Check for updates

ENVIRONMENTAL SCIENCE

Turf algae redefine the chemical landscape of temperate reefs, limiting kelp forest recovery

Shane P. Farrell[1,2]*, Daniel Petras[3,4], Paolo Stincone[4], Dara S. Yiu[1,2], John A. Burns[1], Abzer Kelminal Pakkir Shah[4], Aaron C. Hartmann[5,6], Damian C. Brady[2], Douglas B. Rasher[1]

In temperate regions experiencing rapid ocean warming, kelp forests are being replaced by chemically rich turf algae. However, the extent to which these turf algae alter the surrounding chemical environment or affect the rebound potential of kelp forests (through chemically mediated interactions) remains unknown. Here, we used underwater visual surveys, comprehensive chemical profiling, and laboratory experiments to reveal that turf algae release bioactive compounds into the water that fundamentally alter the reef "chemical landscape" and directly suppress kelp recruitment. Therefore, our study reveals that chemical ecology is critical in shaping modern kelp forest ecosystems and their resilience. Further, it demonstrates that reversing climate-driven state shifts will require not only curbing global carbon emissions but also implementing targeted local interventions that break harmful ecological feedback loops and foster recovery.

Kelp forests dominate much of Earth's temperate coastline and are vital to ocean ecosystem functioning. By creating three-dimensional structures and food resources, kelp forests benefit a variety of residents, from microbes to megafauna, while also modifying water movement, light availability, and carbon fluxes in ways that positively influence other species (*1*–*8*). Kelp forests also provide important ecosystem services, including fisheries and ecotourism, that are worth billions of dollars per year globally (*9*). However, despite their recognized ecological and economic importance, many kelp forests worldwide are threatened with collapse due to climate change and/or overfishing (*10*, *11*).

In areas of rapid ocean warming, kelp forests have recently been replaced by low-lying carpets of chemically rich, filamentous red algae (hereafter "turf algae") (*12*). Documented in Australia (*13*), Japan (*14*), Norway (*15*), the Mediterranean and Baltic Seas (*12*, *16*), and across the Northwest Atlantic (*17*–*19*), these rapid shifts to turf dominance have resulted in ecosystem-level biodiversity loss, decreased fish abundance, altered food web energetics, and changes in nutrient dynamics on coastal reefs (*13*, *20*–*22*). Moreover, some studies suggest that once established, turf algae may directly inhibit kelp recovery, thereby creating harmful ecological feedback loops that lock the system in a qualitatively different state (*18*, *23*, *24*).

The inhibition of kelp recovery by turf algae could be due to their effects on the chemical environment, in addition to space preemption and harboring sediments or grazers (*18*, *23*, *24*). However, no studies to date have considered how turf algae influence the ecosystem's broader chemical environment or whether they engage in allelopathy (i.e., inhibit the recovery of kelp through chemically mediated competition) in such transitions. This is despite the outsized role that allelopathy plays in the recovery dynamics of other iconic ecosystems such as tropical coral reefs (*25*–*27*) and rain forests (*28*, *29*). Assessing how turf algae do or do not chemically alter the recovery potential of kelp forests is therefore critical for revealing their modern ecology, as well as for developing strategies to restore valuable kelp forest ecosystems.

Here, we assessed the role of turf-mediated allelopathy in the recovery dynamics of kelp forests in the Gulf of Maine in the US (Fig. 1A). We previously revealed (*19*) that over the past two decades, kelp forests on the warmest (southwest) stretch of Maine's coastline had collapsed and been replaced by turf algae as a consequence of rapid ocean warming (Fig. 1B), whereas kelp forests had continued to persist in the cooler, northeastern reaches of Maine's coastline (Fig. 1C). In recent years (2021 to 2023), kelp forests have failed to recover on reefs in southwest Maine, as evidenced by a persistent scarcity of adult kelps (Fig. 1D), a lack of new juvenile kelps successfully recruiting to the reef (Fig. 1E), and a constant abundance of turf algae (Fig. 1F) on southern reefs.

Such ecosystem-level patterns suggest that turf algae may be actively suppressing kelp forest recovery through allelopathy. To explore this possibility, we first characterized the "metabolome," i.e., the suite of waterborne primary metabolites (biomolecules essential for normal functioning of organisms), secondary metabolites (compounds typically serving specialized functions for species interactions), and xenobiotics (human-derived synthetic compounds), that defined kelp-dominated versus turf-dominated reefs along Maine's coast (Fig. 1A) using nontargeted chemical profiling techniques (Fig. 2). We then compared reef metabolomes with the chemistry contained within co-occurring seaweeds (here, canopy-forming kelps and the low-lying seaweeds residing under the canopy, including bladed, foliose, and turf algae species) to assess the degree to which chemical features found in the waterborne metabolome are likely produced by seaweeds and to identify specific chemical features that are exuded exclusively by turf algae. Finally, we conducted a series of controlled laboratory experiments using an early life history stage of kelp to assess whether the metabolome of turf-dominated reefs and the specific chemical exudates released by turf algae inhibit kelp recruitment. In doing so, we revealed that turf algae fundamentally alter the reef metabolome and directly limit the rebound potential of kelp forests.

Kelp forests and turf reefs have distinct metabolomes

To compare the metabolomes of kelp- versus turf-dominated reefs, we collected 1-liter water samples ($n = 6$ per site) from within the seaweed matrix (0.5 to 3 cm above the reef), filtered the water, and then extracted the associated dissolved organic matter, i.e., metabolome, through solid-phase extraction (*30*) (Fig. 2). We then characterized each metabolome using nontargeted ultrahigh-performance liquid chromatography–tandem mass spectrometry (UHPLC-MS/MS). The resulting data were processed to identify and align unique chemical features within our samples using MZmine3 and annotated using the GNPS2 feature-based molecular networking workflow, which organizes metabolite features into networks (*31*, *32*). In addition to spectrum-library matching and molecular networking, we predicted molecular structures, chemical classes, and molecular formulas using SIRIUS (*33*–*36*).

In total, 17,732 chemical features (i.e., unique mass-to-charge ratios and retention times) were detected among all water samples, highlighting a diverse array of waterborne chemistry in this ecosystem. However, of these features, only 318 matched chemical spectra in the reference databases [an annotation rate of 1.79% at level 2 identification as defined in (*37*, *38*)], reinforcing the notion that chemicals within seawater are still poorly described partly because of a dearth of studies from temperate ecosystems (*39*).

[1]Bigelow Laboratory for Ocean Sciences, East Boothbay, ME, USA. [2]University of Maine, Walpole, ME, USA. [3]University of California Riverside, Riverside, CA, USA. [4]University of Tubingen, Tubingen, Germany. [5]Perry Institute for Marine Science, Waitsfield, VT, USA. [6]Harvard University, Cambridge, MA, USA. *Corresponding author. Email: shanepfarrell@gmail.com

Downloaded from https://www.science.org at National University of Ireland, Galway on August 20, 2025

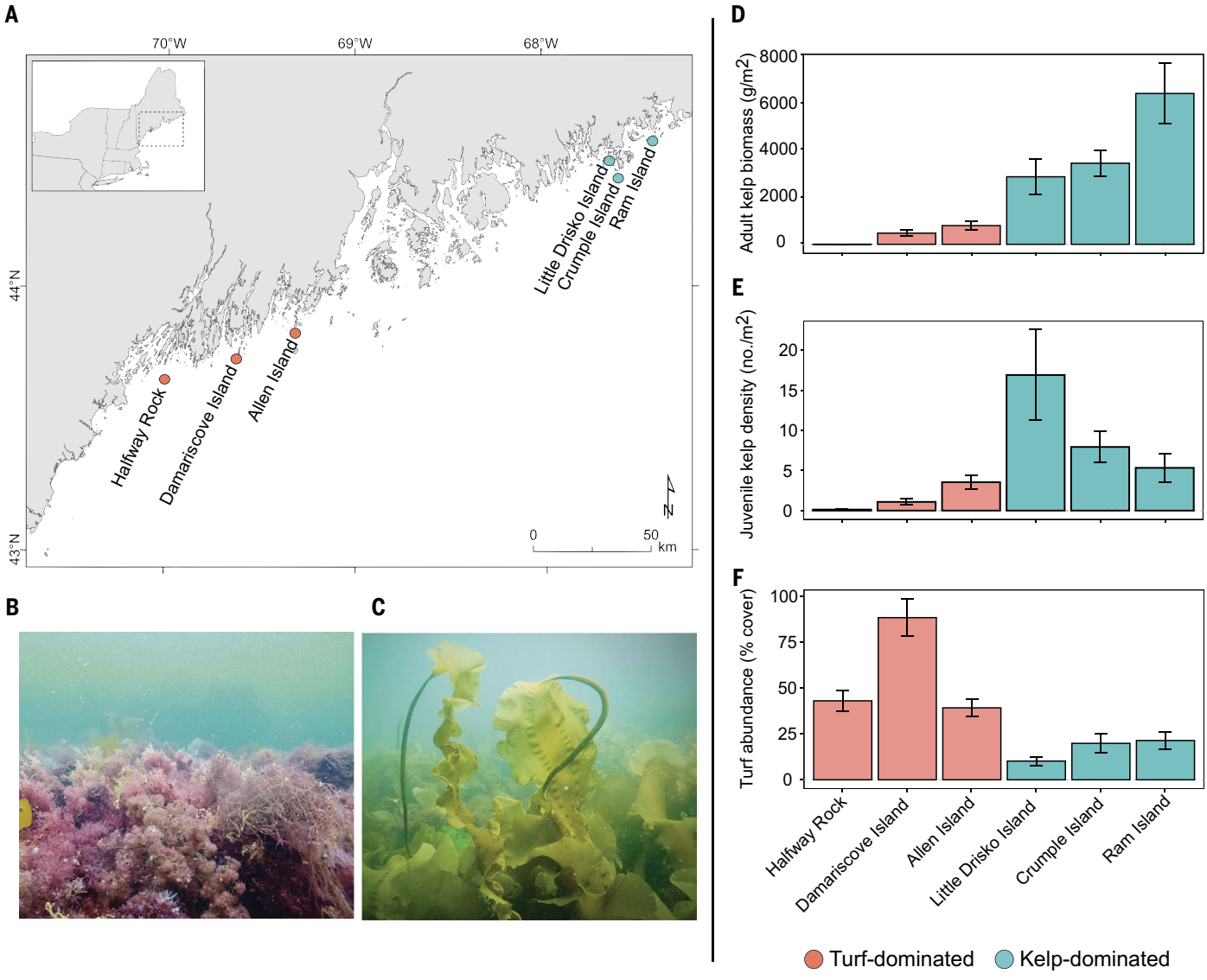


Fig. 1. Study sites and ecosystem-level patterns of reef resilience. (**A** to **C**) Map of study sites across Maine's coast (A), which includes replicate sites in southwestern Maine where kelp forests have collapsed and been replaced by turf algae in recent years (B) and replicate sites in northeastern Maine where kelp forests still prevail (C). Panel (B) photo by D.S.Y.; panel (C) photo by S. P. F. (**D** to **F**) Adult kelp biomass (g/m^2) (D), density of juvenile kelps (number/m^2) (E), and percent cover of turf algae (F) at each of the six study sites from 2021 to 2023. Error bars denote global site-level means ± SE for 2021 to 2023.

We found that kelp-dominated and turf-dominated reefs had highly distinct metabolomes [Fig. 3A; permutational multivariate analysis of variance (PERMANOVA), $P < 0.001$], a pattern driven by the presence of unique chemical features in kelp forests versus turf reefs, as well as shared features that were differentially abundant. Turf reef metabolomes had 1018 unique features compared with 511 found only in kelp forests (fig. S1). Furthermore, 3663 features (20.7%) were shared but differentially abundant on either kelp- or turf-dominated reefs (fig. S2). Using in silico structure and compound class predictions from SIRIUS (*35*), we found that lipids, organoheterocyclic compounds, and organic acids were the most abundant chemical superclasses in each metabolome, accounting for ~90% of features (fig. S3). Turf reef metabolomes were significantly enriched in alkaloids, compounds that are both prevalent and bioactive in terrestrial plants (*40*), whereas kelp forest metabolomes were enriched in lipids and organic acids, as well as benzenoid, nucleoside, organohalogen, organoheterocyclic, organophosphorus, organosulfur, and phenylpropanoid compounds (Fig. 3B; Wilcoxon test, $P < 0.05$).

Seaweed exudates underpin the reef metabolome

The metabolome includes inputs from seaweeds, microorganisms, and xenobiotics. To assess how seaweed exudates contribute to the reef metabolome, we quantified the chemical features that occurred in both the waterborne reef metabolome and the internal tissues of common, co-occurring seaweeds. Although 14,582 features were exclusively found in the reef metabolome, 3150 were shared between seaweeds and the metabolome, indicating that seaweeds release a diverse array of exudates (e.g., specialized metabolites involved in species interactions) into the surrounding seawater (fig. S4). Indeed, when considering only seaweed exudates, differences between kelp forest and turf reef metabolomes were even more pronounced (fig. S5).

Among seaweed exudates, 356 (11.3%) were specific to the turf reef metabolome and 144 (4.6%) were specific to the kelp forest metabolome (fig. S4). To assess the species-specific contributions of seaweeds to the turf reef metabolome, we identified those features that were unique to the turf reef metabolome and those that were unique to

Downloaded from https://www.science.org at National University of Ireland, Galway on August 20, 2025

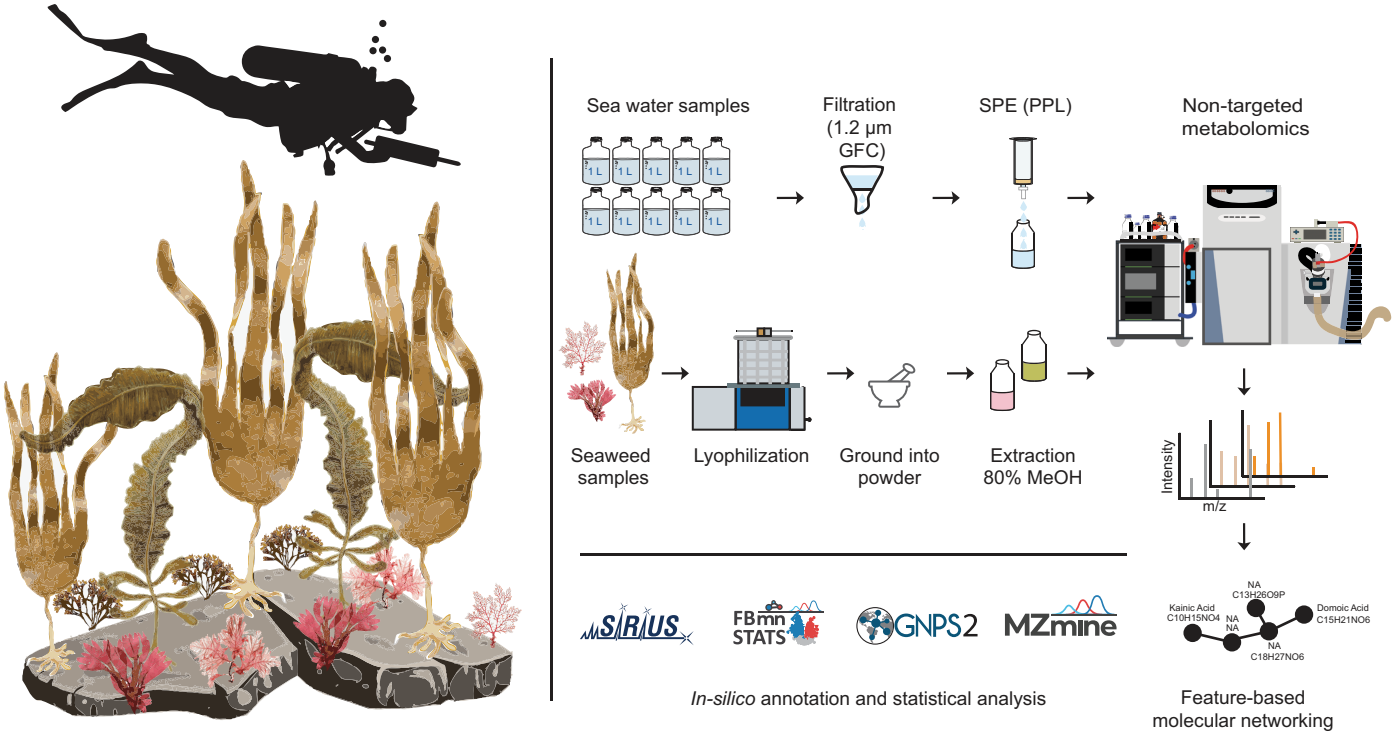


Fig. 2. Sampling and analytical workflow. Dissolved organic matter was collected using custom benthic organic matter samplers (fig. S7). Seaweed tissue samples were collected by hand. Samples were extracted and subjected to UHPLC-MS/MS. After quality control (figs. S8 and S9), data were processed using standardized workflows for statistical analysis, molecular annotation, prediction, and networking. Art credits: P. Stincone and D. Petras; logo permissions: A. Korf (MZmine), M. Wang (GNPS2), and S. Boecker (SIRIUS).

individual seaweed taxa (Fig. 3C). Of the features that met those criteria, 36 (10.1%) hailed from individual turf algae species (Fig. 3C) and an additional 13 (3.7%) were shared between multiple turf species (fig. S4). Furthermore, correlation analysis revealed positive associations (Spearman's rank correlation $P < 0.05$, with a false discovery rate ≤ 0.05) between the abundance of dominant turf algae (*Dasysiphonia japonica*, *Melanothamnus harveyi*, and *Vertebrata* spp.) and the prevalence of unique chemical features in the turf reef metabolome (fig. S6). These results indicate that turf algae produce a suite of species-specific compounds (Fig. 3D) that reside in the waterborne metabolome of turf-dominated reefs.

The turf reef metabolome inhibits kelp recruitment

To determine whether the turf reef metabolome inhibits kelp recruitment and thus may impede ecosystem recovery, we conducted a controlled laboratory experiment with the gametophytes of a dominant kelp species in the ecosystem, *Saccharina latissima*. Gametophytes are the microscopic haploid phase of the kelp life cycle that play a crucial role in sexual reproduction and kelp recruitment to reefs. Gametophytes were subjected to the waterborne metabolome collected from each turf- or kelp-dominated study site (Fig. 1A), and survival was assessed after 96 hours.

Kelp gametophyte survival declined markedly and significantly relative to controls when exposed to observed concentrations (1.2 to 1.8 µg/ml) (*30*) of the waterborne metabolome from two of three turf-dominated sites (up to a 180% decline, $P < 0.005$, two-sample test for equality of proportions with continuity correction). By contrast, gametophyte survival trended positive and did not significantly differ from controls when exposed to observed concentrations (1.1 to 1.2 µg/ml) of the metabolome from any of the three kelp-dominated study sites ($P > 0.05$, two-sample test for equality of proportions with continuity correction) (Fig. 4A). This suggests that the turf reef metabolome is an agent of kelp gametophyte mortality and recruitment inhibition in this ecosystem.

Turf algae exudates inhibit kelp recruitment

To determine whether turf algae are directly responsible for kelp gametophyte mortality (Fig. 4A), we subjected kelp gametophytes to the waterborne molecules exuded by each of the five most abundant turf algae species in the ecosystem, as well as surface-bound molecules from the same species at naturally observed concentrations (*30*). These experiments (Fig. 4, A to C) collectively encompass the suite of chemicals that a kelp gametophyte may encounter while recruiting to a turf-dominated reef.

Kelp gametophyte survival decreased significantly (by ~100 to 500%) relative to controls when exposed to the naturally observed concentrations (0.4 to 2.3 µg/ml) of the waterborne exudates produced by each species of turf algae ($P < 0.005$, two-sample test for equality of proportions with continuity correction) (Fig. 4B). Furthermore, the naturally observed concentrations of surface-bound chemistry from *M. harveyi* significantly decreased gametophyte survival relative to controls, whereas the surface-bound chemistry from the other turf species did not (Fig. 4C). Together, these findings reveal that turf algae strongly suppress kelp recruitment through allelopathy and that such effects occur primarily through waterborne molecules.

Implications

A collapse of kelp forests and subsequent shift to turf algae is occurring at the warm trailing edge of kelp distribution in many regions around the world (*10*, *12*, *14*). However, the mechanisms underpinning this shift are not well known, and the role of chemical ecology in this transition has been ignored. Here, using cutting-edge tools, we have revealed that temperate reefs harbor a diverse array of waterborne chemicals (fig. S3)

Downloaded from https://www.science.org at National University of Ireland, Galway on August 20, 2025

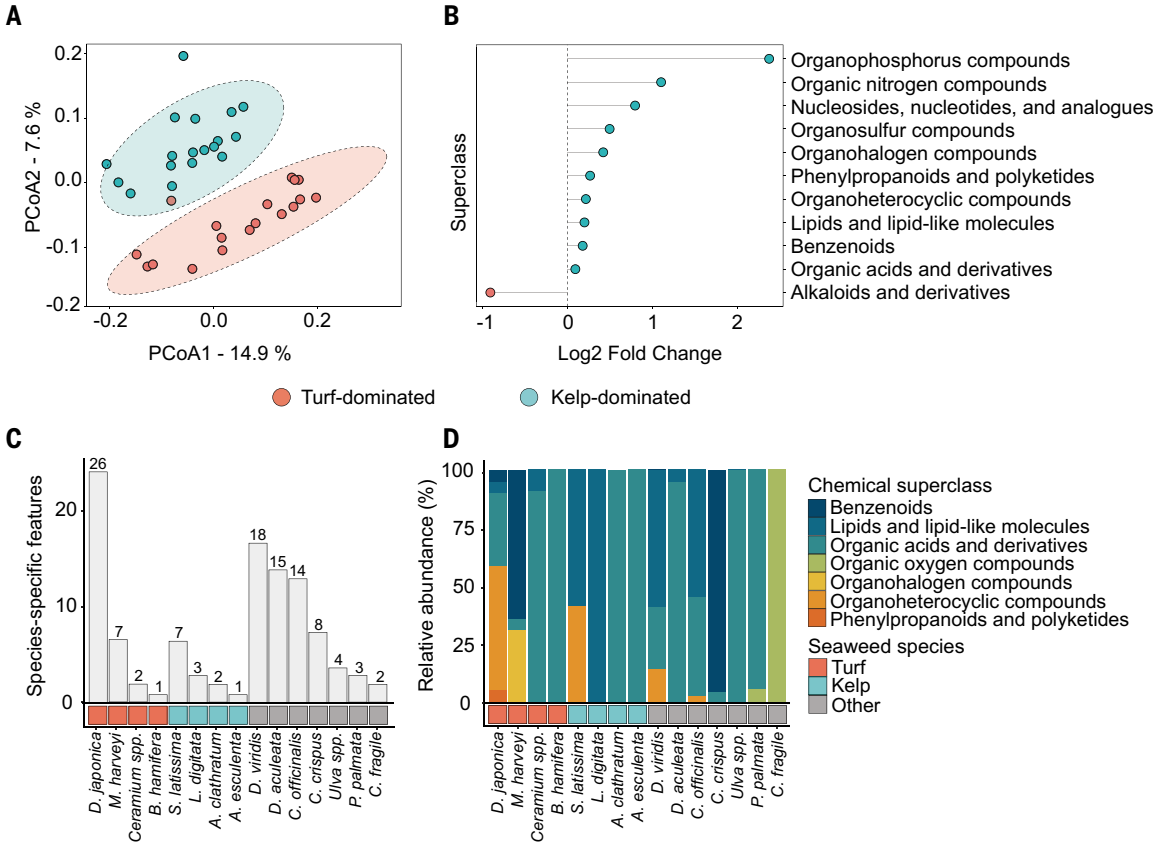


Fig. 3. Kelp forests and turf reefs have distinct and diverse metabolomes driven by the seaweed community. (**A**) Principal coordinate analysis of chemical features found in water samples collected from kelp- or turf-dominated reefs ($n = 6$ per site; $n = 6$ sites). Dots are individual 1-liter water samples colored by whether they were collected from (and assigned to) a kelp-dominated or a turf-dominated reef (PERMANOVA, $P < 0.001$), and ellipses are 95% confidence intervals. (**B**) Differential abundance analysis of average superclass abundance; color denotes a statistically significant difference in abundance of superclass in the kelp forest or turf reef metabolome (Wilcoxon test, $P < 0.05$). (**C**) Number of features unique to both the turf reef metabolome and the internal tissues of a co-occurring seaweed (i.e., kelp, turf algae, or other seaweed species). (**D**) Predicted identity (to superclass) and relative abundance of features that were unique to the turf reef metabolome and co-occurred in a specific seaweed species, as inferred from SIRIUS (*30*).

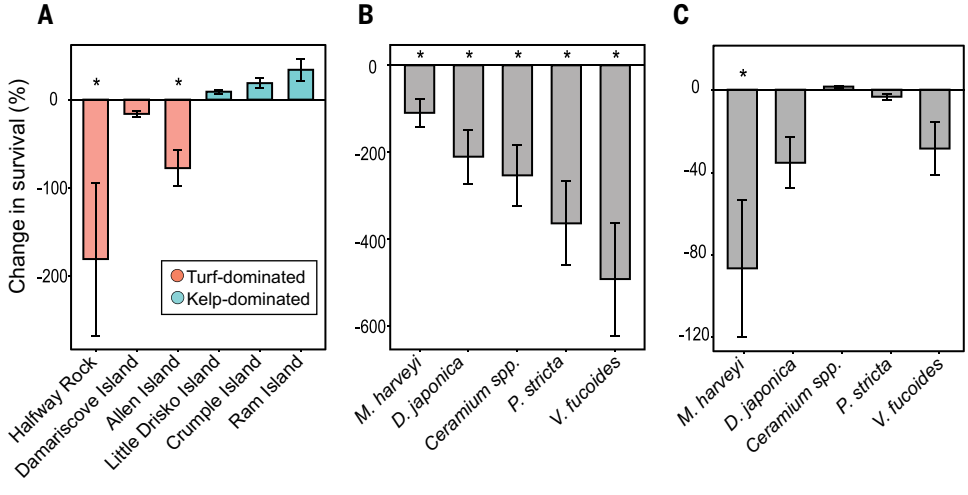


Fig. 4. Turf reef metabolome and waterborne exudates from turf algae suppress kelp recruitment. (**A** to **C**) Change in survival (%, relative to controls) of kelp gametophytes after 96 hours when subjected to the waterborne metabolome from each of three turf-dominated reefs and three kelp forests (A), the waterborne chemical exudates of each of the five dominant turf algae species in the ecosystem (B), or the nonpolar molecules bound to the surfaces of these turf algae (C). $n = 10$ per treatment and control per assay. Bars denote treatment-level means ± SE. Asterisks denote significant differences between the treatment and associated control (two-sample test for equality of proportions with continuity correction, $P < 0.05$). Note differences in *y*-axis scales among panels.

Downloaded from https://www.science.org at National University of Ireland, Galway on August 20, 2025

produced by the dominant seaweeds in the ecosystem (fig. S4), and that the proliferation of turf algae is associated with a profound change in the reef metabolome (Fig. 3). We then reveal through experiments that chemicals exuded by turf algae inhibit kelp recruitment (Fig. 4). Therefore, our study identifies chemically mediated competition as a key process (*18*, *23*, *24*) reinforcing the shift to turf dominance.

It has long been thought that chemical defenses in marine organisms are most important near the equator (*41–45*), and chemically mediated species interactions have been far better studied on tropical reefs (*46*). However, we show here that chemically mediated interactions can be important to the ecology of temperate reefs as well. Temperate turf algae exude the very types of bioactive molecules, including terpenoids, polyketides, and halogenated compounds (*38*), that govern species interactions in tropical marine and terrestrial forest ecosystems (*26*, *47–49*). In addition, turf algae exudates fuel microbial activity, which in turn alters the reef metabolome of degraded tropical reefs (*50–52*), and microbes may be contributing to the altered metabolome and reduced resilience of temperate, turf-dominated reefs as well. Our findings therefore call for a broader and deeper study of the chemical ecology of temperate reefs, especially those becoming turf dominated (*12*, *53*), to advance our ecological insights and reveal new marine natural products.

Finally, and most broadly, our study adds to an emerging body of work showing that climate change is degrading kelp forests not only through thermal stress but also through indirect pathways by facilitating new or altered species interactions that lock the system in an alternate stable state (*54*, *55*). Indeed, once turf algae proliferate due to ocean warming, they change the reef metabolome (Fig. 3) and exude chemicals that limit kelp recruitment (Fig. 4). This indirect effect of climate change, along with turf algae preempting space, trapping sediments, and harboring small grazers (*18*, *23*, *24*), markedly limits the rebound potential of kelp forests (*12*). Consequently, restoration of such ecosystems will require not only curbing global carbon emissions to slow ocean warming and limit kelp forest decline but also human interventions at regional scales that break harmful ecological feedback loops and foster recovery.

REFERENCES AND NOTES

1. D. O. Duggins, C. A. Simenstad, J. A. Estes, *Science* **245**, 170–173 (1989).
2. D. Krause-Jensen, C. M. Duarte, *Nat. Geosci.* **9**, 737–742 (2016).
3. R. J. Miller *et al.*, *Proc. Biol. Sci.* **285**, 20172571 (2018).
4. R. S. Steneck *et al.*, *Environ. Conserv.* **29**, 436–459 (2002).
5. B. L. Weigel, C. A. Pfister, *Front. Microbiol.* **10**, 346 (2019).
6. D. O. Duggins, J. E. Eckman, A. T. Sewell, *J. Exp. Mar. Biol. Ecol.* **143**, 27–45 (1990).
7. H. Teagle, S. J. Hawkins, P. J. Moore, D. A. Smale, *J. Exp. Mar. Biol. Ecol.* **492**, 81–98 (2017).
8. D. A. Smale, M. T. Burrows, P. Moore, N. O'Connor, S. J. Hawkins, *Ecol. Evol.* **3**, 4016–4038 (2013).
9. A. M. Eger *et al.*, *Nat. Commun.* **14**, 1894 (2023).
10. K. A. Krumhansl *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **113**, 13785–13790 (2016).
11. S. D. Ling, C. R. Johnson, S. D. Frusher, K. R. Ridgway, *Proc. Natl. Acad. Sci. U.S.A.* **106**, 22341–22345 (2009).
12. K. Filbee-Dexter, T. Wernberg, *Bioscience* **68**, 64–76 (2018).
13. T. Wernberg *et al.*, *Nat. Clim. Chang.* **3**, 78–82 (2013).
14. A. Pessarrodona *et al.*, *Glob. Chang. Biol.* **27**, 5262–5275 (2021).
15. F. E. Moy, H. Christie, *Mar. Biol. Res.* **8**, 309–321 (2012).
16. B. K. Eriksson, G. Johansson, P. Snoeijs, *J. Phycol.* **38**, 284–296 (2002).
17. K. Filbee-Dexter, C. Feehan, R. Scheibling, *Mar. Ecol. Prog. Ser.* **543**, 141–152 (2016).
18. C. J. Feehan, S. P. Grace, C. A. Narvaez, *Sci. Rep.* **9**, 7078 (2019).
19. T. S. Suskiewicz *et al.*, *Ecology* **105**, e4334 (2024).
20. J. A. Dijkstra, A. Litterer, K. Mello, B. S. O'Brien, Y. Rzhanov, *Ecosphere* **10**, e02923 (2019).
21. B. S. O'Brien, K. Mello, A. Litterer, J. A. Dijkstra, *J. Exp. Mar. Biol. Ecol.* **506**, 1–8 (2018).
22. C. Ramsay-Newton, A. Drouin, A. R. Hughes, M. E. S. Bracken, *Biol. Invasions* **19**, 537–547 (2017).
23. L. Airoldi, *Oceanogr. Mar. Biol. Annu. Rev.* **41**, 161–236 (2003).
24. J. O'Brien, R. Scheibling, K. Krumhansl, *Mar. Ecol. Prog. Ser.* **522**, 1–13 (2015).
25. I. Kuffner *et al.*, *Mar. Ecol. Prog. Ser.* **323**, 107–117 (2006).
26. D. B. Rasher, E. P. Stout, S. Engel, J. Kubanek, M. E. Hay, *Proc. Natl. Acad. Sci. U.S.A.* **108**, 17726–17731 (2011).
27. D. B. Rasher, M. E. Hay, *Proc. Natl. Acad. Sci. U.S.A.* **107**, 9683–9688 (2010).
28. T. J. Massad *et al.*, *Ecology* **103**, e3762 (2022).
29. J. K. Ooka, D. K. Owens, *Phytochem. Rev.* **17**, 1225–1237 (2018).
30. See the materials and methods.
31. L.-F. Nothias *et al.*, *Nat. Methods* **17**, 905–908 (2020).
32. R. Schmid *et al.*, *Nat. Biotechnol.* **41**, 447–449 (2023).
33. K. Dührkop *et al.*, *Nat. Biotechnol.* **39**, 462–471 (2021).
34. K. Dührkop, H. Shen, M. Meusel, J. Rousu, S. Böcker, *Proc. Natl. Acad. Sci. U.S.A.* **112**, 12580–12585 (2015).
35. K. Dührkop *et al.*, *Nat. Methods* **16**, 299–302 (2019).
36. H. W. Kim *et al.*, *J. Nat. Prod.* **84**, 2795–2807 (2021).
37. L. W. Sumner *et al.*, *Metabolomics* **3**, 211–221 (2007).
38. S. P. Farrell *et al.*, Dryad (2025); https://doi.org/ 10.5061/dryad.kd51c5bhd.
39. S. Papadopoulos Lambidis *et al.*, *Environ. Sci. Technol.* **58**, 19289–19304 (2024).
40. M. P. Gomes *et al.*, *Biologia (Bratisl.)* **72**, 113–129 (2017).
41. R. C. Bolser, M. E. Hay, *Ecology* **77**, 2269–2286 (1996).
42. M. E. Hay, *J. Exp. Mar. Biol. Ecol.* **200**, 103–134 (1996).
43. G. Cronin, V. J. Paul, M. E. Hay, W. Fenical, *J. Chem. Ecol.* **23**, 289–302 (1997).
44. A. M. Demko *et al.*, *Ecology* **98**, 2312–2321 (2017).
45. E. E. Sotka, J. P. Wares, M. E. Hay, *Evolution* **57**, 2262–2276 (2003).
46. M. E. Hay, *Annu. Rev. Mar. Sci.* **1**, 193–212 (2009).
47. A. U. Mallik, Inderjit, *Chemical Ecology of Plants: Allelopathy in Aquatic and Terrestrial Ecosystems* (Birkhäuser, 2002); https://link.springer.com/10.1007/978-3-0348-8109-8.
48. A. D. Rodríguez, I. C. Piña, *J. Nat. Prod.* **56**, 907–914 (1993).
49. S. Sun, S. Hu, B. Zhang, X. Sun, N. Xu, *Mar. Pollut. Bull.* **170**, 112673 (2021).
50. A. F. Haas *et al.*, *Nat. Microbiol.* **1**, 16042 (2016).
51. T. N. F. Roach *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **117**, 13588–13595 (2020).
52. L. Wegley Kelly *et al.*, *Front. Mar. Sci.* **8**, 630799 (2021).
53. S. D. Connell, K. J. Kroeker, K. E. Fabricius, D. I. Kline, B. D. Russell, *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **368**, 20120442 (2013).
54. D. B. Rasher *et al.*, *Science* **369**, 1351–1354 (2020).
55. T. Wernberg *et al.*, *Science* **353**, 169–172 (2016).
56. S. Farrell, GNPS (2022); https://gnps.ucsd.edu/ProteoSAFe/status.jsp?task=bee692af684e4097b83bde2f8e12ab10
57. S. Farrell, M. S. Surface Extracts Science, GNPS2 (2025); https://gnps2.org/status?task=5843f1ba09ce4157ab8f854d8e860fe5.
58. Data for: S. P. Farrell *et al.*, Turf algae redefine the chemical landscape of temperate reefs, limiting kelp forest recovery, version 2, Zenodo (2025).

ACKNOWLEDGMENTS

We thank S. Ryan, P. Churney, and R. Francolini for help in the field; T. Schramm, K. Steuer-Lodd, and S. Papadopoulos Lambidis for help with LC-MS/MS acquisition and data analysis; A. St. Gelais, S. Lacourciere, and E. Porter for help with the gametophyte assays; and Bigelow Laboratory for Ocean Sciences for logistical support. This work was conducted with permission from the Maine Department of Marine Resources (special license 2022-36-03). **Funding:** This work was supported through a National Science Foundation cooperative agreement award to the University of Maine from the EPSCoR RII Track-1 program (OIA-1489227 to D.B.R. and D.C.B.), a Louise H. & David S. Ingalls Foundation grant to Bigelow Laboratory for Ocean Sciences (D.B.R.), a German Research Foundation award (EXC 2124-390838134 to D.P.), an Essex Avenue Foundation grant (to D.C.B.), and a PADI Foundation fellowship (S.P.F.). **Author contributions:** Conceptualization: S.P.F., D.B.R.; Funding acquisition: S.P.F., D.C.B., D.B.R.; Investigation: S.P.F., D.S.Y., D.B.R.; Methodology: S.P.F., A.K.P.S., A.C.H., D.P., D.S.Y., J.A.B., P.S., D.B.R.; Project administration: S.P.F., D.B.R.; Supervision: D.B.P., D.R.; Visualization: S.P.F., A.K.P.S., P.S.; Writing – original draft: S.P.F., D.B.R.; Writing – review & editing: All authors. **Competing interests:** The authors declare no competing interests. **Data and materials availability:** Feature-base molecular networking jobs can be found at the Global Natural Products Social Molecular Networking repository (*56*,*57*). Code can be found on Zenodo (*58*). All other data associated with this study are accessible on Dryad (*38*). **License information:** Copyright © 2025 the authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. No claim to original US government works. https://www.science.org/about/science-licenses-journal-article-reuse

SUPPLEMENTARY MATERIALS

science.org/doi/10.1126/science.adt6788
Materials and Methods; Figs. S1 to S9; References (*59–66*); MDAR Reproducibility Checklist

Submitted 10 October 2024; accepted 27 March 2025

10.1126/science.adt6788

Downloaded from https://www.science.org at National University of Ireland, Galway on August 20, 2025