Short communication

Terrie Klinger*

Optimizing seaweed futures under climate change

https://doi.org/10.1515/bot-2021-0036
Received April 27, 2021; accepted September 9, 2021;
published online October 7, 2021

Abstract: Seaweeds play essential ecological and biogeochemical roles and support important industrial applications. Sustaining natural populations of seaweeds under climate change while simultaneously putting seaweeds to use in climate solutions requires that we weave together disparate lines of inquiry—the ecological and the industrial—to create a more holistic perspective and integrated research agenda. Innovation in the use of seaweeds must be more than aspirational—it requires evidence of effectiveness in the short term, and a promise to sustain nature and people in the long term.

Keywords: carbon capture; climate change; invasive seaweeds; kelp; ocean warming.

Seaweeds have emerged at the fore of conversations around global ocean change and climate solutions. These conversations, and the research that underpins them, take fundamentally different forms. The first focuses on the response of seaweeds to climate-associated stressors, especially warming, and includes changes in seaweed distribution and abundance, habitat compression and loss, wholesale community change, biological invasion, and loss of associated resources and services. This perspective is largely ecological, and from this perspective, seaweeds tend to be viewed as casualties of climate change.

The second perspective focuses on seaweeds as contributors to climate solutions. This includes the use of seaweeds to help mitigate climate-associated changes through carbon capture and storage, livestock feed production, and biofuel production, among others. This perspective tends to take an applied industrial view in which seaweeds offer valuable tools for mitigation and adaptation to climate change.

Seaweed ecologists and those focused on industrial applications of seaweeds traditionally have occupied different professional spheres, typically pursuing different research agendas, publishing in different journals, and attending different conferences, thereby creating barriers to integration between the two groups. In this short essay I argue that a more integrated approach in which diverse expertise is brought to bear on an array of climate-associated risks and solutions is likely to provide more benefit to nature and society than are the somewhat siloed approaches that have commonly existed.

A litany of recent papers describes changes to seaweed communities caused by the direct effects of climate change (e.g., Martinez et al. 2018; Smale 2020; Wernberg et al. 2016). A range of macroalgal taxa has been shown to respond to warming temperatures in ways that affect their geographic distribution and ecological roles, in many cases leading to species extirpation (e.g., Smale and Wernberg 2013; Wernberg et al. 2011). Particular focus has been placed on the response of kelps to warming temperatures. For example, sharp declines in kelp biomass associated with decadal-scale warming have been reported in the North Atlantic (Filbee-Dexter et al. 2016), consistent with declines reported from Australia (Wernberg et al. 2013) and elsewhere (Eger et al. 2020 and references therein). Despite these observations, trends in kelp abundance vary between localities, and are neutral or positive in many regions, pointing to the importance of local factors in determining the response of kelps to climate change (Krumhansl et al. 2016). Similar variability has been reported at shorter time scales: observations made following a marine heatwave on the US West Coast showed measurable declines in the abundance of the bull kelp, *Nereocystis leutkeana* (Rogers-Bennett and Catton 2019), but no detectable decline in the giant kelp, *Macrocystis pyrifera*, in response to a heatwave (Reed et al. 2016). These varying responses suggest that a mosaic of positive and negative ecological outcomes is likely in response to warming waters, with negative responses of particular ecological concern.

Climate-induced changes in seaweed distribution, abundance, and community structure will have consequences for ecosystem function. Loss of canopy-forming species is likely to reduce the availability of biogenic

***Corresponding author: Terrie Klinger**, School of Marine and Environmental Affairs, University of Washington, 3707 Brooklyn Ave NE, Seattle, WA 98105, USA, E-mail: tklinger@uw.edu. https://orcid.org/0000-0003-2430-0246

habitat and its associated biodiversity, with repercussions for food web structure and function (e.g., Agostini et al. 2021). Changes in seaweed standing stocks or biomass, and changes in species composition, will influence biogeochemical cycling, including assimilation of inorganic carbon and nitrogen, production of organic carbon, and oxygen evolution (e.g., Pfister et al. 2019). Many of these functions are not easily replaced, especially as functional redundancy among seaweed communities declines with loss of seaweed biodiversity.

Though the subject of some debate, the negative effects of increasing temperature are unlikely to be offset by increased growth due to ocean acidification. While increasing atmospheric carbon dioxide may spur growth in terrestrial plants (e.g., Kimball 2016), increasing seawater carbon concentrations will not have a similar effect on seaweeds because changes in carbon metabolism and limitation of growth by other nutrients will occur (e.g., (Fernández et al. 2015; 2021). Even species lacking carbon concentrating mechanisms have shown no benefit from increasing seawater carbon content (Britton et al. 2019). Consequently, in natural communities, the generally negative effects of increasing temperature will not be offset by increased growth due to carbon enrichment.

Accompanying reported losses of seaweeds are reports of undesirable gains caused by biological invasion, brown tides, green tides, and the rise of turf algae (e.g., Ferriera et al. 2019; Williams and Smith 2007). Species of *Asparagopsis*, *Gracilaria*, *Sargassum*, *Caulerpa*, *Ulva*, and *Undaria* are just a few of the seaweed species known to be prolific invaders. Such invasions can substantially alter ecological processes (e.g., Davoult et al. 2017). Others can be noxious. For example, in recent years, massive brown tides of pelagic *Sargassum* spp. have drifted ashore in the Caribbean, causing sharp reductions in light, oxygen, and pH, and killing fish, crustaceans, corals, and seagrasses, among other species, and affecting human health and local economies (Rodriguez-Martinez et al. 2019; van Tussenbroek et al. 2017). Massive green tides of *Ulva* spp. have been reported in the Yellow Sea, China, causing ecological and economic harm (Zhang et al. 2019). While not exclusively caused by climate change, the rate of biological invasion in marine systems likely is responsive to factors associated with climate change (e.g., Doney et al. 2012).

Despite their vulnerability to warming oceans, seaweeds, and particularly temperate species like kelps, are increasingly recognized for their potential contributions to climate solutions. Indeed, a simple web search will turn up dozens of popular articles on the topic, some more credible than others. The reasons for this rapid embrace of seaweeds following decades of relative inattention are not clear but could partly be due to the urgency of the climate problem (Hoegh-Guldberg et al. 2019) and the burgeoning appeal of blue carbon as a mitigation strategy (e.g., Lovelock and Duarte 2019).

Realization of the large amount of seaweed biomass produced in extensive seaweed farms around the world has also attracted attention to the potential ability of this biomass to sequester carbon (Sondak et al. 2017). For example, seaweeds have been proposed as a means of capturing carbon dioxide from the atmosphere to help achieve negative emissions targets (e.g., Hughes et al. 2012; Moreira and Pires 2016). Among the proposed mechanisms is intensive seaweed cultivation for bioenergy production with simultaneous carbon capture and storage. While this approach is conceptually appealing, and deservedly is the subject of active research, obstacles to implementation exist—for instance, in the enormous amount of ocean area required—and the feasibility of the approach to meet the twin objectives of energy production and carbon capture has been questioned (e.g., Melara et al. 2020). Despite decades of investment, biofuels produced from seaweeds have not yet reached the market, nor has their production been demonstrated to be economically viable (Raven 2017). Moreover, the fate of the organic carbon contained in biofuels is a source of controversy: the carbon fixed via photosynthesis is subject to respiration and remineralization. Consequently, the approach is probably best viewed as a short-term measure that allows organic carbon to be transferred between nearshore, oceanic, and terrestrial reservoirs before being re-released to the atmosphere; such storage is therefore transitory. With respect to emission reductions, the benefits of bioenergy production from seaweeds may lie chiefly in the avoided emissions from burning fuels other than fossil fuels. Sequestration of carbon fixed by seaweeds on longer time scales requires trapping the carbon in deep-sea sediments where it is less likely to be re-released to the atmosphere (Krause-Jensen and Duarte 2016; Raven 2017), though this, too, is controversial and its feasibility is not known. Importantly, the efficacy of seaweed afforestation for carbon dioxide removal will likely be sensitive to planetary feedbacks, raising questions about its contributions to climate change mitigation strategies (Bach et al. 2021).

Differing somewhat from net emission reduction approaches, seaweeds have been proposed as a means of carbon offsetting—that is, compensating for emissions produced by other activities, in much the same way that tree planting is used to offset emissions from aviation. For example, seaweeds might be cultivated in open-ocean settings and sunk in the deep sea to offset emissions produced elsewhere in the aquaculture industry (Froelich et al. 2019). The feasibility of this approach depends on the scale of application, with smaller-scale or regional applications likely more feasible than larger or global scale applications, and its role in mitigating carbon pollution may be limited by practical constraints on aquaculture and other factors (Froelich et al. 2019). Moreover, in any such application, it is essential to consider the fate of the carbon fixed by seaweeds, much of which is consumed or respired before it can be stored or sequestered by any means.

A very different approach to the use of seaweeds as a climate solution comes from the agriculture sector. Methane is about 30 times more potent as a greenhouse gas than is carbon dioxide, and methane emissions from livestock are a significant source of global greenhouse gas emissions. It turns out that the addition of small amounts of *Asparagopsis* to feedstock has been shown in laboratory settings to sharply reduce the amount of methane generated through enteric fermentation by ruminants and decomposition of their manure (e.g., Li et al. 2018; Roque et al. 2021). The numbers are impressive: adding just 5% organic matter content of *Asparagopsis* to feedstock can, in the laboratory, reduce emissions by up to 95% (Roque et al. 2019). Hence, reductions achieved by adding *Asparagopsis* (or other seaweeds) to feedstock could potentially contribute to global emission-reduction efforts. However, the feasibility of this approach is not yet known and is potentially limited by the large volume of cultivated seaweed that would be required, regulatory requirements, and the long-term effects on animal health, among other factors (Vijn et al. 2020).

The growing enthusiasm for the use of seaweeds in climate change mitigation and adaptation reminds us that expectations must be confronted with evidence—they cannot remain in the realm of the aspirational. Moreover, expectations need to be scaled appropriately. Seaweed response to ocean acidification offers a case in point. Despite enthusiastic claims and visible coverage in the popular press, the use of seaweed aquaculture to reverse the effects of ocean acidification (itself a climate-associated stressor) presents a problem of scale. Seaweeds naturally occupy only a tiny fraction of the ocean. Even under conditions of intensive production, natural processes and competing human uses will constrain the area that can be occupied by seaweed and the volume of water that can be treated, ultimately limiting the contributions of seaweeds to improving carbonate chemistry in the ocean. Some of these limitations, however, may be less serious than others, and some problems have been partially addressed, especially in Asia, east Africa and South America where intensive farming is being carried out. Nonetheless, the scales at which seaweeds can grow, even under cultivation, are miniscule compared to the volume of the ocean. The potential for seaweed aquaculture to buffer seawater pH at varying scales is an area of active investigation (e.g., Li et al. 2021) but, even at small scales, the approach will be subject to diurnal cycles of photosynthesis and respiration and seasonal patterns of growth and senescence (Pfister et al. 2019).

Finally, the constraints imposed by financial, regulatory, and political landscapes cannot be ignored. The use of seaweeds to address carbon pollution on any meaningful scale will require substantial and sustained economic investment and will be subject to a host of national and international laws and regulations that govern the use of ocean spaces (Webb et al. 2021). These factors are not trivial and could create impediments to moving forward.

Even so, industrial applications of seaweeds are not new—they have been pursued for well over a century, for example in the intensive seaweed aquaculture common to some areas in Asia, and in the harvest of wild seaweed for fertilizers and as a source of natural products such as potash. An even longer history of utilization comes from Asian and Indigenous cultures from many coastal regions (e.g., Hwang and Park 2020; Kobluk et al. 2021; Thurstan et al. 2018; Tseng 2004; Turner 2003). Our challenge in the coming decades is to sustain natural populations of seaweeds and to maintain and expand their industrial use to abate growing carbon pollution.

Clearly, reducing the dialog surrounding the future of seaweeds to two stark endpoints—ecological losses versus climate solutions—presents a false dichotomy. A range of ecological outcomes is likely, as is a range of climate solutions, and in some cases, positive interactions and synergies could emerge (e.g., Eger et al. 2020). It is exactly through these synergies that the promise of seaweeds is greatest. Are there solutions that can protect or restore the function of natural populations while simultaneously reducing carbon pollution? Can technologies be brought to bear that enhance seaweed production—natural or otherwise—without causing environmental harm? Can the enormous biomass created by some invasive species be used for productive purposes? Can humans learn to protect their seaweed resources while simultaneously harnessing the power of seaweeds to address carbon pollution? Doing so will require shifts in thinking and doing across all sectors, demanding that ecologists embrace the alternative benefits of seaweeds, industrialists embrace the need for protection and restoration of natural populations and habitats, and innovators creatively link the two.

How can these objectives be accomplished? Calls to create integrated, cross-sectoral networks to foster collaboration and learning are rife in the climate adaptation literature, as are calls to develop new policy tools and economic incentives (e.g., Tittensor et al. 2019). Not surprisingly, it is far easier to call for change than to enact change, and examples of the successful creation of integrated networks to address climate change in the ocean remain rare except at small or local scales, suggesting that local scales could be a promising place to begin (e.g., Greenhill et al. 2020). One can imagine new networks forming around the twin challenges of sustaining natural seaweed populations and employing seaweeds as climate solutions. This approach might be most successful when implemented at spatial scales that match scales of ecological response and regional ocean governance. Complementary approaches that focus on the co-benefits of seaweed conservation and cultivation, and those that address the socio-economic benefits of natural and cultivated populations, offer parallel paths forward. Notably, Indigenous cultures that rely on marine resources, including seaweeds, have used traditional knowledge, established social networks, and cultural norms to manage resources of importance for thousands of years (e.g., Poepoe et al. 2007), and could offer helpful models for more holistic thinking.

Acknowledgments: This contribution is in honor of R.E. DeWreede, with gratitude. The manuscript benefitted from the comments of reviewers.
Author contributions: The author has accepted responsibility for the entire content of this submitted manuscript and approved submission.
Research funding: None declared.
Conflict of interest statement: The author declares no conflicts of interest regarding this article.

References

Agostini, S., Harvey, B.P., Milazzo, M., Wada, S., Kon, K., Floc'h, N., Komatsu, K., Kuroyama, M., and Hall-Spencer, J.M. (2021). Simplification, not "tropicalization", of temperate marine ecosystems under ocean warming and acidification. Global Change Biol, https://doi.org/10.1111/gcb.15749 (Epub ahead of print).

Bach, L.T., Tamsitt, V., Gower, J., Hurd, C.L., Raven, J.A., and Boyd, P.W. (2021). Testing the climate intervention potential of ocean afforestation using the Great Atlantic Sargassum Belt. Nat. Commun. 12: 2556.

Britton, D., Mundy, C.N., McGraw, C.M., Revill, A.T., and Hurd, C.L. (2019). Responses of seaweeds that use CO_2 as their sole inorganic carbon source to ocean acidification: differential effects of fluctuating pH but little benefit of CO_2 enrichment. ICES J. Mar. Sci. 76: 1860–1870.

Davoult, D., Le Diouron, G., Stiger, V., Noisette, F., Riera, P., Stagnol, D., Androuin, T., and Poupart, N. (2017). Multiple effects of a Gracilaria vermiculophylla invasion on estuarine mudflat functioning and diversity. Mar. Environ. Res. 131: 227–235.

Doney, S.C., Ruckelshaus, M., Duffy, J.E., Barry, J.P., Chan, F., English, C.A., Galindo, H.M., Grebmeier, J.M., Hollowed, A.B., and Knowlton, N., et al (2012). Climate change impacts on marine ecosystems. Annu. Rev. Mar. Sci. 4: 11–37.

Eger, A.M., Marzinelli, E., Gribben, P., Johnson, C.R., Layton, C., Steinberg, P.D., Wood, G., Silliman, B.R., and Verges, A. (2020). Playing to the positives: using synergies to enhance kelp forest restoration. Front. Mar. Sci. 7: 544.

Fernández, P., Navarro, J., Camus, C., Torres, R., and Buschmann, A. (2021). Effect of environmental history on the habitat-forming kelp Macrocystis pyrifera responses to ocean acidification and warming: a physiological and molecular approach. Sci. Rep. 11: 2510.

Fernández, P.A., Roleda, M.Y., and Hurd, C.L. (2015). Effects of ocean acidification on the photosynthetic performance, carbonic anhydrase activity and growth of the giant kelp *Macrocystis pyrifera*. Photosynth. Res. 124: 293–304.

Ferreira, C.M., Nagelkerken, I., Goldenberg, S.U., Walden, G., Leung, J.Y.S., and Connell, S.D. (2019). Functional loss in herbivores drives runaway expansion of weedy algae in a near-future ocean. Sci. Total Environ. 695: 133829.

Filbee-Dexter, K., Feehan, C.J., and Scheibling, R.E. (2016). Large-scale degradation of a kelp ecosystem in an ocean warming hotspot. Mar. Ecol. Prog. Ser. 543: 141–152.

Froehlich, H., Afflerbach, J., Frazier, M., and Halpern, B. (2019). Blue growth potential to mitigate climate change through seaweed offsetting. Curr. Biol. 29: 3087–3093.

Greenhill, L., Kenter, J.O., and Dannevig, H. (2020). Adaptation to climate change–related ocean acidification: an adaptive governance approach. Ocean Coast Manag. 191: 105176.

Hoegh-Guldberg, O., Northrop, E., and Lubchenco, J. (2019). The ocean is key to achieving climate and societal goals. Science 365: 1372–1374.

Hughes, A.D., Black, K.D., Campbell, I., Davidson, K., Kelly, M.S., and Stanley, M.S. (2012). Does seaweed offer a solution for bioenergy with biological carbon capture and storage? Greenh. Gases: Sci. Technol. 2: 402–407.

Hwang, E.K. and Park, C.S. (2020). Seaweed cultivation and utilization of Korea. ALGAE 35: 107–121.

Kimball, B.A. (2016). Crop responses to elevated CO_2 and interactions with H_2O, N, and temperature. Curr. Opin. Plant Biol. 31: 36–43.

Kobluk, H.M., Gladstone, K., Reid, M., Brown, K., Krumhansl, K.A., and Salomon, A.K. (2021). Indigenous knowledge of key ecological processes confers resilience to a small-scale kelp fishery. People Nat. 3: 723–739.

Krause-Jensen, D. and Duarte, C. (2016). Substantial role of macroalgae in marine carbon sequestration. Nat. Geosci. 9: 737–742.

Krumhansl, K., Okamoto, D., Rassweiler, A., Novak, M., Bolton, J., Cavanaugh, K., Connell, S., Johnson, C., Konar, B., Ling, S., et al. (2016). Global patterns of kelp forest change over the past half-century. Proc. Natl. Acad. Sci. U.S.A. 113: 13785–13790.

Li, X., Norman, H.C., Kinley, R.D., Laurence, M., Wilmot, M., Bender, H., De Nys, R., and Tomkins, N. (2018). Asparagopsis taxiformis decreases enteric methane production from sheep. Anim. Prod. Sci. 58: 681–688.

Li, J., Zhang, W., Ding, J., Xue, S., Huo, E., Ma, Z., Yu, W., Jiang, Z., Fang, J., and Mao, Y. (2021). Effect of large-scale kelp and bivalve farming on seawater carbonate system variations in the semi-enclosed Sanggou Bay. Sci. Total Environ. 753: 142065.

Lovelock, C.E. and Duarte, C.M. (2019). Dimensions of blue carbon and emerging perspectives. Biol. Lett. 15: 20180781.

Martinez, B., Radford, B., Thomsen, M., Connell, S., Carreño, F., Bradshaw, C., Fordham, D., Russell, B., Gurgel, C., and Wernberg, T. (2018). Distribution models predict large contractions of habitat-forming seaweeds in response to ocean warming. Divers. Distrib. 24: 1350–1366.

Melara, A.J., Singh, U., and Colosi, L.M. (2020). Is aquatic bioenergy with carbon capture and storage a sustainable negative emission technology? Insights from a spatially explicit environmental life-cycle assessment. Energy Convers. Manag. 224: 113300.

Moreira, D. and Pires, J. (2016). Atmospheric CO_2 capture by algae: negative carbon dioxide emission path. Bioresour. Technol. 215: 371–379.

Pfister, C.A., Altabet, M.A., and Weigel, B.L. (2019). Kelp beds and their local effects on seawater chemistry, productivity, and microbial communities. Ecology 100: e02798.

Poepoe, K., Bartram, P., and Friedlander, A. (2007). The use of traditional knowledge in the contemporary management of a Hawaiian community's marine resources. In: Haggan, N., Neis, B., and Baird, I. (Eds.), *Fishers' knowledge in fisheries science and management*. UNESCO, Paris, France, p. 328339.

Raven, J.A. (2017). The possible roles of algae in restricting the increase in atmospheric CO_2 and global temperature. Eur. J. Phycol. 52: 506–522.

Reed, D., Washburn, L., Miller, R., Bell, T., and Harrer, S. (2016). Extreme warming challenges sentinel status of kelp forests as indicators of climate change. Nat. Commun. 7: 13757.

Rodríguez-Martínez, R.E., Medina-Valmaseda, A.E., Blanchon, P., Monroy-Velázquez, L.V., Almazán-Becerril, A., Delgado-Pech, B., Vásquez-Yeomans, L., Francisco, V., and García-Rivas, M.C. (2019). Faunal mortality associated with massive beaching and decomposition of pelagic Sargassum. Mar. Pollut. Bull. 146: 201–205.

Rogers-Bennett, L. and Catton, C.A. (2019). Marine heat wave and multiple stressors tip bull kelp forest to sea urchin barrens. Sci. Rep. 9: 15050.

Roque, B.M., Salwen, J.K., Kinley, R., and Kebreab, E. (2019). Inclusion of Asparagopsis armata in lactating dairy cows' diet reduces enteric methane emission by over 50 percent. J. Clean. Prod. 234: 132–138.

Roque, B.M., Venegas, M., Kinley, R.D., deNys, R., Duarte, T.L., Yang, X., and Kebreab, E. (2021). Red seaweed (Asparagopsis taxiformis) supplementation reduces enteric methane by over 80 percent in beef steers. PloS One 16: e0247820.

Smale, D.A. (2020). Impacts of ocean warming on kelp forest ecosystems. New Phytol. 225: 1447–1454.

Smale, D.A. and Wernberg, T. (2013). Extreme climatic event drives range contraction of a habitat-forming species. Proc. Biol. Sci. 280: 0122829.

Sondak, C.F.A., Ang, P.O., Beardall, J., Bellgrove, A., Boo, S.M., Gerung, G.S., Hepburn, C.D., Hong, D.D., Hu, Z., Kawai, H., et al. (2017). Carbon dioxide mitigation potential of seaweed aquaculture beds (SABs). J. Appl. Phycol. 29: 2363–2373.

Thurstan, R.H., Brittain, Z., Jones, D.S., Cameron, E., Dearnaley, J., and Bellgrove, A. (2018). Aboriginal uses of seaweeds in temperate Australia: an archival assessment. J. Appl. Phycol. 30: 1821–1832.

Tittensor, DP., Berger, M., Boerder, K., Boyce, DG., Cavanagh, RD., Cosandey-Godin, A., Crespo, GO., Dunn, DC., Ghiffary, W., Grant, SM., et al. (2019). Integrating climate adaptation and biodiversity conservation in the global ocean. Sci. Adv. 5: eaay9969.

Tseng, C.K. (2004). The past, present and future of phycology in China. Hydrobiologia 512: 11–20.

Turner, N.J. (2003). Ethnobotany of "edible seaweed" (Porphyra abbottiae Krishnamurthy and related species; Rhodophyta: Bangiales) and its use by first Nations on the pacific Coast of Canada. Can. J. Bot. 81: 283–293.

van Tussenbroek, B.I., Hernández-Arana, H.A., Rodríguez-Martínez, R.E., Espinoza-Avalos, J., Canizales-Flores, H.M., González-Godoy, C.E., Barba-Santos, M.-G., Vega-Zepeda, A., and Collado-Vides, L. (2017). Severe impacts of brown tides caused by Sargassum spp. on near-shore Caribbean seagrass communities. Mar. Pollut. Bull. 122: 272–281.

Vijn, S., Compart, D.P., Dutta, N., Foukis, A., Hess, M., Hristov, A.N., Kalscheur, K.F., Kebreab, E., Nuzhdin, S.V., Price, N.N., et al. (2020). Key considerations for the use of seaweed to reduce enteric methane emissions from cattle. Front. Vet. Sci. 7: 1135.

Webb, R.M., Silverman-Roati, K., and Gerrard, M.B. (2021). Removing carbon dioxide through ocean alkalinity enhancement and seaweed cultivation: legal challenges and opportunities, Columbia Public Law Research Paper, Available at: https://scholarship.law.columbia.edu/faculty_scholarship/2739 (Epub ahead of print).

Wernberg, T., Bennett, S., Babcock, R.C., De Bettignies, T., Cure, K., Depczynski, M., Dufois, F., Fromont, J., Fulton, C., Hovey, R., et al. (2016). Climate-driven regime shift of a temperate marine ecosystem. Science 353: 169–172.

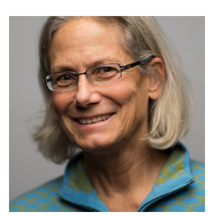
Wernberg, T., Russell, B.D., Thomsen, M.S., Gurgel, C.F.D., Bradshaw, C.J.A., Poloczanska, E.S., and Connell, S.D. (2011). Seaweed communities in retreat from ocean warming. Curr. Biol. 21: 1828–1832.

Wernberg, T., Smale, D.A., Tuya, F., Thomsen, M.S., Langlois, T.J., De Bettignies, T., Bennett, S., and Rousseaux, C.S. (2013). An extreme climatic event alters marine ecosystem structure in a global biodiversity hotspot. Nat. Clim. Change 3: 78–82.

Williams, S.L. and Smith, J.E. (2007). A global review of the distribution, taxonomy, and impacts of introduced seaweeds. Annu. Rev. Ecol. Evol. Syst. 38: 327–359.

Zhang, Y., He, P., Li, H., Li, G., Liu, J., Jiao, F., Zhang, J., Huo, Y., Shi, X., Su, R., et al. (2019). Ulva prolifera green tide outbreaks and their environmental impact in the Yellow Sea, China. Natl. Sci. Rev. 6: 825–838.

Bionote



Terrie Klinger
School of Marine and Environmental Affairs, University of Washington, 3707 Brooklyn Ave NE, Seattle, WA 98105, USA
tklinger@uw.edu
https://orcid.org/0000-0003-2430-0246

Terrie Klinger is a marine ecologist whose research focuses on the dynamics of nearshore systems and the development of management strategies to address the challenges of ocean change. A professor in the University of Washington's School of Marine and Environmental Affairs and co-director of the Washington Ocean Acidification Center, she holds PhD from the Scripps Institution of Oceanography and an MSc from the University of British Columbia.