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TOPICAL REVIEW

Could artificial reoxygenation revitalize dying coastal seas?

C P Slomp[1,*], A Oschlies[2], A H Altieri[3], L T Bach[4], L Bopp[5], D Breitburg[6], A Canning[7,8], D J Conley[9], M Dai[10], B Dewitte[11,12,13], H Enevoldsen[14], E M Ferrer[15], A Galán[16,17], V Garcon[18], M Gregoire[19], B Gustafsson[20], D Gutierrez[21,22], P Handmann[7], A Hylén[23], K Isensee[24], R Lamond[25], M Li[26], K Limburg[27], I Montes[28], J Sterling[29], A Tan Shau Hwai[30], J M Testa[26], D Wallace[31], J J Waniek[32] and M Yasuhara[33]

1 Department of Microbiology, Radboud University, Nijmegen, The Netherlands
2 GEOMAR Helmholtz Centre for Ocean Research, Kiel, Germany
3 Department of Environmental Engineering Sciences, University of Florida, Gainesville, FL, United States of America
4 Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Australia
5 CNRS—Laboratoire de Météorologie Dynamique, CNRS/ENS-PL, Paris, France
6 Smithsonian Environmental Research Center, Edgewater, MD, United States of America
7 Lhyfe SA, Nantes, France
8 Atrium Environmental UG, Kiel, Germany
9 Lund University, Lund, Sweden
10 Xiamen University, Xiamen, People's Republic of China
11 Centro de Estudios Avanzado en Zonas Áridas (CEAZA), La Serena, Chile
12 Departamento de Biología, Facultad de Ciencias del Mar, Universidad Católica del Norte, CEAZA, Chili, Coquimbo, Chile
13 CECI, Université de Toulouse, CERFACS/CNRS, Toulouse, France
14 IOC-UNESCO, Copenhagen, Denmark
15 National Center for Ecological Analysis and Synthesis, UC Santa Barbara, Santa Barbara, CA, United States of America
16 Centro de Investigación de Estudios Avanzados del Maule (CIEAM), Vicerrectoría de Investigación y Postgrado, Universidad Católica del Maule, Talca, Chile
17 Centro Regional de Estudios Ambientales (CREA), Universidad Católica de la Santísima Concepción, Concepción, Chile
18 CNRS, Institut de Physique du Globe de Paris, Paris, France
19 Liège University, Liège, Belgium
20 Stockholm University, Stockholm, Sweden
21 Instituto del Mar del Peru, Lima, Peru
22 Laboratorio de Ciencias del Mar, Facultad de Ciencias e Ingeniería, CIDIS, Universidad Peruana Cayetano Heredia, Lima, Peru
23 University of Antwerp, Antwerp, Belgium
24 IOC-UNESCO, Paris, France
25 Air Liquide, Brussels, Belgium
26 University of Maryland Center for Environmental Science, Solomons, MD, United States of America
27 SUNY College of Environmental Science and Forestry, Syracuse, NY, United States of America
28 Instituto Geofísico del Perú, Lima, Peru
29 IOC-UNESCO, Wageningen, The Netherlands
30 Centre For Marine & Coastal Studies, Universiti Sains Malaysia, Penang, Malaysia
31 Dalhousie University, Halifax, Canada
32 Leibniz Institute for Baltic Sea Research, Warnemünde, IOW, Germany
33 School of Energy and Environment and State Key Laboratory of Marine Environmental Health, City University of Hong Kong, Hong Kong Special Administrative Region of China, People's Republic of China
* Author to whom any correspondence should be addressed.

E-mail: caroline.slomp@ru.nl

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Abstract

Eutrophication and global warming are key drivers of oxygen loss, also termed deoxygenation, in coastal ecosystems worldwide. Artificial reoxygenation has been suggested as a local or regional solution to increase oxygen concentrations and improve water quality by various parties, including water managers and industry. Three main approaches have been proposed: (1) bubbling with air with the aim to destratify and mix the water column (2) injection of pure oxygen and (3) pumping of oxygenated water to greater water depths (downwelling). In this review, we summarize the results of recent field trials and other implementations of artificial reoxygenation in coastal systems, which, to date, only involve small bays and estuaries. We also discuss potential benefits and risks.

While the recent trials indicate that reoxygenation of the water column can be achieved, low oxygen conditions returned rapidly within days to months of discontinuing operations. This illustrates that artificial reoxygenation typically only provides a temporary solution to deoxygenation. Potential side effects of artificial reoxygenation could include enhanced emissions of the greenhouse gas carbon dioxide and, upon bubbling and destratification in shallow waters, also of methane. Additionally, downwelling could lead to warming and an associated increased oxygen demand near the seafloor. Reoxygenation will not necessarily reduce the nutrient availability for phytoplankton, implying that water quality may remain poor. We recommend a careful, case-by-case assessment of the suitability of artificial reoxygenation in coastal systems prior to implementation and monitoring before, during and after each intervention. Any field trials should involve all relevant parties, including scientists and local communities, and results should be reported with full transparency. While in the short-term, artificial reoxygenation may be useful to alleviate oxygen loss in some coastal systems, long-term improvements in the oxygen levels and quality of coastal waters require reductions in nutrient inputs and greenhouse gas emissions.

1. Introduction

Coastal seas worldwide are rapidly losing oxygen. This is altering their productivity, biogeochemistry and biodiversity (Diaz and Rosenberg 2008, Breitburg *et al* 2018). Low oxygen zones in coastal seas, which here refer to both nearshore coastal systems (Dürr *et al* 2011) and (semi-enclosed) continental seas, are often termed 'dead zones' because they are unable to support many forms of marine life, including species of fish and marine invertebrates (Diaz and Rosenberg 2008). The causes of low oxygen in coastal seas are well-known: since the 1950s, phosphorus and nitrogen from terrestrial sources (such as fertilizer and wastewater) and, for nitrogen, also atmospheric sources (from burning of fossil fuels) are increasingly entering coastal waters where they are stimulating phytoplankton blooms that, upon their demise and the decay of the organic matter, remove oxygen. Moreover, global warming is reducing the solubility of oxygen in seawater, is increasing water column stratification and is slowing down vertical mixing and circulation, which all limit ventilation of deeper coastal waters (Breitburg *et al* 2018, Dai *et al* 2023). Oxygen loss in coastal waters can be sporadic, diel, seasonal or permanent, depending on the type of system, and the frequency, duration and intensity are key in determining the environmental impact (Diaz and Rosenberg 2008, Tyler *et al* 2009, Pezner *et al* 2023).

The Baltic Sea is a well-investigated example of a eutrophic coastal sea where nutrient pollution has led to the development of a large near-permanent low oxygen zone and major ecosystem change. Anoxic and sulfidic bottom waters cover most of the seafloor at water depths >70 m, creating a large 'dead zone' in the central Baltic Sea basin that is devoid of higher life. Cyanobacterial blooms have become frequent and widespread (Conley *et al* 2009a, Reusch *et al* 2018) and spawning grounds for cod have been lost (Bryhn *et al* 2022). Trapping of fish in low oxygen areas has been observed to lead to fish kills, which are localized mass die-offs (Grégoire *et al* 2023). Examples of regions where low oxygen is also widespread but is seasonal instead of near-permanent include the Gulf of Mexico, Adriatic Sea and East China Sea (Pitcher *et al* 2021, Dai *et al* 2023). Some coastal systems, such as the Gulf of St. Lawrence in eastern Canada, may be under increased threat of low oxygen because of climate-change driven alterations in oceanic circulation that are lowering local oxygen supply (Jutras *et al* 2020, Wallace *et al* 2023).

Reductions in nutrient inputs from land and, given their role in global warming, also of greenhouse gas emissions, are essential to solve the problem of coastal oxygen loss (Conley *et al* 2009a, 2012). Crucially, the temporal trajectory of recovery from deoxygenation upon implementation of such measures is dependent on the characteristics of a given coastal system (Kemp *et al* 2009). Nutrients have been accumulating in the water column and the sediments of many coastal systems for decades and reducing nutrient inputs will not immediately lead to lower concentrations because of nutrient recycling (Kemp *et al* 2009, Kulinski *et al* 2022). Moreover, nutrient release from agricultural lands continues in many regions because of excess fertilizer use and release of nutrients that have already accumulated in soils and groundwater (Liu *et al* 2024). Current efforts to reduce the global use of fossil fuels and related greenhouse gas emissions remain insufficient to stabilize global temperatures and hence fall short of limiting the impact of global warming on oxygen concentrations in coastal waters (Whitney 2022, IPCC, 2023).

Artificial reoxygenation has been suggested as a potential solution to coastal oxygen loss (Stigebrandt and Gustafsson 2007, Stigebrandt *et al* 2015a, Stigebrandt and Andersson 2022) but the possible benefits come with risks that need to be assessed carefully before implementation (Conley *et al* 2009a, Luo *et al* 2024, Meng *et al* 2024). Such assessments are becoming urgent in the light of the emergence of potential new technologies for artificial reoxygenation of coastal seas linked to green hydrogen production, which, as a byproduct, generates oxygen (Beghoura *et al* 2023, Wallace *et al* 2023, Handmann and Wallace 2024). This oxygen could be used to increase the oxygen supply to coastal waters, particularly when green hydrogen production facilities are located close to the sea.

In this article, we first briefly discuss the controls on oxygen concentrations in coastal waters and describe the goals of artificial reoxygenation efforts and related biogeochemical feedbacks. We then present the most common approaches proposed for artificial reoxygenation of coastal waters. We subsequently discuss the results of field trials in coastal systems and their limitations and potential side effects. Finally, we discuss whether artificial reoxygenation is likely to be a long-term solution to coastal oxygen loss and provide recommendations for the formulation of best practices when assessing the suitability and application of artificial reoxygenation.

2. Goals of artificial reoxygenation efforts and related biogeochemical feedbacks

Coastal seas gain oxygen naturally through air–sea exchange, vertical mixing of the water column, lateral advection and photosynthetic production of organic matter (figure 1). They lose oxygen through respiration in the water column and uptake of oxygen upon respiration of organic matter in the sediment. Surface waters typically remain oxygenated because of rapid air–sea exchange and primary productivity but, in deeper waters, oxygen removal dominates, especially in systems with limited vertical mixing (Fennel and Testa 2019).

Artificial reoxygenation aims to increase the supply of oxygen to deeper waters (Conley *et al* 2009a). The primary goal is to increase the oxygen supply to deeper waters to such an extent that the water and surface sediment become or remain oxygenated. To achieve this, the oxygen supply needs to exceed the oxygen demand of the deeper water and the sediment. This oxygen demand depends on the input of organic matter and the eutrophication history of the system: for instance, if the input of organic matter remains high and/or a lot of organic matter has accumulated on the seafloor, the sediment oxygen demand may remain high for a long time. This 'legacy' effect can hinder the reoxygenation of coastal systems (Turner *et al* 2008). Importantly, the reoxidation of products of anaerobic degradation of organic matter, such as ammonium and hydrogen sulfide, can become the dominant oxygen sink (e.g. Burdige 2006, Testa *et al* 2018).

A secondary goal of artificial reoxygenation can relate to phosphorus dynamics: reoxygenation may reduce phosphorus recycling through increased binding of phosphorus to iron oxides in sediments (Conley *et al* 2009b, Jilbert *et al* 2011, Testa *et al* 2025). This, in turn, may reduce the availability of phosphorus for phytoplankton in surface waters. By lowering the production and sinking flux of organic matter, this may lead to a lower oxygen demand and, hence, higher oxygen concentrations in deeper waters, constituting a positive feedback loop (Conley *et al* 2009a). A change in bottom water oxygen can thus lead to an improvement in water quality by promoting the retention of phosphorus in the sediment (Norkko *et al* 2012, Stigebrandt *et al* 2015a).

Because the same positive feedback loop would release phosphorus upon return to low-oxygen conditions, e.g. after termination of reoxygenation, a persistent improvement of water quality will only be achieved if the phosphorus is sequestered in the sediment permanently (Katsev *et al* 2006). This requires the transformation of the iron-oxide bound phosphorus to sediment phosphorus forms that are not remobilized upon burial, such as the calcium-phosphate mineral apatite or, when there is excess reactive iron over reduced sulfur, the Fe(II) phosphate mineral vivianite (Slomp 2011, Egger *et al* 2015). This illustrates that sediment phosphorus burial is not a simple function of bottom water oxygen but instead depends on a range of factors, including the history of the iron supply and organic matter input to and burial in a system.

Artificial reoxygenation can affect many other biogeochemical processes. For example, nitrogen loss via coupled nitrification–denitrification in the sediment can be stimulated, improving water quality (De Brabandere *et al* 2015, Harris *et al* 2015). Seasonally hypoxic, stratified systems can be used to illustrate some of the expected additional effects. Reoxygenation can change the relative contribution of aerobic versus anaerobic degradation of organic matter in coastal systems (Kemp *et al* 2009), impacting seawater pH, carbon dioxide concentrations and alkalinity (Cai *et al* 2011, Hagens *et al* 2015). The effects are site-specific and depend on factors such as the buffering capacity of the water and whether the water column remains stratified (Cai *et al* 2011, Hagens *et al* 2015). During summer stratification, strong depth gradients in pH and alkalinity can develop, with distinct pH minima below the redoxcline due to oxic respiration or sulfide oxidation. These gradients disappear upon water column mixing (Hagens *et al* 2015, Cai *et al* 2017).

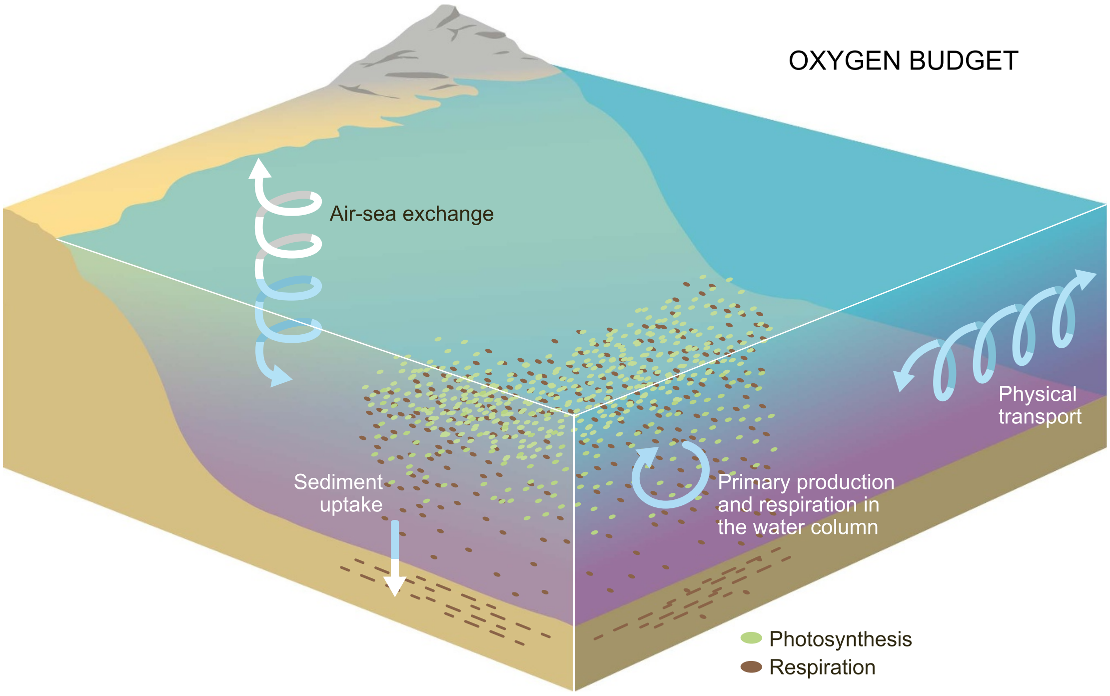

Figure 1. Principal terms in the oxygen budget for coastal systems (Reproduced with permission from Fennel and Testa (2019). Copyright © 2019 by Annual Reviews. All rights reserved). Green shapes: living phytoplankton. Brown shapes: other organic matter. Purple: deeper waters prone to low oxygen. Air–sea exchange: exchange of oxygen between the surface water and atmosphere. Sediment uptake: oxygen uptake upon respiration of organic matter in the sediment. Primary production and respiration: addition and removal of oxygen from the water column upon formation and respiration of organic matter, respectively. Physical transport: oxygen transport via vertical mixing and lateral advective transport of water.

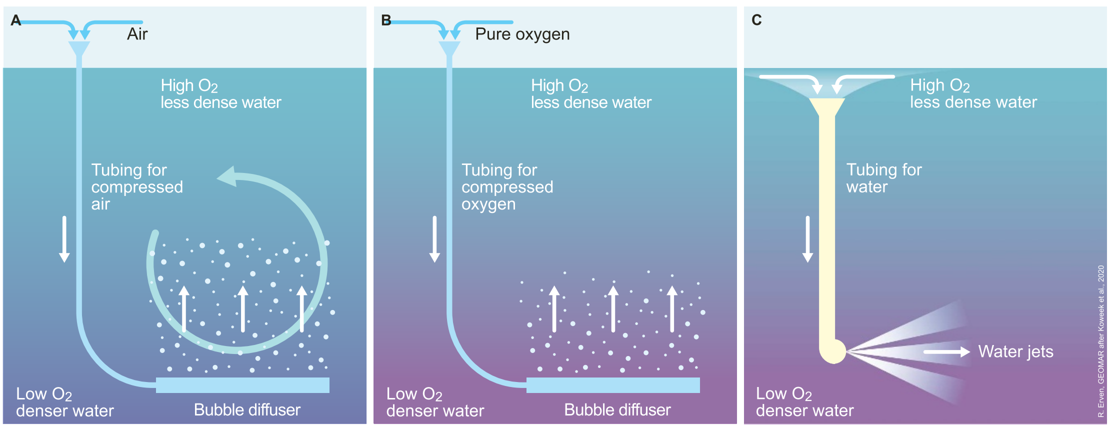

Figure 2. Simplified representation of three main methods proposed for artificial reoxygenation of coastal waters: (A) bubble diffusion with air with the aim to destratify the water column and (B) bubble diffusion to inject pure oxygen, with the aim to directly reoxygenate the deeper water and (C) downwelling. Reproduced from Slomp and Oschlies (2025). CC BY 3.0.

3. Approaches to artificially reoxygenate coastal systems

Inspired by methods used to reoxygenate lakes (Singleton and Little 2006, Mobley *et al* 2019), three main approaches have been proposed for artificial reoxygenation of coastal systems (figure 2). These are (1) bubbling with air (Harris *et al* 2015), (2) bubbling of pure oxygen (Koweek *et al* 2020, Wallace *et al* 2023) and (3) artificial downwelling, which refers to pumping of oxygenated surface water into deeper water (Stigebrandt *et al* 2015b, Lehtoranta *et al* 2022). Below, we discuss the general principles and the observed effects on oxygen concentrations in coastal systems upon application of these approaches; we refer to the literature for technical details.

Bubble diffusers that inject air aim to destratify and aerate the water column by inducing vertical mixing. Such aeration systems have succeeded in raising oxygen concentrations in shallow coastal systems (e.g. small estuaries with water depths of up to several meters) where tides contribute to lateral advection of the oxygen (Harris *et al* 2015) as well as in coastal impoundments (Lamping *et al* 2005). Aeration devices are expected to have the greatest effect on sediment processes when positioned at the seafloor.

Bubbling with pure oxygen is required to oxygenate deeper coastal waters, based on methods for lakes (Mobley *et al* 2019). Applications in the coastal zone should consider that the behavior of gas bubbles in seawater and freshwater can differ (Slauenwhite and Johnson 1999). To date, there are no known applications of injection with pure oxygen in coastal waters described in the literature.

Pumps used for coastal reoxygenation through downwelling take in near-surface water and eject it in deeper waters. Depending on the buoyancy of the injected water and the stratification of the ambient water, downwelling may also affect stratification and mixing (Stigebrandt *et al* 2015b, Lehtoranta *et al* 2022). Downwelling experiments in Swedish coastal bays have demonstrated that oxygenation can be achieved with this method (Forth *et al* 2015, Stigebrandt *et al* 2015b, Lehtoranta *et al* 2022). Notably, the oxygenation of the deeper water column in both cases was the combined result of increased oxygen supply through downwelling and deepwater renewal through lateral inflow from an adjacent basin. This highlights that oxygen levels in neighboring water bodies can determine the outcome of artificial reoxygenation efforts and should be considered when planning such interventions (Stigebrandt *et al* 2015b).

We note that there are also alternative approaches for reoxygenation of shallow (<10 m water depth) small systems, such as the upper reaches of estuaries. As an example, we refer to side stream supersaturation where water is pumped to a dissolution device and supersaturated with pure oxygen prior to discharging it back into the waterbody (Larsen *et al* 2019). This approach has been shown to increase oxygen concentrations in the water column and at the sediment-water interface in a narrow, shallow meandering channel (<100 m wide, <3 m deep) in the Swan River Estuary. Notably, continued pumping was found to be essential to maintain the oxic state (Larsen *et al* 2019).

4. Limitations and potential side effects of artificial reoxygenation

The studies of the effects of artificial oxygenation of coastal bays and estuaries presented in section 3 show that, if no other measures are taken, low oxygen conditions return within days or several months when operations are halted, irrespective of the method employed (Harris *et al* 2015, Stigebrandt *et al* 2015b, Larsen *et al* 2019, Lehtoranta *et al* 2022). The return of anoxia upon discontinuing operations is well-known for lakes (Tammeorg *et al* 2024) and illustrates that artificial reoxygenation alone does not provide a permanent solution to deoxygenation because it does not address its root causes.

Reoxygenation via artificial downwelling of coastal waters may not necessarily increase oxygen concentrations if it causes warming of deeper waters. This is especially a risk when surface water pumps are used to reoxygenate thermally-stratified coastal waters. The transfer of warm surface water to depths near the seafloor may weaken stratification and enhance vertical mixing (or induce lateral inflows of water as noted above). While this may increase the downward transfer of oxygen further, it can also increase the rate of upward mixing of nutrients. This may enhance productivity and, ultimately, could increase the oxygen demand in deeper waters to such an extent that a net decrease in oxygen results (Conley *et al* 2009a, Lehtoranta *et al* 2022). Another potential effect is increased respiration near the seafloor because of a higher metabolic activity of microbes at higher temperatures (Thamdrup *et al* 1998). This may further decrease oxygen concentrations, instead of increasing them as intended (figure 3(A)).

Upon artificial reoxygenation of the water column, wider water quality problems will not necessarily disappear. Deoxygenation is accompanied by nuisance algal blooms in many coastal areas (Breitburg *et al* 2018). Such blooms will remain upon reoxygenation if the availability of nutrients for phytoplankton remains high. In the Baltic Sea, for example, natural decadal-scale reoxygenation of deeper waters linked to lateral inflow of oxygenated North Sea water, does not lead to strong removal of phosphorus to the sediment (Sommer *et al* 2017, Hermans *et al* 2019, Hylén *et al* 2021). This lack of a strong effect of the reoxygenation event, which after the most recent inflow lasted >1 year, results from the highly reducing nature of the sediment. This allows benthic release fluxes of ammonium and hydrogen sulfide to exceed the oxidative capacity provided by the supply of oxygen. The continued flux of reductants hinders the formation of phosphorus-containing minerals in the surface sediment upon bottom water oxygenation. Consequently, recycling of phosphorus is not decreased (figure 3(B), Sommer *et al* 2017, Hermans *et al* 2019, Hylén *et al* 2021), allowing the cyanobacterial blooms to be sustained in what has been denoted as a vicious cycle (Conley *et al* 2009a).

In the pumping experiments in Swedish coastal bays described above (Stigebrandt *et al* 2015b, Lehtoranta *et al* 2022), phosphorus concentrations in the water column decreased during operation of the pumps but increased again within 1 year when operations were discontinued. The decrease was attributed to the combined effect of export of phosphorus to an adjacent basin through lateral flow and retention of phosphorus in the sediment. Unfortunately, the sediment phosphorus speciation and rate of phosphorus

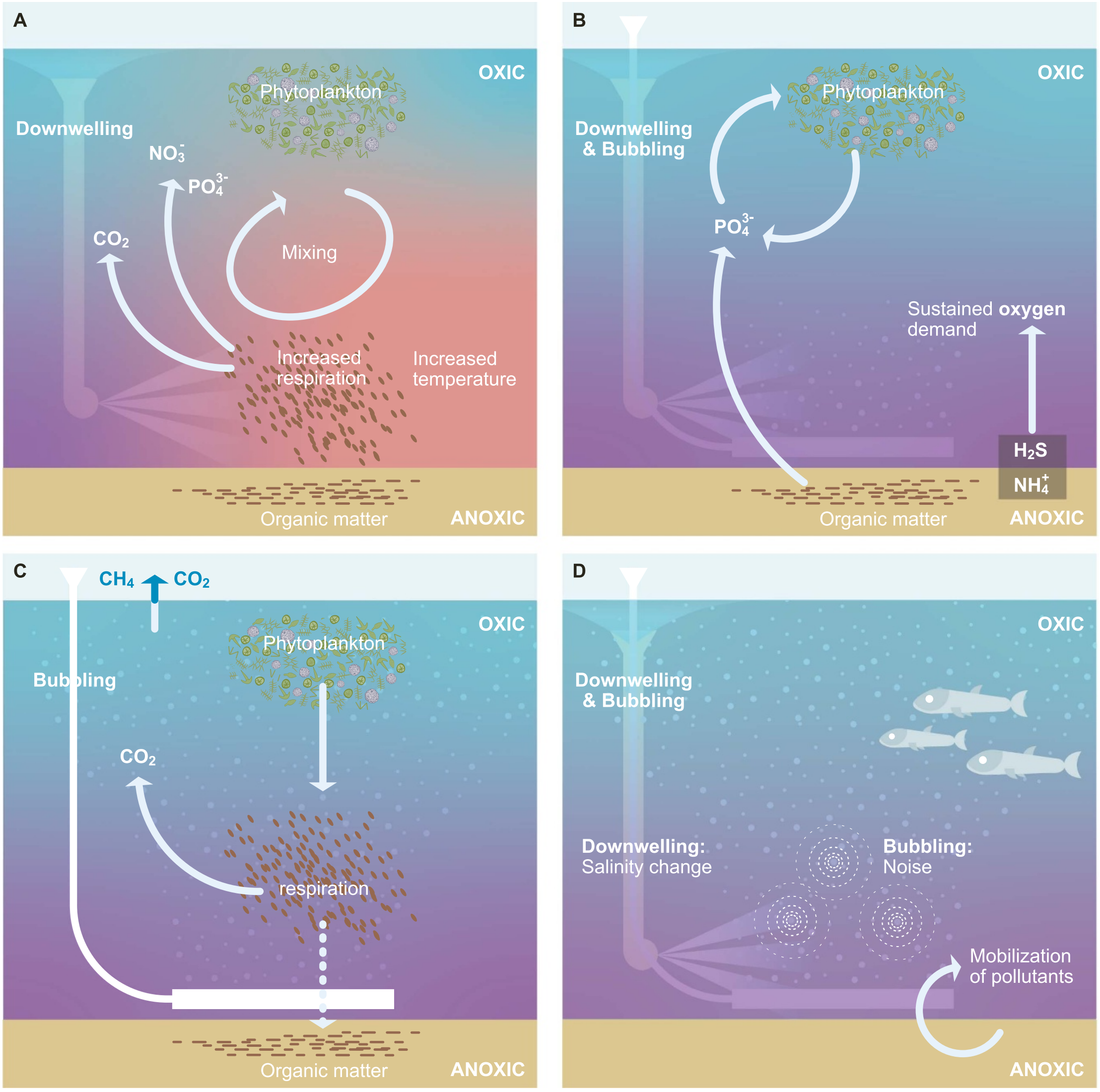

Figure 3. Simplified schematic of potential caveats of reoxygenation initiatives. (A) An increased oxygen demand because of warming-induced increased respiration and increased productivity because of enhanced vertical mixing upon downwelling; (B) limited impact of reoxygenation because of a sustained oxygen demand from the sediment, allowing the vicious cycle between P recycling and bottom water anoxia to be maintained in case of bubbling and downwelling; (C) increased methane emissions linked to bubble transport when using air and increased carbon dioxide emissions due to enhanced aerobic respiration; (D) altered habitat: underwater noise upon bubbling, salinity change and remobilization of toxic substances such as organic pollutants and trace metals. Reproduced from Slomp and Oschlies (2025). CC BY 3.0.

burial were not determined, hindering a detailed evaluation of the relative roles of both processes.

Studies of phosphorus dynamics in a range of coastal systems indicate that reoxygenation does not necessarily stimulate permanent burial of phosphorus (Reed *et al* 2011, Slomp *et al* 2011, Sulu-Gambari *et al* 2018). In some coastal systems, artificial reoxygenation with continued high nutrient loading could create a large, mobile iron-bound phosphorus pool in the surface sediment. Upon termination of the artificial reoxygenation, this iron-bound phosphorus pool could be released to the water column, exacerbating the water quality problems (Conley *et al* 2009a, Reed *et al* 2011). These observations are strikingly similar to those for eutrophic Swiss lakes where a lasting lake recovery is not achieved through artificial reoxygenation when phosphorus loads are not reduced (Gächter and Wehrli 1998, Gächter and Müller 2003).

Artificial reoxygenation may alter the dynamics of greenhouse gases in coastal waters. Increased aerobic respiration will increase carbon dioxide production. This could potentially impact the role of coastal waters as a source of carbon dioxide to the atmosphere (figure 3(C), Laruelle *et al* 2010, Cai *et al* 2021). Furthermore, bubbling with air (with destratification) has been shown to enhance the upward transport of methane in the water column and thereby its emission to the atmosphere upon application in a shallow estuary (Lapham *et al* 2022). There is accumulating evidence that sediments in eutrophic coastal systems can leak methane because of less efficient removal via microbial oxidation of methane (Lapham *et al* 2024, Żygadłowska *et al* 2024a). While reoxygenation will typically reduce dissolved methane concentrations in the water column of coastal systems (e.g. Żygadłowska *et al* 2024b), this will not necessarily suppress the release of methane from the sediment (Żygadłowska *et al* 2024a and 2024b). This implies that, if eutrophication is not addressed in parallel, methane emissions from coastal waters could increase upon reoxygenation via bubbling with air. Further work is needed to quantify these effects (Lapham *et al* 2022).

While an increase in oxygen is generally beneficial for marine organisms, habitats may be altered in other ways. For example, pumps used for bubbling and downwelling generate underwater noise, which may interfere with natural auditory signal processing by marine animals, with potential impacts on feeding, mating and avoidance of predation (figure 3(d), Duarte *et al* 2021, Zhang *et al* 2023). Reoxygenation through bubbling creates turbulence, gas–water interfaces and gradients in oxygen pressure in the water column that may differ from those that occur otherwise, which potentially could affect marine animals. There is also a risk of gas bubble disease in fish, especially when air rather than pure oxygen is used (e.g. Weitkamp and Katz 1980, Wallace *et al* 2023). Artificial downwelling not only changes deep-water temperatures but also alters vertical distributions of salinity. Marine fish and invertebrates are known to be sensitive to changes in salinity and could be affected (Farias *et al* 2024). Increased sediment mixing upon return of bottom-dwelling animals may remobilize sediment contaminants, such as organic pollutants and trace metals (Conley *et al* 2009a). These examples all illustrate that artificial reoxygenation can have unintended consequences for marine ecosystems that should be considered prior to implementation.

5. Assessing artificial reoxygenation as a solution to oxygen loss

According to the precautionary principle, one should, in the absence of full scientific certainty, act to avoid harm, which, in the case of reoxygenation could arise in various dimensions (figure 3). In some cases, this will imply that no measures should be taken. In other cases, this will imply that measures should not be postponed because delay could lead to even more harm. This creates a need for a very careful case-by-case assessment of the suitability of artificial reoxygenation at a given site, and, upon a positive assessment, careful monitoring. Suitability assessments should look beyond impacts on oxygen only and should preferably be embedded in wider ecosystem restoration efforts (Oliveira *et al* 2024). Since rapidly increasing quantities of oxygen might become available as a byproduct of green hydrogen production, there is an urgency to determine if, when, and where artificial reoxygenation can be applied to mitigate the consequences of coastal deoxygenation.

In heavily managed, small and shallow coastal systems, reoxygenation could be a temporary solution to oxygen deficiency, as illustrated by the application of aeration (with destratification) in the sub-estuary of Chesapeake Bay (Harris *et al* 2015, Lapham *et al* 2022) and side stream supersaturation with pure oxygen in the upper reaches of the Swan River Estuary (Larsen *et al* 2019) mentioned above. In the case of the Chesapeake Bay sub-estuary, the oxygenation not only increased water column oxygen concentrations but also decreased hydrogen sulfide concentrations and allowed fish kills to be avoided. Decades of aeration without a reduction in organic matter loading makes the water quality in this system directly dependent on the continuous operation of the aeration infrastructure supported by local communities. As noted by Harris *et al* (2015), widespread applicability of aeration through destratification should not be inferred from this case and, also in this system, a permanent solution to the water quality problems relies on a reduction of the organic matter supply. In general, systems with such short residence times are expected to respond rapidly to both artificial oxygenation (e.g. Fennel and Testa 2019) and nutrient input reductions. The Scheldt estuary is an example of a coastal system where the latter was achieved: in the 1980s, low oxygen conditions were frequent but nutrient reductions led to the return of an oxic state (Soetaert *et al* 2006). Hence, artificial reoxygenation could be a temporary solution until recovery following a reduction in nutrient loads, with the exact timeline depending on the residence time of the water and the nutrients in a given system (Kemp *et al* 2009).

The long-term effects of reoxygenation on large eutrophic coastal systems with strong legacy effects, such as the Baltic Sea, where sediments act as a source of nutrients and sink for oxygen, are more difficult to predict (Conley *et al* 2009a, Reed *et al* 2011, Hermans *et al* 2019). A key reason is that the potential for continued release of nutrients and reductants from the sediments cannot be projected from easily measurable parameters. Lateral exchange of water, solutes and particles will also affect the results of reoxygenation and, in many systems, are difficult to control and monitor. The large size of such systems also makes reoxygenation challenging (Conley *et al* 2009a) while also delaying the response to nutrient load reductions. Notably, taking the Baltic Sea as an example, model results suggest that continued nutrient reductions will lead to a future improvement of water quality on time scales of several decades (Meier *et al* 2022). This emphasizes the value of continued nutrient reduction strategies. The increasingly important role of climatic warming as a driver of low oxygen in the Baltic Sea (Carstensen *et al* 2014) emphasizes the need to also reduce greenhouse gas emissions (IPCC 2023).

In the Gulf of St. Lawrence, a coastal system without strong legacy effects because of its less eutrophic nature, reoxygenation might be harnessed to allow the current oxygen state of the system to be maintained (Jutras *et al* 2020, Wallace *et al* 2023). Subsurface waters (water depths >150 m) in the region are losing oxygen because of eutrophication and, since 2008, primarily via a change in the lateral input of oxygen from the Atlantic. Climatic-related decreases in the supply of oxygen from the southward flowing Labrador Current and a slowing of the Atlantic Meridional Overturning Circulation are key drivers of the deoxygenation, with the oxygen decline thought to be amplified by increased microbial oxygen uptake due to warming (Jutras *et al* 2020, 2023). The annual loss of oxygen in the Gulf of St. Lawrence and adjacent estuary in recent decades and oxygen production of a proposed green hydrogen plant in the region are of the same order of magnitude (2×10^5 and 5×10^5 tons yr^{-1}, respectively), suggesting possibilities for mitigation of at least part of the oxygen decline by oxygenation with pure oxygen. The proposed pure oxygen injection would target the subsurface flows from the Atlantic upon entry into the Gulf. Lateral transfer of oxygen beyond injection areas is expected based on numerical modeling for the global ocean (Beghoura *et al* 2023). At present, no reoxygenation systems have been applied to the water depths and spatial scales relevant to the Gulf of St. Lawrence (Wallace *et al* 2023).

Taken together, long-term, sustainable increases in oxygen levels and improved water quality of coastal systems require reductions in nutrient inputs and reductions of greenhouse gas emissions. Hence, artificial reoxygenation, if applied, should always be only one of various measures to improve the state of coastal waters.

6. Best practices for artificial reoxygenation needed

Analogous to best practices formulated for research on marine carbon dioxide removal (Oschlies *et al* 2023), and associated governance considerations (Johnson *et al* 2024), we point towards the need for the development of a suitability assessment framework (GESAMP 2025) and best practices for scientific research on, and (possible) implementation, of artificial reoxygenation. When sites are found to be potentially suitable for artificial reoxygenation in the form of field trials or deployment, i.e. when the benefits of reoxygenation are perceived to be greater than the drawbacks and reoxygenation is both feasible and desirable, the following aspects should be considered in such best practices:

(1) Performance criteria to define success should be formulated prior to an intervention. This implies that one should decide whether the intervention will only target oxygen concentrations or whether wider water quality measures are a goal such as a reduction in nutrient levels. When evaluating success, potential exchange with water masses in adjacent areas should be considered, since displacement of nutrients is not necessarily a solution. Where possible, historical baselines should be established. This can allow an assessment of whether return to such baselines is achievable.

(2) Pilot studies of artificial reoxygenation should involve relevant government bodies, such as water management authorities, stakeholders, including representatives of local communities, industry partners, and scientists. Feasibility studies should be based on scientific principles and preferably include independent desk studies and lab experiments besides field implementation. Plans should be openly shared and discussed among all involved. Planned field trials or deployments should be announced via a public field-trial registry prior to the experiment or deployment. This should foster knowledge exchange, accelerate learning and ensure maximum information gain of any interventions in the environment.

(3) Any field trial or implementation should respect environmental safety and consider perceived benefits and risks of the intended intervention in the environment including any relevant ethical issues, taking the intrinsic value of nature into account. Governance frameworks are needed to facilitate informed decision-making. In many countries, systematic decision support systems (e.g. environmental impact assessments) are in place to evaluate proposed interventions in water bodies. Such assessments are critical to ensure the best possible approach in view of protecting the environment and human wellbeing. Risks and benefits should be evaluated against the counterfactual of no deployment and should take ongoing environmental change into account.

(4) Key parameters regarding the biology, chemistry and physics of a system should be monitored before, during and after each intervention to determine baseline conditions and assess the potential impacts on water quality and ecology, including termination effects after an intervention ceases. Continued measurements over years to decades are critical to determine long term effects, also considering ongoing global change

and its impacts. A reference or control site, preferably in the vicinity, should be included in each implementation.
Besides oxygen profiling, potential changes in circulation and stratification should be assessed by determining salinity and temperature in parallel. Determining chlorophyll is critical to assess impacts on productivity, whereas hydrogen sulfide is an essential indicator of water quality given its toxic nature. Water column profiles of nutrients (ammonium, nitrate, phosphate, silicate) are key to understanding the level of eutrophication and potential changes in nutrient limitation. Data should have an appropriate spatial and temporal resolution, which will depend on the size of the system and daily or seasonal variability in system characteristics. If, for example, a coastal system is seasonally hypoxic, more frequent sampling is required when compared to a permanently anoxic system.

To assess potential legacy effects related to benthic oxygen demand and nutrient release, the chemical composition of the sediment and porewater and the history of deposition should be assessed. Key parameters that should be included are sediment contents of organic carbon, sulfur, iron oxides and phosphorus and porewater concentrations of ammonium and hydrogen sulfide. Ecological impacts should be assessed by monitoring organisms relevant for a given ecosystem. This could include various types of phytoplankton (e.g. diatoms, cyanobacteria), fish species and benthic macro- and meiofauna.

(5) The costs and greenhouse gas footprint of the intervention should be carefully assessed. This includes that of the required power for the reoxygenation, the infrastructure and oxygen transport. The information on costs, energy demand and greenhouse gas footprint should be communicated to all parties involved prior to an intervention.

(6) Results of any field trials, including perceived failures, should be reported with full transparency and publicly in open data bases and, preferably, in the scientific literature.

(7) When deciding on a potential implementation, the impacts of successful reoxygenation of a given location on the willingness to continue nutrient load reductions should be considered, since the latter have wider benefits.

7. Conclusions

With science-based suitability assessments and ethical and environmentally safe practices, artificial reoxygenation could be useful as a temporary measure at carefully selected sites and might allow detrimental consequences of coastal deoxygenation to be alleviated or avoided. Artificial reoxygenation will rarely be a permanent solution to coastal deoxygenation, however, because it does not address its root causes. Hence, reoxygenation efforts cannot replace essential measures to reduce the input of nutrients to coastal waters nor can it replace reductions of greenhouse gas emissions.

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Data availability statement

No new data were created or analysed in this study.

Author contributions

C P Slomp 0000-0002-7272-0109
Conceptualization (equal), Formal analysis (equal), Visualization (equal), Writing – original draft (lead), Writing – review & editing (lead)

A Oschlies 0000-0002-8295-4013
Conceptualization (equal), Formal analysis (equal), Visualization (equal), Writing – original draft (supporting), Writing – review & editing (supporting)

A H Altieri
Conceptualization (supporting), Formal analysis (supporting), Writing – review & editing (supporting)

L T Bach 0000-0003-0202-3671
Conceptualization (supporting), Formal analysis (supporting), Writing – review & editing (supporting)

L Bopp
Conceptualization (supporting), Formal analysis (supporting), Writing – review & editing (supporting)

D Breitburg
Conceptualization (supporting), Formal analysis (supporting), Writing – review & editing (supporting)

A Canning
Conceptualization (supporting), Formal analysis (supporting), Writing – review & editing (supporting)

D J Conley
Conceptualization (supporting), Formal analysis (supporting), Writing – review & editing (supporting)

M Dai
Conceptualization (supporting), Formal analysis (supporting), Writing – review & editing (supporting)

B Dewitte
Conceptualization (supporting), Formal analysis (supporting), Writing – review & editing (supporting)

H Enevoldsen
Conceptualization (supporting), Formal analysis (supporting), Writing – review & editing (supporting)

E M Ferrer 0000-0002-6709-449X
Conceptualization (supporting), Formal analysis (supporting), Writing – review & editing (supporting)

A Galán 0000-0001-8775-0426
Conceptualization (supporting), Formal analysis (supporting), Writing – review & editing (supporting)

V Garcon 0000-0002-4041-1379
Conceptualization (supporting), Formal analysis (supporting), Writing – review & editing (supporting)

M Gregoire 0000-0002-3726-0426
Conceptualization (supporting), Formal analysis (supporting), Writing – review & editing (supporting)

B Gustafsson
Conceptualization (supporting), Formal analysis (supporting), Writing – review & editing (supporting)

D Gutierrez
Conceptualization (supporting), Formal analysis (supporting), Writing – review & editing (supporting)

P Handmann 0000-0002-5901-4680
Conceptualization (supporting), Formal analysis (supporting), Writing – review & editing (supporting)

A Hylén 0000-0003-4037-0033
Conceptualization (supporting), Formal analysis (supporting), Writing – review & editing (supporting)

K Isensee
Conceptualization (supporting), Formal analysis (supporting), Funding acquisition (lead), Project administration (lead), Writing – original draft (supporting), Writing – review & editing (supporting)

R Lamond 0009-0000-9356-3926
Conceptualization (supporting), Formal analysis (supporting), Writing – review & editing (supporting)

M Li 0000-0003-1492-4127
Conceptualization (supporting), Formal analysis (supporting), Writing – review & editing (supporting)

K Limburg
Conceptualization (supporting), Formal analysis (supporting), Writing – review & editing (supporting)

I Montes
Conceptualization (supporting), Formal analysis (supporting), Writing – review & editing (supporting)

J Sterling
Conceptualization (supporting), Formal analysis (supporting), Project administration (supporting), Writing – original draft (supporting), Writing – review & editing (supporting)

A Tan Shau Hwai
Conceptualization (supporting), Formal analysis (supporting), Writing – review & editing (supporting)

J M Testa
Conceptualization (supporting), Formal analysis (supporting), Writing – review & editing (supporting)

D Wallace
Conceptualization (supporting), Formal analysis (supporting), Writing – review & editing (supporting)

J J Waniek
Conceptualization (supporting), Formal analysis (supporting), Writing – review & editing (supporting)

M Yasuhara 0000-0003-0990-1764
Conceptualization (supporting), Formal analysis (supporting), Writing – review & editing (supporting)

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