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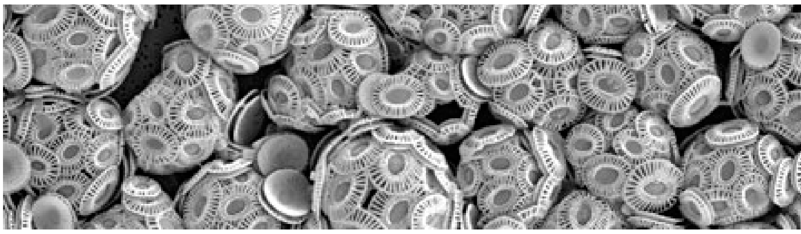
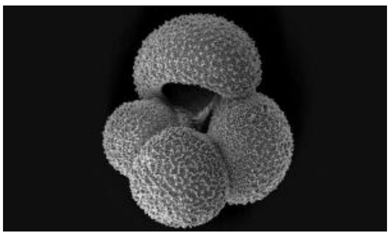
The Significance and Management of Natural Carbon Stores in the Open Ocean

A summary

November 2014





We manage land and the coasts for carbon – so why not the ocean as well?

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Cover photos (clockwise from top): Antarctic (John Weller); globally distributed coccolithophore *Emiliania huxleyi* (Gustaaf Hallegraeff UTAS); floating *Sargassum* sp. in the Gulf of Mexico (Sylvia Earle); shell of the foraminifera *Globigerina bulloides* (Andrew Moy AAD); and adult Antarctic krill (Rob King).

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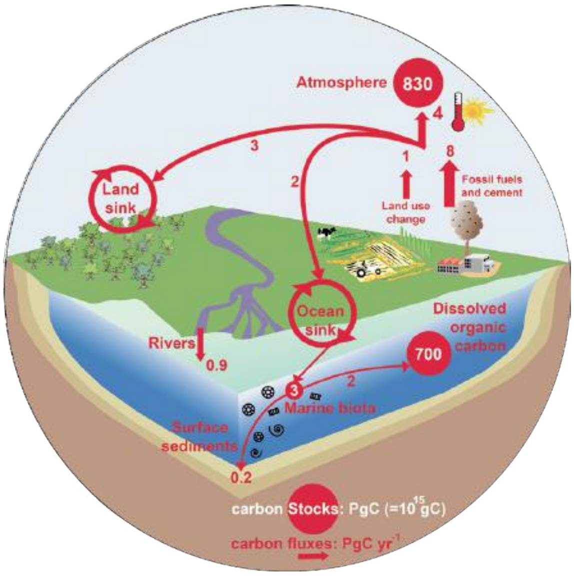
Introducing open ocean carbon sinks and stores

The report has been produced to promote better understanding of how atmospheric carbon is captured, stored and mobilized in the ocean, and how this has a significant bearing on sustainability, the welfare of people, and the future scale and intensity of climate change and ocean acidification. This work focuses on the open ocean, which is often referred to in the literature as the largest carbon sink on Earth. Whilst there has been a significant effort on managing carbon in natural environments on land, in places such as forests and peatlands, the open ocean has to date been largely ignored but is now responding to the full impact of the consequences of our activities.



The global carbon cycle

The last 10 years have seen an increased interest in nature-based solutions to climate change – both for mitigation and adaptation. In particular in recent years significant progress has been made through the Reducing Emissions from Deforestation and Forest Degradation agenda (REDD+), as well as similar initiatives in the coastal zone, although many challenges remain. This lends impetus to the need to better understand and assess the carbon value of the open ocean, and potentially whether and how such ocean ecosystems might be managed directly, wholly or in part, as carbon sinks, or indirectly through better management of human activities that are driving changes to the marine environment. An understanding of the consequences of existing human impacts affecting carbon processes in the open ocean is similarly needed, especially given the feedback loops that are potentially exacerbating current levels of climate change, and the strong potential to continue to do so in the future.

To create this report we asked leading ocean scientists for their perspectives on ocean carbon. The report sets out their views using examples and through this work illustrates the significance and values of some of its major carbon pools and sinks. Their analysis ranges from a focus on microscopic organisms in the plankton that drive the biological pump that take CO_2 out of the air and ultimately trap a proportion as solid carbon permanently in the sediments of the deep ocean, through to groups of animals, which perhaps hitherto have not been considered as very relevant in carbon management, such as krill and fish – and in so doing introduces the notion of 'mobile carbon units'. The report ranges in its attention from the surface waters, where carbon capture is powered by photosynthetic activities, through to the deep ocean. It describes the role and importance of deep-sea microbes, and the recently discovered, increasingly important chemosynthetic pathways through which carbon is converted in the deep dark ocean to organic matter.

This report has been created to address the policy gap in broad scale understanding that exists on the role of the open ocean and its associated carbon stores by describing readily recognizable features of the open ocean ecosystem that have important roles to play in the carbon cycle. This approach provides compelling ways to tell the story and to make it real and meaningful to people. The report reviews and synthesizes the latest scientific information and presents it in a format suitable for informing and influencing ocean planning, management and governance. In particular it is aimed at enhancing awareness in decision making on the impact of human exploitation on ocean carbon sinks and carbon pools, on the ocean's ability to buffer climate change, and on possible actions to safeguard and enhance these functions.

The report attempts for the first time to take stock of and, to the extent possible, quantify the amount of CO_2 that certain key features of ocean ecosystems sequester (carbon sinks) and hold (carbon pools – net productivity). It highlights the role these key features play in natural global carbon management thus dispelling the widely held belief that focusing on forest and peatland management alone will save the day. The report also tries to provide an understanding of the consequences for carbon in the ocean through current feedback loops to climate change, and the influence human actions have on such processes. The latter being a consequence of degradation or changes resulting from human impacts coupled with poor management. This is as much about promoting reasoned, prudent ocean management as about specific tangible steps that can be taken. Finally this new report attempts to promote an understanding of whether, and if so how, features of ocean ecosystems can be enhanced through focused management and stewardship. Are there things we should be doing or should avoid doing to better 'manage' our interactions with specific components of ocean carbon, e.g. fisheries? The net result of this should be a greater policy and legislative respect for how the ocean supports and contributes to sustaining all life on Earth.

This report has three broad target audiences:

- Scientists focusing on oceanic ecosystems and in particular carbon pools and sinks who are involved directly in research activities and are both the primary source and beneficiaries of new scientific findings, and it is hoped that this report will trigger debate, and inspire the identification of key research priorities.
- Government advisers and decision-makers, as well as climate change planners and policy makers who can benefit from enhanced awareness about the ecosystem services provided by the open ocean. This is particularly in relation to its role in the carbon cycle, how this can be better recognized through protection, management, restoration, positive and negative feedback loops to climate change, and actions needed to avoid further significant disruption of carbon processes and stores arising from the impact of human activities on specific aspects, in so far as this can/could be achieved.
- Those responsible for ocean stewardship who can similarly gain knowledge that can improve management of habitats and species in the open ocean. In addition, awareness raising activities will also benefit conservation-minded NGOs and companies working on climate change mitigation or those that need to address their 'carbon footprint'.

The report is a sister publication to the report[1] IUCN published in 2009 on coastal carbon sinks which provided a much-needed overview of the importance and role of coastal ecosystems as carbon sinks, focusing on mangroves, seagrass beds, saltmarshes, coral reefs and kelp forests. This has enabled a shift in and a broadening of the discussion around nature-based climate change mitigation options in coastal and inshore waters, and has been instrumental in the creation of the 'blue carbon' concept. We hope that this new report will stimulate similar interest for open-ocean ecosystems, and recognition that we impact the functioning of the largest carbon sink on the planet, at our peril. Understanding how it functions, respecting those processes, and factoring them into how we manage the ocean must now be the priority.

1 Laffoley, D.d'A. and Grimsditch, G. (eds). 2009. The management of natural coastal carbon sinks. IUCN, Gland, Switzerland. 53 pp;

Take home messages

The key take-home message is that the significance of carbon processes, pools and sinks in the open ocean now need to be centrally factored into decision making at all scales – from global policy issues on climate change, through to resource management at sectoral (e.g. fisheries) and national levels, and even as a criterion in the selection of prospective MPAs. Unless there is greater appreciation and action on the role and importance of ocean carbon systems it is more than probable that efforts to avoid dangerous climate change risk reducing CO_2 only by enough to stabilize Earth's surface temperature, rather than the more aggressive cuts in emissions needed to tackle issues such as ocean acidification.

Factoring in ocean carbon processes and issues such as tackling ocean acidification will require much more dramatic cuts to emissions to ensure we avoid dangerous and effectively irreversible changes. Examples at the regional scale are included in the report where there are clear interactions between ocean carbon and human activities, e.g. fishing, krill extraction, etc. The report demonstrates from multiple angles that continuing with excessive CO_2 emissions from human activities, whilst at the same time ignoring the need for carbon management in the various ways we use and interact with the ocean, is imperiling the ocean system that shields us from more rapid dangerous climate change impacts.

There are a number of recommendations that therefore naturally flow from the report:

- Urgent action is needed to address ocean carbon and protect the systems that regulate planetary processes – the essential role of how ocean ecosystems mitigate the impacts arising from anthropogenic CO_2 emissions - is demonstrated through the case studies in this report. The urgency is illustrated by all the case studies that show that our use and abuse of the ocean is altering the status quo in carbon management.
- Further research is needed to develop the analysis presented in the report - just like IUCN's original report in 2009 on coastal carbon sinks this report is only the beginning, and work both technically and politically is needed. Limits on time and resources meant that issues such as the carbon role of large vertebrates or the benthos could not be covered. More research is also needed to understand how ocean acidification not only affects calcification, but how it (perhaps in turn) affects photosynthesis, and hence primary in the ocean. The focus in this report is mainly on calcification processes in calcifiers, whilst research on these other impacts is needed to help clarify the current uncertainties around the quantification of the open ocean carbon pool.
- Ocean carbon issues need to be addressed through international climate policy routes, such as the UNFCCC, to develop new processes and strengthen relevant existing measures.
- An Implementing Agreement is needed under the UN Convention Law of the Sea to secure a proper conservation and management framework for the High Seas – through which relevant supporting measures for ocean carbon could be taken.
- Sectoral ocean management bodies need to recognize and address ocean carbon budgets and

undertake full environmental assessments of their activities – for example the regional agreements, such as CCAMLR, have for addressing ocean carbon budgets - and entire extractive industries such as capture fisheries and krill fisheries, and the algal harvesting sector need to include carbon in their day-to-day decisions and activities to improve their ecosystem management.
- Often the science is incomplete and sometimes aspects are missing, with important topics yet to be fully investigated, but we already know enough at a broad level to recognize the significance of these ocean carbon processes, pools and sinks. The sheer geographical scale of the world ocean is such that marine carbon pathways and pools are very significant and highly relevant to international policy discussions and actions on carbon emissions, carbon management and climate change. Incorporating the ocean into these discussions and actions is what now needs to urgently happen. We know human pressures on the open ocean are growing – aside from familiar pressures like pollution and fishing, the International Seabed Authority has now entered into eleven 15-year contracts with nations leasing an area for deep sea mining more than twice the size of Germany[1] – so the need for action and proper assessment and management is all the more urgent. Evidence from ecosystem and species case studies in the report underlines the importance of maintaining the health and resilience of biodiversity in the ocean and of respecting the open ocean carbon processes by highlighting the unprecedented changes we believe we are now making to them.

Two main routes to achieve this are by placing new duties on bodies with sectoral responsibility for management of open ocean activities (i.e. under the United Nations Convention on the Law Of the Sea (UNCLOS) by providing a modern management framework within which to manage ecosystems and species on the High Sea), and by further action under the United Nation Framework Convention on Climate Change (UNFCCC). Under the latter Convention the scope should be expanded to include the open ocean. On land, digging up peatland and cutting down forests is closely scrutinized and protective policy frameworks and legislative measures are in place. The same approach now needs to occur for activities in the open ocean.

The report represents the first attempt at connecting all the carbon and climate dots under the UNFCCC, and to fill current accounting gaps. Clearly significant issues remain to be addressed including how to measure ocean carbon emissions and the impacts of particular human activities. Debate around the release of the report may hopefully help quantify this faster than might be imagined given the scope of relevant work being undertaken by scientists around the world. Issues will also emerge over who to attribute the ocean carbon emissions or sinks to - which countries would take responsibility for 'global ocean carbon units' and make them part of their national carbon inventory? This is, however, not an unfamiliar debate as it has arisen before in a different context in relation to sea-level rise and the future fate of Pacific Islanders.

The report has been developed to challenge current thinking – in fact we now show that all aspects of carbon management, not just on the land and at the coast but in the ocean, are critical. Evidence in the report shows the impacts and possible future implications for ocean systems of not addressing them in on-going climate change adaptation and mitigation discussions. Addressing the management of natural carbon pools and sinks in the open ocean may appear (and doubtless is) technically and attribution-wise more complex, but this complexity is no longer a reason for not doing so. The ocean has been a major buffer for the rate of atmospheric CO_2 increase, shielding us from more rapid climate change impacts, albeit with the "side-effect" of ocean acidification. It is now time that the ocean gets more prominent recognition, both as an impacted ecosystem as well as solution provider, in the climate change debate.

Scale of Units Used

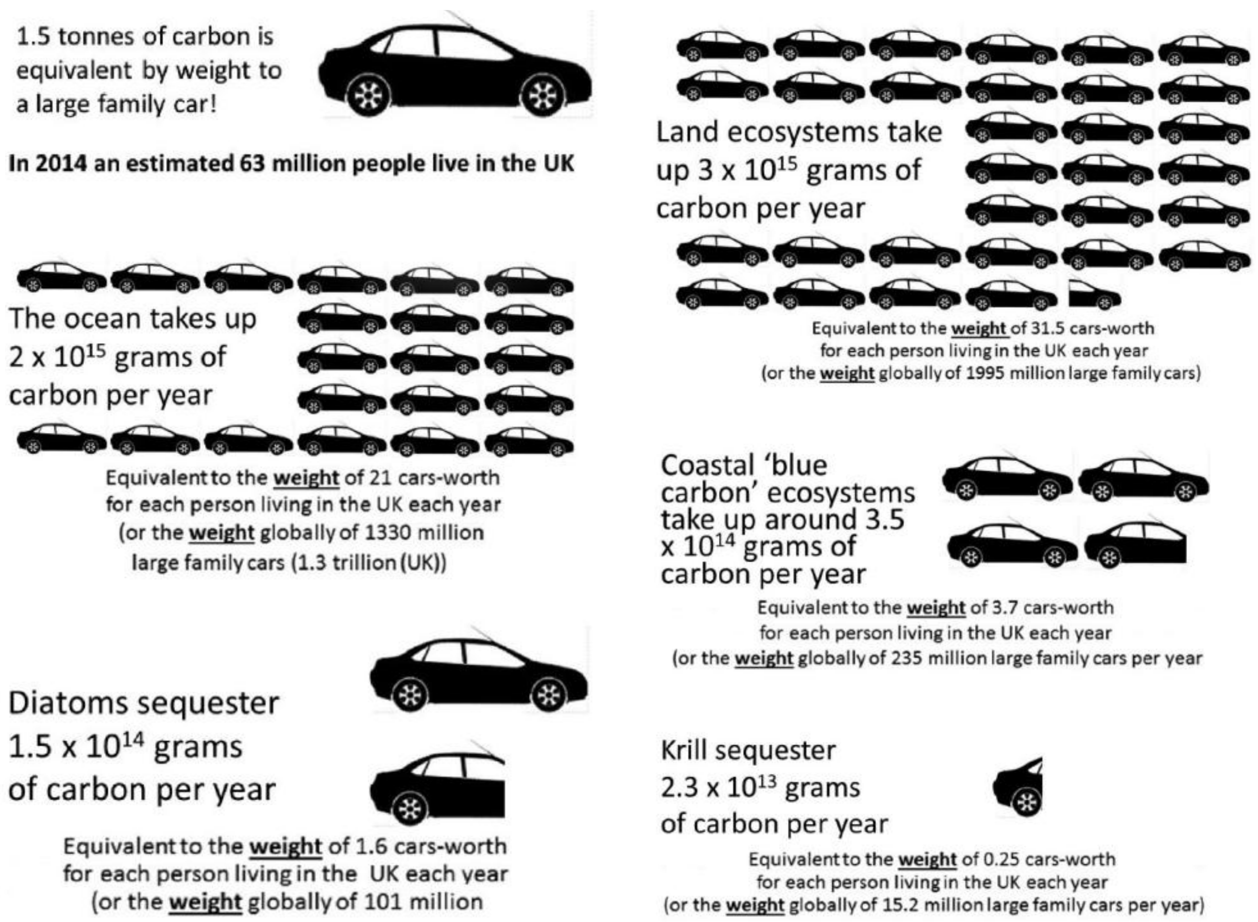
Value	Symbol	Name	Symbol	Value
10^3 g	kg	kilo-		
10^6 g	Mg	mega-	t	1 t
10^9 g	Gg	giga-	Kt	10^3 t
10^{12} g	Tg	tera-	Mt	10^6 t
10^{15} g	Pg	peta-	Gt	10^9 t

1 Mengerink, K.J., Van Dover, C.L., Ardron, J., Baker, M., Escobar-Briones, E., Gjerde, K., Koslow, J.A., Ramirez-Llodra, E., Lara-Lopez, A., Squires, D., Sutton, T., Sweetman, A.K., and Levin, L.A. 2014. A Call for Deep-Ocean Stewardship. Science 16 May 2014: Vol. 344 no. 6185 pp. 696-698. DOI: 10.1126/science.1251458.

Making the ocean carbon numbers *visible*

The aim of the report has been to start to quantify the role that particular habitats and species make to open ocean carbon processes. One of the problems with such work, and in fact any work on carbon around climate change, is that the subject – carbon dioxide – and the processes of carbon sequestration are invisible. Few if any of us have a sense of the scale of the figures quoted when it comes to carbon management through natural systems. The challenge is to explain the significance of the numbers that have been identified in a way people can more readily relate to, making the figures *visible* and tangible.

At the core of this is the fact that a large family car weights about 1.5 tonnes. So if we imagined the weight of carbon processed by the ocean each year, what would it look like by weight in terms of numbers of family cars per person per year based on the population of the UK?



Open ocean calcifiers: Pteropods, foraminifera and coccolithophores – at a glance

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- Calcium carbonate is the basic building block of skeletons and shells for a large number of marine organisms including corals, shellfish and open ocean plankton (both plants – coccolithophores, and animals – foraminifera, pteropods and larval stages of benthic calcifiers) that are known collectively as calcifying organisms or calcifiers.
- Calcifiers are distributed worldwide from the surface to the deep sea and provide critical services to the planet. For example:
  - Pteropods are a major food source for marine organisms with a global biomass equating to 5 x 10^{14} gC (that's more than global kelp forest biomass).
  - A single species of coccolithophore, *Emiliania huxleyi,* plays a key role in ocean carbon uptake, can occur in blooms that appear as vast milky turquoise patches on the ocean surface covering up to 1.4 x 10^6 km^2 (twice the size of Texas) each year.
- The ocean currently stores 50x more CO_2 than the atmosphere and 20x more CO_2 than land plants. Open ocean calcifiers lock away carbon in the form of calcium carbonate and transport it to the deep sea where the carbon is stored for geological time scales. They are also key prey for a wide range of predators including commercially important fish, and cetaceans.
- Calcifiers face significant problems when exposed to lower ocean pH or 'ocean acidification'. Lower numbers of ocean calcifiers, reduced calcification and increased shell dissolution may impact the ocean's capacity to continue to act as a carbon sink.

Globally distributed coccolithophore: *Emiliania huxleyi* (scale bar = 10µm). Gustaaf Hallegraeff (UTAS).

Open algal ecosystems: Diatoms – at a glance

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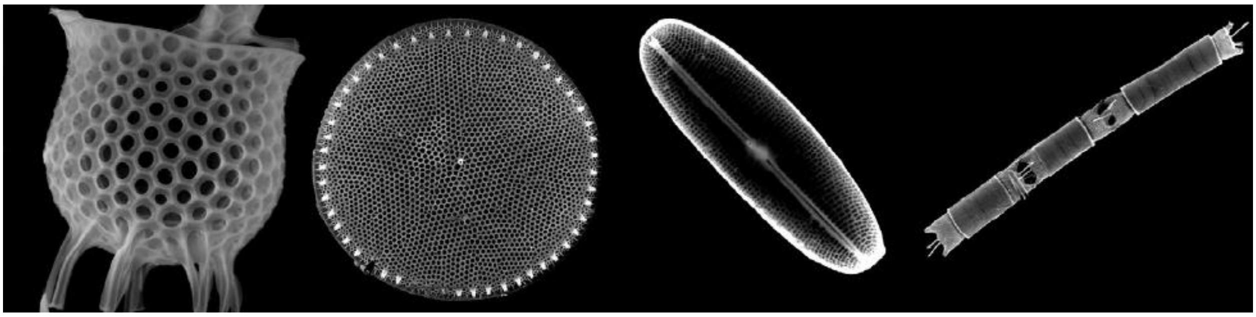
- Diatoms are microscopic algae with silica cell walls, and are especially abundant in nutrient-rich surface waters at high latitudes (>40°N and S) and in coastal upwelling regions.
- Annual carbon production by diatoms is 10.7 x 10^{15} gC, this represents ~7.4% of net primary production on earth (earlier predictions were ~20% NPP on Earth).
- Intense diatom blooms occur in spring and summer, after which ~ 40% of carbon fixed by diatoms sinks to >100m depth, representing a carbon flux of ~4.2 x 10^{15} gC.y^{-1} from the surface ocean. Of this, pelagic food-webs consume ~90% of the carbon, but 1-2% reaches depths > 1000 m where it remains for thousands of years.
- Carbon flux from the surface to deep ocean (>1000m) by diatoms is ~ 0.15 x 10^{15} gC.yr^{-1}, which accounts for ~1.7 % of annual CO_2 emissions from fossil fuels and ~6.5% of the annual sequestration of CO_2 by the ocean.
- Warming of the ocean is indirectly reducing nutrient input to the surface waters, leading to a decline in diatom abundance and slowing of the biological pump, which will ultimately reduce CO_2 sequestration in the ocean and further exacerbate climate change.



Electron microscope images of diatoms: *Stephanopyxis* sp. (x700); *Thalassiosira* sp. (x1080); a pennate diatom (x1080), and a chain forming diatom *Odontella* sp. (x370). Photo credit Cecilia Rad Menendez & Elaine Mitchell.

Floating Seaweed (*Sargassum*) – at a glance

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- Floating *Sargassum*, which occurs in the Sargasso Sea and Gulf of Mexico, constitutes the world's largest biomass of oceanic seaweed.
- A large diversity of marine fauna is associated with *Sargassum*, however, its role in oceanic food-webs and carbon cycles has been under assessed up to this point.
- The annual carbon production by *Sargassum* is 2.7 x 10^{11} gC, which is ~0.5% of the primary production in Sargasso Sea, and constitutes 0.0006% of production by *all* marine primary producers globally. However biological production of *Sargassum* is of significant importance in some areas of the Gulf of Mexico, where it may constitute up to 10% of net primary production.
- Annual carbon sequestration by *Sargassum* is estimated to be > 4.3 x 10^{10} gC via rDOC production and sinking faecal pellets of grazers, and accounts for ~0.002% of the 2.3 x 10^{15} gC of CO_2 annually sequestered by the ocean (Le Quéré *et al.,* 2009; Ciais *et al.,* 2013). However, this estimate does not include the biomass of sinking *Sargassum*, which is currently unknown and is expected to make a significant contribution to carbon sequestration.
- More broadly in terms of mitigation, *Sargassum* occupies a small area of the sea surface, and CO_2 sequestration can be enhanced either by cultivating additional seaweed in the ocean, or by cultivating microalgae on land, and then converting the algae to biofuels.
- In order to limit global temperature rise to 2°C, ~ 3.2 x 10^{15} gC must be removed from the atmosphere, and 10% of this goal could be met by cultivating seaweed in 4% of the oceans exclusive economic zone (EEZ) for the next 100 years.

Floating *Sargassum* sp. in the Gulf of Mexico (Photo credit: Sylvia Earle)

Antarctic Krill – at a glance

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- Antarctic krill is reputed to have the largest biomass of any single metazoan species (all multi-cellular animals besides sponges) on the planet, playing a key role in the structure and function of the Southern Ocean ecosystem.
- They display a circumpolar distribution, south of the Polar Front with a distributional range of 19 x 10^6 km^2, which largely coincides with the extent of winter sea ice. This roughly is equivalent to the size of South America.
- The circumpolar krill stock is calculated to contain approximately 3.5 x 10^{13} gC, which is more than the total peat-carbon stock held in the USA, and their annual carbon production is of the order of 3.1-4.9 x 10^{13} gC.
- Krill sequester 2.3 x 10^{13} gC annually, which offsets ~0.26% of annual global CO_2 emissions from fossil fuel combustion. Krill also play a key role in cycling elements other than carbon, some of which may limit primary production (e.g. iron).
- Declines in krill density and possible recruitment failures in the South Atlantic in recent years have been Suggested and have been linked to reductions in sea ice area caused by global warming.
- Marine organisms are expected to be affected by ocean acidification in a number of ways and long-lived pelagic animals, such as Antarctic krill, may be especially vulnerable.
- The krill population is a large biological carbon reservoir, but krill are probably more important through their control of the carbon cycling processes.

Adult Antarctic krill (Photo Credit: Rob King)

Fish – at a glance

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- Fish make a significant contribution to oceanic carbonate production (0.04-0.33 x 10^{15} g of $CaCO_3$-C per year) in the form of high magnesium (Mg) calcite crystals excreted continuously via the gut.
- The high Mg content suggests rapid dissolution near the ocean surface that would restore surface alkalinity to a greater degree than other biogenic carbonates. This would neutralize much of the CO_2 released as a consequence of the calcification process.
- Temperature and CO_2 forecasts for the next century (+4 °C and 750 ppm) suggest fish carbonate production may become 58% higher than today, contrary to the effect predicted for many calcifiers. Warmer conditions would also increase their Mg content and near-surface dissolution.
- Conversely, there is evidence for preservation of fish carbonates in shallow, tropical sediments. Mid-Cretaceous marine conditions would have massively enhanced production of fish carbonates with much lower Mg content, enhancing their potential for preservation in carbonate sediments and geology.
- Quantitatively, the fate of fish carbonates in the ocean is not yet understood well enough to estimate their role as sources or sinks of CO_2.

Example of a temperate fish species (European flounder) and (sub)tropical fish species (schoolmaster), in tanks showing their white coloured carbonate pellets that have been excreted from their guts.

Deep-sea chemosynthetic carbon production – at a glance

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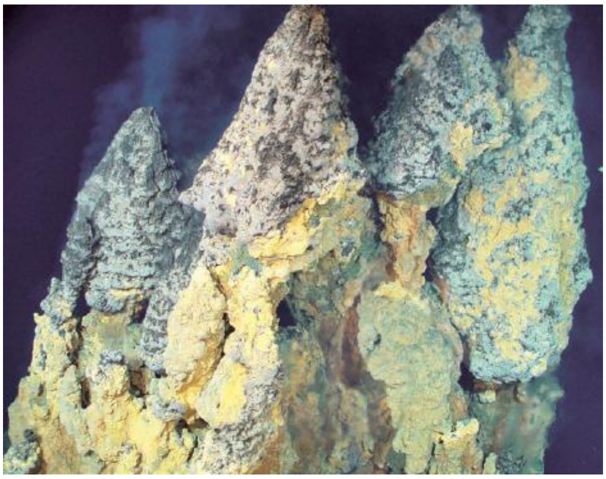
- In the deep sea, chemosynthesis is the only source of primary production. Chemosynthetic (also known as, "*chemoautotrophic*") organisms produce organic matter through the assimilation of inorganic carbon coupled with the use of reduced chemical compounds as an energy source.
- A large variety of microbes synthesize organic matter through chemoautotrophic pathways, including sulfur oxidizers, ammonia oxidizers and methanogens.
- Habitats/ecosystems based on chemosynthetic primary production include hydrothermal vents and cold seeps (including whale carcasses), that deliver reduced chemical species, which are used by microbes and transferred to the food chain.
- Archaea in deep-sea sediments are the major contributors to chemosynthetic production, and chemosynthetic processes in the deep ocean interior are quantitatively more important than previously thought.
- Globally, about 52% of the chemoautotrophic carbon fixation occurs as a result of the activity of nitrifiers in the water column (37% in the euphotic zone and 15% in the dark ocean).
- About 48% of the total oceanic chemoautotrophy occurs in sediments.
- Chemoautotrophic carbon fixation in the deep sea is in the order of 4.0×10^{13} gC.y^{-1}.
- The predicted decrease in oxygen in the deep ocean interior as a result of global climate change (i.e. global warming, altered thermohaline circulation, and increased stratification) could significantly influence prokaryotic chemoautotrophic processes and therefore the overall carbon storage capacity of the ocean.



Mineral resources from deep-sea chemosynthetic habitats. Hot (230°C) fluids create rocky structures at the deep sea-floor hydrothermal vent areas, hosting unique, chemosynthesis-based, faunal and microbial biodiversity. These mineral chimneys, called "smokers", are rich in iron, copper, and zinc sulfides which precipitate from the hot fluids mixing with cold waters. (National Oceanic and Atmospheric Administration/Department of Commerce. Pacific Ring of Fire 2004 Expedition. NOAA Office of Ocean Exploration; Dr. Bob Embley, NOAA PMEL, Chief Scientist).

Deep-sea microbes and their role in the ocean interior – at a glance

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- The ocean interior contains the majority of microbes inhabiting the Earth and deep-sea floor surface sediments contain 10–10,000-fold more cells per unit volume than productive ocean-surface waters.
- Conversely to other biological components of the ocean, the abundance of benthic prokaryotes (i.e. microbes belonging to two domains of life: Bacteria and Archaea) and viruses (biological entities infecting living cells) does not decrease significantly with increasing water depth.
- The prokaryotic biomass, which largely dominates over all other biotic components, is estimated in the order of 0.34 x 10^{15} gC in deep-sea surface sediments.

- Deep-sea prokaryotes and viruses along with their interactions play a crucial role in the decomposition processes and biogeochemical cycling of carbon, nitrogen and phosphorus at the global scale.
- The global heterotrophic carbon production of deep-sea microbes could be estimated in the order of 0.6-1.5 x 10^{15} gC.y^{-1}, contributing significantly to overall heterotrophic carbon production in the oceans at all depths.
- Viruses in the deep sea have the potential to affect all microbial-driven processes, thus influencing material and energy transfer and fluxes. Viral-induced mortality in the deep sea can convert a large part of the prokaryotic biomass into detritus, releasing on a global scale 0.4-0.6 x 10^{15} gC.yr^{-1}.
- It is not possible yet to predict the impact of climate change on deep-sea prokaryotes and viruses, nor if this will be exacerbated by multiple stressors, such as changes in temperature coupled with acidification and shifts in salinity and oxygen concentration, or if it will be buffered by biotic interactions. However, there is increasing evidence that deep-sea microbes are key biotic components that will influence the ocean's feedbacks to climate change.

Deep viral impact. Deep-sea sediments contain large reservoirs of carbon in the form of microbial biomass, and the dynamics of this ecosystem are only now being established. Viral infections result in the death of over 80% of prokaryotic biomass production — close to 100% at depths below 1,000 m - thereby releasing huge amounts of dissolved organic carbon into the deep seas that provides food for other living prokaryotes. (Art courtesy of Mirco Tangherlini).

About the report

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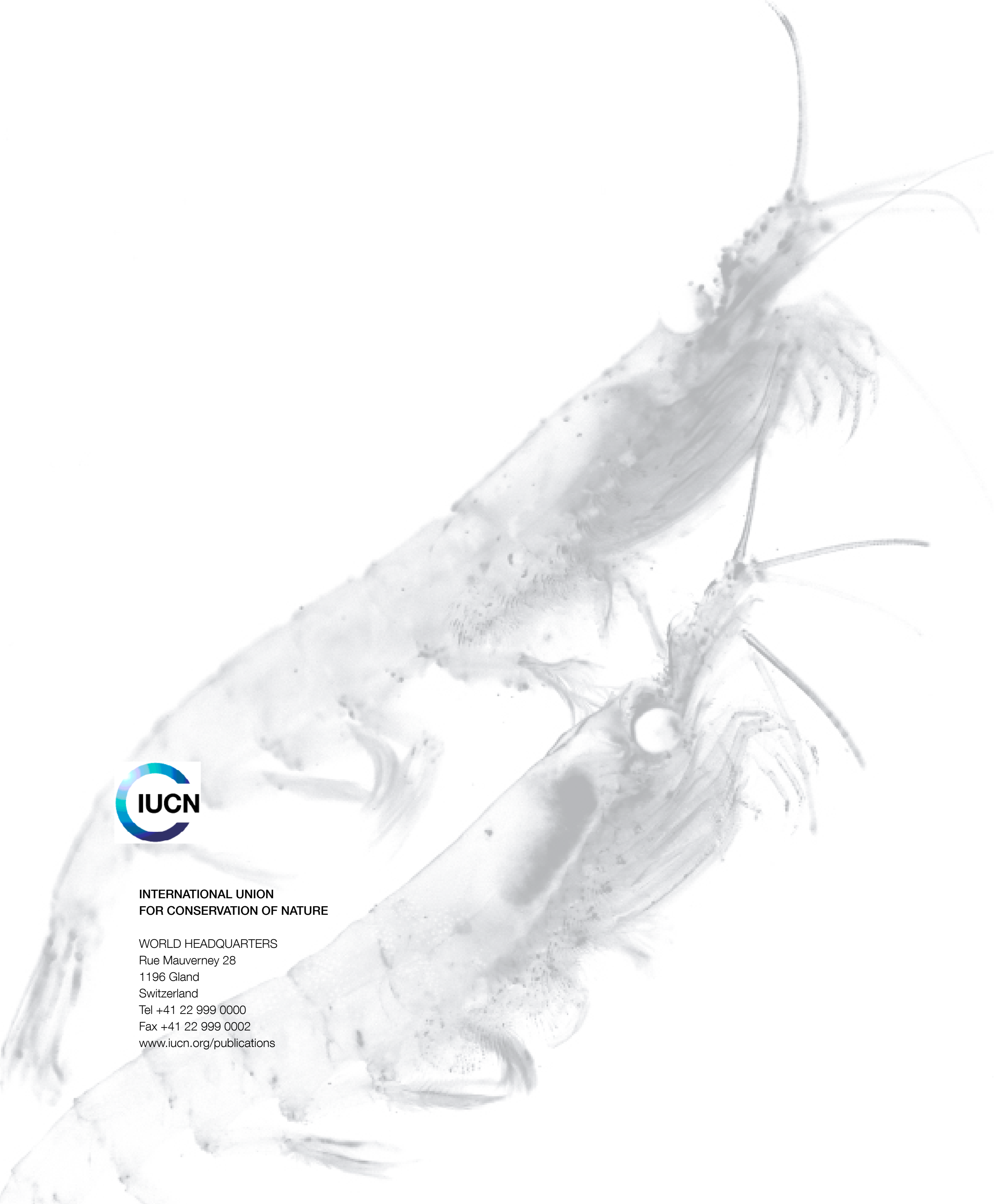

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