# OCEAN FERTILISATION STRATEGIES

Ocean fertilisation has been identified as one of the few methods by which catastrophic global warming and ocean acidification may be averted. There is one proposal that involves the novel concept of using buoyant, long-lasting flakes to deliver lacking nutrients to potentially productive surface waters. The fertiliser flakes would be made sustainably and at low cost from natural and waste materials. On a global scale, this system has the potential to biosequester six to thirteen gigatonnes of carbon per year on a long-term basis. The concentration of ocean biomass, as measured by chlorophyll concentration, could be increased by as much as 2–25 times through fertilisation. As marine catch now removes most adults of desirable species above anchovy size, it may be reasonably claimed that ocean fertilisation could increase sustainable marine catch by as much as fourfold. A related multifaceted benefit would be the reduction in extreme weather events resulting from the cooling of the ocean surface by albedo increases caused by increased phytoplankton concentrations and marine cloud brightening resulting from phytoplankton emissions. The flake fertilisation method has the potential to restore oceanic and atmospheric carbon levels to pre-industrial ones. It could also provide time for a managed transition to a low-carbon economy and stimulate global economic development.

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## INTRODUCTION

Ocean fertilisation has been identified as one of the few methods by which catastrophic global warming and ocean acidification may be averted. Although ocean trials by reputable scientific groups have produced moderately hopeful outcomes, none have yet delivered results that are both sustainable and commercially viable. Whilst no single strategy is applicable to all oceanic areas, there is one proposal that appears applicable to most, as it may be tailored to suit each one. This strategy involves the novel concept of using buoyant, long-lasting flakes to deliver lacking nutrients to productive surface waters. The fertiliser flakes would be made sustainably at low cost from natural and waste materials. The flake materials containing the nutrients would be nearly insoluble and would release the nutrients slowly over a year, unlike fertilisers used previously which required almost fortnightly renewal and most of which were lost to the depths as they sank before they could be utilised. Through ultra-slow-release, balanced marine ecosystems would develop rather than go through booms followed by all-killing busts or toxicity. According to independent researcher, Sev Clarke, on a global scale this system has the potential to biosequester six to thirteen gigatonnes of carbon per year on a long-term basis.

## THE FLAKES

Each flake would become a tiny marine farm made from a single rice husk, coated in a mixture of lignin & ricewater glue, nutrient mineral dust and leavening agent, then baked. Each buoyant flake would act as a nutrient-laden life-raft and habitat for its tiny inhabitants—green phytoplankton. The flakes would be blown from tubes in ships’ holds into the air to cover ~0.2 per cent of the nutrient-deficient ocean surface (roughly half the world ocean). The nutrient minerals would be made from low-grade natural or waste sources and contain phosphate, iron (Fe), silica, selenium (necessary for photosynthesis) and missing trace transition and other elements. Nitrogenous nutrient would be provided by flake-nutriated, buoyant blue-green algae (cyanobacteria) that convert nitrogen from the air into reactive nitrogen. Gigatonnes of near-perfect fertiliser mix are available from the phosphatic clay waste piles in Florida and other sources of non-commercial phosphate, iron and silica.

Flakes would be distributed over nutrient-deficient ocean areas causing ecologically balanced communities of phytoplankton (diatoms and microalgae) and marine organisms above them in the food chain to increase many-fold. Such an increase in marine biomass would transform acidifying carbon dioxide into neutral biomass and oxygen. Furthermore, when marine organisms excrete or die part of their carbonaceous material sinks towards the seabed where, if conditions are propitious, portions are either biosequestered in deep-ocean sediments or are otherwise removed from the terrestrial biosphere for countless years. The de-acidifying effects of these processes are magnified whenever:

* The ocean depths are cold and low enough in oxygen to hinder bacterial degradation of the sunken biomass.
* The rate of descent of the sinking biomass is fast, as is the case with dense aggregates of diatoms and the bodies and excrement of some larger marine species.
* The components of the fertiliser used are tailored to match the specific nutrient deficiencies known to occur down-current or down-wind from the site of buoyant fertiliser dissemination.

The chosen fertiliser-carrier mix would be designed to meet strict requirements of international agreements on ocean fertilisation research and usage (see <http://iospress.metapress.com>). The buoyant fertiliser carrier would comprise rice husks (hulls) with the triple benefit of being:

* A plentiful, benign and naturally occurring waste product.
* Light yet durable.
* High in hydrated silica that diatoms require to make their dense yet porous skeletons (frustules). This would help as ocean areas remote from land are typically nearly as deficient in silica as they are in iron nutrients.

Minerals are added to the oceans by coastal erosion, runoff, upwelling, dust storms, volcanoes, meteoric dust and human activity. However, most are lost to the sunlit biosphere as they sink rapidly. Moreover, massive amounts of iron and phosphorus in the form of fish catch have been, and are being, removed from the oceans by humans and seabirds. This remedial concept has been developed to replace those lost minerals, thereby rendering the oceans more productive and enabling their sediments and deep waters to be a more substantial carbon sink. Eventually, these sediments would typically be transformed into new limestone and fossil fuel deposits.

The buoyant flake method could provide a substantial business opportunities based on carbon credits and additional fish catch. Given the assiduous application of the flake, it is conceivable that the delayed dynamic of transitioning to a sustainable world could accelerate. The chief current roadblocks are vested interests and economics fighting the reduction of fossil fuel emissions. Calculations show that, in combination with other cooling and mitigation methods, if sufficient flakes were disseminated yearly, the total emissions of anthropogenic carbon dioxide might progressively be safely sequestered. The end-state would be reached when the pH of the oceans is restored to pre-industrial levels and a basis established for comfortable transitioning to a low-carbon economy. Each tonne of iron in the flakes could theoretically produce around 1,000 tonnes of algae or 29,000 tonnes of harvestable, dry weight fish. In practice, carbon sequestration and other losses might reduce these last two figures by ~tenfold. Under colonisation by phytoplankton and their tiny predators, each sunlit flake would form a miniature green habitat, farm or nursery that would anchor or shelter eggs, larvae and organisms, feed and provide mates for its resident ecology and a rich hunting ground for larger species. Undesirable eutrophication (bloom, mass die-off and oxygen depletion) would be inhibited by the ultra-slow-release of the fertiliser and the predation this allows.

In addition to the benefits discussed above, multi-component fertiliser released from buoyant flakes produces other desirable results. First, unlike the highly-soluble commercial fertilisers already tested, little is wasted to the dark depths as virtually all is released in the top several centimetres of best-illuminated, and hence most potentially productive, waters. Second, because of the high illumination and partial interruption of sunlight to the depths caused by the presence of sunlight absorbing flakes and extra plankton in surface waters, the growing season would be extended in polar waters, more carbon dioxide would be converted into biomass and there would be more fish stocks than otherwise. It is estimated that after about fifteen years of full operation, the reductive effect of these on global temperatures would substantially offset global warming. Concomitant biosequestration of carbon would progressively reverse ocean acidification in surface waters, then in the atmosphere and intermediate waters. Fertiliser flakes and nutriated plumes of phytoplankton are readily tracked and managed. Once the science has been validated and licences for trials approved under international scientific surveillance, business would do the rest, as it would be profitable to do so. No other method of reversing ocean acidification is thought to be as achievable, rapidly effective, sure, safe, sustainable, beneficial, politically acceptable and indeed profitable as is this concept.

## *Impact Statement*

There would be eight expected major net beneficial impacts and one possible partly-deleterious one. The beneficial effects include:

1. Progressive ocean de-acidification, commencing with a reduction in the rate of business-as-usual acidification.
2. Rapid reduction in overall greenhouse gas pollution and a progressive return to a more favourable atmospheric make-up.
3. Increase in the carbon flux to the middle and deep-ocean depths with consequential carbon sequestration of 6–13Gt C per year.
4. Net increase in marine biomass, fish catch and possibly biodiversity.
5. Increase in the albedo of fertilised oceanic plumes, marine clouds and natural atmospheric aerosols.
6. Increase in phytoplanktonic DMS production leading to an increase in ice particle and rain nucleation, marine cloud brightening and DMS breakdown into recycling atmospheric aerosols. This enhances Nature’s method of Gaian temperature control.
7. Halting and gradual reduction in both the number and intensity of BAU (business-as-usual) extreme weather events, including a possible rollback of desertification.
8. A slowing of the increase, followed by halting and eventually reversal, of global warming and sea level rise.

A possibly deleterious impact may be increased hypoxia (low oxygen) in the deep-ocean and sediments. However, hypoxia and additional food supplies benefit some life-forms and may indeed be needed to ensure the more secure and permanent biosequestration of carbon.

## POTENTIAL BENEFITS

A sustained ecology of enhanced marine life at the sunlit surface would provide several benefits, at least two of which should have commercial potential. Ocean trials have shown that the concentration of ocean biomass as measured by chlorophyll concentration could be increased by as much as 2–25 times through fertilisation. As marine catch now removes most adults of desirable species at or above krill or anchovy size, it may be reasonably claimed that ocean fertilisation could increase sustainable marine catch by as much as fourfold. Royalty streams are already being claimed in some jurisdictional waters for catches. By international treaty, similar revenues might be claimed from fertilised and managed plumes in the high seas. By amendment to a current international treaty, a second revenue stream may be garnered from carbon credits resulting from proven oceanic carbon biosequestration as a result of marine biomass sinking below a kilometre in depth, where its carbon would typically remain for hundreds of years. This biosequestration would generate oxygen and remove carbon dioxide (CO2) as neutral biomass from both the atmosphere and surface waters, which would then become less acidic and more productive. Removing carbon dioxide from the atmosphere would also reduce its greenhouse warming effect.

The other benefits of ocean fertilisation would also be substantial. The one most immediately noticeable to science would be the globally cooling effect of fertilised ocean surface waters with the increase in the albedo (reflectivity) of the green chlorophyll in phytoplankton versus the otherwise dark blue deep-sea, as well as marine cloud brightening effect caused by additional natural chemicals released into the atmosphere by the same phytoplankton that cause cloud nucleation. Both effects would reflect solar radiation from the planet, thereby reducing global warming. A related multifaceted benefit would be the reduction in extreme weather events caused by the cooling of surface ocean currents. Earth systems modelling should show that this: reduces hurricane strength and frequency as well as the incidences of major floods, heatwaves and droughts, stabilises polar vortices, reclaims polar sea ice cover and decreases polar methane emissions.

**Average Chlorophyll 1998–2006**



Green=High biological activity. Blue, orange and grey=Low

## Source: SeaWIFS Project/NASA GSFC and GeoEye, online at <http://seawifs.gsfc.nasa.gov>

## RISK

Both environmental and financial risk may be minimised by cautious and conditional phasing. The validity of the basic science, engineering and logistics could be reviewed, refined and work-shopped by people with the relevant expertise. Laboratory experimentation could at first validate some of the methods to be used and their likely effectiveness. Earth systems modelling could identify the likely results of trialling the system at any site and on any scale. Starting small enough not to require international approval with transparent trials in jurisdictional waters, these could later be carried out in the open sea under international scientific monitoring at increasing scale to establish validity and effectiveness and identify results both expected and unforeseen. From refinements to these proposed methods, together with current and forecast environmental threat levels, plans, collaborations, ventures, financing, marketing, collective action and licensing could be reliably framed.

## COST BY PHASE

As with all risk assessments, costs should follow a cautiously staged approach. The table below provides a preliminary estimate regarding their likely magnitude.

|  |  |  |
| --- | --- | --- |
| **Phase** | **Cost** | **Comments** |
| Document vetting/refinement | Absorbed+ | Academic papers published |
| Laboratory experimentation | $250k | Flakes/marine organisms in tanks |
| Modelling – albedo change | $70k | Determines immediate cooling effect |
| Modelling – ocean biogeochemistry | $400k | Forecasts the effects of flake fertilisation on ocean ecologies |
| Small sea trials | $5–10m | Proves effectiveness and safety |
| International negotiation and conditional approvals | Unknown | ~2016. Costs mainly borne by government-funded bodies |
| Demo flake factory construction | $12m | May take 15 months in ideal site |
| Sea trial up-scaling and analyses | $180m | Could take about 22 months |
| Industrial logistics/licensing development/integration/markets | Investment by industry | Progressive |
| Progressive global rollout | TBA | Progressive from ~2019 |
| Global effects monitored and improved by adjustment | QC paid for by industry/govt | Starts with regional oceanic measurements in ~2020 |

## Global Deployment Parameters and Potential Benefits

|  |  |  |
| --- | --- | --- |
| **Item** | **Amount** | **Comments** |
| Weight of flake disseminated | 191Mt/yr | Uses benign and waste materials |
| Cost of flake on water | $84–100/tonne | Chinese versus American flake costs |
| Cost of flake + dissemination | ~$17.6b/yr | Excludes other costs such as scientific monitoring and policing |
| Sequestration cost/tonne C | ~$11 | Range $1.08-20/t C |
|  |  |  |
| **Net Benefits:** |  |  |
| Global albedo change | -1.7W/m2 | Offsets total current greenhouse gas warming provided tipping points are avoided |
| Biosequestration | 6–13Gt C/yr | ~Offsets yearly CO2 emissions |
| De-acidification | >22Gt CO2/yr | Removed/yr from air and sea surface |
| Sustainable marine catch | Up ~fourfold | To be confirmed by modelling/trials |
|  |  |  |
| Profitability | Positive | Industry will pay for it voluntarily, once trials indicate likely success |
| Downside/Upside | TBD | Benthic hypoxia/Extends biosequestration |

## STRATEGIES FOR DIFFERENT OCEANS

The overall objective is to develop ways by which nutrient-deficient areas of global oceans could be made to offset global warming, extreme weather events and ocean acidification. However different strategies would be required at different locations. This aspect has been indirectly supported by RS Lampitt, *et al* (“Ocean Fertilisation: A Potential Means of Geoengineering”, *Philosophical Transactions of the Royal Society A*, vol366, no1882, 13 November 2008, online at <http://rsta.royalsocietypublishing.org>). CM Moore, *et al* (“Processes and Patterns of Oceanic Nutrient Limitation”, *Nature Geoscience*, vol6, no9, 2013, online at <http://www.nature.com>) provide information on the chemical elements required by marine biomass that are likely to be limiting in a variety of ocean and seasonal environments and hence give evidence for the selections made from the following strategies. Prospective methods, most of which come under these different strategies, may include the following.

**First:** the phosphate-rich but iron and silica deficient areas of global oceans south of 420 South together with some Arctic and sub-Arctic waters could be addressed with buoyant flakes carrying ultra-slow-release iron and silica minerals to generate albedo increase, marine biomass and carbon biosequestration.

**Second:** the highly stratified and nutrient impoverished seas of the Caribbean and many tropical waters may be addressed using flakes bearing a mix of nutrients, chief of which would be phosphate wastes from Florida, Morocco or Australia as well as iron, silica and trace elements. Whilst this provision should help transport dissolved inorganic carbon deeper into the highly stratified sea by the oceanic carbon pump, its main functions would be to generate increased albedo (reflectiveness) of both the ocean surface and of the marine clouds above it, to generate additional marine biomass and to help reduce ocean acidification, ocean surface temperature and consequently hurricane strength.

**Third:** some favourable tropical locations where frigid currents run beneath the surface may use ocean thermal energy conversion (OTEC) pumping mechanisms to generate power, potable water and uplifted nutrient-rich waters needed to fertilise mariculture operations, including those of kelp, mollusc and fish farming.

**Fourth:** the temperature/nutrient/salinity stratified waters of the Gulf of Mexico with their excessively-nutriated benthic waters from the Mississippi and often impoverished surface waters, together with other oceans where needed nutrients are found in deeper water, would be probably best addressed by wave or wind powered pumping mechanisms. These would bring nutrients to the nutrient-deficient surface where they could be used by phytoplankton and in cultivated macrophyta (kelp and sargassum) forests. The process would also cool the warm surface water by mixing it with cooler water from the depths and by increased solar reflection.

**Fifth:** fertilising polar waters with buoyant flakes that include in the fertiliser mix minerals containing tungsten, cobalt, nickel and molybdenum and possibly gypsum (calcium sulphate) together with seed methanotrophs (methane eaters) could play a vital part in converting huge and potentially catastrophic methane emissions into less-hazardous carbon dioxide which may itself then be converted into neutral biomass by nutriated phytoplankton.

**Sixth:** temperate oceans would each need to be treated differently with flakes depending on the mix of the nutrient concentrations already in their water columns and what could be used near the surface by phytoplankton and macrophyta.

**Seventh:** productive ocean areas, coral reefs, seagrass meadows and most inshore waters should typically not be treated at all except conceivably when there are seasonal or otherwise temporary nutrient deficiencies that may be beneficially offset by the use of nutritive flakes.

In many ocean regions, different combinations of the above methods would be optimal. With further study, modelling, experimentation, refinement and quantification, as well as good will, implementing the buoyant flake concept globally should help avoid the more intransigent roadblocks to successful climate and ocean restoration provided we act expeditiously and do not pass too many critical tipping points. Whilst the equations that build the case for any one particular solution are important, it is equally important to get right the parameters to be input to the equations. These would be best confirmed by experiment and modelling, followed by approved, transparent and cautiously scaled-up trials.

## THE CARIBBEAN EXPERIMENT

Whilst climate intervention operations in the Southern Ocean indicate the most promise, these are costly to undertake—more modest approaches would be preferred initially. The easiest environmental problem to address may well be that of testing whether a small amount of buoyant flakes carrying a phosphate and iron-rich fertiliser mix, and possibly some seed organisms, is capable of causing a substantial increment in ocean surface albedo for an extended period in the oligotrophic (unproductive) and highly stratified surface waters of the Caribbean or Central Atlantic and Pacific. This could be twinned with an assessment of what additional marine biomass is produced and how much it reduces surface ocean acidification when done intensively and for an extended period, whilst realising that the more the dissolved inorganic carbon is removed from the ocean surface waters, the more would be absorbed from the atmosphere. Mesocosm trials (typically in large, transparent, vertical tubes set in the ocean) could determine these effects. It has been estimated that the modest change effected in oceanic albedo may on its own be enough to offset current anthropogenic warming.

While the albedo experiment might not attract industry investment, it could well attract philanthropic and government attention and funding, particularly if it is performed in the Caribbean areas exposed to hurricanes. A secondary outcome of likely interest to both industry and governments would be the potential increase in marine catch and royalties from jurisdictional seas. Three good things about this approach are that initial scientific trials may be small enough not to require international approval, the flakes may be formulated to make up what is deficient at each test site (nitrates excluded) and it would be best if the experiments were not conducted in the remote, dangerous and season-limited Southern Ocean waters. The initial experiment could be conducted over as little as ten hectares of ocean surface using less than two tonnes of flakes most of which would consist of benign rice husks and lignin.

A suitable fertiliser mix for the Caribbean purpose might be formulated mainly from phosphatic clay slimes and sandy wastes, particularly at the silty end of the sand–silt grain size spectrum left over from Florida’s phosphate fertiliser processing operations. These wastes include substantial amounts of calcium, iron and silica. To these might be added some finely ground ores containing manganese, cobalt, copper, zinc, nickel and cadmium, which are the other six micronutrients most likely to become limiting (in roughly that order) in Caribbean surface waters. As iron, molybdenum, nickel and cobalt are required for nitrogen fixation, the nutrient mix adhered to the flake by thermoplastic lignin glue should also include an ore containing molybdenum, in case this becomes limiting following a major increase in the diazotroph (nitrogen fixing cyanobacteria) concentration in surface waters following flake fertilisation. The overburden and country rock wastes associated with Floridian phosphate deposits frequently contain significant concentrations of useful trace metals and metalloids, such as iron, cadmium, copper, molybdenum, nickel and zinc, as well as those with an appreciable phosphorus content. Although not all these ores would be in a finely divided state, many should still prove to be useful and economical components to include in the flake fertiliser mix. Small experiments in different parts of the Caribbean should be able to determine which mineral mix and concentration is most effective at each location.

There should be enough husk, lignin and waste mineral produced or available each year to fertilise all deficient ocean areas for many years, once the production of lignin and sugars from straw and wood chips ramp up to meet other developing markets. Although this particular use of flake fertiliser would require higher concentrations of flakes on the sea surface than those simply intended to add missing iron and silica, the method still appears economically viable, particularly as oceanic recycling processes would tend to make the additions somewhat cumulative. As the main macronutrient supplement phosphate could be released over a shorter period than a year, the husks used in the Caribbean would not need to be as durable or as siliceous as rice husks. Hence, North American grain husks of wheat, barley and oats might suffice and the lignin could be derived from their straw. Thus, the Mississippi River, the Midwest and Great Plains grain belts, New Orleans, Tampa and Florida’s phosphatic clay wastes could be used.

The cost of the American made flakes delivered to Caribbean waters would be approximately $100/tonne or a little more than the cost of Chinese flakes delivered to Southern Ocean waters estimated at approximately $84/tonne. A tonne of American flakes would carry the equivalent of 22 kilograms of P2O5 or approximately 10 kilograms of phosphorus, together with other phytoplankton-useful components of phosphatic clay wastes that include silica/silicates, calcium, iron, potassium and selenium. The husks would also include an amount of opaline silica, useful to diatoms. If useful to the nutrients being disseminated, a minor additional amount of potash (~KCl) and seed amounts of microorganisms such as diazotrophs, diatoms and microalgae might be added or disseminated concurrently. Allowances for these additions are included in the cost. According to *Wikipedia*, the *Trichodesmium* species of diazotrophs is the only known one able to fix nitrogen in daylight under aerobic conditions without the use of heterocyst cells needed by all other filamentous nitrogen-fixing cyanobacteria. *Trichodesmium* and other diazotrophs provide nitrogenous nutrients that support complex microenvironments and other species up the food chain. As filamentous diazotrophs possess gas vesicles, they would probable remain in close proximity to the buoyant flakes and thereby be in a good location preferentially to access the slowly dissolving phosphate, iron and trace elements. The minor amounts of radioactive minerals that these particular phosphatic wastes contain is not expected to cause a major problem, as they are not substantial and most would sink to the ocean floor and be buried. The source phosphate rock for the wastes would itself have been originally deposited from organisms inhabiting an earlier shallow ocean. That is one reason why the mineral balance in them is so ideal for use as an oceanic fertiliser.

A preliminary estimation of financial viability of the method is desirable. Using the mineral ratio of phosphorus found in the edible parts of autumn herring (0.25 per cent) as representing all marine biomass, it has been calculated that from each tonne of flake disseminated approximately four tonnes of additional marine biomass would be potentially generated. Allowing 80 per cent for losses and taking the average price received by Norwegian fisheries in 2012–13 for their herring at $1,040/tonne, this could mean that an investment of $100 in flake dissemination could generate an additional $832 worth of marine catch. Even after taking out the cost of harvesting, monitoring, royalties and overheads, this would be a viable business provided that the fertilising agency could garner part of the additional catch benefit. Ocean surface de-acidification and carbon sequestration caused mainly by lignin sedimentation and dissolved inorganic carbon transportation downwards, might provide additional modelled benefits, although these may be difficult to monetise. Regarding approvals, small-scale and transparent scientific trials have been already encouraged by reputable scientific and ocean governing treaties. Moreover, the trials would be below thresholds requiring international approval. Should these trials confirm by practice and modelling that when extended to global nutrient deficient waters the techniques have a significant global cooling effect, then once the costs have been estimated and optimal logistics established, a solid basis for seeking scientific, industrial, governmental and public support for progressively wider deployment would need to be developed. These might be initiated by several of the island governments individually, or perhaps preferably, in concert with other nations under international scientific supervision.

Garnering public support for later-stage and larger trials may not be as nearly impossible as it seems. First, no nation would be asked to bear the costs, as industry would do it for profit under international scientific modelling and scrutiny. Second, the trials could start well below mesoscale level, be conducted in jurisdictional waters, and meet the London Convention/London Protocol requirements as interpreted by each trialling nation. Lastly, by then all nations may well be experiencing even more severe fallouts from global warming. The intellectual property for the buoyant flake concept is offered free. Following limited trials, industrial partners could proceed with developing options, business cases and strategies for successively navigating the remaining roadblocks. Together, they could investigate the viability or otherwise of ocean carbon credits, plume royalties, marine cloud brightening, ocean de-acidification, extreme weather moderation and global warming reversal within fifteen years—all measured against progressive targets set by sophisticated Earth system models.

## THE SOUTHERN OCEAN EXPERIMENT

Results from the Caribbean and other experiments could inform Southern Ocean and Arctic trial planning.

## *The Business and Environmental Case*

Until the concept receives confirmation of its essential validity from reputable scientific authorities, one cannot be sure of its viability. However, even prior to that, an estimation of its potential to address global warming, ocean acidification, food security and the costs and timelines of doing so would be required. The estimates below have been made with the best information at hand. The figures are bound change markedly as more work is done on their validation and modelling. Hence, their correctness cannot be guaranteed. As about 40 per cent of the global surface ocean water is recognised as suffering from major nutrient deficiency at any one time, it may be assumed that one-third of the ocean surface area would be fertilised yearly with buoyant, slow-release flakes incorporating the missing nutrients, nitrogenous ones excluded. Part of the other two-thirds may be given supplementary fertilisation for part of the year, as runoff and pollution already fertilises much of it by other means. In these places, any flake addition would typically be at a reduced density and using less durable flakes. At a surface coverage proportion of 0.2 per cent flake, average flake thickness 1mm, average flake density 0.8t/m3, with 71 per cent of the world’s surface being ocean and global surface area of 510m km2, the calculation for the estimated weight of flake required each year is:

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| --- |
| 510m km2 x 106m2/km2 x 0.71 x 0.33 x 0.002 x 0.001m x 0.8t/m3 = 191Mt flake/yr |

As many of the flake nutrients absorbed by the biosphere would remain in the marine biosphere for periods considerably longer than a year, under this scenario the cumulative levels of ocean nutrients would build up and thereby at some point allow for the density of fertiliser application to be reduced without markedly affecting annual benefits. According to the related document “Costing Flake Fertiliser Production, Distribution and Revenue Potential” (online at <http://envisionation.co.uk>), the expected marginal cost of disseminated Shanghai flakes, once full production has been achieved and most Experience Curve savings made, is estimated at $84/tonne. Such flakes are expected to biosequester carbon in the ocean depths and sediments for a cost of $1.08/t C, although perhaps increasing the conservative estimate for this by tenfold to $11/t C would be prudent, in part because many ocean areas do not lend themselves to long-term carbon biosequestration. Revenue from such biosequestration would depend upon the world agreeing to offer carbon credits for the activity. The credits allowed may need to be considerably more than the cost to allow for scientific monitoring, capital servicing, risk, overheads, other costs and profit margins. They might thus average as high as $20/t C in June 2014 dollars. This cost is far below that of most other known industrial-scale methods.

Flake distribution is also expected to generate revenue from fishing royalties. Whilst those in jurisdictional waters may be readily garnered provided the necessary policing occurs, royalties from moving fertilised plumes of water in the high seas would require a widely accepted international treaty/convention or substantial modifications to existing ones. Given this, revenue from additional and sustainable marine catch is expected to be in the vicinity of $1,040/tonne of flake fertiliser disseminated. The gross margin from this activity would be reduced by allowances for by-catch, on-vessel processing discards, royalty payments, monitoring and other costs. However, as we noted earlier some expected environmental benefits resulting from flake fertilisation are unlikely to be monetisable. These include changing business-as-usual effects to increase global albedo, reducing ocean acidification, reducing the frequency and severity of extreme weather events, and eventually reducing and then reversing sea level rise. Flake dissemination is also expected to benefit biodiversity by increasing the food supply to marine life and by expanding the area where intensive primary production occurs. However, these contentions need to be supported by modelling studies and measurement. Likewise, the activity’s effect of possibly increasing benthic hypoxia needs to be assessed by modelling, including that of the likely positive effects on increasing the supply of food to deep-ocean life as well as of increasing carbon biosequestration’s half life.

The albedo effect resulting from flake fertilisation has two main causes—the increment in ocean surface albedo as a result of the increased phytoplankton concentration and the increment in marine cloud cover and brightness resulting from the additional DMSP/DMS (dimethylsulphide propionate/dimethylsulphide) emissions released from some of the phytoplankton that nucleate clouds. The effect of flake nutriation upon the 40 per cent of the ocean surface that is nutrient-deprived is estimated at roughly 1.5 times that of current anthropogenic forcing of ~1.7W/m2 or 2.6W/m2. However, as other means besides, or together with, flake fertilisation are proposed for two-thirds of the ocean, this would result in a 2.1W/m2 reduction for the surface water albedo and a 0.2W/m2 reduction for marine cloud brightening, making a total contribution of 2.3W/m2. However, to be conservative, it is claimed that only the 1.7W/m2 of this represents complete offsetting of current anthropogenic forcing. Nonetheless, as future forcing is likely to be greater than current forcing, particularly if one or more tipping points are passed, this would have to be improved upon. Thus other methods for ocean fertilisation and albedo increase would be necessary as well.

The reduction in ocean acidification cannot be determined, amongst other reasons because of the effect of other factors such as future emissions. Instead, a ballpark estimation may be made of the carbon biosequestration that removes carbon dioxide from surface waters and the atmosphere resulting from global ocean flake usage. The proposed 191Mt of flakes to be disseminated per year would contain approximately 24Mt of iron or perhaps 6–12Mt with allowances for flakes containing high levels of phosphorus and other useful trace elements. Allowing biomass containing just five per cent of this iron or 0.3-0.6Mt to be sequestered as biomass (some of the biomass would later be transformed into dissolved inorganic carbon) below 1,000m depth means that, using a C:Fe ratio of 20,000:1, an additional 6Gt C (equals 22Gt of acidifying CO2) to 13Gt C would be biosequestered in the deep-ocean each year by the flakes. Current emissions approximate 8Gt C/yr and rising (Lampitt, *ibid*). Estimates of the amount by which flake fertilisation at this rate would mitigate extreme weather events and slow sea level rise is beyond the scope of this paper.

BIOLOGICAL CONTROL OF ARCTIC METHANE EMISSIONS

In the Arctic Ocean seabed, tundra and frozen methane clathrates, increasingly large clouds of methane bubbles have been observed ascending in pools and in seawater. If these cannot be contained or converted, they are likely to cause catastrophic global warming within the expected lifetime of our children. Reducing carbon dioxide and methane emissions dramatically would no longer be sufficient to prevent this from happening. The two best chances are either to have the issuing methane captured and converted into something more benign, or to cool the Arctic quickly. While both appear daunting tasks, they are feasible. This segment focuses on using biological means to convert the issuing methane into biomass. Methanotrophic (methane eating) bacteria do this using one of two metabolic pathways—aerobic or anaerobic. The aerobic route oxidises methane into methanol or formaldehyde that is then transformed into biomass. In the anaerobic route typically used by bacteria resident in ocean sediments, consortia of archaea and nitrite- or sulphate-reducing bacteria produce both biomass and carbon dioxide from methane (“Methanotroph”, *Wikipedia*, online at <https://en.wikipedia.org>). Both routes use enzymes that contain essential metal atoms that are typically in short supply in the area. The metals include tungsten (most importantly), copper, nickel, cobalt and molybdenum. Modelling and subsequent testing should be carried out to establish optimal parameters for buoyant flakes carrying slow-release minerals that provide a balanced “diet” of these essential metals to allow the methanotrophs to proliferate and consume most of the newly emitted methane before it reaches the atmosphere and causes excessive global warming. Where a targeted site does not contain sufficient sulphate for the sulphate reducing bacteria, cheap and plentiful calcium sulphate (gypsum) may be added to the powdered mineral mix. Biological solutions typically have three major advantages—they are a natural form of control, modulate themselves to the extent of the problem, and are usually both economical and fast acting.

Methanotrophs cannot metabolise methane when it is in frozen form in clathrates. Similarly, the methanotrophs in water, sediment or soil must be in intimate and preferably prolonged contact with gaseous or dissolved methane food sources to metabolise it effectively. This is not the case when the methane is given time to aggregate into large bubbles or issue directly into the atmosphere via vents, fissures or eruptions. It is therefore important that the metals be sufficiently available to methanotrophs both continuously and along the entire and diverse pathways of their emission and pre-atmospheric movement. Hence, the minerals should preferably permeate the entire water column (albeit at low concentration), be present in at least the upper layers of sediments and soils, coat the surface of fissures and vents, and lie on the sea ice, tundra or swamp surfaces ready to be elevated to a commanding position on the resulting water surface. The surface may be either that of the sea or of puddles, ponds, lakes and streams that form from rainfall or from thawing ice and permafrost. The minerals should be also economically distributed to all these environments. Small, benign and buoyant flakes do this best as they are readily disseminated pneumatically from ships or planes with acceptable evenness and cost to the most inaccessible areas.

As the flakes slowly release their mineral payloads into the water, dissolution, assimilation and mineral particle sinking take the needed enzymatic metals to where the methanotrophs are present and can metabolise them to proliferate enough to consume the varying amounts of emitted methane. Most of the nutrients from the flakes would presumably enter the biosphere where they would typically recycle many times before being buried deep in sediment. Evidently, some of the newly laid down organically-rich sediment would be re-metabolised into methane or carbon dioxide. However, this in turn would be readily converted back into biomass by the aforesaid processes. The flakes disseminated over the Arctic Ocean may also incorporate other lacking nutrients necessary for the growth of phytoplankton such as iron, phosphate and silica. These would have the additional benefit of cooling the Arctic by increasing its albedo (reflectiveness) by ocean surface and marine cloud brightening. The increase in phytoplankton concentrations may be necessary to ensure any additional carbon dioxide resulting from predation upon the methanotrophs or other causes of methane oxidation is also converted into benign biomass.

ORGANIC MARICULTURE AND BIOSEQUESTRATION

**Phytoplankton: The most Important Organisms on the Planet**



Source: Photograph from <http://seahack.org>

Phytoplankton are responsible for 50–70 per cent of the oxygen in our atmosphere and are the greatest natural carbon dioxide capturing system available. Unfortunately, human pillaging of the seas has greatly reduced the level of nutrient supplies that were in the oceans as little as 300 years ago, with the result that phytoplankton and fish numbers are a fraction of what they once were. The necessity to replace nutrients on land to maintain the fertility of fields was learned long ago. This lesson is also true of the seas. Ocean fertilisation could cause increases in phytoplankton concentration but to date the effects of direct fertilisation have been transitory due to delivered nutrients sinking too quickly through the water column. The flake fertilisation method has the potential to restore oceanic and atmospheric carbon levels to preindustrial ones. It could also provide time for a managed transition to a low-carbon economy, provide jobs and stimulate global economic development. In short, when properly researched, developed and implemented it may represent humanity’s bridge to the future. The need for such a technology is urgent as rapidly increasing atmospheric carbon dioxide levels, ocean acidification and recent scientific commentary suggest that we may be close to, at or even past a global tipping point. By any standard, a failure to remedy this situation poses an unacceptable global risk.

If this method to restore oceans and atmosphere by using buoyant flakes carrying tailored fertiliser mixes were proven to be reasonably safe, timely and cost-effective, it could potentially change the entire dynamic of international negotiations regarding climate change and ocean acidification. Once validated, the method promises the capability of sequestering sufficient carbon to reduce atmospheric carbon dioxide to acceptable levels at an estimated average cost of $11 per tonne of carbon sequestered. Moreover, revenue streams could be engineered to make this a profitable enterprise for industry and government. The implication for the global carbon budget is a way to repay the deficit and make a smoother transition to a sustainable energy economy without the risk of economic collapse. Beyond being a potential global game changer, ocean flake fertilisation could present one of the most significant industrial opportunities of all time, just as agriculture was on land.

## CONCLUSION

Ocean fertilisation holds the best prospect for the restoration of our planet. It requires knowledge and skills that we urgently need to develop. Initial studies may be small-scale, but as these and the knowledge base grow, so too would the need for modelling and monitoring. Efforts to secure international agreement over the management of oceans have become ever more vital. Given that the threat of global warming and mass extinction is real and otherwise imminent, it is hard to see how anybody could responsibly hinder the testing and validation of this technology. Moreover, given that the prospective profitability of the global venture is great, while risks are comparatively modest and typically manageable, and downsides are relatively small compared to the upside benefits with testing well-phased and transparent, governance and policing strong, substantive investment costs borne by industry for likely profit and benefits being equitably distributed, it is hard to see organisations and communities wishing to deny others the net benefit of participation in this international endeavour.