Need for monitoring and maintaining sustainable marine ecosystem services

Health & Medicine

Introduction

The last 10, 000 years, known as the Holocene, have been a relatively stable period in earth's climate history (Petit et al., 1999), but recently human activities have become the main driver of environmental change at the local as well as global scale (Rockström et al., 2009). Humans have significantly altered the biogeochemical cycles on earth (Vitousek et al., 1997); something thought impossible just a few decades ago. Burning of fossil fuels, deforestation, mining, and other activities have increased the concentration of CO_2 in the atmosphere and ocean, elevating the greenhouse effect with rising temperatures as consequence. So far, the oceans have managed to store three times as much heat as the atmosphere (Levitus et al., 2001) and absorb about one third of the human-induced CO_2 emitted into the atmosphere (Steffen et al., 2007). However, recent studies suggest that the ocean's buffer capacity might decrease with further warming (Gruber et al., 2004).

Industrial nitrogen fixation and phosphate mining as well as fossil fuel burning have mobilized nitrogen and phosphorus (Vitousek et al., 1997). Humans have almost doubled the supply of nitrogen from the atmosphere to land, leading to an increased release of the greenhouse gas N_2O (Gruber and Galloway, 2008). Phosphate demands for agriculture have increased phosphorus inputs to the biosphere by factor of almost four (Falkowski et al., 2000). Nutrients applied to land as fertilizers are partly lost to the aquatic environment, eventually the ocean, where they stimulate production of organic matter, a process known as eutrophication (Nixon, 1995). One of the most deleterious effects of eutrophication is the development of hypoxia (Carstensen et al., 2014), having strong ramifications on nutrient biogeochemical processes (Diaz and Rosenberg, 2008 ; Conley et al., 2009).

Human demand on fish has significantly reduced populations of marine top predators (Pauly et al., 1998), altering the flow of energy through food-webs and eventually leading to ecosystem collapses (Jackson et al., 2001). Fisheries landings have increased by more than 50% from 1970 to 2005 (Duarte et al., 2009) and the number of unsustainable fisheries is growing (Vitousek et al., 1997). In addition to reducing the overall population of marine top predators, overfishing has also selected toward smaller populations by removing the largest individuals (Jackson et al., 2001). It is possible that overfishing may exacerbate effects of eutrophication through trophic cascades, disrupting the normal flow of energy through marine food-webs (Scheffer et al., 2005). Another facet of altered energy flows is the global loss of biodiversity caused by overfishing, pollution, and habitat destruction reducing ocean ecosystem services (Worm et al., 2006).

Human pressures on marine ecosystems have increased recently to an extent where every area of the oceans is affected to some degree, although the human footprint is largest in the coastal zones with a high population density (Halpern et al., 2008). The multiple pressures of human activities have eroded the capacity of marine ecosystems to provide services benefitting humans. The oceans no longer constitute an infinite reservoir of natural resources that humans can exploit unconcerned. Therefore, science has an important role in identifying problems as well as their solutions, and conveying this knowledge broadly to the public and particularly, decision makers (Levin et al., 2009).

Assessing Human Impacts on Marine Ecosystems

Our knowledge on human impacts on marine ecosystems has mainly been driven by observations supported by models for extrapolation. However, there is a significant lack of data on human pressures and marine effects, particularly in the open ocean. Data are often scattered in time and space, because they mostly arise from various research cruises and ships-of-opportunity; uncoordinated activities not aimed at assessing changes over time. Therefore, models are needed to integrate these data (e. g., Boyce et al., 2010 ; Halpern et al., 2012), but for many components of ocean health such models do not exist or they are so coarse that the reliability of the output may be disputable (Mackas, 2010 ; McQuatters-Gollop et al., 2010 ; Rykaczewski and Dunne, 2011).

Remote sensing data from satellites overcome the problem of spatial and temporal sampling heterogeneity and can be used for assessing changes in sea surface temperature and ocean color from which proxies for phytoplankton biomass and productivity can be derived (Behrenfeld et al., 2006), but they also have their limitations. Remote sensing applies to the upper surface layer only, and satellites cannot assess processes taking place at deeper depths. Algorithms for processing remote sensing data have mainly been developed for the open ocean, and the algorithms produce biases in shallower coastal waters. The proxy information obtained from satellite imagery provides only a small fraction of information needed to assess human impact on marine ecosystems.

Autonomous sensors typically placed on fixed buoys or floatable undulating devices such as Argo floats complement remote sensing by providing subsurface information on salinity, temperature, oxygen, and bio-optical properties (Roemmich et al., 2009). For instance, Argo float data with the support of global climate models revealed that the deep ocean (> 300 m) was taking up more heat during the recent surface-temperature hiatus period (Meehl et al., 2011). At present, only the most basic physical-chemical variables are measured using these autonomous devices, since other measurements of interest (e. g., nutrient concentrations) typically require more regular maintenance, increasing the operating costs substantially.

Monitoring programs providing more consistent time series across a wide range of different physical, chemical and biological variables are found in certain coastal areas, e. g., the Chesapeake Bay and the Baltic Sea. These were typically initiated in the 1970s and 1980s, when pollution effects became clearly visible, to assess the efficiency of management actions to alleviate human pressure on overstressed marine ecosystems (Carstensen et al., 2006). In addition to assessing physical-chemical status, different organism groups from phytoplankton to top predators in the marine ecosystems were monitored. These monitoring programs have contributed substantially to our present understanding of trophic interactions in coastal areas and the disturbance of these imposed by human activities.

Understanding of long-term variations in ocean waters has so far been based on a few observatories, some of these organized within the Long Term Ecological Research (LTER) Network (www. ilternet. edu). Long-term decreases in pH and aragonite saturation from the Hawaiian Ocean Time-series (HOT) and Bermuda Atlantic Time Series (BATS) have highlighted another problem associated with increased emission of CO $_2$, namely ocean acidification (Doney et al., 2009), which may alter ocean biogeochemistry (Beman et al., 2011). Long-term time series in coastal waters have revealed that pH is governed by changes in inputs from land rather than CO $_2$ in the atmosphere (Duarte et al., 2013). The Continuous Plankton Recorder (CPR) survey has been in operation since 1931 and has provided valuable insights into how climate oscillations affect plankton communities (Edwards et al., 2009). Since 1949 the California Cooperative Oceanic Fisheries Investigations (CalFOCI) program has investigated distributions of phytoplankton, zooplankton and fish distributions off Southern California and showed how changes in the Pacific Decadal Oscillation (PDO) can precipitate sudden shifts in these distributions (McGowan et al., 2003). Nevertheless, despite the value of these unique time series there is a need to establish and maintain ocean time series of high research quality, particularly in subtropical and tropical waters that are severely understudied at present.

Directions for the Future

“ We know more about the surface of the Moon and about Mars than we do about the deep sea floor, despite the fact that we have yet to extract a gram of food, a breath of oxygen or a drop of water from those bodies.” This statement by Dr. Paul Snelgrove clearly articulates the need for improving our understanding of how marine ecosystems function, particularly as they provide essential ecosystem services to humans and because expanding human activities are putting these services under threat.

Our current understanding of marine ecosystem responses to human activities is limited by the availability of data, particularly long-term time series of physical and chemical conditions as well as biological properties. Moreover, efforts should be made to improve the accessibility and comparability of existing time series. Further development of models integrating monitoring data is needed to better assess changes over time and predict future trends, but models cannot stand alone without data. The lack of data is partly technical, as current measurement techniques may not necessarily provide the needed information, and partly financial, as costs of ocean sampling are indeed excessively expensive. Technological developments are expected to contribute more accurate, precise and cost-effective measurements over time. However, many marine monitoring programs are facing budget reductions, which have led to discontinuation of monitoring stations and abandoning sampling of biological components as well as decreasing monitoring frequencies. A possible consequence is loss of invested capital for establishing such long-term time series, simply because their value has to be written down. There is a growing discrepancy between the need for better understanding of human impact on marine ecosystems and the basis for addressing these scientific questions.

Ducklow et al. (2009) have identified seven key elements that will help science address critical issues on marine ecosystem services in times when human pressures on these are intensifying: (1) maintain existing monitoring programs and expand these with additional biological components, (2) establish new monitoring programs in under-sampled regions, (3) increase the use of remote sensing and autonomous monitoring devices, (4) establish targeted research program (process studies) in connection to long-term monitoring sites, (5) improve the integration of monitoring activities with ships-of-opportunity, (6) modify current funding for ecological research to balance consistent long-term research and short-term targeted studies, and (7) improve data access and synthesis using models. If these are recommendations are pursued we may eventually know more about our oceans than the surface of the Moon and Mars. The growing human imprint on marine ecosystems may, if left unmonitored and unattended, result in significant losses of ecosystem services that are crucial to support a globally growing population.

Conflict of Interest Statement

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Behrenfeld, M. J., O'Malley, R. T., Siegel, D. A., McClain, C. R., Sarmiento, J. L., Feldman, G. C., et al. (2006). Climate-driven trends in contemporary ocean productivity. *Nature* 444, 752–755. doi: 10. 1038/nature05317

Pubmed Abstract | Pubmed Full Text | CrossRef Full Text

Beman, J. M., Chow, C.-E., King, A. L., Feng, Y., Fuhrman, J. A., Andersson, A., et al. (2011). Global declines in oceanic nitrification rates as a consequence of ocean acidification. *Proc. Nat. Acad. Sci. U. S. A* . 108, 208–213. doi: 10. 1073/pnas. 1011053108

Pubmed Abstract | Pubmed Full Text | CrossRef Full Text

Boyce, D. G., Lewis, M. R., and Worm, B. (2010). Global phytoplankton decline over the past century. *Nature* 466, 591–596. doi: 10. 1038/nature09268

Pubmed Abstract | Pubmed Full Text | CrossRef Full Text

Carstensen, J., Andersen, J. H., Gustafsson, B. G., and Conley, D. J. (2014). Deoxygenation of the Baltic Sea during the last century. *Proc. Nat. Acad. Sci. U. S. A* . 111, 5628–5633. doi: 10. 1073/pnas. 1323156111

Pubmed Abstract | Pubmed Full Text | CrossRef Full Text

Carstensen, J., Conley, D. J., Andersen, J. H., and Ærtebjerg, G. (2006). Coastal eutrophication and trend reversal: a danish case study. *Limnol. Oceanogr* . 51, 398–408. doi: 10. 4319/lo. 2006. 51. 1_part_2. 0398

CrossRef Full Text

Conley, D. J., Björck, S., Bonsdorff, E., Carstensen, J., Destouni, G., and Gustafsson, B. G. (2009). Hypoxia-related processes in the Baltic Sea. *Environ. Sci. Technol* . 43, 3412–3420. doi: 10. 1021/es802762a

Pubmed Abstract | Pubmed Full Text | CrossRef Full Text

Diaz, R. J., and Rosenberg, R. (2008). Spreading dead zones and consequences for marine ecosystems. *Science* 321, 926–929. doi: 10. 1126/science. 1156401

Pubmed Abstract | Pubmed Full Text | CrossRef Full Text

Doney, S. C., Fabry, V. J., Feely, R. A., and Kleypas, J. A. (2009). Ocean acidification: the other CO_2 problem. *Annu. Rev. Mar. Sci* . 1, 169–192. doi: 10. 1146/annurev. marine. 010908. 163834

Pubmed Abstract | Pubmed Full Text | CrossRef Full Text

Duarte, C. M., Conley, D. J., Carstensen, J., and Sánchez-Camacho, M. (2009). Return to Neverland: shifting baselines affect eutrophication restoration targets. *Estuar. Coasts* 32, 29–36. doi: 10. 1007/s12237-008-9111-2

CrossRef Full Text

Duarte, C. M., Hendriks, I. E., Moore, T. S., Olsen, Y. S., Steckbauer, A., Ramajo, L., et al. (2013). Is ocean acidification an open-ocean syndrome? Understanding anthropogenic impacts on seawater pH. *Estuar. Coasts* . 36, 221–236. doi: 10. 1007/s12237-013-9594-3

CrossRef Full Text

Ducklow, H. W., Doney, S. C., and Steinberg, D. K. (2009). Contributions of long-term research and time-series observations to marine ecology and biogeochemistry. *Annu. Rev. Mar. Sci* . 1, 279–302. doi: 10. 1146/annurev. marine. 010908. 163801

Pubmed Abstract | Pubmed Full Text | CrossRef Full Text

Edwards, M., Beaugrand, G., Hays, G. C., Koslow, A., and Richardson, A. J. (2009). Multi-decadal oceanic ecological datasets and their application in marine policy and management. *Trends Ecol. Evol* . 25, 602–610. doi: 10. 1016/j. tree. 2010. 07. 007

Pubmed Abstract | Pubmed Full Text | CrossRef Full Text

Falkowski, P., Scholes, R. J., Boyle, E., Canadell, J., Canfield, D., Elser, J., et al. (2000). The global carbon cycle: a test of our knowledge of earth as a system. *Science* 290, 291–296. doi: 10. 1126/science. 290. 5490. 291

Pubmed Abstract | Pubmed Full Text | CrossRef Full Text

Gruber, N., Friedlingstein, P., Field, C. B., Valentini, R., Heimann, M., Richey, J. E., et al. (2004). “ The vulnerability of the carbon cycle in the 21st century:

an assessment of carbon-climate-human interactions” in *The Global Carbon Cycle: Integrating Humans, Climate, and the Natural World* , eds C. B. Field and M. R. Raupach (Washington, DC: Island Press), 45–76.

Gruber, N., and Galloway, J. N. (2008). An Earth-system perspective of the global nitrogen cycle. *Nature* 451, 293–296. doi: 10. 1038/nature06592

Pubmed Abstract | Pubmed Full Text | CrossRef Full Text

Halpern, B. S., Longo, C., Hardy, D., McLeod, K. L., Samhouri, J. F., Katona, S. K., et al. (2012). An index to assess the health and benefits of the global ocean. *Nature* 488, 615–621. doi: 10. 1038/nature11397

Pubmed Abstract | Pubmed Full Text | CrossRef Full Text

Halpern, B. S., Walbridge, S., Selkoe, K. A., Kappel, C. V., Micheli, F., D'Agrosa, C., et al. (2008). A global map of human impact on marine ecosystems. *Science* 319, 948–952. doi: 10. 1126/science. 1149345

Pubmed Abstract | Pubmed Full Text | CrossRef Full Text

Jackson, J. B. C., Kirby, M. X., Berger, W. H., Bjorndal, K. A., Botsford, L. W., and Bourque, B. J. (2001). Historical overfishing and the recent collapse of coastal ecosystems. *Science* 293, 629–638. doi: 10. 1126/science. 1059199

Pubmed Abstract | Pubmed Full Text | CrossRef Full Text

Levin, P. S., Fogarty, M. J., Murawski, S. A., and Fluharty, D. (2009). Integrated dcosystem assessments: developing the scientific basis for ecosystem-based management of the ocean. *PLoS Biol* . 7: e1000014. doi: 10. 1371/journal. pbio. 1000014

Pubmed Abstract | Pubmed Full Text | CrossRef Full Text

Levitus, S., Antonov, J. L., Wang, J., Delworth, T. L., Dixon, K. W., and Broccoli, A. J. (2001). Anthropogenic warming of Earth's climate system. *Science* 292, 267–270. doi: 10. 1126/science. 1058154

Pubmed Abstract | Pubmed Full Text | CrossRef Full Text

Mackas, D. L. (2010). Does blending of chlorophyll data bias temporal trend? *Nature* 472, E4–E5. doi: 10. 1038/nature09951

Pubmed Abstract | Pubmed Full Text | CrossRef Full Text

McGowan, J. A., Bograd, S. J., Lynn, R. J., and Miller, A. J. (2003). The biological response to the 1977 regime shift in the California Current. *Deep Sea Res* . 50(Pt. II), 2567–2582. doi: 10. 1016/S0967-0645(03)00135-8

CrossRef Full Text

McQuatters-Gollop, A., Reid, P. C., Edwards, M., Burkill, P. H., Castellani, C., Batten, S., et al. (2010). Is there a decline in marine phytoplankton? *Nature* 472, E6–E7. doi: 10. 1038/nature09950

Pubmed Abstract | Pubmed Full Text | CrossRef Full Text

Meehl, G. A., Arblaster, J. M., Fasullo, J. T., Hu, A., and Trenberth, K. E. (2011). Model-based evidence of deep-ocean heat uptake during surface-temperature hiatus periods. *Nature Clim. Change* 1, 360–364. doi: 10. 1038/nclimate1229

CrossRef Full Text

Nixon, S. W. (1995). Coastal marine eutrophication: a definition, social causes, and future concerns. *Ophelia* 41, 199–219. doi: 10. 1080/00785236. 1995. 10422044

CrossRef Full Text

Pauly, D., Christensen, V., Dalsgaard, J., Froese, R., and Torres, F. Jr. (1998). Fishing down marine food webs. *Science* 279, 860–863. doi: 10. 1126/science. 279. 5352. 860

Pubmed Abstract | Pubmed Full Text | CrossRef Full Text

Petit, J. R., Jouzel, J., Raynaud, D., Barkov, N. I., Barnola, J.-M., Basile, I., et al. (1999). Climate and atmospheric history of the past 420, 000 years from the Vostok ice core, Antarctica. *Nature* 399, 429–436. doi: 10. 1038/20859

CrossRef Full Text

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S. 3rd. Lambin, E. F., et al. (2009). A safe operating space for humanity. *Nature* 461, 472–475. doi: 10. 1038/461472a

Pubmed Abstract | Pubmed Full Text | CrossRef Full Text

Roemmich, D., Johnson, G. C., Riser, S., Davis, R., Gilson, J., Owens, W. B., et al. (2009). The Argo program: observing the global ocean with profiling floats. *Oceanography* 22, 34–43. doi: 10. 5670/oceanog. 2009. 36

CrossRef Full Text

Rykaczewski, R. R., and Dunne, J. P. (2011). A measured look at ocean chlorophyll trends. *Nature* 472, E5–E6. doi: 10. 1038/nature09952

Pubmed Abstract | Pubmed Full Text | CrossRef Full Text

Scheffer, M., Carpenter, S., and de Young, B. (2005). Cascading effects of overfishing marine systems. *Trends Ecol. Evol* . 20, 579–581. doi: 10. 1016/j. tree. 2005. 08. 018

Pubmed Abstract | Pubmed Full Text | CrossRef Full Text

Steffen, W., Crutzen, P. J., and McNeill, J. R. (2007). The Anthropocene: are humans now overwhelming the great forces of nature? *Ambio* 36, 614–621. doi: 10. 1579/0044-7447(2007)36[614: TAAHNO]2. 0. CO; 2

Pubmed Abstract | Pubmed Full Text | CrossRef Full Text

Vitousek, P. M., Mooney, H. A., Lubchenco, J., and Melillo, J. M. (1997). Human domination of Earth's ecosystems. *Science* 277, 494–499. doi: 10. 1126/science. 277. 5325. 494

Pubmed Abstract | Pubmed Full Text | CrossRef Full Text

Worm, B., Barbier, E. B., Beaumont, N., Duffy, J. E., Folke, C., Halpern, B. S., et al. (2006). Impacts of biodiversity loss on ocean ecosystem services. *Science* 314, 787–790. doi: 10. 1126/science. 1132294

Pubmed Abstract | Pubmed Full Text | CrossRef Full Text