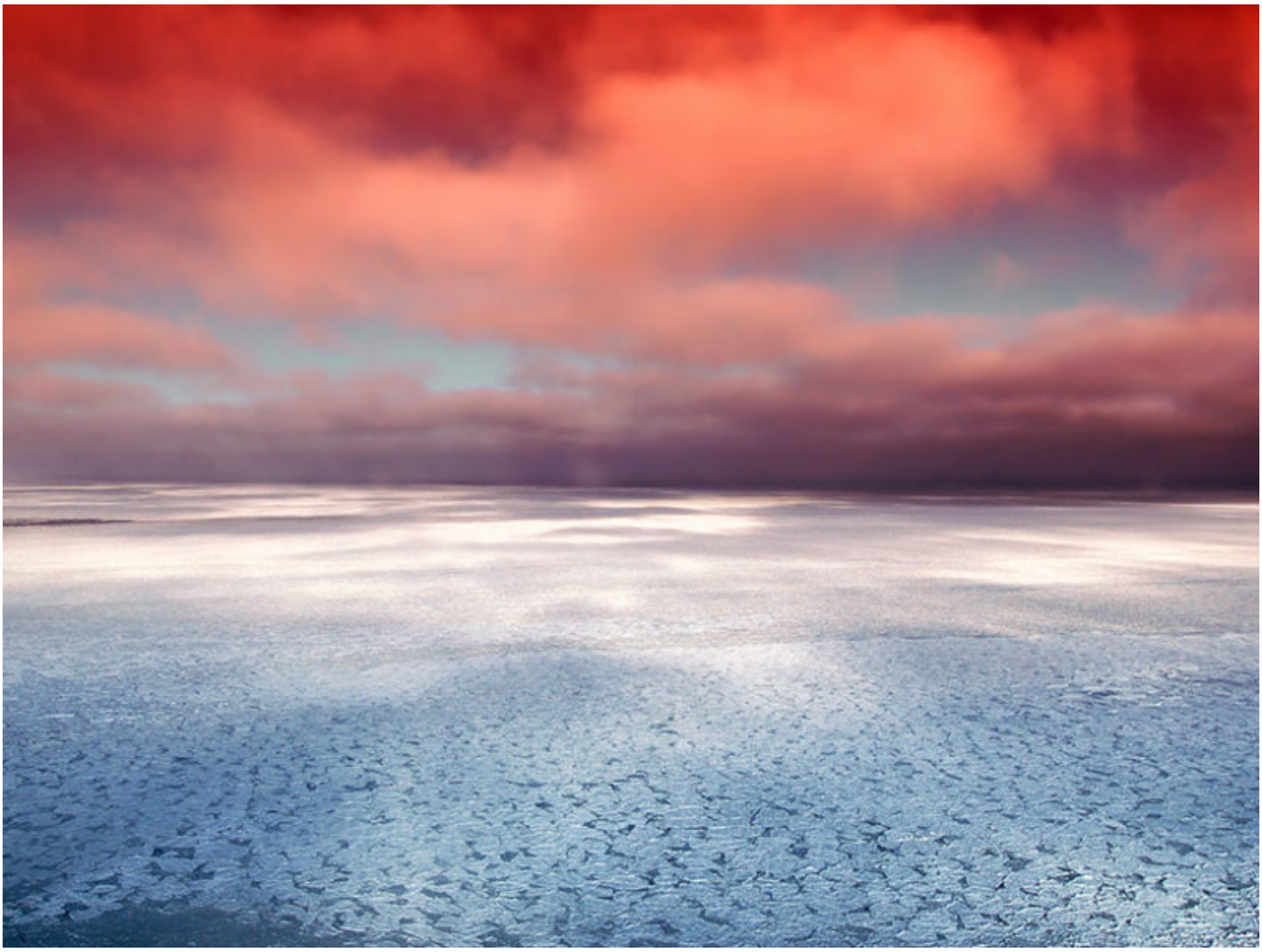
Implications of Sea Ice Management for Arctic Biogeochemistry

Geoengineering strategies to slow sea ice melting would affect not only Earth's climate but also the biology and chemistry of the oceans, atmosphere, and ice.



Sea ice covers part of Hudson Bay in Canada. Credit: David Mark, Pixabay

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As the world faces the reality of anthropogenic global warming, substantial human ingenuity is being directed not only toward mitigating and adapting to the changes occurring on our planet but also toward direct, technological interventions in the climate system—geoengineering. Most geoengineering proposals fall into one of two categories: negative emission (https://www.carbonbrief.org/explainer-10-ways-negative-emissions-could-slow-climate-change) technologies that

remove carbon dioxide (CO_2) from the atmosphere and solar radiation management (https://www.carbonbrief.org/explainer-six-ideas-to-limit-global-warming-with-solar-geoengineering) technologies that increase the amount of sunlight reflected by Earth, the planetary albedo. Some solar radiation management proposals suggest raising the albedo of the Arctic Ocean by restoring lost sea ice, which would shield the ocean below and limit its absorption of solar radiation.

Given the fundamentally invasive nature of these climate intervention proposals, the scientific community must thoroughly investigate and discuss the consequences to inform policy decisions on whether and how to proceed.

Two proposals to artificially restore Arctic sea ice have received particular attention. One suggests thickening sea ice by pumping seawater onto the top of the ice in winter, an approach we will call "flooding" [*Desch et al.* (https://doi.org/10.1002/2016EF000410), 2017]. The low air temperatures would quickly freeze that water, thickening the ice faster than it would grow naturally, and the resulting thicker sea ice cover would better withstand summer melt. In contrast, *Field et al.* (https://doi.org/10.1029/2018EF000820) [2018] propose spreading highly reflective glass microspheres as a form of artificial snow on the sea ice, which would sufficiently increase its albedo to reduce melt.

Given the fundamentally invasive nature of these climate intervention proposals, the scientific community must thoroughly investigate and discuss the consequences to inform policy decisions on whether and how to proceed [*Boyd and Vivian* (https://doi.org/10.1038/d41586-019-01790-7), 2019]. To date, discussions of the potential efficacy and impacts of sea ice restoration have focused on the physics of the radiative balance (https://www.weather.gov/jetstream/energy) [*Zampieri and Goessling* (https://doi.org/10.1029/2019EF001230), 2019], impacts on fish and birds, the economics and industrial carbon footprints of broad implementation, and reversibility—that is, how quickly the effects of an intervention would be reversed if the deployment were halted. Those issues are certainly important, but amid the discussions, the potentially substantial effects on biogeochemistry in the sea ice, the underlying water, and the overlying atmosphere—and whether these effects too would be reversible—have received little attention.

Living and Breathing Sea Ice

Sea ice is a complex and biogeochemically active medium, with channels and pockets of concentrated brine containing highly adapted biological communities [*Thomas*, 2017]. As sea ice freezes and melts through its annual cycle, it exchanges material with both the atmosphere and underlying waters [*Vancoppenolle et al.* (https://doi.org/10.1016/j.quascirev.2013.04.011), 2013]. During initial freeze-up, young ice is extremely permeable, and biological and geochemical processes within ice brines release CO_2 and aerosol precursors. As winter advances, the ice thickens. Brine drainage coupled with lower temperatures reduces the permeability of the upper ice, and biological communities become concentrated at the bottom of the sea ice. During spring, the ice again becomes more permeable as

melt advances, accelerating material exchanges with the atmosphere and the water while algal communities in and under the sea ice bloom, fundamentally contributing to the entire Arctic Ocean ecosystem [*Wassmann and Reigstad* (https://doi.org/10.5670/oceanog.2011.74), 2011].

Sea ice is also nearly always covered with snow, except in high summer. Because it absorbs salt from the underlying ice, natural snow atop sea ice is always at least somewhat salty and is highly chemically reactive, which makes it an important source of aerosols (https://eos.org/editors-vox/atmospheric-aerosol-in-the-changing-arctic) to the atmosphere [*Abbatt et al.* (https://doi.org/10.5194/acp-12-6237-2012), 2012]. When the ice surface is flooded with seawater, which occurs naturally when a thick snow cover accumulates on thin ice, typical sea ice is not produced, but rather a mixture called "snow ice" is. The structure of snow ice is quite different from that of either upper sea ice or snow, and their permeabilities follow different trajectories through formation and melting, affecting material exchanges with the atmosphere.

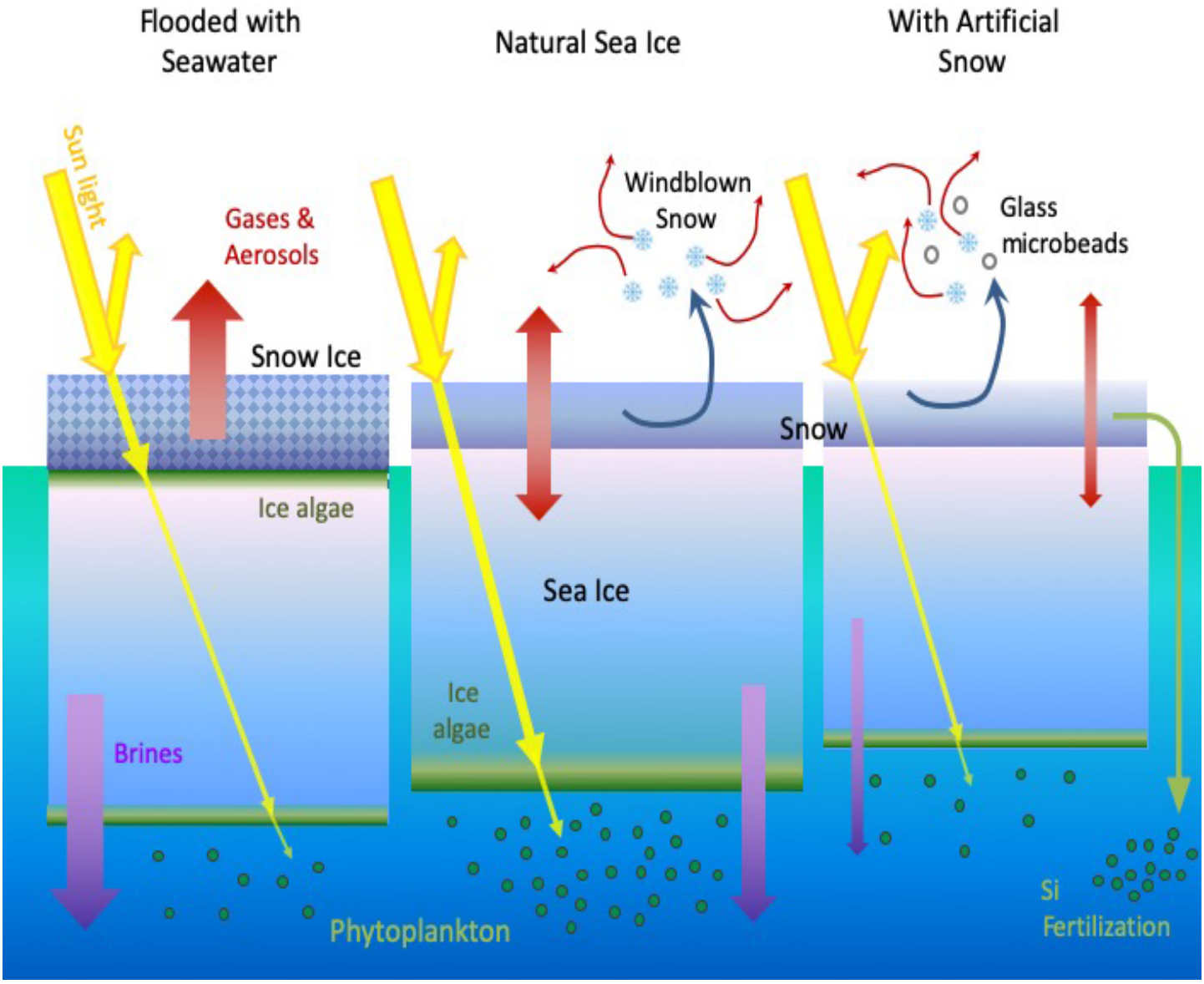

Fig. 1. Sea ice restoration approaches like seawater flooding and artificial snow would affect solar radiation absorption (yellow arrows), gas and aerosol fluxes (red arrows), brine release (purple

arrows), and primary production (green, in both ice and water) in the Arctic.

The seasonal evolution of sea ice and its interfaces with the air and water are thus fundamental in polar and global biogeochemical cycles. The proposals to artificially increase sea ice thickness would alter the radiative, thermal, structural, and chemical characteristics of the ice, with consequences for the biogeochemistry and ecology of the sea ice, the ocean, and the atmosphere (Figure 1).

Gases and Aerosols

Both flooding and artificial snow in the form of glass beads would change the release of reactive substances from sea ice into the Arctic atmosphere.
Both flooding and artificial snow in the form of glass beads would change the release of reactive substances from sea ice into the Arctic atmosphere, in particular, halogen (e.g., bromide from sea salt or methyl iodide from algae [*Abbatt et al.* (https://doi.org/10.5194/acp-12-6237-2012), 2012]) and sulfur (e.g., dimethyl sulfide from algae) compounds. These emissions affect atmospheric chemistry and aerosol loading. Flooding could result in large biological communities at the top of the ice (as often occurs naturally in Antarctic sea ice), and such surface communities may release reactive material to the atmosphere. On the other hand, inert, artificial snow could decrease the overall aerosol source to the atmosphere by dampening gas fluxes to the atmosphere from the underlying sea ice.

In the absence of sunlight, an increase in atmospheric aerosols would warm the winter Arctic atmosphere, and conversely, a decrease in aerosols would cool temperatures [*Willis et al.* (https://doi.org/10.1029/2018RG000602), 2018]. However, with a seasonal increase in light and photochemical reactivity, matters become much more complicated, and both aerosol and gaseous halogen chemistry could have myriad contrasting impacts on the Arctic atmosphere. For example, halogens released from freezing sea ice are associated with ozone depletion and mercury deposition (https://nsidc.org/daac/sop/2013/mercury-raining) events [*Simpson et al.* (https://doi.org/10.5194/acp-7-4375-2007), 2007]. Changes in the timing and locations of those emissions have implications for mercury contamination in Arctic food webs.

Artificial snow cover would also dampen CO_2 fluxes between sea ice and the atmosphere and would thermally insulate the ice, reducing the freezing rate at the bottom and limiting CO_2 injection into the underlying water. In contrast, wintertime flooding would initially increase CO_2 release to the atmosphere because rapid, low-temperature freezing would increase salinity and decrease CO_2 solubility in the resulting brines [*Vancoppenolle et al.* (https://doi.org/10.1016/j.quascirev.2013.04.011), 2013]. This CO_2 emission would likely be larger than that which occurs during natural autumn freezing both because of lower temperatures and because CO_2 release to the underlying water would be blocked by the established, relatively thick, and impermeable ice cover. On the other hand, flooding and the formation of snow ice would also increase the total thermal conductivity (https://www.khanacademy.org/science/physics/thermodynamics/specific-heat-and-heat-transfer/a/what-is-thermal-

conductivity) of the ice column, thereby increasing basal freezing and, potentially, CO_2 release to the water. In addition, snow ice resulting from flooding would severely limit atmospheric CO_2 drawdown into the ice well into the spring melt period.

Light and Life

Snow on sea ice not only affects the heat absorbed by the ice but also very strongly controls the light available (https://eos.org/articles/light-permeates-seasonally-through-arctic-sea-ice) for photosynthesis in sea ice and oceanic ecosystems [*Leu et al.* (https://doi.org/10.1016/j.pocean.2015.07.012), 2015]. High-albedo artificial snow could delay the onset and reduce the magnitude of algal blooms both within and under the sea ice. The timing and magnitude (https://eos.org/research-spotlights/as-artic-sea-ice-disappears-what-happens-to-ecosystems) of these blooms have direct consequences for community structure and the life cycles of zooplanktonic grazers (https://marinebio.org/creatures/zooplankton/), with cascading impacts on Arctic Ocean ecosystems [*Falk-Petersen et al.* (https://doi.org/10.1007/978-3-540-48514-8_9), 2007] and the biological CO_2 sink. The optical properties of artificial snow and its interactions with natural snow (e.g., impacts on snow metamorphosis, which would also influence gas fluxes) could increase or decrease the light available for primary production (https://www.nature.com/scitable/knowledge/library/the-biological-productivity-of-the-ocean-70631104/). Algae introduced to the top of sea ice by flooding would shade and delay growth of algae at the bottom of the ice and in the water beneath, reducing food available to grazers.

Perhaps one of the most wide-ranging impacts of deploying artificial snow composed of glass beads would be the potential to fertilize oceanic ecosystems with silicon. Silicon fertilization, particularly when coupled with changes in the timing of sea ice melt and surface water stratification, could have a substantial impact on spring bloom dynamics and community succession (https://theconversation.com/disappearing-sea-ice-is-changing-the-whole-ecosystem-of-the-arctic-ocean-117433).

Local and Distant Feedbacks

Sea ice can travel long distances, so the biogeochemical impacts of interventions could accumulate far from deployment sites.

In evaluating climate intervention proposals, we must also consider local biogeochemical effects of the industrial-scale infrastructure that would be required to implement the interventions. The positioning of large numbers of massive seawater pumps needed for flooding, ice cover disruption by ships deployed to spread artificial snow, and the aerosol emissions from those ships would also affect the biogeochemistry and ecology of Arctic systems.

Many of the processes we have identified would have opposing impacts on the climate system and on biogeochemical cycles. Furthermore, sea ice can travel long distances, so the biogeochemical impacts of interventions could accumulate far from deployment sites. In total, it is clear that sea ice and its

interactions with the atmosphere and the ocean are highly complex, and biogeochemical feedbacks in these systems are much less predictable than the radiative balance.

Look Before You Leap

In the face of widespread anthropogenic impacts on the global Earth system, humanity has a responsibility to consider and investigate ways to limit the damage. However, Earth is a complex system, and the law of unintended consequences is incontrovertible. Dependable predictions of the total effects of artificial sea ice restoration approaches are currently unavailable and require extensive further research. Laboratory, numerical, and possibly field experiments need to focus both on detailed processes, such as the dissolution of glass microbeads and potential sintering between glass and ice, and on how natural systems will respond over wide areas and long time periods, for example, with respect to carbon export into deep waters and silicon fertilization.

Any interventions to alter the progress of climate change will have repercussions throughout the environment. In the worst-case scenario, the time may come when the global community decides that some geoengineering cures are preferable to the climate change disease. However, discussions about implementing intentional climate interventions must examine all possible side effects in depth and with clarity. As a contribution to that multidisciplinary discussion of potential climate interventions, we encourage the polar science research community to assess in detail the biogeochemical consequences of artificial Arctic sea ice restoration.

Acknowledgments

This article arose from the Biogeochemical Exchange Processes at Sea Ice Interfaces (BEPSII (https://sites.google.com/site/bepsiiwg140/)) steering committee, and we thank the entire BEPSII community for all our discussions and insights into sea ice and its contributions to global biogeochemical cycles. BEPSII thanks the Climate and Cryosphere program, the Scientific Committee on Antarctic Research, and the Surface Ocean-Lower Atmosphere Study for their generous and sustained support.

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Citation: Miller, L., F. Fripiat, S. Moreau, D. Nomura, J. Stefels, N. Steiner, L. Tedesco, and M. Vancoppenolle (2020), Implications of sea ice management for Arctic biogeochemistry, *Eos, 101,* https://doi.org/10.1029/2020EO149927. Published on 30 September 2020.
