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Hurricane Harvey in 2017 caused $125 billion in damages in the U.S. (NOAA 2021). Could we spread reflective glass foam tiles on the north Atlantic gyre to cost-effectively reduce storm damage and reflect solar energy to space? The tiles might be made of sand from the Sahara desert with energy from photovoltaic panels. The tiles can be designed to slowly release an alkalizer to raise the pH of the water surface to increase absorbance of atmospheric CO_2 or release nutrients to promote growth of carbon-fixing organisms. The alkalizer and nutrients can be dissolved from fine grains of mineral adhered to the tile's bottom surface, avoiding the need for expensive extra-fine grinding of the mineral. Because the ability of oceans to absorb CO_2 will go down as ocean water gets warmer, reducing ocean heat gain with reflective floating tiles is synergistic with CO_2 absorption. Because surface currents in gyres converge toward the center, the half-life before washing onto beaches would likely be about three years, much longer if the tiles can be designed to have very low windage. Tiles washed onto beaches may be collected and redeployed. When they break and erode, the tiles revert to sand. Considering the benefits of reducing tropical storm damage, removing CO_2 from the atmosphere, and reflecting solar energy to space, deploying such tiles in the North Atlantic Gyre may be cost effective.

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I. INTRODUCTION

Between 1980 and 2020, tropical cyclones (called hurricanes in north America) caused $997.3 billion in damages in the U.S., an average cost of $50 billion per year, and caused 6,593 deaths (Smith 2021).

In 2011, Seitz proposed reducing global warming and tropical storm intensity by making ocean surfaces more reflective with machine generated sea foam (Seitz 2011). Gabriel *et al* studied application of the foam in select regions and concluded this method could work (Gabriel et al. 2017). Unfortunately, no-one has found a way to make long-lasting sea foam without adding chemicals that are too expensive and would likely have deleterious side effects. Ortega and Evans analyzed the energy requirements and capital equipment requirements to make the foam with added surfactants and concluded that, if the duration of foam bubbles cannot be greatly increased, the method will not be cost effective (Ortega and Evans 2017). A potential alternative is to place floating, reflective glass foam tiles on ocean surfaces.

Kheshgi (1995) proposed enhancing ocean alkalinity by adding finely ground alkaline minerals such as ultramafic rocks (e.g. olivine) to oceans to raise surface pH and thereby increase absorbance of CO_2 into the oceans. Martin and Fitzwater (1988) proposed absorbing CO_2 into the ocean surface by fertilizing with iron to stimulate

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phytoplankton growth in high-nutrient, low-chlorophyll waters where the growth limiting factor is availability of iron. Other ocean areas might be best fertilized with other metals, nitrogen, phosphorus, or silica (NASEM 2021). Each of these methods will be effective if the CO_2 is naturally incorporated near the surface into materials that sink to great depth in the ocean. The oceans have enough CO_2 storage capacity to hold all the excess CO_2 now in the atmosphere. Unfortunately, with modelling, Mongin et al. (2021) concluded that such materials spread on the ocean surface sink deep into the water column before they dissolve and will not be as effective as desired, reducing by more than half the amount of CO_2 that could be absorbed from the air if the particles stayed near the surface while they dissolve. Despite this inefficiency, the authors conclude that artificial ocean alkalinization can entirely offset the effects on the Great Barrier Reef of ocean acidification. Floating reflective glass foam tiles can release over time at the surface of the water nutrients or alkalizers from relatively large grains of mineral adhered to the bottom sides of tiles and fine grinding to about one micron size is not required (NASEM 2021).

The lowest cost solid material for making foam is silica sand (SiO_2) which can be made into foamed glass tiles. Grains of a slowly dissolving alkalizer or nutrient fertilizer can be adhered to the tiles to raise the nearby pH to increase absorption of CO_2 from the atmosphere and promote growth of CO_2 fixing organisms. The silica sand, alkalizer, and nutrients can be selected to be benign for the environment.

This article proposes experimenting with solar-reflective, long-lasting, floating glass foam tiles that release an alkalizer and/or nutrients and spreading them on oceans, particularly in gyres and up-current from coral reefs. The objectives are to:

1. Reduce absorbance of solar energy and reduce water temperatures to reduce tropical cyclone damage and reduce coral damage;
2. Increase absorbance of CO_2 from the atmosphere by maintaining high pH at the water surface over months and by reducing solar heat gain of the water;
3. Increase absorbance of CO_2 from the atmosphere by supplying at the surface nutrients to promote growth of organisms that fix carbon;
4. Reduce acidity to reduce suppression of coral growth when deployed up-current from coral reefs; and
5. Reduce the Earth's energy imbalance to reduce global warming by reflecting solar energy to space.

In December, 2021, the National Academies of Sciences, Engineering, and Medicine (NASEM 2021) published a comprehensive report reviewing and summarizing all research to date on nutrient fertilization and ocean alkalinity enhancement to increase absorbance and sequestration of CO_2 from the atmosphere and urging that further research be done, proceeding now to mesoscale experiments. The floating glass foam tiles can be used as a vehicle to deliver experimental nutrients and alkalizers and hold them at the water surface while they dissolve, achieving a greater effect than if the nutrients and alkalizers dissolve well below the surface and avoiding the expense of grinding the materials to one micron particle sizes.

II. WHERE TO LAUNCH FLOATING REFLECTIVE TILES

A location for launching tiles where there would be benefits greater than merely the benefits for Earth's energy balance and atmospheric CO_2 reduction is the tropical North Atlantic Gyre (Figure 1) to also reduce hurricane damage. There are few beaches within the gyre that would receive substantial deposits of tiles, merely the small islands of Bermuda, Azores, Madeira, Selvagens, and Canary Islands. An industry of independent operators might gather tiles off beaches for redeployment in exchange for payment upon delivery.

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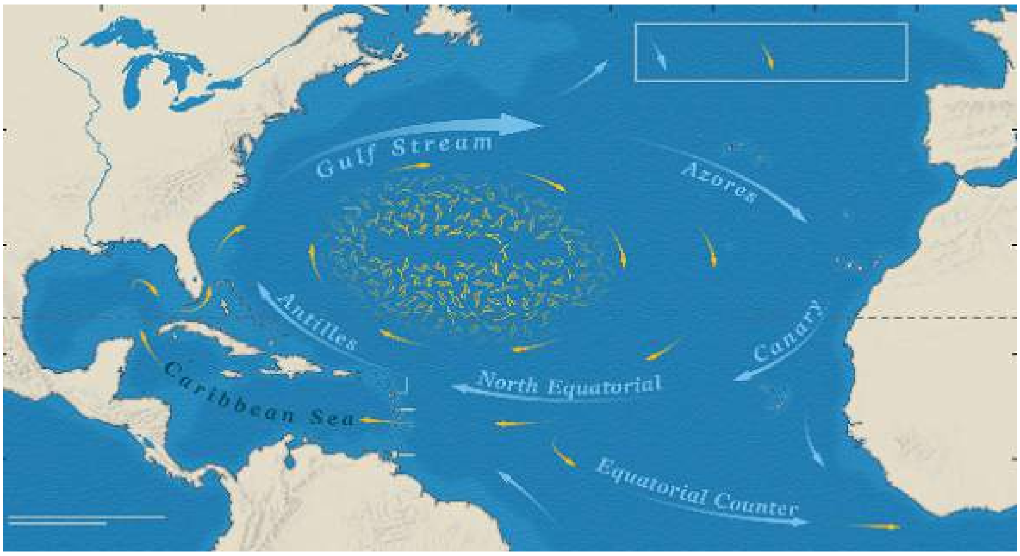

Figure 1: The North Atlantic Gyre showing where floating Sargassum seaweed is retained in the gyre

A factory could be located on a shore where there is a low cost supply of silica sand and electricity generated without burning fossil fuels. The best location might be the west end of the Sahara desert, such as in Mauritania or Western Sahara, where electricity could be generated with photovoltaic panels and silica sand is plentiful. The tiles would be loaded onto barges and dumped in the optimal location within the gyre, which might be near the northwest Africa coast to minimize transportation costs.

Cogley (1979) reports that mean albedo of waters of the North Atlantic Gyre is about 5-9%, presenting an opportunity for about 80% gain in solar reflectivity from highly reflective tiles. Reducing heat gain of the North Atlantic Gyre water under tiles by 80% will reduce strength of hurricanes in North America and reduce coral damage. It will also enhance the ability of surface water to absorb CO_2 by increasing solubility of CO_2 in the water (NASEM 2021). If the absorbed CO_2 is well fixed near the surface, currents of the gyre will carry the fixed CO_2 toward the center of the gyre and then downward, accelerating decent to a preferred depth. Considering the high cost of tropical cyclone damage in the North Atlantic, the benefits of removing CO_2 from the atmosphere, the benefits of reflecting solar energy to space, and the relative lack of beaches in the North Atlantic Gyre where tiles would wash up shortly after launch, launching huge quantities of such tiles at an optimal location in the North Atlantic Gyre (Figure 1) may be cost-effective.

III. TARGET DESIGN TO ACCOMMODATE ORGANIC GROWTH

Due to Coriolis effect, ocean gyres have surface currents that converge toward their centers and then sink (downwelling). Floating objects with low windage (how much the surface wind moves the tiles relative to the surface water), such as Sargassum seaweed in the North Atlantic Gyre and human trash, often remain floating at gyre centers for many years or decades, forming what are sometimes called garbage patches. The most crucial issue for design of the tiles and research on feasibility and cost effectiveness is the problem of organic growth on tiles that would cause them to sink (Kaiser et al. 2017). This may require that the tiles start with high windage. The tiles should protrude above the surface of the water enough to remain reflective white on top rather than covered with organic growth, but, to minimize windage and thereby extend the average length of time before washing onto a beach, they should protrude no more than necessary. Thus, the buoyancy of the tiles would ideally increase at the same rate that organic growth decreases total buoyancy so the windage constantly remains optimally low. Buoyancy of the tiles can be designed to increase over time by adhering to the tiles slowly dissolving/ablating alkalizer or nutrient grains heavier than water. And, by slowly ablating, the grains may cause shedding of organic growth to extend the time until biofouling causes tiles to sink. The next steps for researching whether the tiles will be effective is to determine how high a flat top object must float above the sea water surface to not grow seaweed on top and how high it must start to not be pulled below that level by weight of growth over the target lifetime; then determine the windage of this design.

For a starting estimate of windage, Novelli et al. measured the windage of toroidal drift trackers that protruded 3 cm out of sea water (Novelli 2017). Most of the drift trackers had drogues but some were released without drogues. Off the coast of Florida, the trackers without drogues had a measured actual windage of 2%, which suggests that the tiles will have a windage of 2% or less. Protruding 3 cm out of the water surface is likely much more than is needed to prevent growth of seaweed on top.

IV. EXPECTED HALF-LIFE BEFORE WASHING UP ON A BEACH

In a particular gyre, the stronger the surface current toward the center, the greater the windage the current can overcome to keep the tiles from washing up on a beach at the edge of the gyre. Sargassum floating seaweed is retained by centering currents in the North Atlantic Gyre indefinitely. No such seaweed has been reported in the North Pacific Gyre. Therefore, we assume that the centering currents in the North Atlantic Gyre are at least as strong as the centering currents in the North Pacific Gyre, and we assume that tiles would remain in the North Atlantic Gyre at least as long as they would remain in the North Pacific Gyre. Models of drift by floating objects and data from the North Pacific Gyre that has been used to refine the models give us a rough estimate of likely half-life for tiles in the North Atlantic Gyre.

Maximenko et al. gathered data from debris washed into the Pacific ocean by the Great Japan Tsunami of 2011 to compare with predictions of five models of movement of floating objects across the North Pacific Gyre (Maximenko 2018). In all the models, debris with a windage higher than about 3% (meaning the velocity of drift is 3% of the wind velocity added to the velocity of the surface water) was blown past the gyre by prevailing westerly winds and landed on beaches of North America, while debris with windage lower than about 3% turned with the gyre current toward the center of the gyre and experienced a much longer half-life before leaving the gyre. Of the objects that made the first turn into the gyre, most having windage lower than 3%, the average prediction of models was that those objects would experience a half-life of 3.4 years before leaving the gyre (e-folding duration of 4.85 years). Maximenko et al. compared the various model results and found all the models gave relatively consistent results for objects with 2% windage. The model results had the highest agreement with data from floating objects at windages ranging from 1.1% to 2.8%.

If the proposed tiles have windage higher than 3%, the Maximenko data for the North Pacific Gyre suggests that more than half will likely be blown out of the North Atlantic Gyre within a year. If the windage is about 2% as suggested by the Novelli data, the Maximenko data suggests that the half life duration in the North Atlantic Gyre will likely be about 3 years.

V. MAKING FLOATING GLASS TILES

Tiles can be made with a foam of closed-cell gas bubbles. Target formulation, density, and tile thickness may be selected to (a) float on sea water over a target lifespan, (b) release an alkalizer or nutrient at an optimal rate, and (c) optimize solar reflectivity, absorption of CO_2, environmental effects, and cost. Ingredients that might make the tiles toxic, such as lead, mercury, asbestos, and perhaps nickel, can be avoided. Energy to make glass foam tiles can be generated from carbon-free sources such as photovoltaic panels. Tile material may be made in large slabs and cut or broken to dimensions at least five times greater than the thickness.

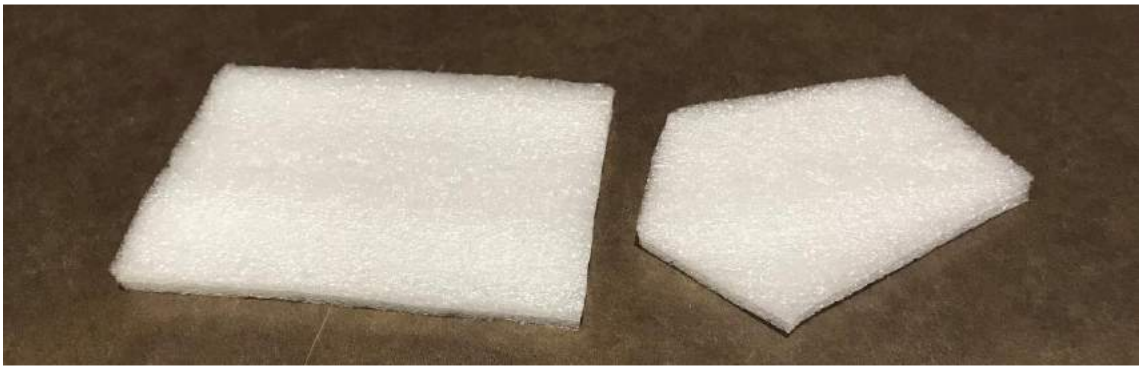

Figure 2: Models of glass foam tiles

5.1 Making solar reflective glass tiles with a density lower than water

Following Mie theory, transparent material such as glass can be made highly solar reflective by forming alternating pockets of air and glass where the air pockets and glass pockets each have average diameters of roughly one micron. This is why snow and clouds are white. Larger air pocket sizes are also highly effective. The density of solid glass is about 2.5 times that of water. To make tiles that will float on ocean water (Figure 2), the tiles must, by volume, be no more than 40% glass and at least 60% gas with an internal pressure about the same as atmospheric pressure at sea level. Work by Wang et al. (2021) with transparent polymer having pores of .2 microns to 5 microns shows that 95% solar reflectivity is achievable with 60% porosity. Haley (2021) reports a solar reflectivity of 95% in Entek polyethylene film open cell foam with pore sizes from .05 to 1 micron. Ninety-five percent solar reflectivity is likely the upper limit of what can be achieved with glass foam. To float high enough that they will not sink from the weight of alkalizer and nutrient or biofouling within the target lifetime, the tiles may need to be up to 80% gas.

5.2 Present commercial method of making glass foam

Technology to make foamed glass with bubbles of 10 to 300 microns is well known and used to make inert heat insulating material such as for a concrete additive (Dennert Poraver 2001) or an insulating lower layer under road pavement to prevent frost heaves (Figure 3) (Segui et al. 2016).

Figure 3: Chunks of glass foam for insulation under roads

To make the foam, particles of glass and particles of a chemical gas generating agent are mixed, placed in a furnace, and heated to around 800-900°C to obtain the viscoelastic state of glass. This temperature causes the chemical agent to release a gas, forming bubbles in the glass, and the mixture is then formed into a desired shape and cooled. While it is cooling, it may be cut to desired shapes and sizes when partially hardened. Using current manufacturing methods, the resulting foam density (relative to pure water) ranges from .3 to .9. A detailed article on making foam glass is linked in the references (Scarinci et al. 2005).

This technology can be adapted to make highly reflective tiles by using very small particles of both glass and the gas forming agent. Particles of preferred sizes have average diameters in the range of 50 nanometers to two microns, made by pulverizing such as with a ball mill. Larger sizes are likely also effective. Using very small particles results in smaller bubble sizes provided the mixture is not heated to a point of low enough viscosity that the bubbles rise upward or merge together.

5.3 Making glass foam under pressure

Instead of adding a gas forming agent, using a method invented by Willis (1941), ground particles of glass with pockets of air in the interstitial cracks can be pressurized to increase the amount of gas in the interstices, then heated until the glass melts to surround all air pockets but still has a high viscosity, then depressurized so the air bubbles expand to at least 60% of the volume, and then cooled in a sheet. The resulting material can be broken or cut to suitable sizes.

5.4 Tiles made by syntactic aggregation of glass microspheres

Technology has been known for more than 50 years for making individual glass microspheres (a/k/a bubbles or microballoons) as small as 5 microns diameter (Koopman et al. 2004) with a density (relative to pure water) ranging from .1 to .6 (3M Corp 2007). The process might be modified to make microspheres with an average diameter of one to five microns. Suitably large tiles with a density less than 1 may be made by gluing together such microspheres to make tiles of syntactic foam (Ramadin et al. 1996). The glue might be liquid sodium silicate glass (water glass) with a slow rate of dissolution or Type I poly-vinyl-acetate (PVA). The mix is poured into a slab and the water is evaporated to make solid tiles. With this formulation, as the tiles slowly disintegrate, microspheres that are released will float and continue to maintain a higher albedo at the water surface.

VI. COATING THE TILES WITH A SLOWLY RELEASED ALKALIZER

Alkalizers that might be adhered to the tiles include mineable magnesium or calcium silicate minerals such as wollastonite, olivine, anorthite, brucite, portlandite, forsterite, and peridotite or carbonate minerals such as, calcite (chalk or limestone) and dolomite (Renforth and Henderson 2017, NASEM 2021). The minerals could include iron, which is common in olivine rocks, or other nutrients (NASEM 2021). The preferred method of adhesion is to apply hot mineral grains to hot tiles before they finish cooling where the mineral grains are hot enough to melt the glass surface which adheres them strongly as it cools. The size of the grains should be selected to take more than two half lives (likely 6 years) to finish dissolving in seawater. The tiles can be launched with the mineral grains side down. If the tiles are turned over by wind and waves or ship collisions, most of them will end up grainy side down because it is more dense than the glass foam. To facilitate the tiles righting themselves when turned over by wind, the tiles can be cut long and narrow. (Figure 4).

Figure 4: Long and narrow tiles with mineral grains adhered on one side

Instead of adhering mineral grains by melting the surface of the glass foam, grains can be adhered with a slowly dissolving water soluble glass silicate of an alkali metal, (sodium, potassium, or lithium), preferably sodium, traditionally called water glass or soda glass (sodium silicate). Soda glass slowly dissolves releasing sodium oxide (Na_2O) which, in water, forms sodium hydroxide (NaOH, lye, $Na_2O + H_2O \rightarrow 2\ NaOH$), a strong base, which is a favored absorbent for capture of carbon dioxide (Cambier 2017, Stolaroff et al. 2008). The glass foam itself might be made with soda glass. Douglas and El-Shamy (1967) report a suitably slow enough rate of dissolution for some formulations of soda glass.

If minerals are adhered with alkali silicate, the minerals can be ground to roughly one micron particle size to maintain high Mie scattering solar reflectivity so the tile is still highly reflective if it turns over. Calcium carbonate particles with an average cross-section diameter of about .5 microns used as pigment in an acrylic paint achieve a solar reflectivity of 95.5% (Li et al. 2020). The adhesion process might involve coating a sheet of glass foam with liquid adhesive and then dusting on a layer of powder. Figure 4 shows foam glass beads coated with calcium carbonate powder made by applying liquid poly-vinyl-acetate glue, dusting with chalk powder, and drying (Figure 5).

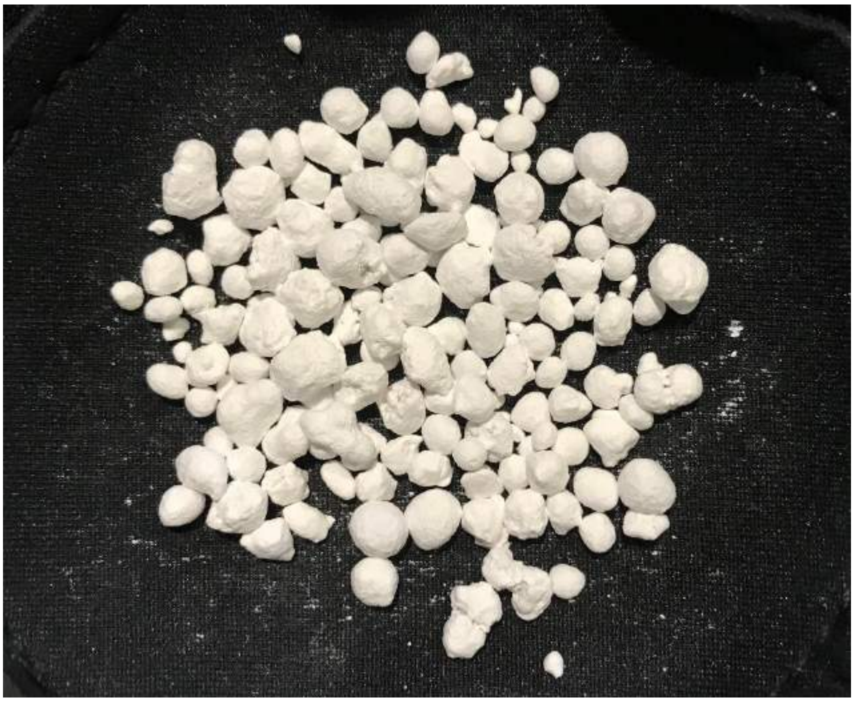

Figure 5: AGSCO (Wheeling Illinois) glass foam beads coated with adhered chalk dust

Like marine buoys, the tiles might be designed to have low enough density after all alkalizer and adhesive are dissolved that the tiles will keep floating despite the maximum amount of growth within the designed life of the tiles. Up to that point, the release of alkalizer to raise local pH is expected to reduce organic growth on the tiles (Qin 2015).

VII. POTENTIAL RISKS TO BE INVESTIGATED

7.1 The tiles will reduce photosynthesis

Reflecting solar radiation will reduced growth of phyto-organisms, reducing strength of the biological sinking of carbon into deep water (NASEM 2021). Studies should be undertaken to estimate whether this detriment outweighs reducing tropical cyclone damage, increasing removal of CO2 from the atmosphere, reducing Earth's energy imbalance, and reducing heat and acid damage to coral reefs.

7.2 Termination shock

If the tiles are applied every year as the climate grows hotter, the tiles will limit adaptation by corals and, if application is then skipped one year, the corals may experience a fatal shock. Before commencing extensive deployment, we should be confident this method can be continued until the method can be slowly reduced in density to let corals slowly adapt.

7.3 Tiles high on beaches might reduce beach values

The tiles would build up as a new form of very white jetsam on some beaches and take time to crumble into fine sand. Some people might view this as pollution. Machines or low cost labor could groom the beach by picking up tiles to relaunch them on the sea.

7.4 Tiles on beaches may harm beach life

Tiles on beaches may be designed to slowly leach sodium oxide and form lye with rain water as they crumble into fine sand. Close to each tile, the lye may be concentrated enough to harm beach organisms.

7.5 Fish might eat so many tiles that they suffer adverse effects

The affected fish may adapt and stop eating the tiles.

7.6 Tiles on a beach might blow in wind

The tiles should be made high enough density and suitable shapes to prevent blowing in a common wind after washing up on a beach.

7.7 Mining sand and alkaline/nutrient rocks

Mining on land may cause local pollution and CO_2 emissions.

VIII. CONCLUSION

Considering potential benefits of reducing tropical cyclone damage, removing atmospheric CO_2, and reducing Earth's energy imbalance, the proposed method deserves further investigation. The next steps are to determine how high a tile must float above the sea water surface to not grow seaweed on top and how high it must start to not be pulled below that level by weight of growth over the target lifetime; then determine the windage of this design. Experiments should be conducted to determine likely optimal tile density, thickness, alkalizer/nutrient type and and grain size, then determine extent of toxic effects, and show that the tiles last a cost-effective duration and are not made ineffective by organic growth. Nutrient concentration and pH in ocean water around floating prototype tiles should be measured to estimate amounts of CO_2 that will be absorbed from the atmosphere. Effects of tiles should be modeled to estimate minimum numbers to obtain adequately scaled benefits. Ways of making and deploying tiles should be investigated and projected costs tallied for cost-benefit analysis assuming a factory large enough to obtain economies of scale. The National Academies report (NASEM 2021) provides a detailed recommendation for further research on nutrient fertilization and alkalinity enhancement and urges mesoscale experiments as the next step (NASEM 2021). The use of floating reflective glass foam tiles to deliver the nutrients and alkalizers should be incorporated into those experiments.

Authors' contributions: All JTH except JMN contributed to estimate of windage and half life of floating tiles

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