Anthropogenic CO2 emissions have greatly increased atmospheric CO2 contributing to global warming and leading to ocean acidification (Figure 1). As reflected in the recent IPCC report, the scientific community's consensus is that emissions reductions alone are not sufficient or timely enough to avoid a global warming catastrophe. Thus, negative-carbon-emission technologies are needed to avoid atmospheric CO2 overshoot scenarios and limit global warming.
to less than 2°C by the end of this century per the Paris Agreement. Due to the urgency and scale of the issue, multiple negative-emission technologies should be evaluated and adopted with broad community involvement to address our society’s pressing climate crisis. The goal is to remove at least 10 Gt-CO2/year from the atmosphere by the mid to late century, which is more than the current annual anthropogenic CO2 uptake by the global ocean (Figure 1). Among various ocean negative-carbon-emission approaches or ocean-based carbon dioxide removal (CDR) technologies, ocean alkalinity enhancement (OAE) is an approach that will decrease sea surface pCO2 via the addition of alkaline materials and promote CO2 uptake from the atmosphere. Additionally, as the oceanic dissolved inorganic carbon (DIC) reservoir is nearly 50 times the atmospheric CO2 content, the sequestered CO2 can remain in the ocean DIC pool as bicarbonate (HCO3–) for centuries. OAE is viewed with high confidence under the efficacy criterion and medium on environmental risk in the recent report by the National Academies of Sciences, Engineering, and Medicine.1

Several fundamental questions have not yet been answered regarding OAE. These include “how realistically and effectively can highly alkaline source materials such as NaOH and Ca(OH)2 mix into natural seawater without forming substantial secondary mineral (CaCO3) precipitation” and “how realistically will readily available carbonate and silicate minerals dissolve in seawater?” This is because ocean-surface water conditions are supersaturated with respect to CaCO3 minerals and unfavorable to the dissolution of silicate minerals such as olivine.3 Thus, how to appropriately and efficiently add alkaline materials to the ocean to achieve OAE and CDR is a tremendous challenge before us.

SEWAGE ALKALINITY ADDITION

We postulate here the novel idea that OAE can be applied to safely and permanently and cost-effectively sequester atmospheric CO2 using wastewater-treatment-plant effluent (Figure 1). As wastewater (sewage) has low pH, high pCO2, and high concentrations of organic acids, it can be used to deliver strong bases without substantial secondary precipitation (i.e., CaCO3) and is solvable as bicarbonate (HCO3–) for centuries. OAE is viewed with high confidence under the efficacy criterion and medium on environmental risk in the recent report by the National Academies of Sciences, Engineering, and Medicine.1

We focus on sewage as waste alkalinity addition because of the following reasons.2

1) It is a cost-effective and readily available alkalinity source. The current global wastewater production is about 140 billion m3/year, and an estimated 10% of wastewater is alkaline (pH > 7) in the United States. Low pH and organic-acid-rich wastewaters provide an ideal site where these minerals can dissolve in seawater.4

2) We apply alkalinity addition on the basis of the ocean’s DIC change, which subsequently promotes a strong CO2 uptake from the atmosphere. Thus, the latter is a more efficient pathway for ocean-based CDR than CaCO3 dissolution (Figure 1). An important distinction between OAE and ocean acidification lies in the levels of pCO2 and pH change. In the ocean-acidification consideration, the change or modification is from 280 ppm to about 1000 ppm (early next century business-as-usual prediction), corresponding to a pH decrease from 8.2 to 7.7. In contrast, in the OAE consideration, the need to reduce sea-surface pCO2 in the open ocean is small, well within recent historical levels. For example, on a global ocean scale, and assuming an equilibrium between surface ocean and the atmosphere, if we can reduce, on average, sea-surface pCO2 by a total of 25, 50, and 100 ppm to 395 (mid 2010s level), 370 (early 2000s), and 320 ppm (late 1960s), we can achieve a CO2 uptake rate of 13.5, 24.4, and 46.2 Gt-CO2/year, respectively, assuming that atmospheric pCO2 will be stabilized at 420 ppm (mid 2020s) (Figure 1). This is equal to or higher than the global CDR goal of removing at least 10 GT-CO2/year. Though it is unlikely that pCO2 can (or needs to) be reduced by 50–100 ppm everywhere in the global surface ocean, and adding alkalinity may take decades, we clearly do not need to reduce sea-surface pCO2 or modify seawater pH greatly to reach the CDR goal. As illustrated in Figure 1, this pCO2 reduction can be induced by raising sea-surface TA by <1%–3%. Thus, in the ocean, where most CO2 uptake occurs due to its vast area, the modification of carbonate chemistry will be minimal, and the likely environmental, biological, and ecosystem impacts are expected to be small. However, numerical models at both regional and global scales should be carried out to simulate the amount, rate, location, and duration of TA additions and assess the efficacy and impacts of this proposed CDR strategy.

ADVANTAGES OF OUR APPROACH

A sewage-delivered OAE approach is a novel concept in the ocean-based CDR family and has the following advantages over other OAE approaches. (1) Direct application of NaOH and Ca(OH)2 into the open ocean will unavoidably induce CaCO3 or even Mg(OH)2 precipitation and alkalinity loss at the release points, while low pH wastewater may allow us to avoid this problem. (2) Most ocean waters are supersaturated with respect to CaCO3 minerals and are dissolution unfavorable to silicate minerals no matter how finely they are pulverized. Low pH and organic-acid-rich wastewaters provide an ideal site where these minerals may dissolve at meaningful rates for CO2 sequestration purposes. (3) Coastal waters are often CO2 sources to the atmosphere and have suffered from severe seasonal ocean acidification due to the synergistic effects of anthropogenic and respiration-induced CO2. Application of alkaline materials in wastewater treatment plants and their effluents will reduce CO2 release and ameliorate acidification in estuaries, providing co-benefits for environmental health and fisheries. (4) Applying mineral alkaline sources to coastal waters is economically viable than transporting them to the open ocean because transportation of minerals using >1000 ships is a major factor in the cost and energy-consumption estimation of the known OAE approaches.1 We advocate the sewage-delivered OAE approach, we strongly recommend that impacts on environments, organisms, and ecosystems be carefully evaluated because coastal zones have already been facing multiple environmental and climate-related stressors and are more vulnerable than the open ocean.

CONCLUDING REMARKS

Using sewage and other low pH coastal waters as a means to add alkalinity to the ocean is novel and has many advantages for achieving ocean alkalinity enhancement and CO2 removal with the co-benefit of ameliorating ocean acidification in both the coastal and open ocean. Regional- and global-scale numerical model simulations should be used to more fully evaluate the efficacy of this proposed approach in ocean negative carbon emissions or CDR, while water quality and biological impacts in coastal environments should be monitored and studied.

REFERENCES

1. National Academies of Sciences, Engineering, and Medicine (2021). A research strategy for ocean-based carbon dioxide removal and sequestration (The National Academies Press).
2. Renforth, P. (2019). The negative emission potential of alkaline materials. Nat. Commun. 10, 1401.
3. Hangx, S.J.T., and Spier, C.J. (2009). Coastal spreading of olivine to control atmospheric CO2 concentrations: a critical analysis of viability. Int. J. Greenh. Gas Control 3, 757–767.
4. Lu, L., Guest, J.S., Peters, C.A., Zhu, X., Rau, G.H., and Ren, Z.J. (2018). Wastewater treatment for carbon capture and utilization. Nat. Sustain. 1, 750–758.
5. Yang, X., Yue, L., Li, Y., et al. (2018). Treated wastewater changes the export of dissolved inorganic carbon and its isotopic composition and leads to acidification in coastal oceans (Environmental Science and Technology).

ACKNOWLEDGMENTS

This publication was made possible by National Science Foundation of China grant no. 42188102, the National Science Foundation EPSCoR grant no. 1757353, the state of Delaware, and the ONCE program partnered with UNESCO-IoC, PICE, and ICES.

DECLARATION OF INTERESTS

The authors declare no competing interests.