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Integrated actions across multiple sustainable development goals (SDGs) can help address coastal ocean acidification

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Cristian A. Vargas[1,2,3] & Stefan Gelcich[2,4,5]

The Sustainable Development Goals (SDGs) adopted by the United Nations in 2015 constitute a set of 17 global goals established as a blueprint for achieving a more sustainable and equitable world for humanity. As part of the SDGs, target 14.3 is focuses on minimizing and addressing the impacts of Ocean Acidification (OA). We argue that moving forward in meeting the targets related to pH levels in the coastal ocean can be facilitated through accounting for various drivers of pH change, which are associated with advancing a suite of SDG goals. Addressing 'coastal acidification' via a suite of linked SDGs may help avoid inaction through connecting global phenomena with local impacts and drivers. This in turn can provide opportunities for designing novel place-based actions or partnerships that can aid and provide synergies for the joint implementation of programs and policies that tackle a suite of SDGs and the specific targets related to coastal ocean pH.

Anthropogenic carbon emissions and ocean acidification

Since the beginning of the 19th century the ocean has absorbed more than 500 billion tons of CO_2 from the atmosphere, around 31% of anthropogenic CO_2 emissions since the third industrial revolution in the 1970s[1]. As a major consequence, seawater has experienced an increase in acidity, and changes in its chemistry are occurring worldwide, a global process known as Ocean Acidification (OA)[2]. As a consequence of OA, biodiversity, ecosystem functioning, and biogeochemical cycles could be profoundly impacted, leading to major concerns for human food security and well-being[3–5]. Minimizing OA is a big challenge for humanity that requires collective action on a global scale[6], including the reduction of atmospheric CO_2 emissions[7], supporting renewable energy, promoting sustainable production practices[8], the protection and restoration of oceanic and coastal ecosystems[9], raising awareness and education[10], as well as supporting scientific research[6]. During the last decade, the threat of OA has increasingly reached the public and political spheres. OA is now a headline climate indicator for the World Meteorological Organization (WMO)[11] and is part of the 2030 Sustainable Development Goals, SDGs (IOC-UNESCO), which incorporated target 14.3 focused *on* "minimizing and addressing the impacts of OA"[12]. For such purposes, some actions have been established, including "the monitoring of average marine acidity (pH) measured at agreed suites of representative sampling stations in both coastal and open ocean" (Indicator 14.3.1). Through this indicator, governments, organizations, and individuals are encouraged to work together to protect and restore seawater pH levels, to ensure the well-being of both marine ecosystems and human communities.

Minimize and address the impacts of ocean acidification and the use of an indicator for a global scale process

At present, an SDG 14.3.1 Data Portal has been implemented for the submission, collection, validation, storage, and sharing pH of data (https://oa.iode.org/). An indicator methodology for this SDG has been shared within the scientific community, which addressed multiple logistic concerns. Sampling strategy protocols recommend the use of *'long-term monitoring of water quality'* in coastal areas as a useful source of historical records for seawater pH and an ideal location for OA monitoring[13]. While it is critical to

[1]Coastal Ecosystems & Global Environmental Change Lab (ECCALab), Department of Aquatic Systems, Faculty of Environmental Sciences & Environmental Sciences Center EULA Chile, Universidad de Concepcion, Concepcion, Chile. [2]Coastal Social-Ecological Millennium Institute (SECOS), P. Universidad Católica de Chile, Santiago, Chile. [3]Millennium Institute of Oceanography (IMO), Universidad de Concepcion, Concepcion, Chile. [4]Facultad de Ciencias Bologicas, P. Universidad Católica de Chile, Santiago, Chile. [5]Center of Applied Ecology and Sustainability (CAPES), Faculty of Biological Sciences. Pontificia Universidad Católica de Chile, Santiago, Chile. e-mail: crvargas@udec.cl

sample these areas, data derived from '*coastal water quality monitoring*' typically show great natural variability in seawater pH and other carbon chemistry parameters caused by factors other than those driven by OA, especially due to freshwater discharges, organic matter and/or nutrient loading[14,15] (Fig. 1). Moreover, methods and data quality (QC, quality control) for addressing water quality objectives are distant from those needed to describe the rate of OA trends (i.e., 0.01–0.02 decade^{-1})[16]. Therefore, data aiming to evaluate OA progression must be collected using standardized measurement protocols with common reference materials (CRM)[11]. Besides recognizing that sites designated for water quality monitoring may not be optimal for OA monitoring, it is strongly recommended to also individualize monitoring programs focused on global-scale drivers (i.e., the increasing ocean uptake of CO_2 emissions derived from human activities), of those sites focused on water quality monitoring or other local factors influencing changes in seawater acidity. While coastal pH monitoring can support different objectives (e.g., pollution and ecosystem restoration), the use of this indicator complicates the monitoring of the target 14.3 (i.e., addressing the impact of global OA), since multiple factors and actors are driving decadal trends in seawater pH in the coastal ocean.

Multiple local drivers of decadal changes in seawater pH in the coastal ocean

Despite the high observed temporal variability, a decadal linear trend in seawater pH can be observed in coastal areas, although substantially driven by other local factors than only global OA, such as anthropogenic nutrient loading or changing river alkalinity[15,17,18]. For instance, chlorophyll concentration, a proxy for phytoplankton biomass, and dissolved oxygen are both commonly used as indicators of high primary production and eutrophication in coastal zones, as they link nutrient enrichment with algal biomass and nutrient-fueled-respiration respectively. Both indicators have been consistently correlated with seawater pH in coastal environments (Fig. 1). Just using two examples from different continents, different ecosystems (estuary and embayment), and with enough temporal longitude (i.e., >20 years data) confirms this statement. For instance, a 24-year' time-series in a Florida estuary[19] evidences the decreasing trends for both pH and oxygen in this coastal area (Fig. 1A), and a 34-year' time-series of seawater quality monitoring in coastal Hong Kong demonstrates the impacts of eutrophication, resulting in high phytoplankton biomass (i.e., chlorophyll) in the 1980s and 1990s, which then declined gradually stabilizing the chlorophyll and pH levels in this coastal area (Fig. 1B). There are increasing lines of evidence that changing land use in river basins can also drive significant changes in quantity and quality of terrestrial riverine material exported to the adjacent coastal areas, impacting seawater alkalinity, partial pressure of carbon dioxide (pCO_2), and pH[20,21]. Importantly, fluxes of terrestrial carbon have been altered on decadal scales due to the impact of climate change on hydrological cycles[22], and the anthropogenic impact on both river flow regimes (i.e., damming and irrigation)[23] and changing land uses[24,25]. In addition, coastal upwelling regimes, which also impact the carbonate chemistry of shallow waters[26] are also changing over decadal scales due to climatic forcing [27,28]. Finally, ocean warming [29] could also be playing a role in the decreased solubility of CO_2 at increased temperatures and in decreasing alkalinity by ice-melting in high latitudes[30,31]. Accordingly, decadal patterns of pH in coastal areas have been driven by atmospheric CO_2 emission associated with fossil fuel use and industrial processes, but also other human activities such as increased waste, nutrient loadings, and changing land uses[32]. Therefore, monitoring seawater pH can be a key indicator to assess marine acidity and coastal sustainability, although interacting drivers can confound the direct links with OA, an ongoing process caused by the current ocean uptake of human-derived CO_2 emissions.

Future scenarios of changing pH in coastal habitats are extremely difficult to predict due to the multiple drivers of coastal pH[33,34]. Indeed, for some specific coastal regions, increasing river alkalinity over decadal time scales could increase the seawater pH and slow the OA trend (e.g., Gulf of Mexico[35]). Hence, factors leading to ocean and coastal acidification often occur concurrently and follow different patterns[36,37], (Fig. 2), leading to the emergence of average decadal or yearly trends but also deviating from seasonal extremes due to all those pH/pCO_2 controlling variables (e.g., temperature, dissolved inorganic carbon, and alkalinity)[38]. Despite these complexities, we can move forward in meeting the 2030 agenda for sustainable development in relation to pH levels in the ocean, by accounting for linkages among different drivers and their relationship with advancing key sustainable development goals (SDGs), which can jointly allow us to take actions to ensure healthy ocean chemistry in coastal areas.

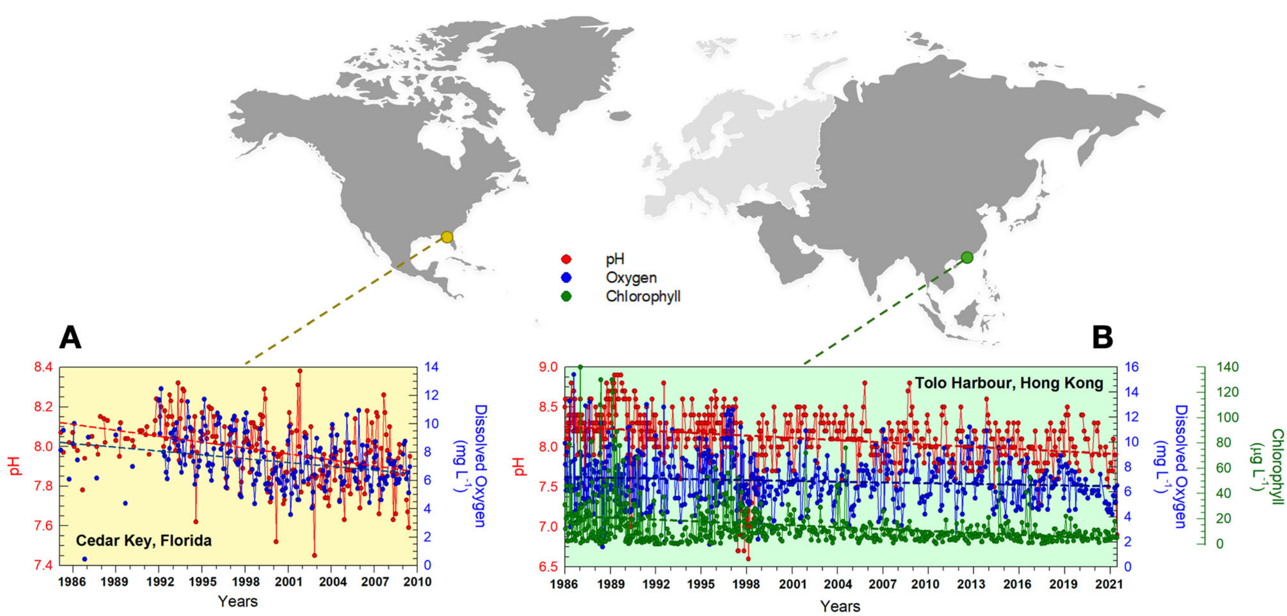

Fig. 1 | Decadal changes in coastal pH and dissolved oxygen in a coastal area. A A 24-year time-series of pH and dissolved oxygen as part of the water quality monitoring assessed by the Florida Department of Agriculture and Consumer Services (FDACS), (Robins & Lisle[19]) (Data source: (http://www.freshfromflorida.com/Divisions-Offices/Aquaculture), and **B** a 34-year time-series of pH, dissolved oxygen, and chlorophyll in the framework of the Marine Water Quality Data, from the Environmental Protection Department, Government of Hong Kong (Data source: https://cd.epic.epd.gov.hk/EPICRIVER/marine/).

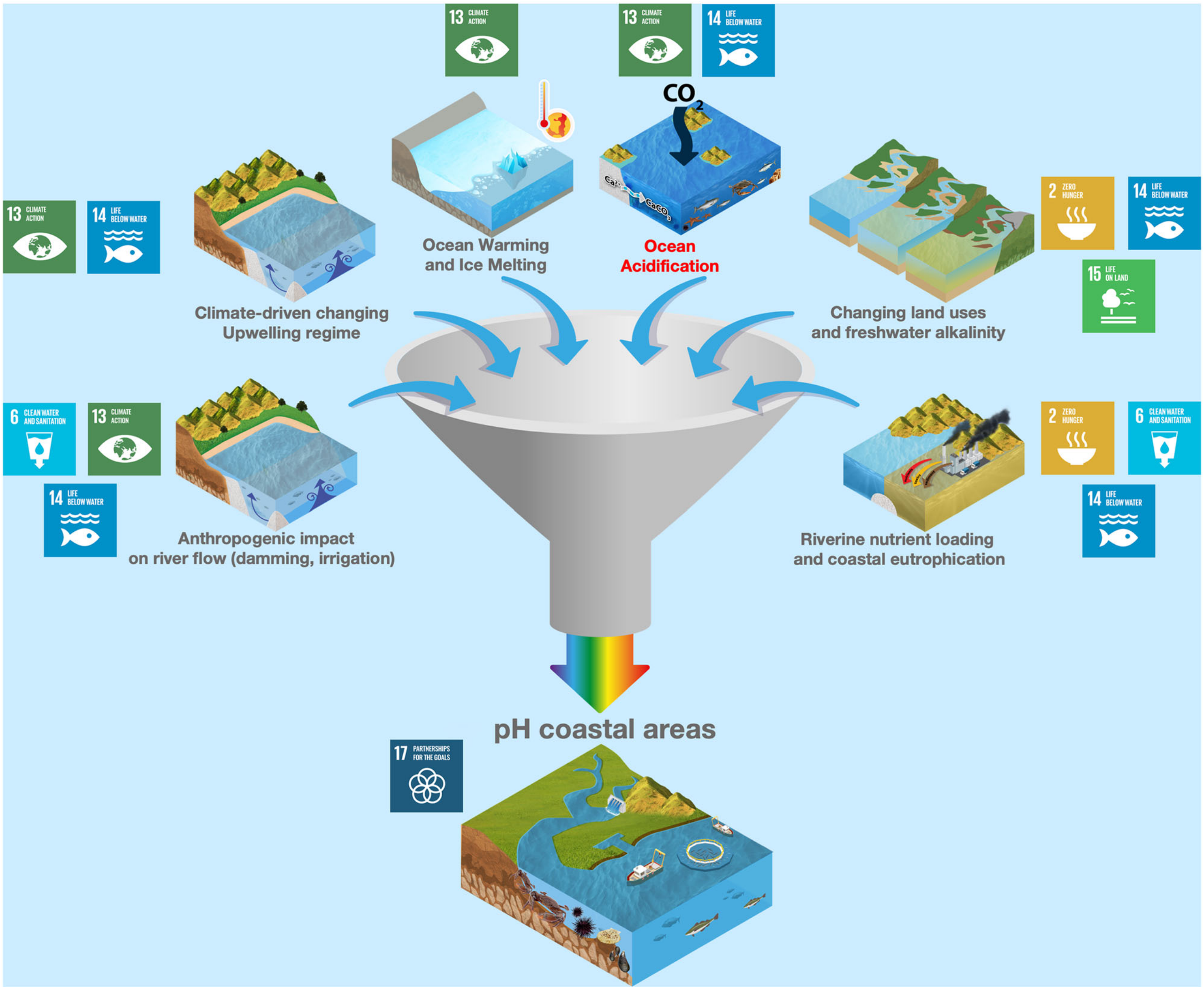

Fig. 2 | Long-term changes in coastal seawater pH can be driven by multiple processes both influenced by inland and shallow marine waters. Different processes determine the long-term variability in coastal pH, including decadal changes in the upwelling regime, the long-term impact of ocean warming on ice melting at high-latitude, decadal anthropogenic forces, such as modifications of natural river flow by damming, changing land uses and freshwater alkalinity, and nutrient loading. Global ocean acidification also has a signature at the decadal scale on coastal pH, and therefore, the combination of drivers may have significant implications for carbonate chemistry in the coastal ocean and marine life. Minimizing the impact of acidification in coastal areas implies multiple actions from different SDGs, such as SDG 2, 6, 12, 13, 14, 15, and 17.

Linking different SDGs with drivers of coastal acidification

Meeting the 2030 Global Agenda for sustainable development will be challenging and will require partnership, innovation, and holistic and harmonized approaches and strategies at multiple scales. An understanding of the social and environmental contexts[39] that drive coastal pH is needed in order to realize how to address the issue from multiple perspectives. As a result of the combination of drivers in coastal habitats, a deeper understanding and public discussion about the societal causes and policy actions to tackle changes in relation to seawater pH is needed[40]. Minimizing and addressing the impact of changing pH requires a dialog between the policy and scientific communities, but also requires establishing linkages among the different drivers. Although there is recognition of the need to address linkages among SDG 14 targets[41], and there have been calls to support synergies and minimize tradeoffs between SDGs[42,43], there is still little discussion regarding the role that other SDG goals can play in addressing the impacts of acidification on coastal areas. Research has mainly highlighted the co-benefits of reducing OA for other SDG targets (e.g., lead to greater productivity and reduce poverty and hunger)[44], but has focused less on exploring how addressing different SDGs can influence coastal acidification, thereby signaling place-based initiatives that can help limit changing coastal pH trends. In this respect, an example is taking place in Washington State (https://oainwa.org/).

The lack of discussion about how we can link different SDGs with changing seawater pH in the coastal ocean could relate to the fact that indicator 14.3.1 is assumed to exclusively measure a specific global target (i.e., minimize and address the impact of OA). However, such indicators, measured in coastal areas, are, in fact, driven by different factors. The assumption that seawater pH in coastal environments is an issue that is exclusively related to anthropogenic CO_2 emissions may paralyze action at local scales. On the other hand, recognizing that addressing coastal pH requires actions across many different SDGs, targets, and indicators may improve action at local scales.

Here, we provide some examples of linkages between pH and its direct and indirect association with SDGs 2, 6, 12, 13, 14, 15, and 17 (Table 1). For instance, Target 2.4.1. of SDG 2, which addresses sustainable agriculture and improvement of land and soil quality, might have direct consequences on changing land uses and nutrient loading in watersheds and, therefore, on coastal pH[15,18–21]. SDG 6 indicators linked with improving water quality through pollution reduction and protecting and restoring water-related ecosystems (e.g., rivers) also have direct effects on nutrient loading, eutrophication, and coastal pH trends[15,17,18] (Table 1A). Achieving the

Table 1 | Examples of relationships between targets and indicators of some relevant SDGs, and different processes driving decadal changes in seawater pH in the coastal ocean

TARGET	INDICATOR	pH DRIVERS: River Flow	Upwelling	Warming	Ice Melting	Changing land uses	Nutrient loading	Atmospheric CO_2	Ref
A. Zero Hunger – SDG 2									
2.4 By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality.	2.4.1 Proportion of agricultural area under productive and sustainable agriculture.	/	/	/	/	●●	●●	/	15, 19, 20, 21, 22 25, 26
B. Clean Water and Sanitation – SDG 6									
6.3. By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally.	6.3.1 Proportion of wastewater safely treated	/	/	/	/	●●●	●●●	/	15, 34, 37, 47, 48
6.3. By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally.	6.3.2 Proportion of bodies of water with good ambient water quality	●● (gray)	/	/	/	●●●	●●●	/	15, 18, 19, 20, 21, 22, 34, 36, 37
6.6. By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes.	6.6.1 Change in the extent of water-related ecosystems over time.	●●●	/	/	/	●●	●●	/	21,22, 23, 24, 25
6.b. Support and strengthen the participation of local communities in improving water and sanitation management.	6.b.1 Proportion of local administrative units with established and operational policies and procedures for participation of local communities in water and sanitation management.	●●	/	/	/	●●●	●●●	/	55
C. Responsible consumption and production – SDG 12									
12.4. By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, **water** and soil in order to minimize their adverse impacts on human health and the environment.	12.4.2 (a) Hazardous waste generated per capita; and (b) proportion of hazardous waste treated, by type of treatment	/	/	/	/	● (gray)	● (gray)	/	34, 37, 47, 48
D. Climate Action – SDG 13									
13.2. Integrate climate change measures into national policies, strategies and planning.	13.2.1 Number of countries with nationally determined contributions, long-term strategies, national adaptation plans, strategies as reported in adaptation communications and national communications.	●●● (gray)	●●● (gray)	●●●	●●● (gray)	●●●	●●●	●●●	23, 24, 26, 27, 28, 29, 30, 31, 32, 33
13.2. Integrate climate change measures into national policies, strategies and planning.	13.2.2 Total greenhouse gas emissions per year.	●●● (gray)	●●● (gray)	●●●	●●●	●●● (gray)	●●● (gray)	●●●	23, 24, 26, 27, 28, 29, 30, 31, 32, 33
E. Life below water – SDG 14									
14.1. By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution.	14.1.1 (a) Index of coastal eutrophication; and (b) plastic debris density	/	/	/	/	/	●●●	/	15, 19, 20, 34, 37, 47, 48
14.3. Minimize and address the impacts of ocean (coastal) acidification, including through enhanced scientific cooperation at all levels.	14.3.1 Average marine acidity (pH) measured at agreed suite of representative sampling stations	●● (gray)	●●● (gray)	● (gray)	●● (gray)	●●●	●●●	●●●	14, 15, 18, 19, 20, 21, 22, 27, 31, 32, 34, 36, 37, 38, 46, 47, 48
14.5. By 2020, conserve at least 10 per cent of coastal and marine areas, consistent with national and international law and based on the best available scientific information.	14.5.1 Coverage of protected areas in relation to marine areas	/	/	/	/	/	●	●●●	9
F. Life on Land – SDG 15									
15.1. By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements.	15.1.1 Forest area as a proportion of total land area	●●●	/	/	/	●●●	●●●	/	21, 22, 25, 26
15.2. By 2020, promote the implementation of sustainable management of all types of forests, halt deforestation, restore degraded forests and substantially increase afforestation and reforestation globally.	15.2.1 Progress towards sustainable forest management	●● (gray)	/	/	/	●●	●●	/	21, 22, 25, 26
15.3. By 2020, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land-degradation-neutral world.	15.3.1 Proportion of land that is degraded over total land area	●● (gray)	/	/	/	●●●	●●●	/	21, 22, 25, 26
G. Partnerships for the goals – SDG 17									
17.7 Promote the development, transfer, dissemination and diffusion of environmentally sound technologies to developing countries on favorable terms, including on concessional and preferential terms, as mutually agreed.	17.7.1 Total amount of approved funding for developing countries to promote the development, transfer, dissemination and diffusion of environmentally sound technologies	●● (gray)	/	●● (gray)	●● (gray)	●●	●●	●●	50, 55
17.14 Enhance policy coherence for sustainable development.	17.14.1 Number of countries with mechanisms in place to enhance policy coherence of sustainable development.	●● (gray)	/	●● (gray)	●● (gray)	●●	●●	●●	50, 55

Dots represents confidence level of linkages between indicators and pH drivers (● Poor; ●● Moderate; ●●● High), and gray and black colors, represent indirect and direct effects, respectively. Some references supporting the direct/indirect relationships between the indicators and processes driving pH changes are included (**Ref**).

management of chemical and all wastes stated in SDG 12 also has an indirect effect on coastal pH drivers, such as changing land uses and nutrient loading[45–47] (Table 1B). One of the more evident linkages between SDGs is those related to Climate Action (SDG 13), since Indicators related to Target 13.2 (i.e., greenhouse emissions) have direct influences in almost all processes driving pH changes in the coastal ocean (e.g., river flow, upwelling intensity/duration, ocean warming and ice melting, changing land uses, riverine nutrient loading, and atmospheric CO_2) (Table 1C). Even within SDG 14, various SDG indicators are closely connected to the primary drivers of pH changes in the coastal ocean over decades ('coastal acidification'), rather than solely focusing on global ocean acidification (Table 1D). SDG 15, which considers the management of forest areas and land uses, has shown direct consequences over pH driven by changing land uses, and some evidence on nutrient loading [20,21] (Table 1E). Finally, those indicators related to necessary partnerships for the goals highlighted in SDG 17 can also evidence some linkage with most drivers of changing coastal pH (Table 1F). Importantly, the strength of the interactions between SDGs and pH can vary in space and time, depending on local and changing conditions. Establishing adaptive monitoring programs[48], which assess different SDGs and their interactions with pH, can further aid in exploring these linkages and dimensions in a policy-relevant way.

Addressing drivers of coastal pH as opportunities for place-based actions

The synergies among various SDGs with the mitigation of coastal acidification enable the linkage of local and national impacts to global phenomena. This offers opportunities for location-specific interventions that facilitate the design and emphasis of coordinated implementation of programs and policies addressing the SDGs. Some specific examples of how addressing SDGs at a local scale could effectively reduce a regional trend of decreasing seawater pH in coastal waters include;

(a) Reducing nutrient loading, residential and agricultural runoff has positive effects over pH in coastal ocean, and therefore, mitigates global OA impacts on marine populations[49].
(b) In the same line, land use regulation through regional planning or zoning can help reduce both drivers of atmospheric CO_2 emissions (SDG13), and therefore, ocean acidification (SDG 14.3), and drivers of pollution and water quality (SDG 6) and coastal acidification.
(c) While in many nations, it might be easier to measure pH directly, in some circumstances, while capacity is being developed, monitoring other biological indicators could provide important complementary information. For instance, Pacific Island states or other countries with coral reef ecosystems may also use current legislation for developing biological indicators of water quality for acidification in order to assess if a coastal area is impaired based on the negative trend of a specific biological indicator (e.g., coral biodiversity and biomass)[50]. This approach could also be useful where monitoring ocean acidity has been patchy over large temporal scales and could even provide further support for the implementation of monitoring programs and policies that integrate SDGs[51].
(d) Mitigation strategies for controlling ocean alkalinity could be also applied in this context of multi-drivers of coastal pH, such as liming riverine waters, by adding neutralizing materials to lower soil acidity, and/or water quality regulations (SDG6) for increasing freshwater alkalinity creating a buffer for OA in the adjacent coastal ocean[35].
(e) Another potential approach to mitigate the regional trend of decreasing seawater pH relates to the potential of returning crushed shell material to coastal habitats to mitigate localized acidification impacts on shellfish populations[52,53].
(f) Finally, although education is an indirect action with a long-term quantifiable benefit, it can create awareness and concerns that might result in coalitions of different actors, such as local governments, industry, and other stakeholders, for taking additional actions[54], a partnership for the goals (SDG17) (Table 1).

As indicated, making synergies explicit could aid local and regional authorities in implementing new or existing policies to address many drivers of changing pH in coastal areas. Importantly, considering linkages could also help identify possible tradeoffs, which could be managed and accounted for in policy (see[43] for suggestions). For instance, actions to meet Goals 2 and 8 (eliminate hunger and increase economic growth) might generate negative impacts when growth in some economic activities might lead to resource exploitation practices that increase nutrient loading and negatively affect pH in watersheds and coastal zones[18,20,21,24,46,47]. Indeed, different studies have established how nutrient loading or land use changes for agriculture or farming can lead to changes in alkalinity and reductions in pH[20,21,24].

Conclusions

Dealing with ocean pH from an integrated perspective is important. In addition, if indicator 14.3.1. is intended as an instrument for assessing the long-term trend in OA forced by the increase in atmospheric CO_2, rather than 'coastal acidification', monitoring the average marine acidity (pH) requires some specific recommendations for global actions, including the monitoring of coastal sites located away from the influences of freshwater runoff, upwelling areas, and major human activity driving nutrient loading and eutrophication, and more specifically the selection and more intensive monitoring of oceanic sites, which are less affected by anthropogenic coastal signatures. Unfortunately, at present, only two pH time series data sets are long enough to estimate long-term anthropogenic trends in the open ocean (WHOTS and Strattus) and make it possible to separate the anthropogenic signal from natural variability[55]. Nevertheless, the scientific community may be able to make more headway in addressing Indicator 14.3.2 by using pCO_2 time-series data in conjunction with Total alkalinity–salinity relationships to expand our understanding of changing acidity in open oceans. While monitoring pH is important and necessary, deepening our knowledge and understanding of the linkages between pH in coastal areas and the developments associated with different SDGs can provide key opportunities for coastal acidification to be addressed as part of synergistic interactions between SDGs. Engaging with coastal acidification through other SDGs can inform on what capacities, policies, and governance structures could be prioritized guiding different local actors towards necessary action.

Data availability

Data for Fig. 1 was extracted from a Water Quality Monitoring assessed by the Florida Department of Agriculture and Consumer Services (FDACS), (Robins & Lisle[19]); Data source: http://www.freshfromflorida.com/Divisions-Offices/Aquaculture, and a 34-year time-series of pH, dissolved oxygen, and chlorophyll in the framework of the Marine Water Quality Data, from the Environmental Protection Department, Government of Hong Kong, Data source: https://cd.epic.epd.gov.hk/EPICRIVER/marine/.

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Author contributions
Both C.A.V. and S.G. provided input into data availability, main structure of the study and preliminary discussions. C.A.V. carried out data analysis of time-series.

Competing interests
The authors declare no competing interests.

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Correspondence and requests for materials should be addressed to Cristian A. Vargas.

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