup>15,16</sup> ipsi Lima-Mendez, <sup>19,20</sup> Julius Lukeš, <sup>20,15,27</sup> Shrutti Malviya, <sup>21</sup> Matthieu Maillet, <sup>22</sup> Eleonora Scalo, <sup>23</sup> Raffaele Siano, <sup>24</sup> ana Zingone, <sup>25</sup> Céline Dimier, <sup>1,2,3</sup> Marc Picheral, <sup>17,18</sup> fanie Kandels-Lewis, <sup>25,26</sup> Tara Oceans Coordinators; Bork, <sup>23,27</sup> Chris Bowler, <sup>8</sup> Gabriel Gorsky, <sup>17,18</sup> Nigel Grimsley, <sup>28,29</sup> aiele Iudicone, <sup>25</sup> Fabrice Not, <sup>1,2</sup> Hiroyuki Ogata, <sup>21</sup> Ieron Raes, <sup>21,13,15</sup> Michael E. Sieracki, <sup>20,23</sup> Sabrina Speich, <sup>20,28</sup> linchi Sumagawa, <sup>21</sup> Jean Weissenbach, <sup>9,10,29</sup> Eric Karsenti<sup>26,30</sup>



# A new world of marine protists



Diplonemids are the most diverse eukaryotic group in the ocean



Current Biology  
**Report**

**Morphological Identification and Single-Cell Genomics of Marine Diplonemids**

Ryan M.R. Gawryluk,<sup>1,\*</sup> Javier del Campo,<sup>1</sup> Noriko Okamoto,<sup>1</sup> Jürgen F.H. Strassert,<sup>1</sup> Julius Lukes,<sup>2,3</sup> Thomas A. Richards,<sup>3,4</sup> Alexandra Z. Worden,<sup>3,5</sup> Alyson E. Santoro,<sup>3,6</sup> and Patrick J. Keeling<sup>1,3,7,\*</sup>

CellPress

CellPress

Current Biology  
**Report**

**Extreme Diversity of Diplonemid Eukaryotes in the Ocean**

Olga Flegontova,<sup>1,2,11</sup> Pavel Flegontov,<sup>1,4,11</sup> Shruti Malviya,<sup>3,11,12</sup> Stephane Audic,<sup>5,6</sup> Patrick Wincker,<sup>7,8,9</sup> Colomban de Vargas,<sup>2,6</sup> Chris Bowler,<sup>3</sup> Julius Lukes,<sup>1,2,10</sup> and Ales Horak<sup>1,2,13,\*</sup>

OCEAN PLANKTON

**Eukaryotic plankton diversity in the sunlit ocean**

Colomban de Vargas,<sup>1,2,\*</sup> Stéphane Audic,<sup>1,2</sup> Nicolas Henry,<sup>1,2</sup> Johan Decelle,<sup>1,2</sup> Frédéric Mahé,<sup>3,12</sup> Ramiro Logares,<sup>4</sup> Enrique Lara,<sup>4</sup> Cédric Berney,<sup>1,2</sup> Noan Le Besoc,<sup>1,2</sup> Ian Probert,<sup>5,7</sup> Margaux Carmichael,<sup>1,2,8</sup> Julie Poulain,<sup>9</sup> Sarah Romac,<sup>1,2</sup> Sébastien Colin,<sup>1,2,6</sup> Jean-Marc Aury,<sup>9</sup> Lucie Bittner,<sup>10,11,8,1,2</sup> Samuel Chaffron,<sup>12,13,14</sup> Michal Dunthorn,<sup>2</sup> Stefan Engelen,<sup>9</sup> Olga Flegontova,<sup>11,16</sup> Lionel Guidi,<sup>17,18</sup> Ales Horak,<sup>11,14</sup> Olivier Jaillon,<sup>20,20,20</sup> Gipsi Lima-Mendez,<sup>20,20</sup> Julius Lukes,<sup>10,15,20</sup> Shruti Malviya,<sup>2</sup> Raphael Morard,<sup>22,15</sup> Matthieu Mulot,<sup>2</sup> Eleonora Scalo,<sup>22</sup> Raffaele Siano,<sup>24</sup> Flora Vincent,<sup>12,8</sup> Adriana Zingone,<sup>23</sup> Céline Dimier,<sup>1,2,8</sup> Marc Picheral,<sup>17,18</sup> Sarah Seaton,<sup>17,18</sup> Stefanie Kandel-Lewis,<sup>25,26</sup> Tara Oceans Coordinators; Silvia G. Acinas,<sup>4</sup> Peer Bork,<sup>23,27</sup> Chris Bowler,<sup>3</sup> Gabriel Gorsky,<sup>17,18</sup> Nigel Grimsley,<sup>28,29</sup> Pascal Hingamp,<sup>20</sup> Daniele Iudicone,<sup>23</sup> Fabrice Not,<sup>1,2</sup> Hiroyuki Ogata,<sup>21</sup> Stéphane Pesant,<sup>20,22</sup> Jeroen Raes,<sup>21,13,14</sup> Michael E. Sieracki,<sup>20,22</sup> Sabrina Speich,<sup>20,20</sup> Lars Stemann,<sup>17,18</sup> Shintehi Sunagawa,<sup>22</sup> Jean Weissenbach,<sup>9,10,20</sup> Patrick Wincker,<sup>9,10,20</sup> Eric Arsenti<sup>26,6</sup>

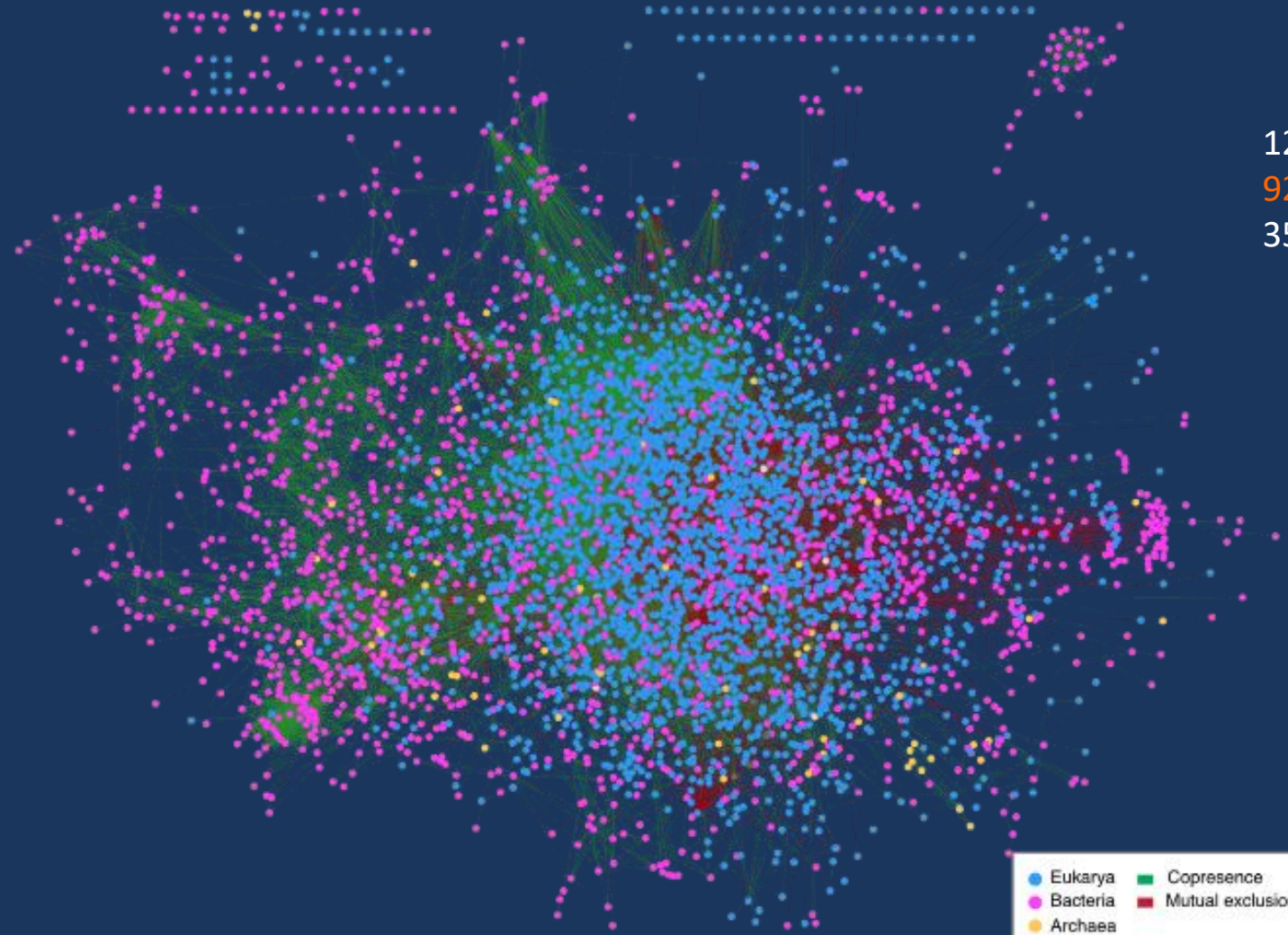


# Defining the plankton interactome in the global ocean

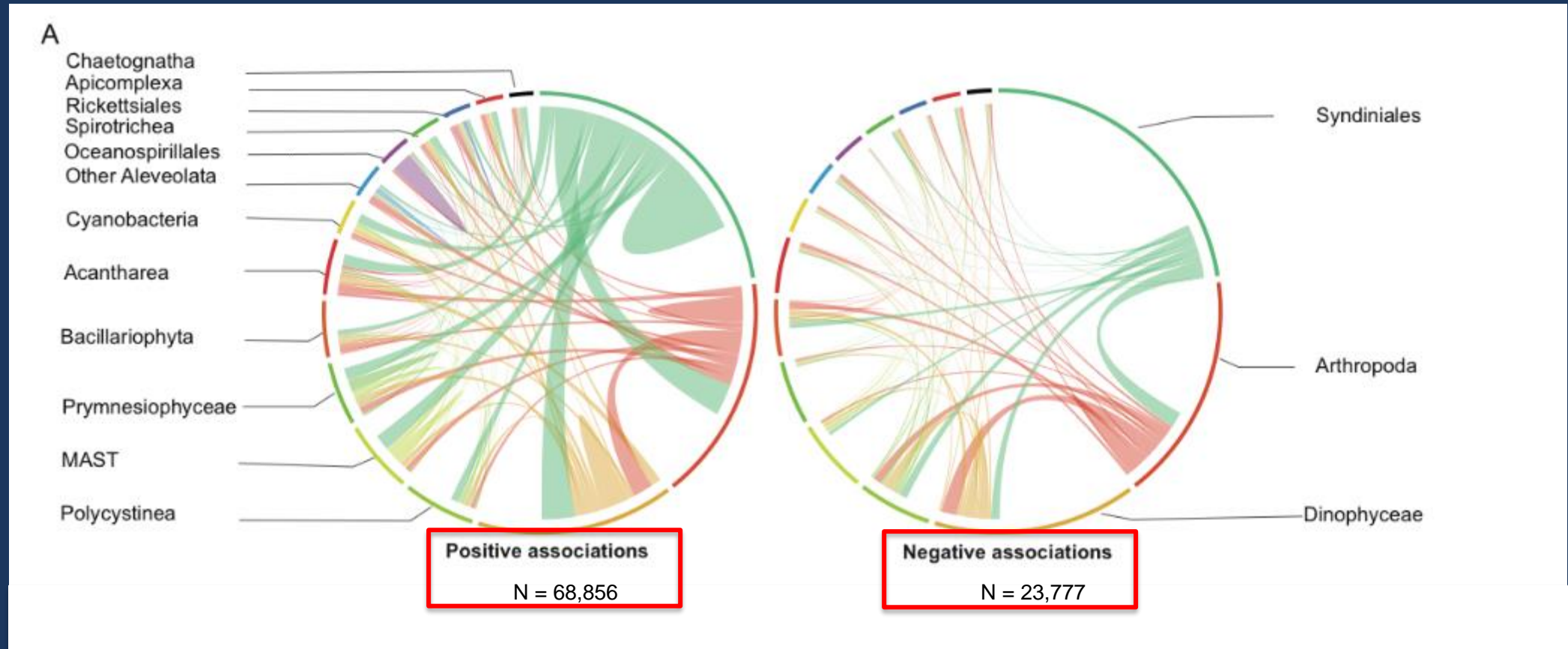
a.k.a The Ocean's 



# The global plankton interactome – an integrated “network of networks”



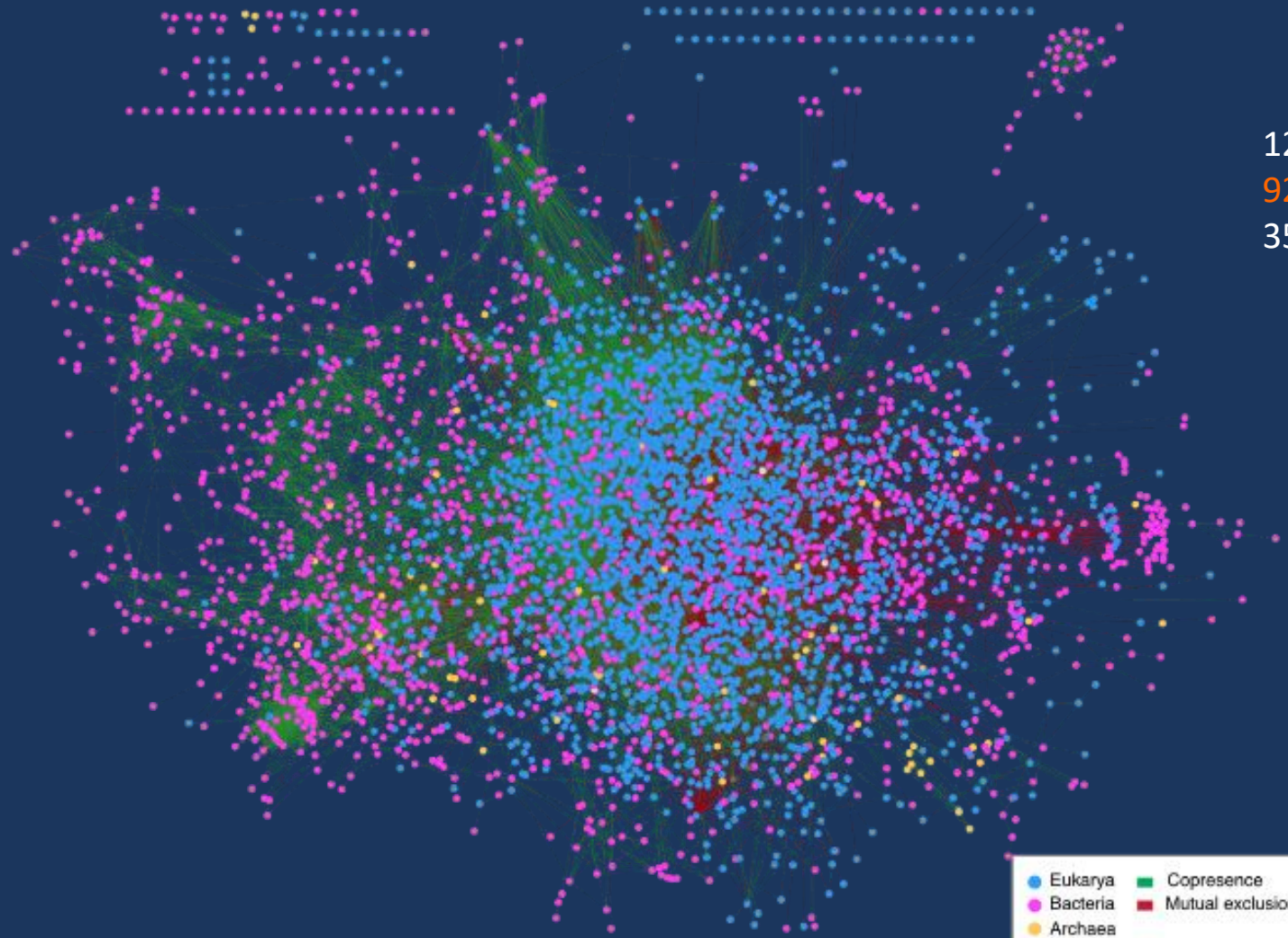
# Most interactions are positive ...



Cooperation is more important than competition



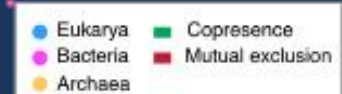
# The global plankton interactome – a playground to discover new interactions



127,995 associations

92,633 taxon-taxon

35,362 taxon-env

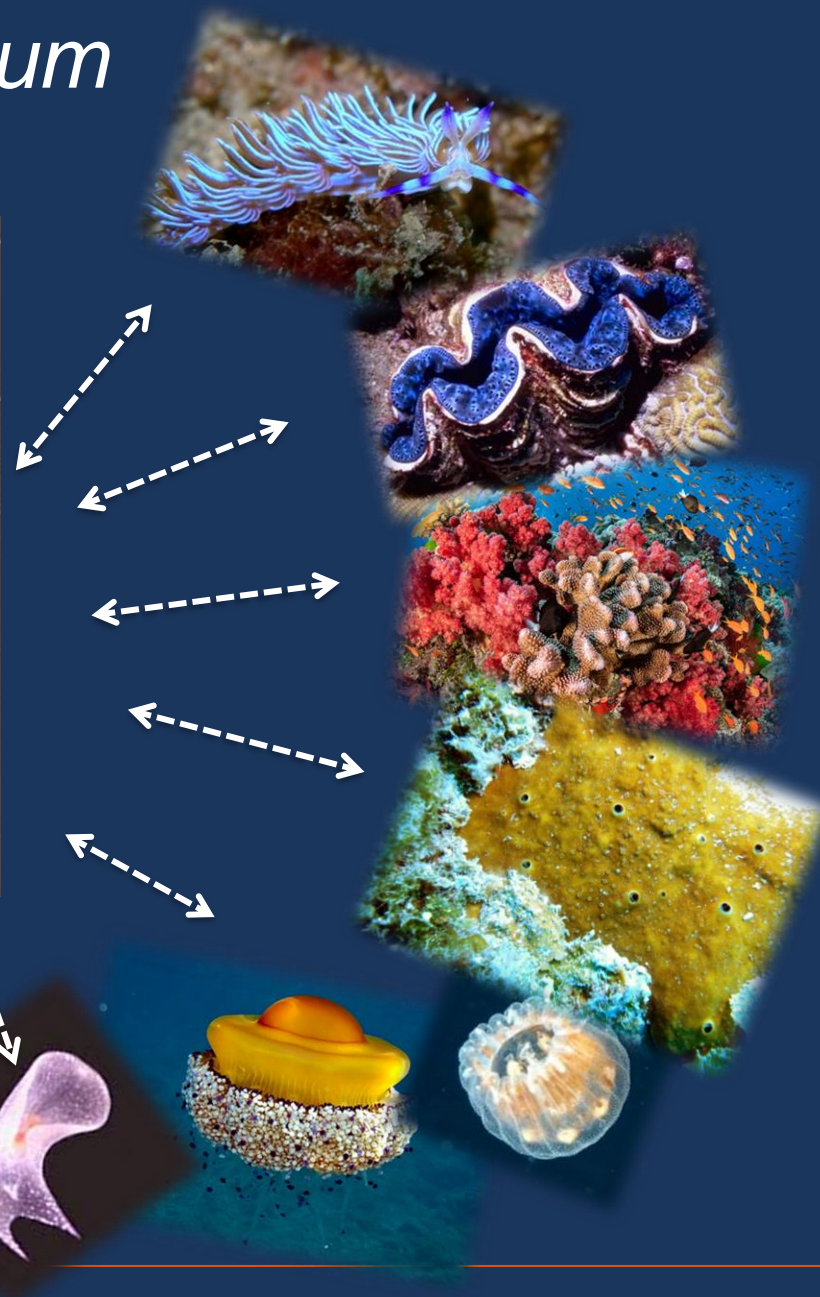


OCEAN PLANKTON

### Determinants of community structure in the global plankton interactome

Gipsi Lima-Mendez,<sup>1,2,3\*</sup> Karoline Faust,<sup>1,2,3\*</sup> Nicolas Henry,<sup>4,5\*</sup> Johan Decelle,<sup>6,7</sup> Sébastien Collin,<sup>8,9\*</sup> Fabrizio Carillo,<sup>10,11</sup> Samuel Chaffron,<sup>12,13</sup> J. Cesar Ignacio-Espinoza,<sup>14</sup> Simon Roux,<sup>15</sup> Flora Vincent,<sup>16</sup> Lucie Bittner,<sup>17,18,19</sup> Youssef Darzi,<sup>20</sup> Jun Wang,<sup>21</sup> Stéphane Audic,<sup>22</sup> Léo Berline,<sup>23,24</sup> Gianluca Bontempi,<sup>25</sup> Ana M. Cabello,<sup>26</sup> Laurent Coppola,<sup>27,28</sup> Francisco M. Cornejo-Castillo,<sup>29</sup> Francesco d'Ovidio,<sup>30</sup> Luc De Meester,<sup>31</sup> Isabel Ferrera,<sup>32</sup> Marie-José Garret-Delmas,<sup>33</sup> Lionel Guillard,<sup>34,35</sup> Elena Lara,<sup>36</sup> Stéphane Pesenti,<sup>37,38</sup> Marta Royo-Llonch,<sup>39</sup> Guillen Salazar,<sup>40</sup> Pablo Sánchez,<sup>41</sup> Marta Sebastian,<sup>42</sup> Caroline Souffran,<sup>43</sup> Céline Dimier,<sup>44,45</sup> Marc Pezard,<sup>46,47</sup> Sarah Seaton,<sup>48,49</sup> Stefanie Kandels-Lewis,<sup>50,51</sup> Tara Oceans coordinators; Gabriel Gorsky,<sup>52,53,54</sup> Fabrice Not,<sup>55</sup> Hiroyuki Ogata,<sup>56</sup> Sabrina Speich,<sup>57,58</sup> Lars Stemann,<sup>59,60</sup> Jean Weisenbach,<sup>61,62</sup> Patrick Wincker,<sup>63,64</sup> Sylvia G. Achen,<sup>65</sup> Shinichi Sunagawa,<sup>66</sup> Peer Bork,<sup>67,68</sup> Matthew R. Sullivan,<sup>69</sup> Eric Karsenti,<sup>70,71</sup> Chris Bowler,<sup>72</sup> Colomán de Vargas,<sup>73,74</sup> Jeroen Raaij,<sup>75,76</sup>

# The super symbiont *Symbiodinium*

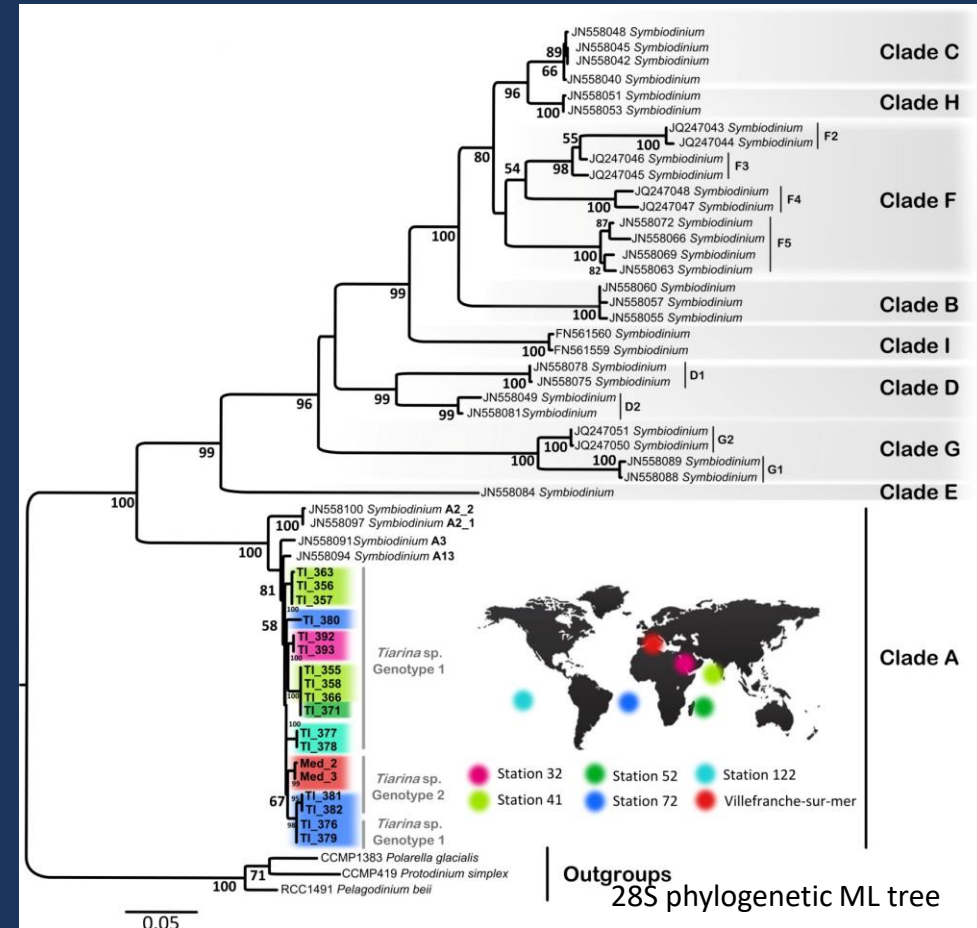
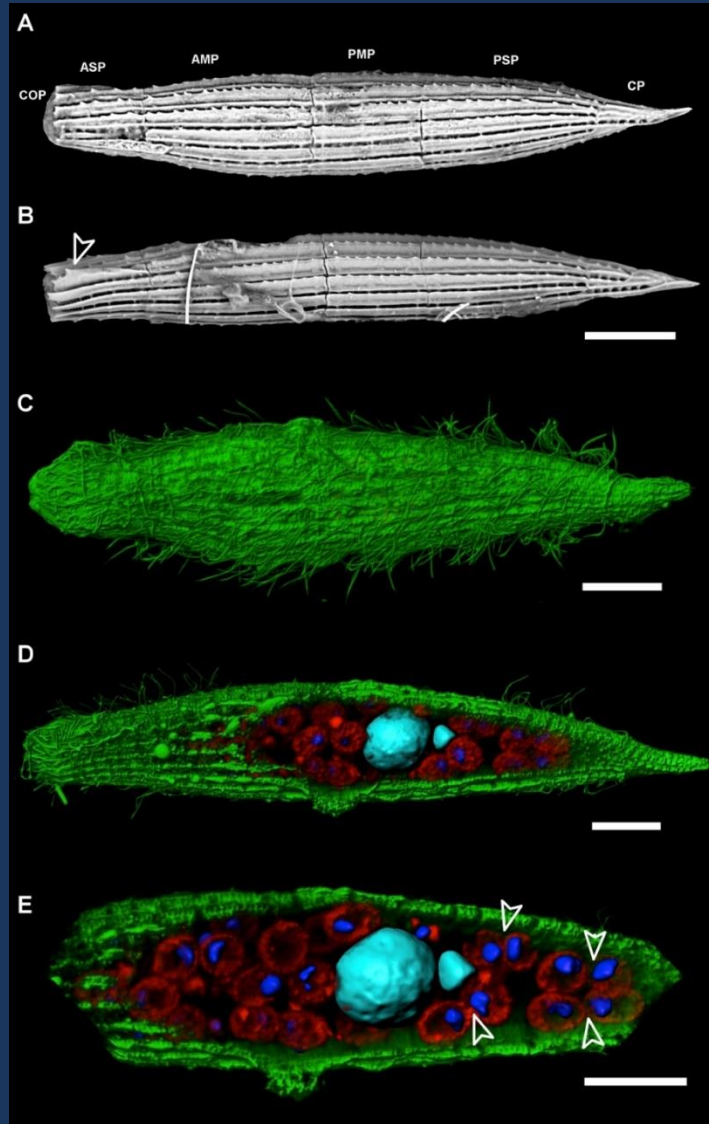


→ Do we find *Symbiodinium* in symbiosis with plankton ?



# Symbiodinium in symbiosis with a planktonic ciliate

...widely distributed in the ocean



## The *Tara*'s inspiring 20 years at sea

**A research ship's voyages to understand marine biodiversity show how visionary thinking can boost understanding of the natural world – and help to better preserve it.**

Scientists have known for decades that the biodiversity we know is a fraction of the biodiversity that exists. Even when it comes to perhaps the simplest measure, the number of species, researchers estimate that there could be anywhere between 3 million and 100 million species, of which some 1.7 million have been described. Every year, the names of some 10,000 new ones get added to the list.

Gathering good biodiversity data can be a mission in itself, especially on marine biodiversity. One dependable source is a schooner called *Tara*, which celebrates 20 years at sea as a research ship this year. *Tara* has been to the Arctic Ocean and the Mediterranean Sea. Last week, researchers reported the results of its latest voyage, Tara Pacific, a two-year expedition across the Pacific Ocean, published in a collection of articles in Springer Nature journals ([go.nature.com/45puzhk](https://go.nature.com/45puzhk)).

Coral reefs are among Earth's most diverse ecosystems, supporting 25% of marine life and providing services such as food, jobs and coastal protection to nearly one billion people worldwide. One region of the Pacific, the Coral Triangle – which includes the waters of Indonesia, Malaysia and the Philippines – has around 75% of the world's coral species. But these nurseries for marine life are under threat: globally, around 50% of living corals have been lost since the 1950s (T. D. Eddy *et al.* *One Earth* **4**, 1278–1285; 2021). Moreover, climate change poses a large risk to their continued survival.

One of Tara Pacific's research groups has been focusing on genetic diversity – in particular, that of microbial communities (bacteria and archaea) living in Pacific Ocean corals. The scientists, led by marine microbiologist Pierre Galand at the Banyuls Oceanological Observatory in Banyuls-sur-Mer, France, collected more than 5,000 samples, and focused on analysing the 16S ribosomal DNA marker gene, which is used to identify and classify microorganisms. They found around half a million distinct DNA sequences known as amplicon sequence variants (ASVs), which can be used as a measure of the genetic diversity in a sample (*Nature* <https://doi.org/kddz>; 2023). From these data, the researchers estimated that the microbial diversity of coral reefs globally is probably around 2.8 million ASVs (P. E. Galand *et al.* *Nature Commun.* **14**, 3039; 2023). For comparison, this is close to the lower end of one genetic-diversity estimate of all of Earth's bacterial and archaeal communities – a proposed range of 2.72 million and 5.44 million ASVs (S. Louca *et al.* *PLoS Biol.* **17**, e3000106; 2019). Galand and his colleagues' work, which



The *Tara* during its 100,000-kilometre voyage around the Pacific Ocean.

**“The research has a stirring and unusual back story.”**

builds on smaller-scale studies of coral reefs (M. Chiarello *et al.* *Proc. R. Soc. B* **287**, 20200642; 2020), confirms that Earth's microbial genetic diversity is much higher and richer than previously thought.

The research ship has a stirring and unusual back story. Its original captain was Peter Blake, a much-decorated professional yachtsman from New Zealand. After retirement, Blake became an environmental envoy to the United Nations but was killed by pirates at the mouth of the Amazon River while on an expedition in 2001. Agnès Troublé, a French fashion designer known as Agnès B, and her son Etienne Bourgois acquired the boat, determined to continue Blake's original vision. They established the Tara Ocean Foundation and invited scientists and research funders to join them on various missions.

The logistics of converting a schooner into a floating laboratory and taking it on a 100,000-kilometre journey cannot be underestimated, especially considering the present complicated relations between Pacific nations. And then there's the logistics of the research itself: organizing 3,000 dives; sending samples for PCR analysis en route; keeping the voyage on track.

Researchers must continue to build on the work being reported and refine our understanding of the importance of diversity for safeguarding ecosystem stability and function. The project is a great example of visionary thinkers such as Troublé and Bourgois working closely with funders and scientists to help us to understand the breathtaking diversity of the world around us before it is too late. When it comes to preserving the natural systems we all depend on, more such collaborations are needed.

FRANÇOIS AUBRY/TARA OCEAN FOUNDATION



**TARA OCEANS**



A large research vessel, the R/V Tara, is shown from a front-quarter perspective, sailing on a calm sea. The ship's hull is white with a prominent orange stripe and the word "TARA" written in blue. The vessel has a complex rigging system with multiple masts and a large white sail. The background is a clear, light blue sky. A semi-transparent grey horizontal band is overlaid across the middle of the image, containing the title text.

*Tara* Oceans  
and climate change

# *Homo sapiens* – the superpower








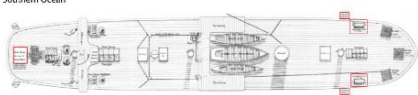

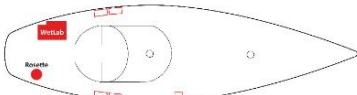
# *Tara* Oceans and climate change

- ✓ Digging into the past - Evidence for effects of ocean acidification





# Evidence of the effects of ocean acidification on marine ecosystems ?

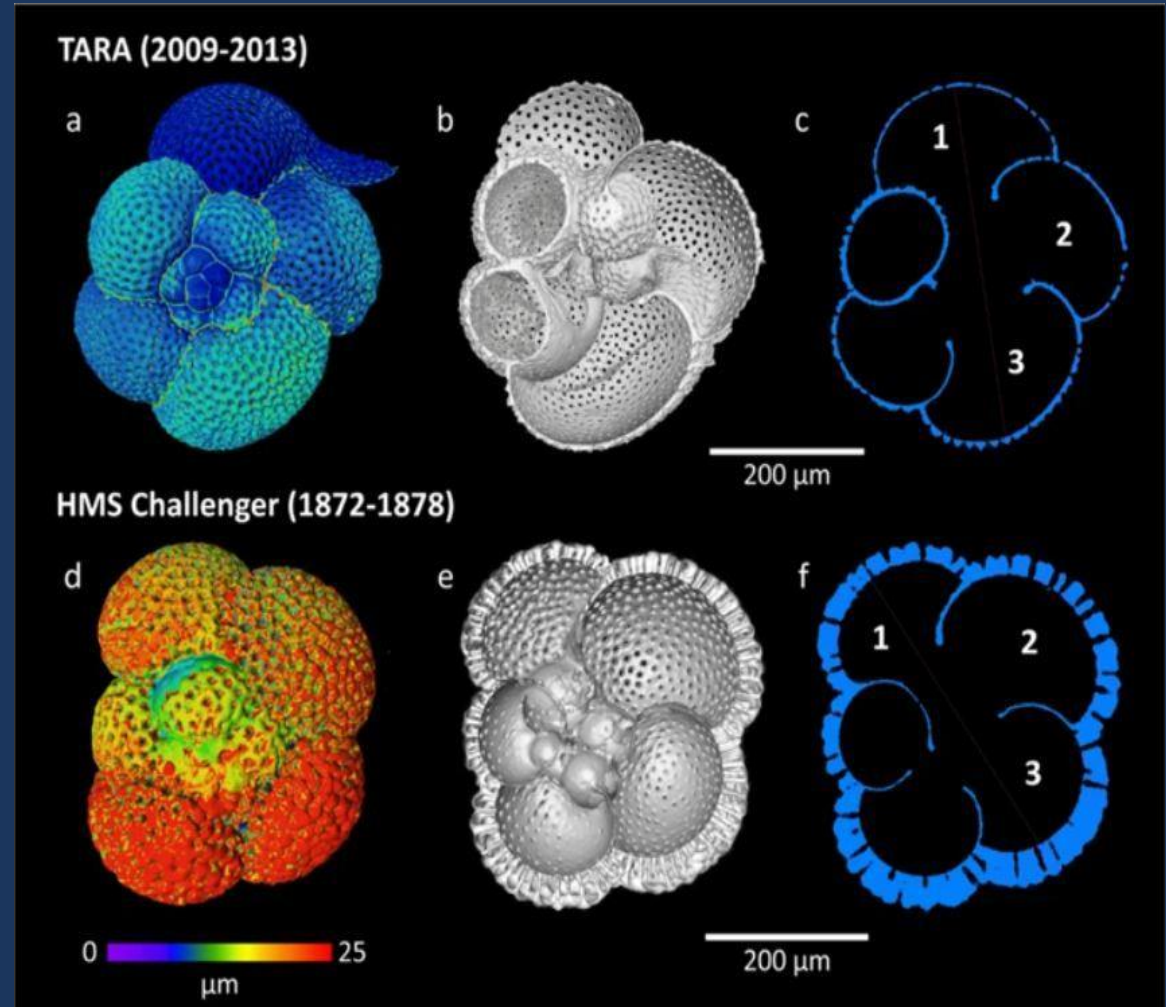
 <p>John Steven Dews (b.1941) H.M.S. Challenger in Royal Sound, Kerguelen Island, in the Southern Ocean</p>	<p><b>Name:</b> HMS Challenger <b>Builder:</b> Woolwich Dockyard <b>Launched:</b> 13 February 1858</p> <p><b>Equipage</b> Crew: 243</p> <p><b>General characteristics</b> Length: 68.66 m Beam: 12.29 m Depth of hold: 7.29 m Displacement: 2,137 tons Sails: 777 m<sup>2</sup></p> 	 <p>Yann Chavance 2018 Tara V, Clipperton Island, in the Pacific Ocean</p>	<p><b>Name:</b> Tara <b>Builder:</b> SFCN Bouvet - Petit <b>Launched:</b> 10 May 1989</p> <p><b>Equipage</b> Crew: 16</p> <p><b>General characteristics</b> Length: 36 m Beam: 10 m Depth of hold: 2.50 à 3.50 m Displacement: 130 tons Sails: 400 m<sup>2</sup></p> 
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Foraminifera calcification has decreased in the last 150 years

**SCIENTIFIC REPORTS**  
nature research

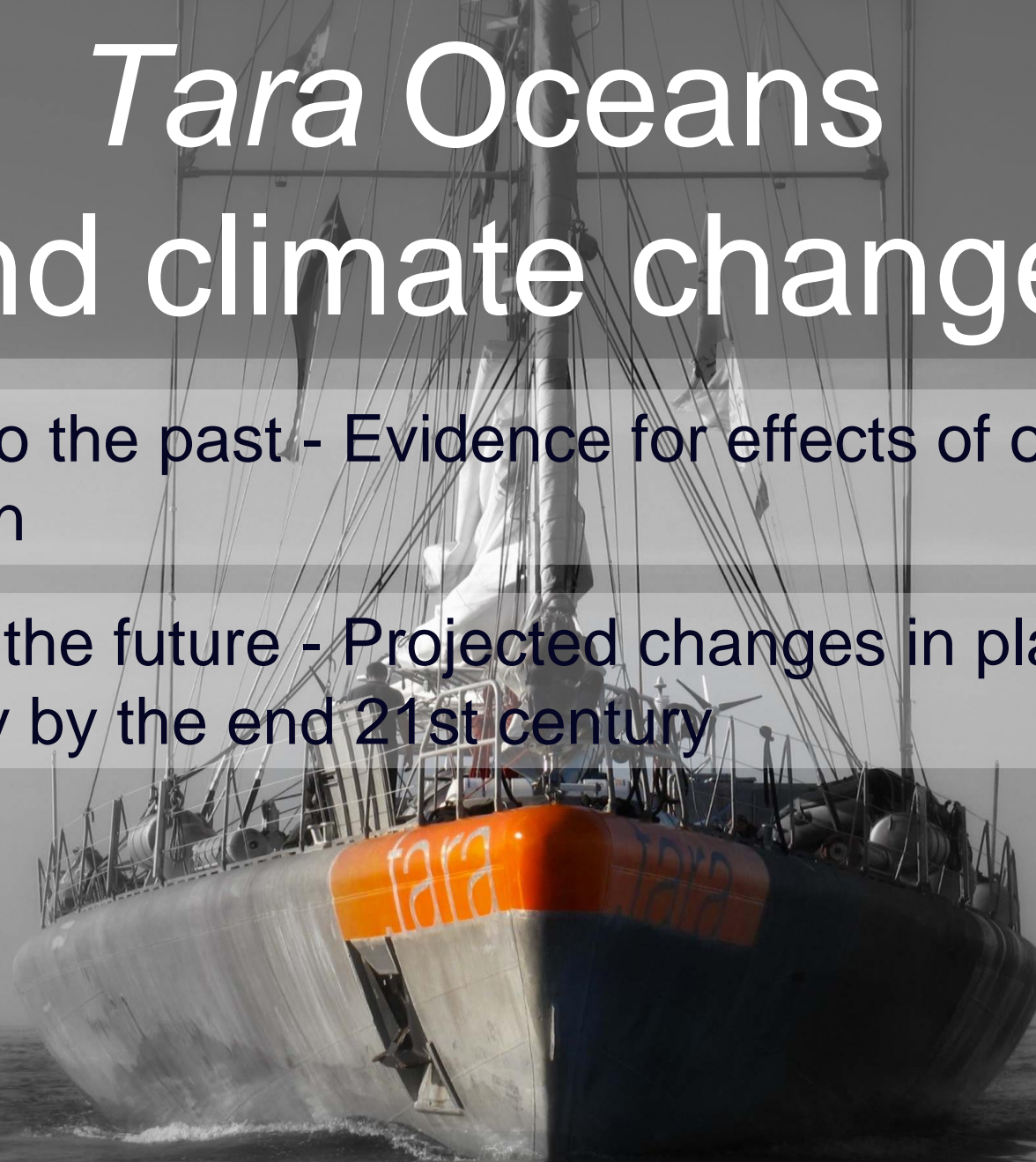
**Quantifying the Effect of Anthropogenic Climate Change on Calcifying Plankton**

Lyndsey Fox<sup>1,2\*</sup>, Stephen Stukins<sup>1\*</sup>, Thomas Hill<sup>1,3</sup> & C. Giles Miller<sup>1,4</sup>



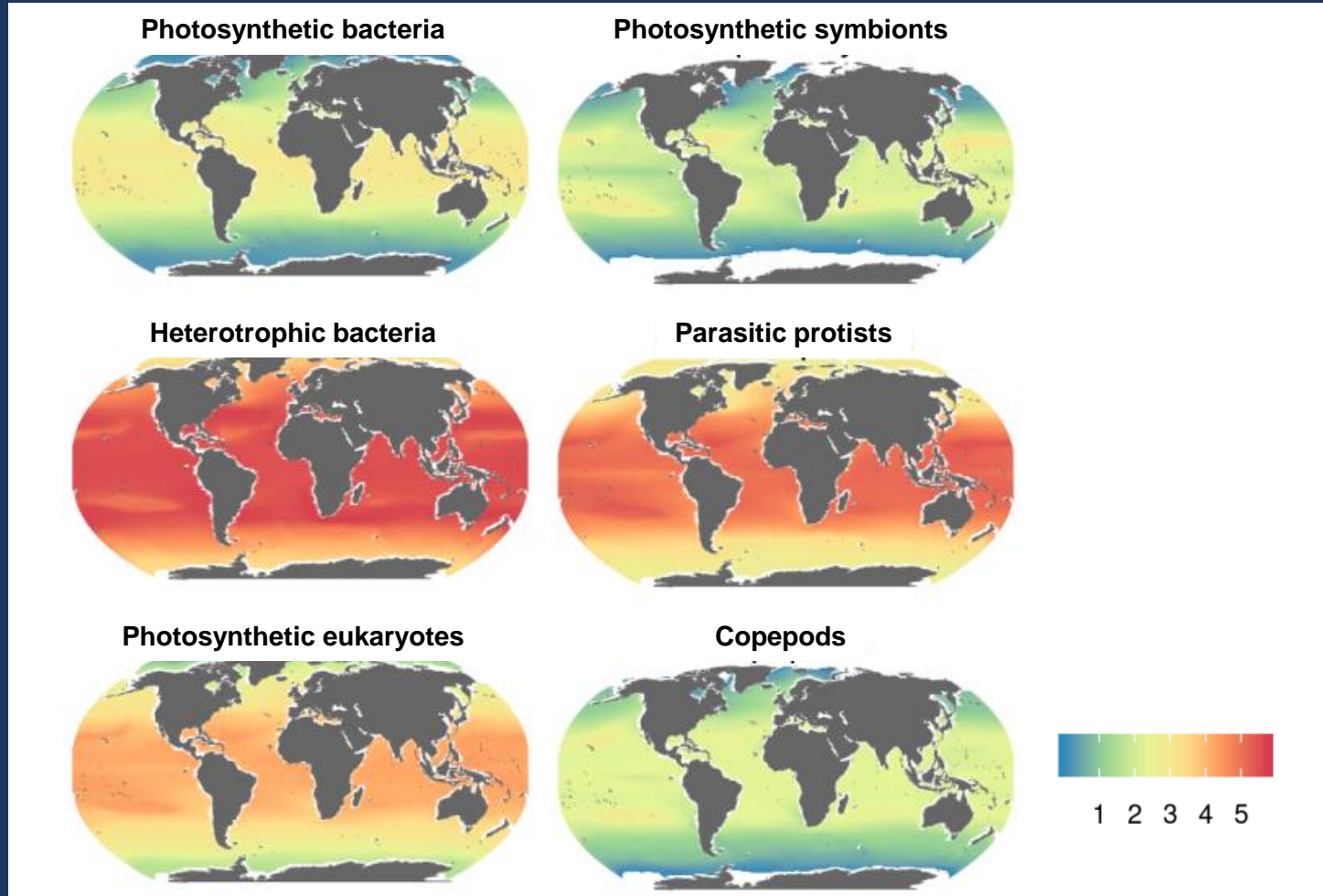
# *Tara* Oceans and climate change

- ✓ Digging into the past - Evidence for effects of ocean acidification
- ✓ Looking to the future - Projected changes in plankton biodiversity by the end 21st century





# Current patterns of diversity of major plankton functional groups

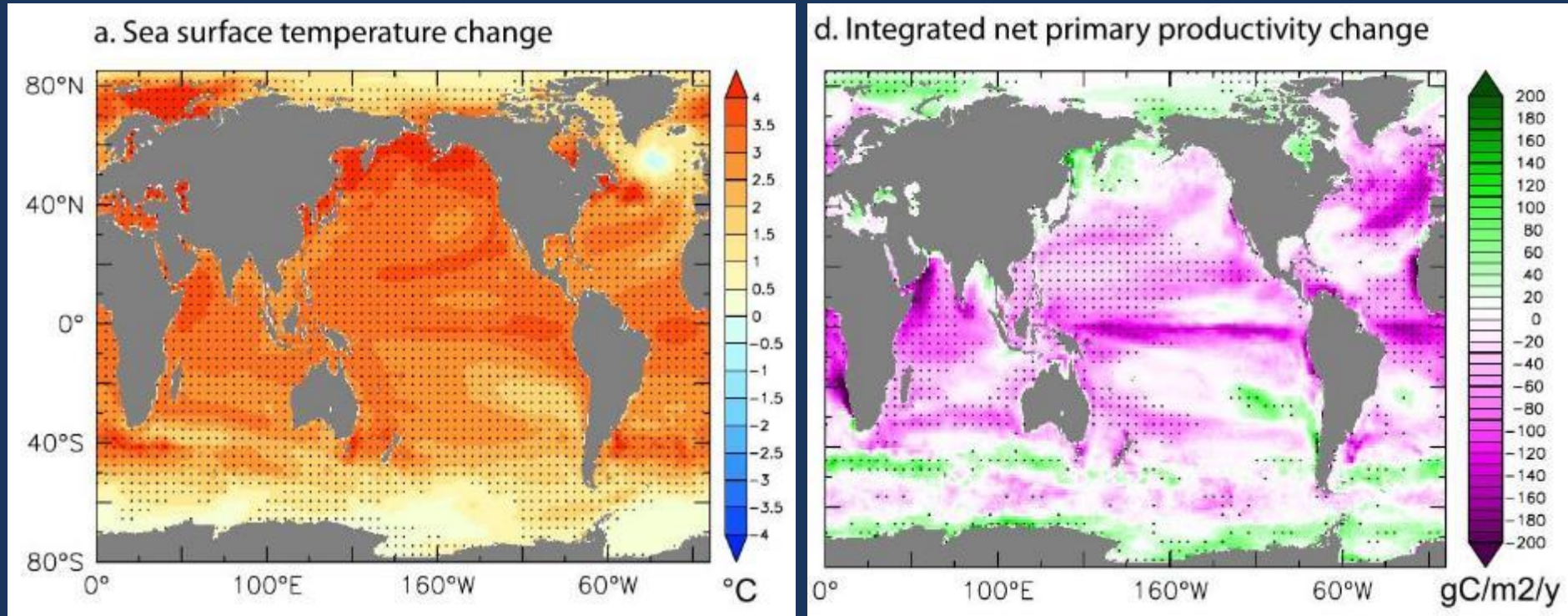


Six plankton functional groups have highly explanatory GAMs



Cell Article  
**Global Trends in Marine Plankton Diversity across Kingdoms of Life**  
Federico M. Ibarbalz,<sup>1</sup> Nicolas Henry,<sup>2,3</sup> Manoela C. Brandão,<sup>4</sup> Séverine Martini,<sup>4</sup> Greta Bussenel,<sup>5</sup> Hannah Byrne,<sup>6</sup> Luis Pedro Coelho,<sup>7</sup> Hisashi Endo,<sup>8</sup> Josep M. Gasol,<sup>8,10</sup> Ann C. Gregory,<sup>11</sup> Frédéric Mahé,<sup>12,13</sup> Janaina Rigonato,<sup>14</sup> Marta Royo-Llonch,<sup>15</sup> Guillem Salazar,<sup>16</sup> Isabel Sanz-Sáez,<sup>16</sup> Eleonora Scalco,<sup>17</sup> Dodi Sovladan,<sup>18</sup> Ahmed A. Zayed,<sup>11</sup> Adriana Zingone,<sup>9</sup> Karine Labadie,<sup>19</sup> Joannie Forland,<sup>17</sup> Claude Marec,<sup>17</sup> Stefano Kandel,<sup>18,19</sup> Marc Picheral,<sup>1</sup>

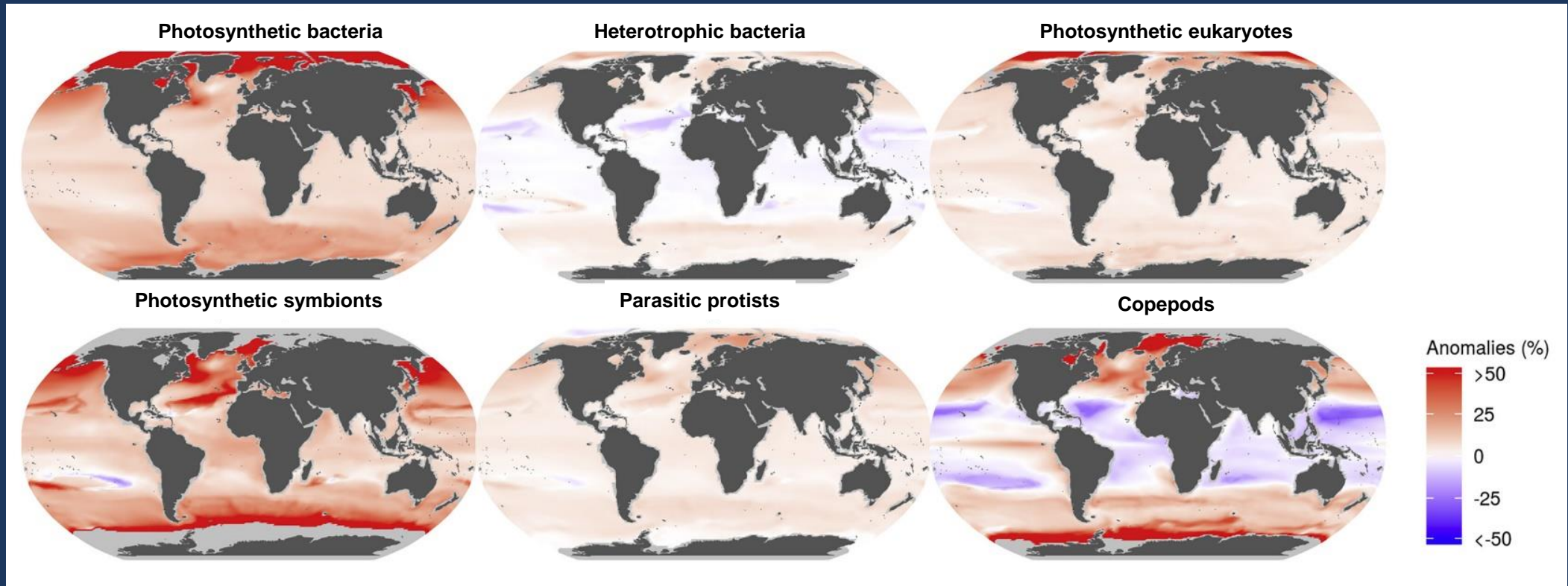
# Projected changes in ocean temperatures and primary productivity by 2100



IPCC CMIP<sub>5</sub> model outputs  
Bopp et al. 2013  
Dots show areas of highest certainty



# Projected diversity anomalies by end of 21<sup>st</sup> century



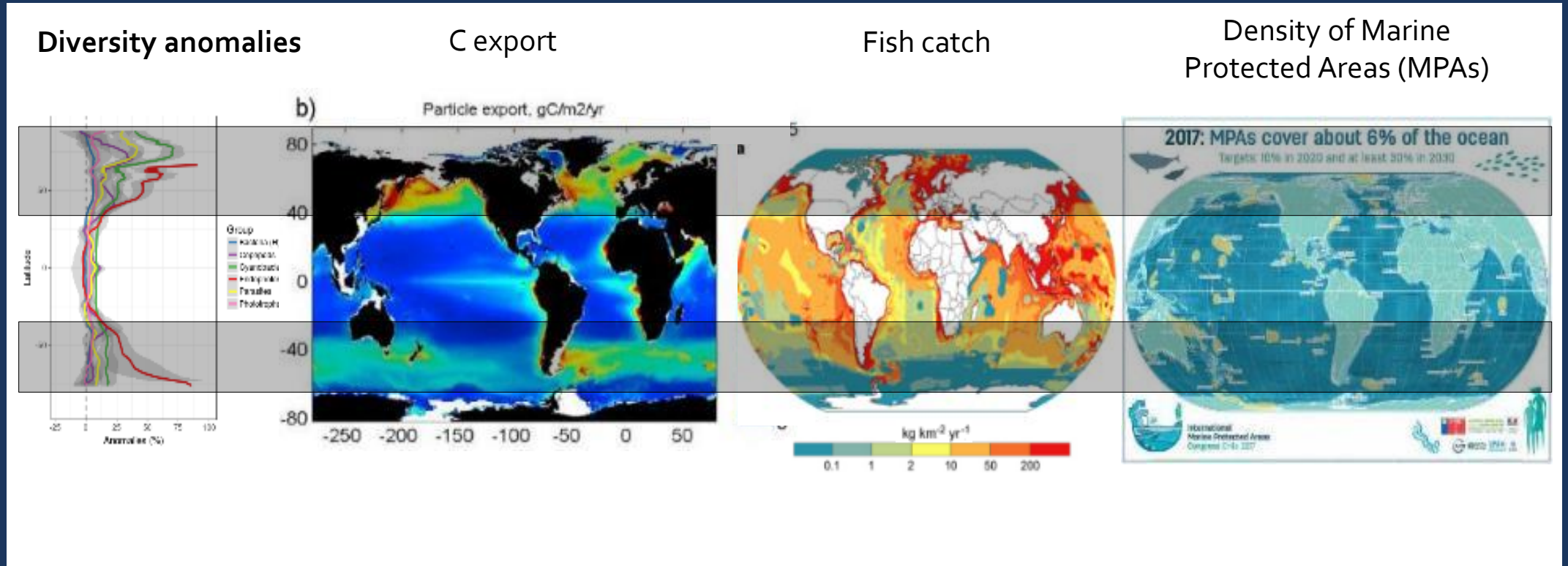
Cell

Article

## Global Trends in Marine Plankton Diversity across Kingdoms of Life

Federico M. Ibarbalz,<sup>1</sup> Nicolas Henry,<sup>2,3</sup> Manoela C. Brandão,<sup>4</sup> Séverine Martini,<sup>5</sup> Greta Bussenel,<sup>6</sup> Hannah Byrne,<sup>6</sup> Luis Pedro Coelho,<sup>7</sup> Hisashi Endo,<sup>8</sup> Josep M. Gasol,<sup>9,10</sup> Ann C. Gregory,<sup>11</sup> Frédéric Mahé,<sup>12,13</sup> Janaina Rigonato,<sup>14</sup> Marta Royo-Llonch,<sup>15</sup> Guillem Salazar,<sup>16</sup> Isabel Sanz-Sáez,<sup>17</sup> Eleonora Scalco,<sup>18</sup> Dodi Soviadan,<sup>19</sup> Ahmed A. Zayed,<sup>11</sup> Adriana Zingone,<sup>20</sup> Karine Labadie,<sup>11</sup> Joannie Ferland,<sup>17</sup> Claudie Marce,<sup>7</sup> Stefanie Kandels,<sup>18,19</sup> Marc Picheral,<sup>1</sup>

# Projected effects of diversity changes on marine ecosystems, fisheries, and biogeochemical cycles





# The *Tara* Oceans multiverse

- ✓ Our eco-systems biology approach has shed light on a complex invisible ecosystem at global scale
- ✓ Multiple new discoveries have been made about ocean life, together with a wealth of open-access resources
- ✓ Provides a baseline for understanding the effects of climate change on marine ecosystems



EMBL



# TARA OCEANS



**INSTITUTIONS**

- CNRS, EMBL, CEA, ANR, ENS, UPMC, VIB, MIT, NASA, ICM, CSIC, 京都大学, 中国科学院, 中国科学院, Aix-Marseille, MAINE, Bigelow, RESEARCH

**LABORATORIES**

- Station Biologique de Roscoff, LOCEAN, veolia, TAKUVIK, EMBL-EB, etc.

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**20** YEARS

**FOR THE OCEAN**

