#  ORGANIC MARICULTURE AND BIOSEQUESTRATION

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## INTRODUCTION

This document describes a concept and technologies designed to reverse global warming and ocean acidification, to improve global food supplies profitably, and to sequester carbon dioxide as carbonaceous solids in deep, sea sediments for long periods by simply enhancing naturally occurring processes. The concept may also be called Diatomic BioSequestration (DBS), as it is chiefly the photosynthetic microorganisms called diatoms that do the work.

The concept is relevant to industrial strategy for two reasons. First, its successful development would transform the iron-rich, ‘red mud’ tailings wastes from alumina refining operations, and from otherwise uneconomic mineral deposits, into valuable resources. Second, it would provide companies owning such minerals with sustainable earnings from new customers that use fertilisers produced in low-cost processes to produce marine food and carbon credits.

You may have heard how the ancient, South American Indians used organic farming methods and biochar (charcoal) to turn their infertile soils into some of the most productive ones on Earth. These black soils still exist and are called ‘terra preta’. By making their land fertile this way, the Indians also happened to sequester large amounts of carbon dioxide in the soil as solid biochar. Tests have shown that, whilst vegetable and animal matter tends to last only a few years in the soil before it is converted into new living matter, methane, or carbon dioxide, biochar that results from the conversion of organic into inorganic matter can remain there safely for thousands of years. Moreover, its presence has many other beneficial effects, including retaining water and nutrients, making the soil more friable, reducing erosion, providing habitats for worms and for the microbes that replenish available nitrogen in the soil.

Similar beneficial effects can result from fertilising the surface waters of nutrient-deficient oceans with iron and possibly with other, somewhat-less-essential nutrients that are lacking there. Provided this is done carefully, just as farmers take care not to add too much fertiliser, much good can result. The DBS concept details how cheap, plentiful, and natural materials, such as rock waste and rice husks, can be made to provide low-risk, low-cost ocean fertilisation. Although low-grade, iron-rich rock particles are very nearly insoluble in water, they are not quite insoluble, particularly when roots or microorganisms assist in the dissolution process. Thus, rock particles containing some of the key but absent nutrients, when attached to buoyant rice husks, can increase ocean biomass or living matter dramatically. Without this supplementation, the diatom and fish population there will be much less than could otherwise be supported. We desperately need a share of this sustainable food source and to reduce carbon dioxide levels.

Now, fish and microorganisms also provide the planet with vital, additional services: their excrement and dead bodies tend to sink, taking with them carbonaceous material. Some of this material ends up being sequestered in the deep ocean sediments, where it no longer contributes to global warming or the harmful acidification of the seas.

Many experiments over the past decades have confirmed that life flourishes when nutrient-deficient ocean areas are fertilised. However, it has now been shown by the Alfred Wegener Institute for Polar and Marine Research (see <http://www.sciencedaily.com/releases/2012/07/120718131744.htm>) that substantial amounts of carbonaceous material are indeed transported to the deep ocean by iron fertilization. The indications are, that it would then be stored in the underlying seafloor sediments for time scales of well over a century, sometimes millions of years.

This paper explains how these benefits might profitably be achieved within several years. The first part is written for lay people and the second for scientists, engineers and business analysts. The third part explains the reasoning behind the choices made, provides additional technical material, and suggests future development options.

## NON-TECHNICAL DESCRIPTION

The scientific experiments in this area have typically used commercial, chemical fertiliser. This is good for the scientists, as it provides a precise amount of a single nutrient and quick results. However, it is not appropriate for industrial use for several reasons. First, commercial fertilisers are too costly and usually require too much fossil fuel for their production. Second, they typically require the mining of high-grade and depleting ore bodies, for which we have better uses. Third, they release all their fertilising power at once, when what is required is slow release over many months. Fourth, both highly soluble fertilisers and granular mineral material, even fine dust, tend to sink, be carried by currents or eddies, or diffuse fairly rapidly away from sunlit surface waters where they can be of most use. By these means, much of their nutrient value becomes no longer available to the photosynthesising diatom and algal populations that require sunlight. And fifth, the soluble sulphate fertiliser commonly used has a malign effect in certain circumstances, see later. Modifications are therefore required to make a good industrial solution.

That solution combines three innovations. First, like the material in the dust storms that periodically fertilise the oceans with iron, a fertiliser can be made from mixed, ground-up, low-grade ores, from processing wastes, or from vast deposits that are unlikely, in the foreseeable future, to be economical to refine. Second, this material can be stuck onto tiny floating platforms made from abundant, but nearly worthless, organic material: rice husks. Third, the particles of mineral fertiliser can be glued onto the husks by the most abundant, renewable, cheap and durable glue that there is on Earth: lignin from plants. When distributed in an ocean gyre (a slowly moving, rotating eddy in the sea that typically covers millions of hectares), plume or area of ocean, these husk-based fertiliser flakes provide both an ultra-slow-release mechanism for the nutrients and tiny vessels on which, together with dissolved carbon dioxide, diatoms and algae can feed and grow, thereby converting sunlight into food.

When scattered over the sea surface, each flake becomes a tiny, green, floating farm. The green algae and diatoms on the farms are grazed upon by tiny herbivores, which are in turn eaten by crustaceans and fish further up the food chain.

The flake farms are small enough not to be easily destroyed by wave action or ice formation. However, they are eventually broken up by rubbing against each other, by ultraviolet rays degrading their organic material, by dissolution of their mineral content, and by being otherwise consumed. Most material in degraded forms ends up on the sea floor, together with some of the new carbonaceous material that has been formed from its substances, CO2 and light into biomass.

The small, rice husk vessels or flakes are easily made by heating lignin until it becomes sticky, then using this to glue low-grade, iron-rich mineral fertiliser to the husks. Whilst the glue inside the husk capsules is still a bit sticky, the husks are rolled flat to make them smaller in volume and hence cheaper to store and transport. Heating the husks can be done cheaply using a combination of recycled heat, concentrated solar and gas heating. The completed fertiliser would resemble small flakes of breakfast cereal.

Until a more economical means of ocean delivery is constructed, old, bulk carrier vessels can be used to deliver the flakes to their destination, whereupon they can be sucked from the holds and blown through tall, angled pipes in different arcs far downwind to where they are widely distributed and needed.

In order to render this concept and technology profitable, and not just generally beneficial to the planet, a few things need to be established. First, the cost and effectiveness of the product, after its delivery to an appropriate gyre or area of ocean, needs to be established by experiments similar to that of the Wegener Institute. Monitoring would need to cover a longer period, because of the slow release of the fertiliser and the need to establish the longevity and any other effects of the husks and fertiliser delivery. The second thing that needs to be established is the legal position of both making progressively larger fertiliser distributions and the ability of an organisation to establish licensing rights over fish taken within the managed gyre or area. The third thing to establish is the ability of such a method of carbon sequestration in the deep, oceanic sediments to attract saleable, carbon credits.

## TECHNICAL DESCRIPTION

### MATERIAL SOURCES AND PROCESSING

The rice husks are a by-product of the harvesting and winnowing processes that separate the grains of rice from their bran and husks. Typically, they are packed into large bags at the mill, though they can also be transported in bulk. Because of their low density, and hence large volume, they are expensive to transport. Because of their high silica content, low food value, abrasiveness, and resistance to compression for transportation purposes, they are also difficult to find profitable uses for, except as animal bedding or as low-grade, heavily-slagging boiler fuel. They are only just beginning to have minor commercial use in the production of cellulosic ethanol and other chemicals. Even their landfill disposal tends to be difficult and costly, particularly as it may also soon attract emissions charges on top of disposal charges.

Should a major industry result from ocean fertilisation, and their transport for longish distances in raw state be required, it is advisable to see whether the husks might be densified for transport to the processing plant, perhaps by bagging in large, strapped bales, or by passing the half husks through a wringer or set of rollers to crush and them, possibly aided by heat or superheated steam. However, this last method may well have downsides as it might well damage the silica frustules and the buoyancy-making pores in the husks. Moreover, flattening the husks prior to them being coated might incur a silicosis hazard to the workers. One way around this notional problem is to coat the husks first with an interim glue. Happily, the raw materials for a cheap and available glue are available at the rice mills themselves, in the form of mill dust and the smaller pieces of broken rice grains. Mill dust is likely to contain rice dust, siliceous dust from broken rice husk frustules and earth, and particles of lignocellulose. When this mix is boiled long in water it turns into a thin, rice and mineral colloidal paste that is sticky and forms an effective-enough glue or adhesive upon drying.

When this liquid glue is sprayed thinly and finely onto a layer of husks, which is then covered by another layer of husks, the sandwich of husks and glue can be passed through perforated, heated rollers via conveyor belt, where they are flattened to a thin, paperlike sheet. The paper may then either be packed into cut sheets, bales or rolls, or broken up into component flakes, glued pairs, or small agglomerations for bulk handling. The light, canoe-shaped raw husks may thereby be transformed into dry, flat, reasonably dense flakes suitable for transportation in their now much denser forms by barge, train, truck or ship. Some such paper might also find other uses before it is recycled into a substrate for ocean fertiliser.

It seems unlikely that the thin film of rice adhesive would unduly compromise the later, stronger adhesion of the husks to the lignin binder, even when immersed. Even if it did, each separate husk, or small agglomeration of still-adhering husks, would still end up wholly encased in a lignin and mineral capsule and thus still be able to provide the necessary buoyancy.

Such a simple process of collecting and transforming the materials into flat flakes should readily be conducted at most rice mills, by purchasing and operating only modest additional equipment, particularly when it means they will be getting rid of their waste products profitably. Even when not sited with economical barge access, rice millers could sell their flakes to be trucked or taken by rail or ship to various ocean fertiliser or building material factories in the region or around the world. Although the flat flakes are now more dense, they would still be able to be handled economically by either pneumatic or traditional methods, such as conveyor belt. Nor would barges require additional handling equipment, as the receiving factories or ships would probably have their own pneumatic means of off-loading the flakes.

Loading and unloading of both husks and flakes might be done pneumatically. Flake dispersal at sea could use tubes, set at different and adjustable angles from each hold, to eject the airborne flakes pneumatically at high velocity in arcs to cover a wide ship’s track of ocean, possibly as much as kilometres wide when wind-assisted. In low-wind conditions, tubes would project the flakes from both sides of the vessel. Each dissemination tube might be tapered to increase muzzle velocity, telescoped for ease of handling and storage, and guyed for strength and directability upon four sequential universal ball joints, two each serving above and below the hatch cover. Typically, each tube would be mounted, together with its own powerful extraction fan and motor, through one of its hatch covers, from the underside of which would project downwards a remotely-guided flexible and extending suction hose designed to suck the flakes from each horizontal part of the cargo in turn, in order to keep the vessel trim and under minimal stress. Each telescoping tube muzzle might be extended as far as 100m or more from its base above the hatch cover. Its flake projection direction could be chosen as anywhere within the restricted hemisphere above the hatch cover.

Lignin powder is not expensive. Moreover, its cost is currently tending to decline, due to the development of better industrial methods and the global proliferation of biorefineries designed to produce sugars, alcohols, biofuels and chemicals from lignocellulosic materials, such as sugarcane bagasse, corn stover, husks, cereal straw, energy crops, wood, forestry and pulpmill wastes. These, or their lignin by-products, are often still burned to produce local power or heating. Higher grade uses than lignin’s current ones are emerging, as some lignin is now being used to form carbon fibre, nanocarbon products and chemicals. Overall, the development of lignin as a major industrial input should help keep the price of lignin within bounds, whilst increasing its availability. Current global lignin production (much of which is in the less-useful lignosulphonate form) is around 45Mt/yr, most of which is a non-commercialised waste product. This should increase maximally as the new methods of extracting sugars from agricultural wastes, such as straw and stover, and as new crops of miscanthus, switchgrass, reed, willow and poplar, leave a co-product of pure lignin. It is also likely that pulp and paper mills will move their production method from the energy and chemical intensive, and polluting Kraft process that produces lignosulphonate, to one that produces pure lignin that itself is acquiring more uses.

Both the lignin and mineral powder components to make the flakes are suited to ordinary, bulk cargo transportation and handling. They may even be suitable enough for pneumatic loading and unloading, though by conveyor belt would be more usual. Whilst separate handling systems may be used for raw husks, bonded husks, lignin, red mud dust, and finished flakes, it may also be possible to use the one handling system for more than one of these.

Whilst the iron content of the red mud waste left over from alumina refining alone should be sufficient for many fertilisation purposes, three other low-grade mineral sources may be pulverised and mixed to form the fertiliser. These are ironstone, gypsum (CaSO4) and rock containing apatite, a phosphatic mineral. The high silica content of the husks also makes a useful contribution. Whilst iron is the main nutrient in which the concentration is too low for optimal fertility in many oceans, phosphorus, silicon, sulphur, calcium and nitrogen may also become limiting nutrients, should iron be added. As new oceanic nitrates are delivered to surface waters by lightning strike, by blue-green algae (cyanobacteria), by upwelling, and by runoff from the land, and as adding nitrate otherwise is likely to be uneconomical, this paper concentrates on the addition of the other three limiting nutrients. Besides, when iron is added, it facilitates the production of nitrogenous nutrients from dissolved, atmospheric nitrogen by cyanobacteria and global warming is expected to double the rate of lightning strike.

Ironstone is widely available worldwide. The grades to use would be those that are fairly rich in iron, yet are uneconomical to refine for one or more of the following reasons: low grade, the concentrations of undesirable other minerals, insufficient size of resource, unfavourable inclusion size, unfavourable logistics, or sovereign risk. Typically, ironstone ores have an iron content ranging from 15% to 40%, mainly in the form of iron oxides and silicates. Phosphorus ores that are uneconomical to refine, but still usable for our purposes, are scarcer but not uncommon. Silicon is present to varying degrees in both iron and phosphorus ores, as well as in the husks. It is likely that the opaline or hydrated silica in the phytoliths (plant stones) of the husks is more soluble than the silica or silicate that is present in most ore minerals. Phytoliths are the siliceous spikes and spicules produced by plants to protect them from attack or make them less digestible. These are most concentrated in rice husks. In fact, as phytoliths make up a good percentage of silica in most topsoils, it may be these that provide most of the silica for dust-storm-fertilised diatoms. Moreover, as the shape of phytoliths is often not compact and their density ranges from 1.5-2.3 gm/cc, which is less than the 2.65 of compact quartz (SiO2) sand grains, phytoliths are likely to be sucked up by strong winds more easily than are sand grains and be carried further. Thus, the presence of hydrated, amorphous silica in the rice husks is likely to be a key growth-inducer for diatoms. This is so because silicon, in the form of dissolved silicic acids, is used by diatoms to make their protective silica skeletons called frustules. Yellow-brown microalgae also make use of silica but, having no such shells or skeletons, other microalgae and cyanobacteria do not require it for this purpose, although some organisms make calcareous shells of calcium carbonate.

Where silicic acid and bicarbonate are the main limiting nutrients in an ocean region, consideration should be given to the use of either powdered olivine or serpentine rock. Both of these react slowly with CO2 and water to produce magnesium bicarbonate (Mg(HCO3)2) and silicic acid (H4SiO4). The bicarbonate can be used to make marine shells and the silicic acid is used by diatoms to create their opaline silica skeletons. Both minerals also contain a modest amount of iron. Olivine may also be useful should the silica/silicate component of red mud or laterite not be readily enough absorbed and metabolised by diatoms.

It may not be economical to use the fertiliser on and in husks to provide a fully balanced dietary supplement of these elements for an optimal mix of marine microorganisms. This is so because they need much less iron per gram of biomass than they need silicon or phosphorus. The average proportions of the Fe:Si:P elements in fish muscle are 1:2.6:123 (FAO). Ho et al, 2003, say the ratio of Fe:P for marine phytoplankton (excluding the hard parts) is the similar ratio of 1:133. However, as iron deficiency will typically be the most limiting factor, as well as being the cheapest to provide in the required quantity to generate a given amount of extra biomass growth, its provision will tend to govern the nutrient mix provided.

The iron content of marine algae varies by one to two orders of magnitude, depending on such factors as species, acclimation, and season. The average alga is around 0.1% iron by dry weight and the average for fish (not just fish muscle) is around 0.0035% iron by dry weight. This means that a tonne of iron fertiliser could potentially produce 1,000 tonnes of algal biomass or around 29,000 tonnes of fish, both by dry weight, although, of course, there would be fertiliser losses that reduce produced amounts.

The ore grade, the cost of extraction, mineral balance and the costs of comminution (size reduction) and of transportation to each flake-processing port will determine which wastes or ores to source, from where, for delivery to that port.

There is likely to be a fairly narrow range of mineral particle diameters that is optimal for gluing to the husks for the most effective, slow-release dissolution. Red mud particle sizes, which typically range from 0.2-200*μ*m with a mean particle diameter of around 10*μ*m, may well fit this range, or could be made to fit the optimal range. A mix of particle sizes may well be beneficial in order to generate a more even release of nutrient over the entire year. The proportion in which to mix the ores of the nutritive elements will depend on the ore grade, on the nutrient deficiencies in the particular oceanic region for delivery, on the proportions required for optimal biomass production, and on the effectiveness with which the required elements are extracted from the ores and binders before they sink.

As red mud contains aluminium oxides and hydrates, some of which can be toxic to certain organisms, it would be well to test whether fertiliser made from it, when released ultra slowly and strongly diluted by seawater, has any major deleterious effect on marine life. Most of such tests might be conducted in a fish tank or aquarium that is given agitation similar to that found in the Southern Ocean, possibly by the use of small paddle wheels. Should it have net unfavourable effects, then low-grade iron ores, saprolite, laterite or ironstone may need to substitute for red mud.

### FLAKE CONSTRUCTION

The rice husk fertiliser platforms that form the tiny farms or flakes are easily made, possibly at the transit or aggregating ports to which the raw husks are delivered. Typically, the husks would require no pre-treatment. The initial process design has the husks being spread some 2-3cm deep on wide conveyor belts that pass through long, conduit ovens, with rakes to mix the husks so that they heat up evenly. In the oven, the husks are heated to around 1800C, which is just above the melting point of lignin. Progressive drying and heating of the husks, lignin and red mud powder might occur using warm, recycled air from the process, followed by using parasitic heating by hot flue gas from an adjacent facility, such as a power generation plant, or from concentrated solar power. It is also possible that the particulates in such flue gas, if extracted, might also form a useful addition to the flakes’ mineral mix, provided that they do not contain too great a concentration of minerals that are toxic to marine life. Many elements, even notionally poisonous ones, and most in minute quantity, are important to the development of healthy and vigorous marine life. Species can use some elements to substitute for a dearth of more preferred ones.

If required, additional heating to the husks might be provided by burning fuel, probably natural gas, within the externally-insulated, outer conduit. Direct flame should be kept away from the flammable husks. Both the flue gas and the combusting gas would pass through a counter-current heat exchange conduit surrounding the conveyor-borne husks. Such a system would permit continuous operation 24x7, even when sufficient solar and flue gas heating were not available. The number of conveyor belts activated could be used to adjust flake production rate.

The conveyor belts tip the wide streams of husks into long but narrow, vertically-vibrating colanders (sieves with round holes), located inside the top of a tower. In the colanders the bouncing husks are heated by sensor-controlled, overhead, infra-red lamps or radiators to perhaps 2000C. From the colanders’ holes the husks fall down the tall, conical- or wedge-shaped, Teflon-lined tower in an evenly-spaced, narrow but wide shower. This tower may in fact not be a single tower, but a series of identical modules each made from readily-assembled, mass-produced parts. Standardised modules should reduce scale-up and maintenance costs, as well better allowing for design evolution. A cone shape may help to reduce the amount of construction material used in their construction because of its ability to withstand external air pressure better than flat-sided structures, should the contents of each cone be placed under less than atmospheric pressure to reduce flake component billowing and fire hazard. As the flat-sided shower of husks descends, twin streams of lignin particles fall, or are otherwise projected diagonally down into the husk stream from opposite sides.

The rate and velocity at which both the lignin and the red mud dust are projected into the shower of falling, heated husks can be controlled by means of a powered roller at the bottom exit of each section of feed hopper. Each roller is fairly thick in diameter, with a series of shallow, longitudinal feed slots or low-rise paddle blades along it to provide controllable delivery of the feedstock. The roller’s rotational speed is also controllable, such that the feedstock can be projected centrifugally from the hopper, at any required velocity, into the shower of husks. The intermittency of the pulsed deliveries also helps to ensure that turbulent mixing occurs.

Previously, the lignin dust has been warmed to around 1100C, which is just below its softening point. When a warm lignin particle hits the hot surface of a husk, it tends to stick. As more particles stick on the way down through the turbulent, combined stream, the outside of each husk becomes coated with liquid, lignin adhesive. Further down the tower, iron-rich mineral particles, of a variety of small sizes, and heated to around 2000C, are projected at velocity into either side of the expanding stream. These particles create additional turbulence that tumbles the husks, thereby exposing all their surfaces to bombardment by the mineral particles. Most of these stick to the now hot, liquid lignin forming a non-sticky coating over it. This process is repeated until perhaps three layers of mineral have been applied.

Near the bottom of the tower, the husks have cooled to around 1200C, in part because ambient air is pumped gently into the base of the tower and finds its way out near the inlet hoppers, thereby cooling the lower, coated husks whilst warming the other input materials. At the bottom, any unattached lignin and mineral particles will have cooled to under 1000C.

The warm, coated husks and any non-adhered material land on an offtake conveyor belt made of an open mesh fabric that allows the fines to fall through. Husks having an insufficient coating, being lighter, would stay longer in the deposition zone. As it moves along, the offtake mesh belt is vibrated and the husks are raked and severally overturned, so that any unattached fines are separated by falling through its mesh. These mixed fines are then comminuted to a suitable size and are recycled to the lignin or mineral hoppers. The coated husks are then transferred to a vibrating conveyor belt that is moving at high speed. The high speed and vibration are used to spread out the flakes so that most of them do not overlap. Water-cooled rollers may then be employed to flatten each flake and to increase its integrity, care being taken not to remove too many of its buoyancy-producing air pockets. The flakes are then further cooled with heat-exchanging air on the conveyor belt, until they are transferred to another conveyor belt that takes them either directly to a ship for ocean delivery or to a storage silo.

The silo may be little more than a big pile of coated husks under cover that is protected from rain, strong winds and fire. The nature of the coated husks is such that they should keep well in storage for long periods. This is desirable, as much of the flake production may occur in the few months following the regional rice harvest. Rice husks harvested at different times, in different hemispheres or latitudes, might help smooth ocean deliveries as well as minimise stockpiles of both husks and flakes. Disseminating vessels may restock at different ports in succession in order to minimise unproductive passages.

The flattening of the husks is eminently desirable as it reduces their volume by as much as 70%, thereby making both storage and shipping less costly. However, it may be no bad thing if, after a short period in the ocean, many of the husk capsules revert to their original canoe shape, as this would provide a more protected habitat for some of the microorganisms and possibly a greater surface area to aid mineral leaching, microorganism adhesion and multiplication. This might be arranged by ensuring that the bonding between adhered husk surfaces weakens when in contact with water.

An alternative and simpler method of flake construction is to let the husks fall through a mist of rice water glue made by boiling and macerating low-grade rice and mill dust in water. To this glue is added lignin powder and a small proportion of ammonium bicarbonate (NH4HCO3) as a leavening agent. As the husks become wetted with glue they increase in density and fall faster. On leaving the dense zone of mist, they can then be coated by a cloud of mineral dust. Falling onto a conveyor belt, covered in perhaps a double layer of dry husks to keep the belt from becoming encrusted, a double layer of husks could then be added on top, forming a three-layer sandwich. The sandwich is then flattened and partially dried by heated rollers. Loose dust and under-coated husks are then removed pneumatically and are separately recycled. Further layers of glue and mineral may be added by passing the once-coated flakes through a similar coating process, one or more times. The continuous sheet of sandwiched material is then passed through an oven or under infra-red lights to cook it. The initial cooking process converts the rice-lignin glue into a closed-cell, solid foam. The sandwich is then broken up into separate flakes, each possibly containing a few husks stuck together and well coated. Further cooking partially melts the lignin particles so that they adhere to their neighbours, the husks and the powdered minerals. Such further cooking may well reduce the size of each flake and its foamed interior. In an industrial scale factory, the ammonia, steam and carbon dioxide gases released from the ammonium bicarbonate as it degrades releasing the leavening gases are recovered and are sustainably converted back into more bicarbonate. Should it improve flake duration in rough seawater, the temperature of the cooking process may be increased so that the rice glue is partially or wholly carbonised. Such carbonisation will also improve the longevity of the carbon in the ocean and its sediments, as carbonisation tends to render biomass resistant to faunal, fungal, microbial and viral attack and hence its conversion into either other biomass, methane or CO2.

Until a safer and more economical means of ocean delivery is constructed, old bulk carrier vessels may be the best option, operating at the times in the dispersal locations when sea conditions are not at their worst, that is to say avoiding winter storms, summer hurricanes and tornadoes. Each of these vessels would be loaded and navigated to a gyre or plume that is in need of initial fertilisation, of replenishment, or enlargement. Large pneumatic suction hoses and pipes would take the flakes from the surface of each hold and distribute them in arcs downwind by air, as the vessel is navigated to new areas requiring fertilisation. Typically, a vessel might head first to the centre of a gyre or plume, or to the inside of an EEZ, then spiral its way out in a curving path designed to ensure optimal fertilisation or re-fertilisation of the entire zone.

The pneumatic suction hoses or pipes might be moved around the hold by powered cables so that they gradually sucked up all the flakes. To avoid undue wear on the pneumatic fan blades or clogging, use might be made of the Venturi effect where the lowered pressure of a fast-flowing stream is used to suck in fluid or material from outside or to keep an object, such as a ping pong ball, immersed in an air stream inside it. Venturi effects are made use of in pumped or pressurised spray cans to suck up the liquid into the gas stream so that it forms an aerosol. Should the pipe be formed from ball-jointed lengths of titanium, or be a semi-flexible tube, then a strong stream of air, pumped by fan, pump or turbine, and flowing through the pipe would tend to suck up flakes through short, streamwise-sloping entryways into the pipe in the immediate vicinity of it. In large ships, dynamic positioning control of the pipe might be done by an AI system so that all the flakes in the hold eventually found their way into the pipe at regulated flow rates. Reversed, the same system might be used to load the flakes into the hold, or transfer loads between vessels, when conveyor belts or other better means were not available – though billowing could be a problem.

Although a successful operation would cause an increase in the albedo (the reflectiveness) of the ocean, resulting in more sunlight being reflected back by the oceanic microorganisms and colonised fertiliser flakes (both of which reflect more sunlight than the dark blue sea) into outer space, thereby cooling the planet, it seems unlikely that such an effect could be easily monetised. Similarly, the additional precursor to dimethyl sulphide (DMS), DMSP, produced by the additional algal biomass that increases albedo by facilitating the production of more and whiter marine clouds and of sunlight-reflecting sulphate aerosol particles (resulting from the photo-oxidation of DMS) is unlikely to be monetisable. However, given: that cloud albedo is so very high; that the albedo of even modestly-dense algal and diatomic blooms is likely to be substantial; that perhaps most of the world’s oceans could be beneficially affected; and that oceans fertilised in such a manner are likely to persist in having substantially elevated albedos throughout the year, rather than just for relatively short periods, the net effect on global albedo is likely to be substantial enough to have major beneficial effects on reducing global warming, without the undesirable effects of placing extensive artificial materials in the atmosphere or sunlight-intersecting space. Moreover, as the effects will tend to be spread across most or all ocean areas, it is likely that the resulting modest rainstorms will diminish the occurrence and severity of more extreme weather events. Powdered gypsum (calcium sulphate), or a similar sulphur-rich mineral or waste product, might be added to the minerals in the fertiliser mineral mix, should the area of ocean to be fertilised be deficient in either sulphur to produce the DMS or calcium to produce the shells and bones of many species of marine biomass.

Such supplementation will become more important, the more the sea ice and ice caps melt to produce a surface stratification of low-nutrient fresh water that also has a damagingly low pH. Supplementation would also mean that the resulting high iron content of the surface water would tend to favour the larger phytoplankton that generate DMS and produce a large carbon flux to the deep ocean, rather than the pico and nanoplankton which do not.

Although such increments in global albedo may not be accurately attributable to any single or localised set of ocean fertilisations, they may still be worthwhile doing as a public good. This is because the addition of sulphate (either in readily soluble form or otherwise) to the fertiliser mixes to help produce DMS may be a low-cost option, particularly when done using giant, self-powered and liquid-filled bladders. The dilute, liquid fertiliser can readily and cheaply be generated using the water-sprayed acidic flue gases from biomass power generation leaching through low-value, iron-rich waste materials that are of too low a grade or are too mixed with other materials to be worth converting them into steel. The material for leaching would be placed in a sand matrix to allow effective contact and percolation.

Following depletion of the available metallic iron and other algal nutrients in the material for leaching, the leach pile, or gently-sloping valley partly filled with leach material, may be remediated by the introduction of a dilute ammonia leach, followed by a leach of secondary-treated sewer, storm or river water, each of which can be added beneficially to the oceanic fertiliser leachate. The remaining fertilised and neutralised sand and residuals is then likely to be suitable for planting with trees without further monitoring.

## DEEP TECHNICAL, POLITICAL AND BUSINESS REASONING

### Blue Ocean/Green Ocean

Ocean areas that are dark blue tend to be deficient in both fish and other biomass. It is those areas that are green with photosynthetic microorganisms, on which most marine life depends, that are most productive. This paper shows how to use red, iron-rich minerals to transform the less-productive blue areas of oceans to green. It does this because tiny amounts of iron make large amounts of green phytoplankton.

What we seek to achieve is to create living, emerald waters from sapphire ones. Productive, clouded emerald green waters are much to be preferred to relatively lifeless and increasingly acidic, dark sapphire blue ones.

Whilst many coastal waters are harmfully over-nutriated with dust from storms, volcanoes, muddy river water from eroded lands, sewage, industrial wastes, and run-off from land onto which has been supplied highly-soluble, and hence mobile, chemical fertilisers, the high seas and oceans surrounding small or coralline islands are often impoverished, particularly in their surface waters. By fertilising mainly the surface waters of these, or ocean areas that are seasonally impoverished in one or more essential nutrients, the precise fertiliser mix and regional dissemination of the buoyant flakes can be targeted to where they will do the most good.

### Fertilisation by Wind-blown Dust

The size range of dust particles that are blown long distances, typically thousands of kilometres, is 1-5μm (microns) in diameter, with a mean around 2μm. 80% of particles are typically less than 10μm in diameter. Mineral particles of 3μm diameter tend to sink at a rate of around 0.6m/day. As photosynthesis mainly occurs in the top several metres of the sea, and tails off almost entirely by 100m depth, this means that the bulk of the nutritive benefit of a dust storm on phytoplanktonic growth will largely cease within a few weeks and vanish within a few months.

Our major improvement on this, fertilisation by mineralised rice husk, is likely to continue at an optimal rate for perhaps a year or more, particularly if the sizes and concentrations of the different, attached mineral particles are carefully chosen.

Presumably, many minerals in wind-blown dust contribute to oceanic fertilisation, including the oxides, silicates, and other complexes of many essential nutrients. Nutritive dust is also deposited in the wake of icebergs and from meteoritic dust. Microorganisms have developed various methods of adapting to, and concentrating, minute levels of dissolved nutrients from seawater, including those of chelation and of mineral capture, concentration and transportation by specially-developed microorganism proteins or ligands. However, as shown by the CARUSO experiments, iron and light are often required for the effective uptake and utilisation of these nutrients to occur, even when they are in good concentration.

From a map of average sea-surface chlorophyll, it can be seen that most ocean areas are biomass deficient. That is to say, they lack one or more essential nutrients or sufficient light. Our method of fertilisation appears capable of addressing the first of these deficiencies, at almost any scale required, both profitably and sustainably. Moreover, as iron can improve light utilisation, both deficiencies are addressed.

When fertilising nutrient-deficient areas, each fertilisation regime should result in the increase of fish biomass concentration by many times. One experiment indicated that a thirty-fold increase had been achieved. In cold waters, there should also be substantial increases in biotic flux to the seabed (biosequestration). A portion of the sunken biomass would then be biosequestered long-term, some of it for geological time spans. Even gases produced by benthic (deep sea and seabed) organisms from part of the biomass would likely be sequestered for hundreds or thousands of years. This is particularly the case when they are transformed into ice clathrates.

### Dust Metabolisation

Aeolian mineral dusts and depositions from meteoric material disintegrating as it passes at white heat through the atmosphere are not in what is thought of as readily bioavailable form. Moreover, though typically dust-like in size, such dense and minimally-soluble particles tend to sink rapidly out of the photic zone in the ocean where their contained nutrients would provide greatest benefit to photosynthetic life. What allows much of their nutrient content to enter the marine food chain is an effect discovered by Schmidt et al. (2016) and reported in a *Current Biology* paper titled “Zooplankton Gut Passage Mobilizes Lithogenic Iron for Ocean Productivity”. Potentially, the acidic digestion processes of zooplankton, krill and presumably other filter feeders that sweep up sinking mineral dust particles mobilise its iron and presumably many other nutrients, thereby making them bioavailable to cycle throughout the food web. The same processes should operate on mineral particles released by slowly degrading and abrading buoyant flakes. They should also operate on at least the external surfaces of flakes consumed by larger marine life forms. As flakes will preferentially be disseminated in regions far from glacial runoff and river discharges, they should therefore allow for the generation of key and bioavailable nutrients across the entire global ocean, whereas these are typically deficient across possibly as much as 60% of ocean surface in one or more seasons. Moreover, as these deficiencies get worse under progressive global warming, as ocean stratification increases as a result of surface warming, glacial melt and increased overall (though erratic) precipitation, the prospective contribution of buoyant flakes to ocean surface fertilisation will increase in importance.

### Oceanic Methane Emission Reduction

In *Nature Geoscience* (2016) in a paper titled “Marine methane paradox explained by bacterial degradation of dissolved organic matter”, Repeta et al. have discovered why the surface waters of the world’s oceans are saturated with methane. The answer is that some photosynthetic bacteria release phosphated polysaccharides whilst others break these down to acquire the scarce and vital phosphorus nutrient, producing methane, ethylene and propylene gasses as by-products. Because this occurs in surface waters, most of the methane escapes into the atmosphere. However, should buoyant flakes include a component of tungsten, molybdenum and copper-rich mineral dust, it is conceivable that the methanotroph enzymes that this nutrient encourages to proliferate would metabolise a goodly proportion of this methane before it escapes into the atmosphere.

### Sealing the Pores on the Husks

The lignin glue might also have the beneficial effect of sealing many of the pores and inter-particle voids on and throughout each flake, thereby making it more buoyant and thus able to carry a greater weight of mineral by preventing capillary effects occurring to fill the pores and voids with seawater. This sealant effect may be the more important if the processing temperatures are high enough to degrade the water-repelling wax and/or cutin polyester coating on the inner side of the rice husk.

### Increasing Flake Buoyancy

Should either greater or more permanent buoyancy be sought from each rice husk and subsequent flake, a method is available to do this. It is done by adding some powdered lignin and a leavening agent to the cooled rice glue. When a fine spray of this gooey mix is sprayed onto a moving, single-but-compact layer of rice husks and is then covered by another single layer of falling or converging husks, and when the resulting ‘sandwich’ is passed through a series of heated rollers, each having a soft, non-adhesive surface that will only gently and temporarily compress the sandwich, whilst heating it to cooking level, it will subsequently rise like a quick-baking pancake, thereby forming a solid foam between the outer husks that can be used to increase the buoyancy to almost any desired amount.

Should it be found to have desirable effects, the pancake might be heated enough in a non-flammable nitrogen atmosphere partially to carbonise the rice glue foam and to link some of its distinct lignin granules as the bubbles contract into a thinner-walled and more ligniniferous foam, thereby making the foam both more resistant to weakening when seawater eventually intrudes and more resistant to metabolic action. The residual lignin foam is likely to remain intact even after any residual rice glue is dissolved or consumed. It will be necessary to limit the extent of this over-cooking so that the strength of the husk backbone is not unduly weakened. This over-cooking will also serve to drive off most of the remaining moisture.

After these processes, the sandwich sheet is then chipped, broken or shredded to the desired size range, prior to flake formation. Typically, each chip will be its own little sandwich, with the two husk layers separated by a semi-carbonised rice glue and lignin foam.

Should the partial carbonisation, or pyrolysis, proceed far enough without excessively weakening the sandwich, it may be possible to retrieve enough evolved hydrocarbon and other fuel gases from the sandwiches to use them as fuel with which to partially pyrolyse incoming husk sandwiches. Effective heat exchange and the addition of a gas or gas mix that is high in oxygen might be necessary to obtain optimal heating value from such a resource.

Should even greater buoyancy be required, then leavening agent might be mixed with mineral and lignin powders prior to them being coated onto rice-glue moistened husk sandwich material. Subsequent baking would tend to produce largely sealed vacuoles within the lignin-mineral matrix.

Prior to flake dissemination onto the sea, the carbon dioxide and ammonia gases inside the foam is likely to be largely replaced with air by an osmotic process of gas exchange. Because of the three layers of lignin added to the outside of each chip in the tower, it is expected that the resulting flakes themselves will be largely waterproof until those layers are eventually sufficiently degraded by the combined action of sun, sea, abrasion, phytoplanktonic attack, and mineral extraction. The more lignin and red mud layers that are added to the outside of each chip, and the thicker and denser the lignin layers are made, the more durable will each flake become. Thus, to a degree, flake durability may be matched to the severity of conditions expected in any particular ocean dispersal site, such that flake destruction and residuum sinking can be timed to occur just after the great bulk of the nutrients have been extracted from the flake. There is little need for concern should the flakes last much longer at the ocean surface. Even when denuded of nutritious minerals, the flakes might still perform useful habitat, energy interception and albedo functions that are otherwise almost absent in most ocean areas.

It should also be noted that, as the ligands of the phytoplankton that attach to the flake preferentially extract the some of the highest density components of the flake, and as these phytoplankton are removed by grazing pressure, the total density of the flake will likely decrease, thereby making the residuum less prone to early sinking.

The leavening agent mentioned above could be a 14:5 ratio by weight of well-mixed sodium bicarbonate and monocalcium phosphate powders. If so, the calcium phosphate component will add to the fertiliser payload. However, to save cost and high-grade resource, the phosphate might well be reasonably low-grade feed phosphate rock, with the 14:5 ratio above decreased to offset the lower grade. The iron, aluminium, magnesium and/or carbonate content of this ore might be able to be high, and hence the cost low, as no difficult and costly beneficiation, except comminution, would be required. The same ore might also be mixed with the red mud outer mineral coatings, should it be economically justified. It may also be possible to use the phosphorus-rich tailings from earlier phosphate beneficiation operations. These would typically have the substantial benefit of already being finely comminuted and therefore of minimising process energy inputs. However, tests would first need to be made to ascertain whether phytoplankton could extract the phosphate, iron and/or silica from these possibly highly-insoluble waste products.

### Flake Colonisation

The nutritive, mineral-coated husks are likely to be an ideal habitat for microorganisms. The flashing light regime underneath the rafts or armadas of flakes that is caused by the moving flakes should also promote near-optimal diatomic and algal productivity. Heavier-than-water microorganisms, such as diatoms, could use buoyant flakes to avoid death by over-deep sinking. As more, possibly slightly heavier-than-water microorganisms attach themselves to a flake, more mineral will be extracted from it. This offsetting effect makes the flake lighter and tends to keep the whole assemblage buoyant for as long as possible. Interstices within and between mineral grains would give a level of protection from predation by larger microorganisms, such as copepods and amphipods, whilst providing algae and diatoms with beneficial filtered light and nutrients. Deposited eggs, larvae and larger organisms would attach themselves to a flake or find shelter between or under flakes. Against a moving background of flakes, other organisms would be harder to be discerned from below by predators. Still others would use the floating flakes to moor their eggs and shelter and succour their larvae, particularly those flakes that had opened up to their original canoe shape, thereby providing shell-like protection. Flakes sinking due to an excess of attached eggs might become nutritious food to some marine organisms. Some of the most prized habitats in the oceans, especially the high seas, are floating or suspended solids. Birds might find it harder to perceive small fish and squid because of the moving camouflage backdrop caused by the flakes, though the greater concentration of prey might offset this effect on predation. Flakes would also provide habitat for cyanobacteria, whose nitrogen-fixing activities, predation, and digestion would indirectly benefit most other inhabitants. Whilst providing a habitat for small marine life, not unlike that of elements of a coral reef, the dispersions of flakes would be patrolled by predators seeking to make an easy meal in such a productive habitat. In turn, these concentrations of predators would form rich pickings up the food chain.

### Flake Insolation and Planktonic Generations

Whilst ocean surfaces at high latitudes reflect most radiation due to the low angle of incidence, this is not the case for floating flakes. Because of their profile above the sea surface, their surface roughness and colour, these can absorb light that impinges at the lowest incident angles. They will even absorb sunlight when embedded in, or are underneath, sea ice. Strong insolation is also important because it facilitates photoredox cycling that increases the bioavailability of many trace elements. Because of these factors, phytoplankton on them will begin proliferating in the spring some time before their more deeply submerged brethren. Likewise, will their reproductive season be extended further into autumn. The very heat that is absorbed and emitted by both flake and plankton will also have some small, but useful, effect upon the temperature of the polar water surface. Hence, the plankton will be able to grow and proliferate for a longer season, thereby multiplying the number of their generations in any one year. However somewhat counteracting this, the flakes may also facilitate the nucleation of sea ice in polar regions. In temperate waters the beneficial effect will be similar, only for a longer period and with possibly greater diurnal effect due to the low angle of solar incidence at sunrise and sunset. In tropical waters other effects, such as shading and evaporation, may also be important.

Fertilisation by means of buoyant flakes has a unique advantage in nitrate-deficient waters. Because most marine diazotrophs (nitrogen-fixing organisms) contain gas vesicles, they float (typically in filamentous masses). This means that they will benefit most from other nutrients released from any flakes floating alongside them. Thus, even in highly stratified and nutrient-deficient water, when powered by the stronger sunlight at the surface they will be enabled to generate the nitrate nutrients and acquire the other ones necessary for their own growth. Furthermore, when diazotrophs are predated by zooplankton, the metabolic activity will ensure that most of their nitrate and other nutrients becomes available for other species, thereby generating a rich and balanced ecology in what previously could well have been oligotrophic (barren or life impoverished) waters.

Diazotrophs occur in most tropical, subtropical, temperate and cool ocean waters. Types vary from buoyant, matted or dispersed, filamentous *Trichodesmium* species (sea or sailor’s sawdust) to unicellular cyanobacteria and symbiotic diatom-diazotroph assemblages (DDA). In the cold Baltic Sea, heterocystous cyanobacteria generate reactive nitrogen at a very high rate, slightly greater than the substantial N-productivity of *Trichodesmium spp*. Whilst cold seas are often rich in reactive nitrogen, for those that are not or where their reactive nitrogen might quickly be consumed by predators, seeding the surface waters with heterocystous cyanobacteria, buoyant iron, phosphate and selenium minerals might be an option to investigate if there are no local species available to fertilise. Diazotrophs depend upon the presence of iron to fix nitrogen from the atmosphere and photosynthesis in phytoplankton depends upon the presence of minute amounts of selenium in at least one of their enzymes.

### Biosequestration Effectiveness and Criticism

In a study on marine particle dynamics, McDonnell (2011) found that biosequestration is likely to be far more effective in cold waters, such as those off Antarctica, than in warm waters, such as those off Bermuda. This is because, in cold waters, the consumption (or remineralization to CO2) of the sinking biomass by microbes was so low that it could not be detected by his instruments, whereas that in warm waters was substantial. The nature of sinking biomass in cold waters also tends to contribute to its more rapid sinking. These effects mean that sinking biomass in cold waters is less likely seriously to denude the colder, deeper water of oxygen, because of metabolic action being much slower there, making biomass last longer.

Diatoms are particularly useful in biosequestration because their heavy, siliceous skeletons tend to form mucilaginous chains that, on death or growing to excessive size, sink rapidly away from the light-filled, warmer, and highly-oxygenated region, where their residual biomass otherwise would be devoured by bacteria. By providing iron, silicon, and phosphorus, which are acutely deficient in some ocean regions, the fertiliser flakes facilitate maximum biosequestration of carbon on, in, and under the seabed. In time, much of this biomass will become limestone and fossil fuel.

The Southern Ocean is the largest upwelling region in the world. It is relevant that it is the only one where the bulk of the upwelling macronutrients of nitrate, phosphate and silicate are returned with the cold, salty down-welling surface water to the ocean interior (Smetacek, n.d.). Thus, for this region, and possibly only at certain seasons, it may be fertilisation only with iron and silicon that is important, as the two key macronutrients, nitrogen and phosphorus, are provided naturally. All that human-mediated fertilisation would do to the Southern Ocean would be to replicate what the continental shelves, rivers and North African aeolian (wind-borne) dust already does for the North Atlantic and what nutritive dust from Central Asian deserts does for North Pacific waters. Such fertilisation would also just be replacing the fertiliser that we had removed by fishing over hundreds of years. Large-scale ocean fertilisation with iron, silicon, and phosphorus has been occurring naturally for millions of years, with *only* beneficial effects, but neither continuously nor globally.

Fertilising diatoms with iron, silicon and/or phosphorus in deficient sub-polar and polar waters should result in the most long-term carbon biosequestration. In nutrient-deficient tropical and temperate ocean regions, fertilisation of algae, cyanobacteria and diatoms should produce the most fish biomass. To increase the long-term biosequestration effect, fertilisation might initially concentrate upon those ocean areas in which there are gyres that subduct surface water faster than does the normal carbon flux. In the Southern Ocean there are several such gyres or giant, but largely imperceptible, whirlpools and water subduction zones, not least those caused by the formation of sea ice, with the concurrent formation of cold, dense brine that sinks rapidly. A similar subduction effect occurs in some Arctic regions where it is all the more important as it keeps the thermohaline circulation current (sometimes called the Gulf Stream or ocean conveyor belt) going that prevents Western Europe from experiencing harsher winters and elsewhere causes the productive upwelling of nutrient-laden waters.

Many marine species depend on the formation and extent of sea ice. Notable amongst these are the algae that grow on its underside and the krill larvae, juveniles and adults that feed on these during winter. As fertilisation by our flakes begins to de-acidify the Southern Ocean and Arctic surface waters and thence to reduce the concentration of atmospheric carbon dioxide above and produce more high-albedo clouds, the area should cool, thereby increasing the amount of winter sea ice and hence biomass. A virtuous cycle is then likely to replace the current vicious one in the Arctic that sees progressive reductions in sea ice coverage. Complementing this effect would be my extension of Zhou and Flynn’s (2005) concept that proposed pumping seawater on top of Arctic sea ice to thicken it in the colder seasons to form thickened ice floes. The extension conceives the construction of floating, or eventually grounded, ice mountains, and a better means of effecting this by using anchored buoys supporting wind turbines to power the pumps and de-ice the turbine blades and pipes, as well as to bring nutrients to the surface in relatively warm seasons. Such means might also be used to retard the emission of methane and CO2 from Arctic seas and soils. Furthermore, such permanent ice mountains might form useful, insulated bases for scientific observation and other activities.

It is assumed that nutrient-deficient water might require flake coverage from 0.02% to 2%, with an average cover required to produce iron-sufficient surface water of perhaps around 0.2%. Now, the dry weight of an average rice husk half is approximately 0.0037gm. When flattened and coated as a flake it is expected to have a flattened area of approximately 50mm2, depending upon the species of rice and flake processing. Around 132Mt (million tonnes) of rice husk is produced per annum, of which 100Mt may be available for ocean fertilisation purposes. Husks from other grains might add to this amount, when rice husks were not required for their durability, low density and silica content. Thus, a year’s supply of rice husk-based flakes would cover 1.35m km2. Hence, at an areal density of 0.2%, these flakes could fertilise 675Mkm2. Now the area of ocean is only 335Mkm2 and only 40%, or 134Mkm2, of that is known to be deficient in iron. Hence, there would be enough flakes to nutriate the iron-deficient ocean areas to an areal density of about 1% of flake. The areal amount of iron supplementation per square metre of ocean from this intensity of annual fertilisation would be around 7mg/m2, which in theory is enough to generate nearly 1,400kg/Ha of additional, dry marine biomass. Losses to iron dissipation to non-photic zones and carbon sequestration in the depths might reduce this, perhaps by as much as 80%, to around an additional 280kg/Ha/yr of dry biomass. In practice, different areas would be nutriated more or less than 7mg/m2 of iron, and with different concentrations of other mineral nutrients, according partly to the evolving nutrient deficiencies occurring there.

There are large areas in most oceans that have low nitrate and iron concentrations, yet have residual or excess phosphate (Lampitt et al. 2008). The evidence is strong that iron and phosphorus provide pivotal co-limitation of nitrogen fixation (Mills et al. 2004). Thus, our method of fertilisation should produce much biomass and fish, though possibly not huge amounts of biosequestration where the ocean surfaces are warm, because most of the biomass there is consumed by bacteria before it reaches cooler depths. However, even in temperate and tropical waters there are icy, deep waters and currents, so that fertilisation above them might still biosequester carbon reasonably effectively, particularly when it is in a form that sinks rapidly. Moreover, the lignin component of this carbon flux is likely to resist digestion by bacteria and most other marine organisms.

Regarding ocean acidity, fertilisation is likely beneficially to reduce or reverse the current trend of decreasing pH (ocean acidification), particularly in the euphotic (photosynthetic or growth) zone, but also elsewhere. However, in deeper, stiller water the increased supply of particulate organic carbon (POC) might tend to lower pH as part of it was remineralised, although only probably to a modest degree.

There have been several criticisms made of both ocean iron fertilisation (OIF) and of the experiments conducted to establish its effectiveness. Whilst the work of Smetacek et al. and other studies established that OIF using iron sulphate could, under certain circumstances, result in significant increments in the carbon flux to the deep ocean, the results were variable for largely unknown reasons. Criticisms have also been made that, largely because of the high cost of keeping research vessels on station in Antarctic waters for months, the measured results were made over too little duration to establish their full effect. This may well be so, but there are stronger reasons for thinking that the resulting carbon flux has been seriously underestimated by the methodologies used. Typically, these have used sediment traps set at various depths in the water column, both under and somewhat outside the boundaries of the fertilised plume. It is submitted that these provide flawed measures of biosequestration for three reasons, four if one counts the use of buoyant, ultra-slow release fertilisation.

The first flaw is that such experimental design wholly ignores the effects of pelagic species consuming the biomass within the biomass-enriched plume, but which release their faeces and the biomass of their consumed bodies elsewhere. The second flaw is that the sinking ‘marine snow’ that comprises most of the carbon flux will still remove carbon from the surface waters, even if much of it is remineralised by bacteria before it hits the lower sediment traps, some of which were set a kilometre or more deep. This is still an effective method of carbon sequestration and thus of extracting more carbon dioxide from the atmosphere. It is just typically not as long-lasting as those deeper and often more durable forms of carbon such as benthic biomass, carbonate rock, Dissolved Organic Carbon (DOC), methane clathrates, Dissolved Inorganic Carbon (DIC), or other carbonaceous material buried deep in ocean sediments. The third flaw is that the various methodologies seem to have taken no account of the most important, but typically less-mobile, organisms that feed within the surface waters of each fertilised plume. Near the end of each night, these tend to migrate to the dark depths to escape predation. However, any submarine current that they encounter that differs even slightly from what is occurring at or near the surface will tend to remove them, their predated bodies, and their faeces from below the plume and the sediment traps set there. Worse still, these may then contribute to the material in the traps that are set outside the plume, thereby serving to reduce the difference in measured carbon flux between the two sets of traps. Moreover, the biomass of those that excrete or die below the sediment traps is entirely omitted. Hence, all such comparative measures to date will tend to have given serious underestimations of the additional carbon flux delivered by OIF.

Thus, key criticisms to date of the OIF concept, whilst providing useful criticism of previous experimental results, approvals and methods, miss their mark. They actually harm research endeavour, our search for good solutions and investment when they appear to generalise their criticism to all methods of OIF.

Finally, when one considers the additional safety, economy, effectiveness and environmental benefits prospectively delivered by our buoyant, ultra-slow flakes, this particular form of OIF should be given development effort and a fair trial.

There have been justifiable criticisms of various carbon biosequestration methods, that they either do not scale well, or do not remove carbon dioxide sufficiently fast from the atmosphere not to have their beneficial global cooling and ocean de-acidification effects largely offset by the evolution of CO2 from the ocean and upwelling movement. Neither of these criticisms can apply with much force to buoyant flake fertilisation. Once of proven safety and biosequestration effectiveness, the flakes could be applied at such a rate that over half the oceanic surface waters of the world would lose a significant portion of their dissolved inorganic carbon (DIC) content, thereby turning the waters into fast-acting and more effective sinks for atmospheric CO2. Such fertilisation should (positive feedbacks allowing) be able to be maintained at such a rate as to exceed the sum of both terrestrial CO2 emissions and transfers from the deeper levels of the global ocean. If necessary, the partially carbonised husks of cereals such as wheat, barley and oats might temporarily be pressed into service, should there be an insufficient supply of rice husks, or the flakes themselves be needed to last for a lesser duration.

### Jellyfish, Salps and Large Excretors As Efficient Carbon Flux Transporters

Whilst much of the carbon flux to the deep ocean results from sinking diatoms, microalgae and faeces, research by Lebrato et al. (2013) has established that the mass and density of dying jellyfish serve to transport their carbonaceous material to the benthic depths far more rapidly than does most other material. Typically, jellyfish biomass will sink at rates of around 1km/day. This is at such a speed that microbial decay that releases CO2 is minimised, resulting in a high percentage of the material reaching the cold (but possibly warm too), typically hypoxic (low oxygen) depths of the sea, where carbon is typically sequestered for long periods. Indeed, effective long-term biosequestration seems to depend upon there being hypoxic, or possibly anoxic (no oxygen), conditions to ensure that biomass and methane are not destroyed by either consumption or oxidation. So, ensuring that such conditions are established and maintained may well be critical to reversing, or at least halting, global warming and ocean acidification.

As jellyfish and pelagic tunicates (filter and mucosal net feeders, such as sea squirts) consume algae, cyanobacteria and small organisms above these in the food chain, this means that the increasingly large populations of jellyfish (due to climate change and overfishing/killing of jellyfish-consuming sharks and turtles) play an increasingly substantial part in carbon transportation and biosequestration. This part would become even more important when diatomic growth was limited by the exhaustion of available silica, something that would tend to occur even when the available silica was supplemented by our proposed iron-silica fertilisation.

Whilst carbon biosequestration by diatoms would be most effective when and where there were cold surface waters, biosequestration by jellyfish would also be effective where the deep sea and sea sediments were cold, possibly as a result of cold, submarine currents, regardless of the temperature of the surface and mid-depth waters. As the oceans degrade further with global warming, jellyfish numbers could explode (Gershwin, 2013), thereby making this form of carbon transportation to the depths even more important and effective in carbon sequestration.

Salps, which are free-swimming tunicates or sea squirts, are also good at improving the carbon flux to the depths because they excrete digested phytoplankton in heavy faecal pellets that sink rapidly. Similarly, are the excreta of some larger marine organisms either transported rapidly by sinking fast, or are sometimes excreted at depth.

It has also been shown by Riebesell et al. (2013) that elevating CO2 levels favours the proliferation of pico and nanoplankton at the expense of larger plankton that form the key part of the food web, generate DMS, and carry carbon to the depths for storage. As nutriating surface waters favour these larger plankton, deploying flake fertiliser should thus prevent disruption to the marine food web, mitigate any diminution of the carbon flux, and also assist with global cooling via marine cloud brightening.

### Natural Replacement of Fertiliser

Whilst some marine nutrients are partially replaced by upwelling, storm-driven mixing, riverine, Aeolian, atmospheric, meteoritic and anthropogenic sources, there may also be net fertilisation resulting from the diurnal migration between mesodepths and photic levels by organisms such as krill, tunicates and squid. Whales and other mammalian feeders, together with seabirds including penguins, may do the same at each dive. These tend to excrete at the surface. Non-mammals may transport nutrients either way. Whilst much predation will tend to occur in the biomass-rich surface waters, that upon bacteria which feed upon marine snow and dead organisms will tend to occur at depth. The net result may be the retrieval of a substantial fraction of the carbon flux and its entrained nutrients before they are lost to the abyssal depths. Whales are particularly efficient and effective about bringing the nutrients in their faeces resulting from deeper sea predation for release at the ocean surface.

### Fertiliser Balance

Our system is able to match the fertiliser composition to one or more of several factors: to the specific nutrient deficiency of a given region of ocean; to the concentration at which the fertiliser is delivered; to the season in which it is to be delivered; and to the possibly-multiple objectives of the agency paying for the fertilisation. Thus, fertiliser with a relatively high concentration of iron and/or phosphorus would tend to maximise the growth of microalgae in all sunlit waters, leading to maximising fish stocks. A similar fertiliser mix, but with a different composition of micronutrient minerals, might favour the proliferation of nitrogen-fixing cyanobacteria species to remedy nitrate-deficient seas. A mix with a relatively high concentration of silicon from the hydrated silica in husks, from other opaline silica sources, such as opal mining tailings, diatomaceous earth, and from other siliceous minerals, wastes and plant material (grasses and some weeds tend to have fairly high concentrations of protective, opaline silica in their leaves), would favour the proliferation of diatoms that could best sequester carbon in cold, deep-sea sediments. A mix with a relatively high concentration of available sulphur, possibly in the form of the mineral gypsum (hydrated calcium sulphate) or slowly-oxidising iron sulphide ore (iron pyrites or fool’s gold), would favour the production of dimethyl sulphide (DMS), thereby increasing bright marine cloud formation downwind, increasing albedo, reducing coral bleaching, reducing biodiversity loss, and reducing the driving force of hurricanes and cyclones by cooling the temperature of the lower atmosphere and surface waters.

The fertiliser balance may also be upset by incautious additions. The malign effect, referred to earlier from the highly soluble ferrous sulphate fertiliser additions used in most ocean iron fertilisation experiments, results in part from the disablement of nitrogenase enzyme, or nitrogen-fixing activity, by high levels of sulphate (Stal et al. 1999). This would otherwise help maintain nitrate nutrient sufficiency under high phytoplanktonic growth rates.

There are several other micronutrients that may become limiting in surface waters, once the main deficiencies for strong phytoplanktonic growth have been remedied. These include manganese, cobalt, nickel, copper, zinc, cadmium, molybdenum, strontium, and vitamin B12. For instance, cobalt is an essential element required for the production of vitamin B12 in phytoplankton (Naqvi & Smetacek, 2011). Once a vitamin, lipid or other bioactive has been produced by phytoplankton, it therefore tends to become available up the food chain. Most of these nutritive elements can be found at sufficient (modest) concentration for flake inclusion in low-cost ores or wastes.

The essential trace element, selenium, is deficient in many human diets and its deficiency in ancient ocean waters has recently been linked to several global mass extinction events, see <http://www.businessinsider.com.au/elementary-new-theory-on-mass-extinctions-that-wiped-out-life-2015-11> Selenium is also necessary for photosynthesis to occur. Fortunately for humanity, selenium is one of the trace elements present in Florida’s 1.5 gigatonne hills of phosphatic clay wastes and is probably present in other such waste piles in other places. Hence, using these as part of the mineral content of buoyant flakes should address the deficiency sustainably and at no additional cost. Indeed, as Florida’s phosphatic clay wastes from older mining areas contain approximately 18% Si, 5.2% P, 3.5% Fe and Se 46ppm, Cu 75ppm, Mn 1,230ppm, Mo 9ppm, Ni 53ppm, Cd 18ppm, Sr 750ppm and Zn 195ppm, see <http://fipr.state.fl.us/wp-content/uploads/2014/12/02-020-012Final.pdf> with particle size less than 2μm, this mineral source might be used on its own in buoyant flakes for most nutrient-deficient ocean areas. Removing the problematic phosphatic clay wastes from Florida would allow approximately 100,000 acres on which they stand to be used for other purposes. Whilst Florida’s phosphatic clay wastes are sufficient to nutriate deficient global surface waters for a few decades, wastes from elsewhere and uncommercially low-grade or difficult to refine phosphate resources appear to be sufficient to do this for thousands of years.

Because of the high water content in phosphatic clay waste, even after many years standing, a substantial area may well be required for its harvesting in sufficiently dry form. This might best be achieved by scarifying the clay surface, solar drying the thin scarified layer, then removing it as nodules and dust by scraping and lifting the scarified and dried layer into a collecting vehicle. At each possibly-daily pass, this process might only remove a couple of centimetres of the previously consolidated clay. Hence the need for a large collection area for industrial amounts of clay to be dried, collected, and stored under cover. After rain, harvesting would need to be suspended until the slick surface dried out with a crust. Even so, specialised vehicles, possibly ones with balloon tyres or wide tracks, would need to be used, because of the little support provided by the underlying thick band of clay. The clay surface might be humped into elevated roads and provided with runnels to remove excess water that otherwise might pond.

Perhaps a better method than scarification is to drag behind a tractor or specialised vehicle what amounts to a large carpenter’s plane or potato peeler. This is basically a crosswise-curved metal plank that is dragged transversely behind the vehicle. A slot and knife-edge skim from the clay surface parallel sheets of clay 2-4mm thick. These are cut into ribbons 2-4cm wide and are curled partly over transversely so that they have minimal ground contact and maximal air contact when they land back on the moist ground. Blades projecting from the upper surface of the after part of the plank make the cuts and curls. To lubricate the plank surfaces in contact with the clay, weepholes in the plank and on the blades conduct water to their surfaces that contact the clay. The weepholes typically emerge in a backwards-facing groove to minimise clogging and spread the lubricating fluid out thinly. A battery of micropumps in the form of tube inset with an inner rotating offset ‘camshaft’ force water at specified rates through each weephole. The lubricating water is held in a tank on the vehicle.

After the ribbons have dried sufficiently well in the sun, they are swept or vacuumed up into a storage container on the vehicle. This harvesting system may either be fitted on to the front of the ribboning vehicle or be mounted on a separate one. Should further drying be required, then the collected ribbons might be spread over black-dyed concrete or bitumen (perhaps an unused road or airport runway).

### Net Biodiversity Effects

There may be three effects on biodiversity and biomass of implementing the concept. The first likely effect is for the upper and middle depths of the world ocean to be increasingly oxygenated and de-acidified by dint of the increased photosynthesis occurring in surface waters, part of which oxygen is transported downwards. This effect is also expected to increase both biomass and biodiversity. A second effect results from the increased flux of carbonaceous material to the depths. This provides additional food for middle, deepsea and benthic species. In particular, this would benefit cold-water coral reefs and deep-sea ecosystems that depend on the flux of food from the surface that is already diminishing under ocean warming. At the same time a third set of effects is caused by bacteria consuming this additional food and thereby causing more of the originally sparse oxygen there to be transformed into CO2. It may also cause some of the biomass to be turned into various forms of methane, such as methane clathrates. Advanced modelling should be able to determine the combined effect of these processes. However, it seems likely that, whilst the net effect will be positive, some deep sea levels may become more hypoxic, or even anoxic, and thus less friendly to most lifeforms, whilst thereby probably becoming better able to biosequestrate carbon for long periods.

Countering this, it has recently been discovered that these anoxic zones are by no means devoid of life, see <https://www.whoi.edu/oceanus/feature/the-most-inhospitable-places-on-earth>. In fact, they may well provide an increased level of biodiversity that is valuable in its own right. So increasing the size of hypoxic zones of some deep sea environments to what they may have been in earlier times could actually be a good thing for three reasons: better long-term carbon biosequestration; the zone extension of some rare ecologies; and a possible increase in the number of distinct ecologies.

### The Form of Iron Nutrient: Valency, Crystallinity and Surface Area

As is noted elsewhere in this document, the particle size and valency of the iron in the mineral nutrient are important for its bioavailability to microorganisms, the double valency of the ferrous ion, Fe2+, being generally much more soluble than that of the triple valency ferric ion, Fe3+. Furthermore, the degree of crystallinity of the mineral is reported by Visser et al. (2003) as being important for bioavailability. They used the growth rate of two large diatom species to show that amorphous iron-rich mineral was the more bioavailable form than its crystalline counterparts. They also established the importance of the surface roughness/area of particles, as well as their size and mineral type. Bioavailability can also be increased by complexing the iron, but that will be left to the ligands on microorganisms.

### No Justifiable Alternative to Conserving Non-renewable Resources

Future global implementation of this technology does not mean that we can slacken in our commitment and endeavours to develop a sustainable economy, though it may provide us with more time to do this well. This is so for three reasons. The first is that providing the oceans with adequate iron nutrient, whilst it would generate considerable extra biomass and carbon biosequestration, only brings us up against the next element that then becomes deficient, and the next, and so on. In order, the first few elements giving rise to subsequent deficiencies might well be silicon, phosphorus and nitrogen. Whilst some nitrogenous nutrients might be provided by iron-boosted nitrogen-fixing cyanobacteria, silicon and phosphorus cannot. In fish muscle, silicon is about 2.6 times more prevalent than is iron, and phosphorus is about 123 times more prevalent than is iron. Thus, these may represent the rough order of multiples that their minerals would need to be added to deficient ocean areas in order to prevent nutrient deficiency in these elements from developing. Whilst a modest level of nutriation with silica (preferably in its hydrated or opaline form) is viable, especially given its providential presence in rice husks and red mud and its carbon biosequestration potential in rapidly-sinking diatoms, providing increased sufficiency in the phosphate nutrient that is required by all microorganisms would provide a lesser contribution to corporate profits, even though the flakes can readily be formulated to provide some limited supplementation in phosphate and trace elements. With increased phosphatic fertilisation over time, this phosphate may even become enough to offset the phosphate that we remove from the ocean through continued fishing and seaweed harvesting. Whether providing phosphate sufficiency to nutrient-deficient ocean areas is profitable will be a matter of logistics. The degree to which phosphate and other nutrients are worth disseminating as buoyant ocean fertiliser may be at the point where economy of scale balances the law of diminishing returns. However, even if it is found to be unprofitable from a corporate view at a given point, the public benefits in terms of public health, food security, protection of land and infrastructure, insurance premiums, ecological and species survival value, including that of our own species, may well justify publicly-subsidised phosphatic fertilisation to a higher level.

Some data relevant to oceanic nutrient supplementation decisions can be found in Finkel et al. (2010) where the carbon:nitrogen:phosphorus:iron (C:N:P:Fe) geometric mean molar ratios for key microorganism types can be calculated respectively to be approximately: Diatoms 47,000:7,000:800:1; Green algae 20,000:2,400:100:1; and N-fixing cyanobacteria 5,500:1,000:20:1. For healthy natural assemblages of marine plankton, the C:N:P molar ratios tend to cluster around the Redfield ratio of 106:16:1. Harrison et al. (2004) report that the C:Si atomic ratio for three species of nutrient-replete (non-limited) marine diatoms ranges from 5.8-9.4:1. So, unless the carbon credits for the activity are high, it seems unlikely that this buoyant fertiliser method could profitably do more than offset to a minor degree the silicon deficiency in most Si-deficient ocean areas, even though a proportion of the silica in the frustules of diatoms and minerals is recycled.

The second reason why moving rapidly towards sustainability is vital, is that every extra tonne of greenhouse gases that is emitted over what is soon safely sequestrated increases the likelihood of a cascading succession of positive feedbacks that may well cause catastrophic changes that even deploying technology, such as this ocean fertilisation one widely and rapidly, is unable to prevent. It is this reason that has validity, rather than the dubious one that biosequestration by any method might spuriously be perceived by some to give a moral licence not to reduce, to continue, or even to expand our extraction and consumption of depleting fossil fuels.

The third reason is simply that, on Earth, many of the high-quality mineral resources on which we depend for other purposes are being depleted as we extract, transform, use, then discard, them into oft-polluting forms and places, and into grades so low as not to be economically recoverable. This reason for conservation of high-quality mineral reserves, together with the ability of marine organisms to extract nutrients from even low-grade mineral resources, are why it is important that only wastes, unprofitably-low-grade or uneconomically-combined mineral resources be permitted to be used for ocean fertilisation.

### Flake Quality Control and Plume Identification

Fertiliser flake is likely to be made in several locations, using materials from many different sources, and to many different specifications. These differences may designedly be used to identify: whose flakes they are; when and where they were disseminated; the rate at which they released their fertilisers; and their longevity. Thus, even in the unlikely event of fertiliser plumes merging at their edges, a boundary between them might still be scientifically determined.

### Flake Rafting

Except when beached or meeting an ice barrier, it is thought that flakes would be unlikely to agglomerate into dense or mixed rafts for two reasons. At macro scale, each flake and each plume of flakes would tend to be acted on in similar fashion by winds, currents, and wave action. Thus, they would tend to move in concert rather than differently. At micro scale, the accumulation of slightly-negatively charged algae growing on the flakes would tend to repel other flakes electrostatically, though this last effect might be countered somewhat by flakes borne by breaking waves or wind falling onto other flakes, to which they might then glutinously adhere by virtue of their attached algae. On beaches, against ice floes, and jostling against each other, flakes would tend to break up into nutritious sand under wave action, abrasion and ultraviolet light.

Whilst winds in a particular direction may tend to generate aggregation of disseminated flakes into bands on the surface by the Langmuir effect, these should have negligible effect upon the distribution of the ultra-slowly released nutrients into surface waters for several reasons. First, the Langmuir bands and the spaces between them are typically of widths of only some metres. Second, the slowly writhing bands themselves tend to move slowly over the ocean surface, thereby moving bands that contain flakes to ocean surfaces where they were absent a little time earlier. Third, there are always at least slight variations in wind direction over time. Therefore, Langmuir bands that do form will continually be breaking up, reforming and re-aligning to cover different parts of the ocean surface. And fourth, there are other forces at work that will tend to disseminate temporary aggregations of flakes and to distribute their released nutrients more evenly. These include entropy, flake buoyancy differences, up and down-welling, blowing spume that contains flake, rainfall, hail, gyres, eddies, cross-seas, gusts, currents, breaking waves and wavelets, and disturbances at the surface caused by marine organisms, birds and vessels.

### Flake Sponginess and Surface Area

The porosity of the rice husks, the finely-divided form of the mineral particles, and the voids and fissures initially made, and progressively forming, between dissolving mineral particles and lignin would ensure that the surface area of each flake remained large compared to its bulk dimensions. This in turn would ensure that even the least soluble mineral fertiliser component would be exposed to dissolution by seawater, ultraviolet degradation, extraction by ligand, or nanoparticle consumption by microorganisms. Some microorganisms might well take up sheltered residence within such pores and fissures.

### Flakes, Bubbles and Foams

A paper by Aziz et al. (2014) at UCL proposes that ocean surface albedo, and hence global cooling, might be enhanced by the generation and dispersal of long-lived but biodegradable reflective foam. This concept might be used synergetically with the distribution of buoyant flakes. The prospective synergies are several: the same vessel might be used for concurrent dispersal of both foam and the flakes, with the foam being disseminated either pneumatically from the stern of the ship or piped just fore of the submerged propellers; parasitic heat from the vessel’s propulsion system might be used to warm an agitated mixture of seawater and the surfactants to a temperature of ~900C whereupon energy-efficient fluidic oscillator (FO) bubbles of air of millimetre-plus diameter could be injected to produce the foam; the foam might create additional habitat for microorganisms; long-lived nanobubbles (with durations measured in weeks) or microbubbles might also be produced by FOs (possibly using the ‘free’ pressurised ship’s engine exhaust gases after vortex removal of its particulates to generate the FO bubbles), without necessarily requiring surfactants, and having the additional major benefit of reducing the impedance caused by a vessel’s passage through the water, and thereby of improving its fuel-efficiency, speed and sustainability; some half of the bubble-prolonging surfactant material might be sourced from proteins and fatty acids extracted from marine microorganisms attached to flakes that are harvested and processed progressively by the vessel from earlier disseminations, the denuded flakes then being returned to the ocean surface to continue their fertilisation role; should there be good value in them, other fractions from the organisms might be retained and processed for sale; and finally, the skimming off the ocean surface of the flakes might be used also to capture buoyant ocean pollution, such as harmful plastic items. The plastic and other floating material would then be separated from the flakes, possibly processed further on-ship, and stored for subsequent sale or safe disposal. Particularly suitable areas for such collection would be the gyre containing the Great Pacific Garbage Patch or Pacific Trash Vortex that is located in the central North Pacific Ocean and in the other such oceanic gyres. Some vessels might even be made capable of transforming the plastic into suitable forms of marine fuel.

### Legality and Opportunity

Most countries have signed the UN Convention on Biological Diversity (CBD) and although the members agreed in 2008 to a temporary moratorium on ocean fertilisation, the moratorium was conditional upon further research. It can be argued that that research has now been done by the Alfred Wegener Institute and other organisations and that trials have demonstrated that there are strongly beneficial effects, with no apparent deleterious effects, of such fertilisation, particularly once the fertiliser is changed to a buoyant one, made largely of natural materials and wastes that release their fertiliser ultra-slowly.

It should also be noted that the CBD itself has now been recognised as going too far and is likely to be either amended or superseded, see Abate and Greenlee, 2010. The next logical step is to conduct progressively more and larger trials, preferably using more-natural, slower-release, yet more economical and sustainable fertilisers and better delivery systems, over progressively longer terms, thereby meeting aspects of the precautionary principle. This new fertiliser is what a company could offer, although its customers may have to accept that there would be parallel, monitoring and R&D activity by an international scientific organisation of their activities. Presumably, this could also help to improve the mariculture process and to provide independent proof of the effectiveness of the biosequestration, thereby possibly allowing the generation of substantial carbon credits.

It can also be argued that carbon dioxide concentrations have been rising to dangerous levels so rapidly that this form of ocean fertilisation may be the single best, safest, quickest, cheapest and most easily achievable method of limiting its further rise, thereby giving us time until this and other methods can be implemented further to help stabilise and then reduce concentrations. Otherwise, the steep rise in CO2 concentration, both in the atmosphere and oceans, *will* continue to cause increasingly severe reductions in global biodiversity and fish stocks, together with increases in global warming, extreme weather, coral bleaching, sea level rise, and ocean acidification under the continuation of business-as-usual (BAU) activity.

It may also be useful that the 1992 UN Framework Convention on Climate Change (FCCC) asks Parties to promote the enhancement of natural carbon sinks and reservoirs, including the oceans and marine ecosystems, where appropriate. The 1997 Kyoto Protocol asks the Parties to protect and enhance carbon sinks and reservoirs, and to research, promote, develop and increase the use of sequestration technologies. Despite it only dealing with land-use practices, perhaps using minerals derived from the land to enhance sequestration in earth under the sea might be included. Participating organisations would then just be following these exhortations. Carbon credits, or emission reduction units from these activities, and their trading are authorised under Kyoto.

In a 2002 paper <http://iospress.metapress.com/content/l3nrrdt64f6v0cb0/fulltext.pdf> Dr Julia Jabour-Green notes that there are six key issues regarding the political and legal aspects of open-ocean iron fertilisation in the Southern Ocean: substance, action, intention, consequences, location, and jurisdiction. Our system appears to clear all six implied hurdles. A 2010 paper by Abate and Greenlee makes complementary and supporting points, as well as some useful suggestions for the proper governance of ocean fertilisation proposals and activities <http://www.academia.edu/2296425/Sowing_Seeds_Uncertain_Ocean_Iron_Fertilization_Climate_Change_and_the_International_Environmental_Law_Framework>.

### Benefits of Slow Release Fertiliser

The ultra-slow release of the buoyant flake system is likely to be particularly appealing, as this should allow predator zooplankton species to increase concurrently, thereby preventing eutrophication (oxygen deprivation) by the collapse of an algal bloom. It also helps match the nutrients released with their complementary counterparts resulting from ocean mixing, atmospheric deposition and upwelling. Slow release may also prevent toxic species predominating, as they might tend to be out-competed by species not investing metabolic energy in toxins or being partial to hypoxic conditions. Slow release may well deter species that can develop toxins from doing so, because like some bacterial species, they may tend only to develop the latent capability when their chemical intercommunication system detects that they are in sufficient concentration to mount an attack that is likely to overwhelm its target, be it a prey organism or competing species. In a balanced ecology, this is less likely to occur. Slow release is also likely to produce an ecologically-sound diversity of phytoplankton and zooplankton species that prevents the occurrence of plague concentrations and sudden diebacks. The slow release of the fertiliser may be prolonged even further by the incorporation of some larger particles in the mineral mix or by the incorporation of smaller particles inside a closed-cell lignin matrix. The former is due to their relatively smaller surface area to mass making dissolution take longer – and vice versa. The latter because it would take time for the lignin matrix to be abraded, degraded or consumed, thereby exposing the mineral particles. Most of any released lignin is also likely to biosequester carbon over long terms, because of its high resistance to chemical and biological attack and because of a study by Strand et al. (2009) on recycling crop residue carbon to deep sea sediments and one by Glover et al. (2013) on the exceptionally well-preserved anthropogenic wood observed on the Antarctic seafloor.

A long-lived, continuous, slow-release, buoyant fertiliser that delivers iron, silicate, phosphate and minor but important nutrients to surface waters is likely to be particularly effective and efficient. This is so because the phytoplankton that it feeds can therefore take advantage of whatever water column mixing and upwelling that occur to bring nitrogenous and other nutrients to the surface, as well as them being able immediately to use those nutrients that fall continuously from the sky or which are generated by nitrogen-fixers and digestion. In other words, there may be several constraint-removal or multiplier effects operating in concert. Carefully selected flake supplementation could therefore transform the vast areas of ocean that are currently either permanently or seasonally oligotrophic (~barren), because they lack one or more of the key nutrients, into productive, carbon sequestering and reflective ones.

The flake-based release system is likely to be particularly effective in making iron available to microorganisms, as the flakes keep the iron mineral right at the sea surface, where photochemical reactions that release soluble iron from iron ore (typically haematite) particles are strongest (Morel et al. 1991). It is a phytoplankton’s cell-surface-based, Fe-transport ligand proteins that extract the soluble iron strongly from seawater or ‘insoluble’ iron from solid surfaces. The ligands may resemble the hydroxamate siderophores of terrestrial bacteria, but are attached to the phtytoplankton’s outer cell wall rather than released into the environment. The ligands occur in inverse proportion to the amount of iron present. They are highly effective at extracting needed nutrients from minute concentrations in seawater or from much richer solid materials, including suspended nanoparticles and bulk material, such as is embedded in the flakes.

As magnetite iron ore is less-soluble, and thus probably a less-suitable mineral for metabolisation by microorganisms than is haematite, ores containing magnetite in significant proportion might be oxidised to haematite by roasting them in air to around 4000C, before their adhesion to the husks. This oxidation should be beneficial, even though oxygenated seawater will tend to convert the more soluble Fe(II) to the highly insoluble Fe(III) form (Martin, 1990, citing Sung & Morgan, 1980). However, care must be taken with the roasting if there is apatite present, as, in the presence of alkaline oxides and silica, apatite can lose its phosphorus by the evolution of toxic P2O5 gas at temperatures above 8000C.

### Feed Depth

The depth of feed on the input conveyor belts may be varied by varying the depth the bottom of the hopper is above the belt.

### Material Delivery

In order to separate the husks, at the end of the input conveyor belt the husk stream strikes an adjustable, shaped bar or vanes that help spread the husks more evenly over a tray in which there are regularly-spaced holes, rather like those of a colander. The tray is vigorously vibrated vertically to keep the husks in air suspension. By this means, each husk will find its way to one of the colander’s well-spaced holes that are made just large enough to allow the largest husk to pass readily. There is thus maintained a shower of well-spaced husks that is much wider than it is thick. The husks are therefore much less likely to stick together when they become coated with lignin glue that there own heat has made sticky.

### Heating Fine Control

Near the exit end of the oven, banks of light pipes or infra-red lamps and sensors could provide fine control over the temperature of the raw husks. The lamp emissions might be able to be tuned to those wavebands that are absorbed by rice husks, in order to minimise power usage. Similar banks of lamps are suspended above the vibrating trays to bring the temperature of the husks to around 2000C, which is below their carbonisation temperature, although it may affect their wax coating and hence their water-repellent properties. This additional heating ensures that, as the husks fall and cool a little, their temperature is still sufficient to melt and adhere their surfaces to the warmed, impacting lignin dust particles.

### Concentrated Solar Heating

The roof area of the big, finished-product silo might be used to collect sufficient sunlight to provide most of the heating to the input materials. Light pipes might conduct the light energy to where it could be focused onto the materials on their conveyor belts and trays, perhaps by long Fresnel lenses. For fire safety, focusing should be to a band, not a line. The power would need to be redirected whenever the conveyor belt slowed or stopped, in order to prevent a fire.

When the unit was not processing husks, or there was an excess of insolation (sunlight), the concentrated solar energy could be redirected onto photovoltaic panels, a boiler or molten salt to generate heat or power for internal use, sale, or storage.

Solar concentration might be effected by one of two methods, both analogous to those used in the solar power industry. One of these uses banks of strip reflectors, something in the form of venetian blinds, with horizontal (as opposed to vertical) slats, laid nearly horizontally to reflect sunlight into one or a few long reflectors that are slightly incurved parabolically on their transverse dimension, such that they direct one or more concentrated bands of light into the material passing below them on conveyor belts. When heating was not required, a photovoltaic strip would be moved to interrupt each light beam, thereby converting the concentrated sunlight into electric power. This method would work best near the equator, where the incoming sunlight angle varies mainly with the time of day, rather than also (and strongly) with the season, which otherwise would require considerable and changing elevation in one or more end of each reflector.

An alternative method uses panels and tracking supports akin to those used for some solar panels. However, instead of the sunlight being converted into power in each solar cell, it would be concentrated by funnelling it into a light pipe leading to the material to be heated. Banks of funnels would be vacuum-formed from thin, transparent, PET polymer sheet into waffled shape. This would be aluminised to provide high, internal reflection. The upper surface of the waffled sheet would then be heat-sealed with a thin sheet of non-reflective, water and dust shedding, transparent, PET polymer. The shedding property may be increased using nanotexturing of either the polymer itself or by implanting a nanotextured mineral, such as silica or titania. Ventilation holes or pores may be formed in the PET sheets to allow for the egress of hot air. Each funnel at its widest would be in the form of a square, rectangular or close-packed hexagon. As it narrowed, it would become circular in cross-section. Its end would be inserted into a tubular light pipe that would conduct the light to where it was required. At its widest part, each funnel might be 9-49cm2 in aperture. Each might narrow to, perhaps, 0.025-0.25cm2 depending on light-piping techno-economics. The light pipes might be arrayed in a matching, waffled, polymer-sheet bank. Into this bank would be inserted the bank of slightly-narrower funnel ends. Nearly 100% internal reflection should ensure that little energy was lost in transmission. For neatness and protection, light pipes leading from a bank of funnels might be placed in their own, ventilated conduit.

### Benefits of Reducing the Tower Pressure

It may be useful to have the tower operate at reduced, internal pressure, so that there are weaker air eddies inside to displace some of the streams of light husks and dusty inputs, and to reduce heating costs. This might be arranged simply by having a semi-sealed tower and strong extractor fans pulling out the used air through large-area filters. To prevent filter clogging, slowly-moving filter material might unroll from a reel, to pass over the exhaust flue. With care, little air would penetrate through the material in the hoppers. Thin air inside would also reduce fire risk.

Whilst reducing tower pressure somewhat will reduce the chance of explosion and conflagration, to reduce these still further, nitrogen gas might be used for the atmosphere within the tower.

### Electrostatic Precipitation

It may be possible to place static charges on the husks and opposite charges on either or both the lignin and minerals, such that like particles will repel like, but oppositely charged surfaces will attract each other, thereby ensuring better coating and less waste. This technique is used in spraying automobiles to reduce waste and pollution.

### Dust Stream Separation

Similar to the husk stream, the lignin and mineral streams, coming off their respective conveyor belts, are intercepted by shaped and angled vanes that cause each dust stream to separate into several separate streams and to billow turbulently. This helps ensure better coating of the husks.

### Lignin or Sodium Lignosulphonate

Ligniniferous material may be produced by more than one process. Acceptably pure lignin may be derived from lignocellulosic material, including rice straw, via the removal of cellulose and hemicellulose from it by hydrothermal, chemical or biological treatment. An economical way would be for it to be treated with subcritical water to free the lignin oligomers (see a separate invention).

Sodium lignosulphonate is a waste product of one type of paper pulp production that uses harsh and polluting chemicals. For our purposes, it is likely that relatively pure lignin will be the better adhesive in a marine environment. Fortunately, the pure lignin is currently of less commercial use for most other purposes, though this will change.

### Lignin Modification

Lignin can be rendered less thermoplastic, and consequently less suitable as an adhesive, by its source, by the method of its derivation, by either chemical or heat-mediated repolymerisation. Unless treated, freed lignin by itself is thermally unstable. Lignin that is newly-severed from its lignocellulosic matrix may be treated with a methylating agent, such as dimethyl carbonate (DMC), to render it suitably stable, thermoplastic and adhesive. In turn, DMC may be produced sustainably and cost-effectively from kiln-dry lignocellulose, anhydrous methanol and CO2 by the Winwick DMC Synthesis (WDMCS) method (see separate document).

Cereal straw is likely to be the optimal source for lignin for use in buoyant flakes, though other low-protein, low-nitrate and low-ash sources, such as corn stover, bagasse, wood chips, nut shells, reeds, grasses, and newspaper are also likely to be good sources. Of the many possible methods of lignin separation, only some do not render the lignin suitable as a seawater-insoluble, thermoplastic adhesive. Amongst these treatments are: enzymatic hydrolysis, various organosolv methods, ionic liquids, and some hydrothermal methods. Other methods tend to produce unsuitable lignin.

The method to be considered here combines the organosolv, hydrothermal and Winwick Drillhole reactor (WDR) methods for: separating lignocellulose (straw) into its three constituents (cellulose, hemicellulose and lignin); dissolving the hemicellulose into a soluble fraction ready for further depolymerisation into its constituent pentose sugars; dissolving then stabilising the lignin; and leaving the cellulose fibres either intact or depolymerised and dissolved into its constituent hexose sugars, whichever may be required at the time.

The theoretical basis for this is a combination of the Acetocell and the Winwick Hydrothermal Liquefaction (WHL) processes. These are given additional capability by the use of dimethyl carbonate (DMC) and use a mixture of anhydrous acetic acid and methanol as the solvent. Under certain, relatively mild, WDR conditions, the solvent dissolves the hemicellulose and acid-soluble lignin from the lignocellulose. The presence of a calculated small proportion of DMC has the effect of methylating, and hence of stabilising, the reactive sites on the lignin as it is dissolved or chemically cut from the lignocellulosic matrix. The hemicellulose is partially depolymerised in the process into its oligomers and monomer pentose sugars. When the now-solubilised hemicellulose and stabilised acid-soluble lignin are together dissolved away from the cellulose fibres and residual alkali-soluble lignin, these liquid and solid fractions may be separated by simple filtration. The fibres may then be used for paper-making or the cellulose content may be enzymatically or otherwise hydrolysed to glucose, leaving behind the acid-insoluble/alkali-soluble, or Klason, lignin. This typically represents approximately 90% of the total lignin in the lignocellulose. As Klason lignin is soluble in alkali under mild conditions, it can be thus be dissolved in alkali, with DMC to stabilise its liberated fragments, and then precipitated as a powder via pH change using pressurised CO2. Powders of the two kinds of liberated lignin may then be combined for the purpose of binding minerals to husks to form buoyant flakes. The high temperatures (~2000C) involved in the binding process may tend to polymerise the lignin further, despite its methylation, rendering it even less soluble in seawater and longer lasting as a deep-sea carbon store.

The processes are designed actually to proceed as follows. Kiln dry straw or chaff and a powdered dessicant mixture, such as that of silica gel and type 3A zeolite, and a catalyst are mixed into a mixture of warm, anhydrous acetic acid and methanol. The resulting slurry is pumped down the inner tube of a WDR, along with fluidic oscillator-generated microbubbles of a mixture of CO2 and possibly nitrogen. As the slurry descends, it is heated by heat exchange, adiabatically, possibly exothermically and, at nanoscale by decavitation. The CO2 dissolves into the liquid under increasing pressure. The slurry also progressively increases in temperature as it descends. At around 800C, and with catalytic assistance, the dissolved CO2 begins to react with the methanol to produce dimethyl ether (DMC) and water. The water is selectively absorbed by the zeolite, thereby favouring the forward reaction. Whilst at atmospheric pressure, DMC will tend to begin breaking down into DME and other undesirable products above 1150C, the high pressure in the lower part of the WDR should tend to prevent this from happening. At far below methanol’s critical temperature (2400C), but probably well above its critical pressure (78.5atm), first the hemicellulose and then the lignin begin to depolymerise and dissolve in the solvent mixture. The released lignin is largely prevented from repolymerising and redepositing because the newly-formed DMC reacts with the lignin’s newly-broken bonds, thereby methylating them and stabilising the dissolved lignin so that it remains in a form that is separated from the cellulose fibres and one that is in a potentially thermoplastic and adhesive form, suitable for binding rice husk to mineral particle.

On the upward, outer passage, vanes spin the slurry such that the solid dessicants, catalysts and cellulose fibres migrate centrifugally towards the outer wall, any emitting gas migrates inwards, and the liquid fraction, together with the dissolved hemicellulose and lignin, remains midway between the two. The trace amount of residual DMC liquid (S.G. 1.07g/ml) will mainly reside in this liquid phase. At the surface, the gas, liquid and solid components are separated whilst still under pressure. Desirable components are recovered from the gas. The hemicellulose and lignin components are separately removed from the carrier liquid by selective precipitation, filtration and evaporation. The solvents are recycled. The hemicellulose, its oligomers and monomers may then be converted by special enzymes or microbes into C5 sugars or alcohol. The cellulose fibres may be washed to clear them of powdered material, or else be enzymatically hydrolysed into glucose, which can then be drained away from the dessicants and catalyst. These last are then washed, dried and recycled.

Recently, an improved variant of the organosolv process has been developed by Dominguez et al. in patent WO/2012/110231 that should form powdered lignin with near-optimal properties for flake usage. The method is called OrganoCat. It uses two solvents, aqueous oxalic acid and 2-methyltetrahydrofuran (2-MTHF) to partly depolymerise, dissolve and separate the hemicellulose and lignin components of lignocellulose from the solid fibres of cellulose at temperatures around 1300C and 15bar pressure. Under these mild conditions, the lignin is very little degraded and hence is likely to retain both its thermoplastic and its slightly alkaline water (as in seawater) insoluble properties. The C5 sugars from the hemicellulose remain dissolved in the aqueous fraction, lignin powder precipitates when its solvent MTHF is evaporated from its separate liquid phase, and the cellulose fibres are strained off first. Promoted by the energetics of decavitating microbubbles and the much higher passive pressures in a Winwick Drillhole Reactor, both the energy inputs and the time for the reaction to take place (typically 2-6hrs) might be dramatically reduced, even without initial fine pre-comminution of the preferred, straw biomass input.

### Sourcing of Mineral Ores

There are many prospective sources of iron minerals that are unsuitable for the production of metal. These are *just* the ones that should be considered for the purposes of ocean fertilisation. Some of these sources are not mineral deposits, but are by-products or wastes from other processes or uses. Typically, these will either be too low in iron content, or too contaminated with undesirable elements, to be worth refining into metal. They might contain from 15-50% Fe, but those with undesirable elements for metal production, such as sulphur, silicon, aluminium, titanium, calcium, and phosphorus, might be even higher in iron content. The sources include the following: low-grade or uneconomic iron ore deposits, such as ironstone, limonite, serpentinite, saprolite, laterite or lateritic soil; iron-rich waste material from ore beneficiation processes, the ores being those of several different, iron and iron-associated elements; red mud from alumina refineries; low-grade iron mill scale; unwanted stockpiles of ore; or iron ore from closed, mothballed or marginal operations. Of these, the largest and most widely distributed source would be ironstone and laterite. However, the most economical sources might well be by-product or waste material that has already been extracted, is partly or fully comminuted, is already in the commercial system, and/or may otherwise incur disposal and monitoring charges. Of these sources, red mud is currently the most beneficial and prospective. Using such a source could reduce or avoid increasing the size of red mud tailings ponds. It would control the costs of their monitoring and stockpile re-vegetation. It might even avoid the necessity for rinsing the raw red mud with seawater to reduce its severe alkalinity, as alkalinity is of some advantage in reducing ocean acidity.

The world also has extensive deposits of phosphorus-bearing minerals of which the lower grades, or those which are waste products, or have contaminants that preclude their beneficiation into higher-grade fertiliser or other industrial uses, make them ideal for ocean fertilisation use.

Apart from red mud, crushed low-grade iron ore, fines, ironstone, saprolite, limonite or laterite, all of which are available from many global sources, possibly the best mineral fertiliser source to process is the combined, igneous, phosphate and iron deposits at Sukulu in South Eastern Uganda on the Kenyan border. The deposits are extensive, particularly when there is included the associated residual soils that, at some places, are up to 50% magnetite (Fe3O4), with phosphoric apatites making up another 20%+. There are also some siliceous minerals to complete the requirement.

The total reserves of the residual phosphates at Sukulu have been calculated as 230 million tonnes averaging 12.8% P2O5 (Van Kauwenbergh 1991). Tororo Industrial Chemicals and Fertilizer Ltd mined and treated residual soil there from 1962 to 1977 to produce superphosphate. In 1977 their treatment plant was destroyed, probably by internecine warfare. The ore contains 32% apatite and 57% magnetite and goethite, a most desirable mix for us. The main Sukulu phosphate deposit has yet to be developed (unless action has occurred since 2002), in part because of the high and risky capital investment required in such a politically unstable area.

In addition to Sukulu, there are the nearby Busumbu deposits of phosphate and iron-rich residual soils that were partially mined still earlier. These, like those at Sukulu, comprise both soft rock and hard rock reserves. They total in excess of 8.4 million tonnes, grading around 12.6% P2O5. The key ore treatments would comprise crushing, ball-milling and sieving, though further treatment may also be desirable.

The beauty of our requirements is that these deposits require no very large investment in an unstable area of Africa, and much of the plant and equipment investment there would be readily transportable. Moreover, several of the impurities found in some phosphatic ores (e.g. Fe, Si, Sr, Cd, Mg, Mn, Ca, Zn, K, S, Cl, F, Na, Cu, As, organics and carbonatites) that are detrimental or costly to remove in the production of concentrated phosphatic fertilisers, are neutral or actually beneficial for our purposes. They do not need to be removed. Because of the softness of the residual soil ore part of the deposits, it may well be possible just to scoop out the soil, truck it to the nearby railway line, then transport it 700km through Southern Kenya to the port of Mombasa for drying, comminution, simple magnetic extraction of the purest magnetite particles to be used in steel manufacture, and processing of the residuum into flake.

Because of the very low density of rice husks and the cost and difficulty of compressing them for transportation (unless compressing them flat with heated rollers and possibly boiled rice glue were to work), it will usually be more economical to take the mineral to ports where husks are aggregated and processed into flakes, rather than otherwise, though processing at both ends of the voyage may also be viable, given the backloading possibilities and Mombasa’s proximity to the both the Indian and Southern Oceans. Allowing for the hazard of piracy, Mombasa still appears to be positioned well to access the main rice-producing regions, suitable mineral deposits, solar energy, and Southern Ocean, together with some of the most mineral-deficient, tropical and temperate oceans.

The same bulk cargo ships that transported the treated ore from Mombasa or elsewhere to rice husk processing plants might then take the fertilised and flattened husks to the Southern, Indian, Atlantic, and Pacific Oceans for ocean distribution. The ships might then return to Mombasa in a ‘round’ trip, making only one leg of the three-leg voyage empty. Similar round trips for bulk carriers might be arranged for key alumina ports. One such triangular voyage might lead from Rio Tinto’s Yarwun alumina refinery at Gladstone in Queensland, Australia (possibly then North to Townsville to collect ball-milled phosphorus ore), to one or more Asian ports in Eastern SE Asia or China, to the Southern Ocean, and back to Australia. A similar voyage around the Indian Ocean might lead from Mombasa to rice ports in Southern India, Thailand, Malaysia and/or Indonesia, thence to the Southern Ocean and back to Mombasa. Flake processing facilities in China would give ready access to the Pacific, Indian, Southern and Arctic oceans. If desired, distribution of the fertilised husks might occur in deficient ocean areas throughout two legs of each voyage, that is to say in tropical, temperate and polar seas. Routes could vary to achieve maximum ocean coverage at minimum cost.

The deposits around Rum Jungle, Northern Territory, Australia, may also be good ones to use, possibly in a mix with those of Broken Hill to suit different deficiency conditions. Rum Jungle is only 65km from Darwin and is on the railway line and main road to Darwin and its port. The phosphorite deposits there are of appropriately modest grades that average 11% P2O5 (or 5% phosphorus) and thus probably are not of cheaply refinable quality. Fortuitously, the ores are associated with hematitic (iron-rich) stone, so that both minerals can be obtained from each deposit, although in very different proportions and with different, often useful or important, minor elements. Drilling at Rum Jungle in the 1960s outlined at least 2.3 million tonnes of ore in 18 deposits, but this is likely to be an underestimate of what is there, because the exploration was incomplete. Estimated reserves are 4 million tonnes, with a 6% Fe2O3 component. Korab Resources Limited plans to quarry phosphate there at a place called GeolSec in 2013 to provide finely-ground phosphate rock as an organic fertiliser. Only a plant capable of producing 30ktpa is planned, but presumably this could be expanded to meet a much larger demand. This ore might advantageously be combined with iron-rich, red mud from alumina refining operations at nearby Gove and husks from SE Asia, the Indian subcontinent, or China.

Mixed ironstone deposits containing 30% Fe (iron), 4.5% MnO, 3.2% P2O5 and 5% CaO are available from the Broken Hill district in New South Wales (NSW), Australia. These NSW deposits are also close to good rail and road transport that link them to several ports in SE Australia, the closest of which may be Port Pirie in South Australia.

There are also huge ironstone deposits around Robe River, Western Australia (WA). Similar deposits are found over much of the Hamersley Basin, both 200km East-Northeast and East of Exmouth in WA. They contain iron ore grading up to 60% Fe. These deposits are near the coast, but are not particularly near a port. Onslow, Dampier and Karratha are the closest ports. The deposits are of iron-making grade and thus, perhaps, should not be considered. However, some of them, or the lower-grade ore surrounding them are likely to be of not such a high grade and hence can be considered. Moreover, it is likely that some mining companies have now planned, or are in process of planning and establishing, rail links that might be used to transport this lower-grade ore economically to bulk ships at port, provided that berths can be made available. Trucking may be another, but probably a poorer, option.

With powerful partners, Legend International Holdings (Legend) has well-developed plans to build a multi-purpose fertiliser plant at Mt Isa in Queensland (Qld), using ‘as-mined’ phosphorite ore deposits that exceed half a billion tonnes and are located 100km to the north of the city. The cost of transporting rock mineral from the deposit to Asian ports appears to be around USD$70/tonne. As the cost of extracting the ore is about the same, the cost of raw ore delivered to Asian ports appears to be about USD$140/tonne, though it would be much less if only nearby red mud fertiliser were to be used, possibly as low as $10/tonne delivered. The cost of fine comminution, processing and profit margins would be extra. Thus, even before their fertiliser plant is constructed, raw ore of grade around 15% P2O5 might be delivered to Asian ports, thereby substantially improving the Legend project’s risk profile and profitability. A company might be able to take advantage of these considerations, particularly because the fertiliser plant has struck approval difficulties with the local shire council. The photograph on the cover of the company prospectus suggests that there may also be ironstone deposits in the same vicinity. For details, see http://www.lgdi.net/resources/i/legendpresentation\_sep11.pdf?legend=0b3adbdae09ddb5766ba86448fa25589

For alternative development, one might consider the nearby phosphate resources of the Duchess area of Queensland that may amount to 1,000 million tonnes of ore averaging 17.5% P2O5 (Notholt & Sheldon in Cook & Shergold, 1986). These deposits have ready access to the rail and highway that link Duchess to the distant East coast port of Townsville.

China, Vietnam, Sri Lanka, and India also have substantial phosphate deposits that are already being worked in the region. However, many of these are inappropriate for this use, being of too high a grade or costing too much to transport.

Far distant Morocco rightly claims the bulk of global phosphate resources. Hence, low-grade phosphatic minerals from this source, should they exist, might work well in collaboration with iron-rich mineral sourced from the alumina refining operations or from the existing, red mud tailings dams of Canadian, European or Russian alumina refineries. Rice husks might be sourced from China and North Asia, the Indian subcontinent, Southeast Asia, North and South America, the Middle East, Australia, Japan, the Caribbean or West Africa. Fertilisation could occur from the Arctic Sea, down through the entire Atlantic, Pacific, and Indian Oceans to the Southern Ocean.

Low-grade deposits of iron can be found in most countries. However, establishing the optimal regional and seasonal mixes and the landed cost of minerals may require blending ore from several sources, as well as some experimentation.

Manganese (Mn), strontium (Sr), zinc (Zn), copper (Cu), cobalt (Co), and cadmium (Cd) are other essential trace elements for phytoplankton, although these are not nearly as important as iron (Fe), silicon (Si) and phosphorus (P). Also important are sulphur (S), potassium (K), magnesium (Mg), and calcium (Ca). Tungsten (W) for frigid waters and molybdenum (Mo) for warmer ones, or preferably both together with some copper, are also vital for the production of enzymes needed for methane emission suppression by methanotrophs metabolising dissolved aqueous methane into biomass and CO2. Thus, mineral deposits that contain appreciable proportions of some or all of these elements are particularly desirable. However, these elements may not all be deficient in a given ocean area contemplated for fertilisation. Matching element mixes to counter mineral deficiencies will be important, whilst noting that, for some trace elements, phytoplankton can sometimes replace the function of one with another of the same chemical group.

### Shanghai Central

Of the many locations in the world that could produce the fertiliser flake product economically, perhaps Shanghai in China has the most advantages. Upriver is the greatest concentration of rice producing areas in the world, from which may be derived both lignin from rice straw, and rice husks. China also has access to the twin, global giants of alumina, and hence of red mud, production. China itself produces 21.7Mt/yr, with relatively-nearby northern Australia producing 21.3Mt/yr of alumina, as well as having vast deposits of cheap ironstone and low-grade phosphatic rock suitable for the purpose. Production in both countries might allow profitable two-way, bulk shipping, as well as taking advantage of the iron-deficient areas of the Pacific Ocean, Australian sunlight and southerly territories and EEZs. Lying between China and Australia are also the great rice-producing nations of Vietnam, Thailand, India, Cambodia, Malaysia and Indonesia. It is also noteworthy that some key cities of resource-providing nations, namely Shanghai, Guangzhou, Zhanjiang, Shenzen, Nagoya, Osaka, Ho Chi Minh City, Bangkok, Jakarta, Palembang, Mumbai, Dhaka, Khulna, Miami, Greater Tampa, and New Orleans are amongst those most threatened by sea-level rise, and that effective and widespread ocean fertilisation by this method would limit its harmful effects on these cities more quickly, safely, and profitably than by any other known method. Other low lying cities are: New York, Tokyo, Boston, Singapore, Venice, Guayaquil, Abidjan, Amsterdam, Los Angeles, Jakarta, Hamburg, St Petersburg, Alexandria, Barranquilla, Naples, Sapporo, Santo Domingo, Hong Kong, Calcutta, Hanoi, Brisbane, and Melbourne.

### Mineral Processing in Mombasa

On reflection, it will probably be more economical to process the Sukulu mineral mainly in Mombasa. This is so for ten reasons. First, the ‘soft rock’ earthy Sukulu deposit is likely to have a high percentage of moisture in it. Reducing moisture before the ore is loaded onto a ship will make it both lighter and possibly easier to handle, although it would then become more dusty. Second, heating the ore before despatch would ensure that the cargo included no living matter of concern to customs officials. Third, the average sunlight intensity in Mombasa is 5.87kWh/m2/d versus 4.62 for Singapore (as a port representative in its solar conditions of most rice producing regions), a 27% difference. Solar powered heating is thus cheaper and more effective in Mombasa or Australia with equivalent insolation, particularly when the throughput rate can be allowed to vary to match the input solar energy. Fourth, the material from Mombasa may eventually need to go to many different ports around the world. Transhipping it from Asian ports makes no economic sense. Fifth, land and labour for processing the mineral are likely to be cheaper in Mombasa than in most Asian ports. Sixth, as both the ‘hard rock’ and ‘soft rock’ or earthy residual soil ore from Sukulu will require comminution, it probably makes sense to do this noisy, dirty, and fairly low-tech work in Mombasa where the material reaches its first seaport. Seventh, storing large amounts of both raw ore and finished mineral at Mombasa would allow the just-in-time (JIT) demands of (eventually) many different destination ports to be met most efficiently. Eighth, as both soft and hard rock mineral forms are high in magnetite content, and as high-grade magnetite is so easy to extract magnetically, once the ore has been dried and finely comminuted, it may well be advantageous financially for a mining company to extract a portion of the magnetite for steel-making first. Some of the manganese content might also be extracted at the same time. Profitable extraction of a portion of these minerals is likely to be better than sticking all the ore onto the husks, particularly when that use does not require high-grade material. Ninth, magnetite becomes desirably more soluble when roasted and oxidised to become haematite. Roasting might well be integrated with drying, provided that the drying temperature did not interfere with subsequent magnetic extraction before roasting. For maximum efficiency, energy for warming should come in part from the hot gas exhaust of the solar roasting process. This parasitic energy should be used in a counter-current heat exchange process to dry, warm, and sterilise the incoming ore, before its oxidation by solar roasting in air. And tenth, the Kenyan Government is likely to look more favourably on operations on its soil that provide mineral upgrading jobs and revenues, including possibly that of steel making and forming, rather than just the relatively meagre fees justifiable for raw ore transhipment. Furthermore, should flattening husks, using heated rollers and boiled rice glue be possible to improve the economics of their transportation, Mombasa might also become a centre for producing fertiliser flakes, with consequential logistical advantages.

### Mineral Requirements

About half of the world’s ocean is extremely nutrient-poor (Kallmeyer, 2012). An idea of the potential amount of minerals required per year may be estimated from the fact that global yearly rice husk production is in the vicinity of 100 million tonnes plus (Olivier, PhD thesis *The Rice Hull House*), whilst rice production is about 678 million tonnes. Husk, lignin, and red mud have densities around 0.4, 1.3 and 3.3gm/cm3. They can be bonded together to form a hard, sponge-like or sintered material that floats in seawater that itself has a density of around 1.025. Assuming that the materials are combined in the proportions of 60:15:25, this means that the yearly global production of rice husk could support around 42 million tonnes of red mud (or ironstone or lateritic soil) and apatite (density 3.19) fertiliser in seawater. The bulk density of phosphatic clay waste, 0.9gm/cm3, is presumably roughly the same as finely crushed apatite. Although the husks of other cereals, plus bark, stalk, twig and leafage are less-ideal materials, these too may be used to support mineral fertiliser if required. This being the case, there is no practical limit to the area of ocean that might be fertilised, both continuously and sustainably by this method.

It is instructive that Martin (1990) states in his seminal paper that the whole Southern Ocean could be fertilised for a year with only 430,000 tons of iron, and that this would support the removal of 3Gt (gigatons) of carbon. If all the iron in minerals having 30% Fe content were taken up by microorganisms, this would require only 1.3m tonnes of the iron-rich mineral per year to be processed and delivered on husks. Making some allowance for phosphatic and siliceous minerals and for mineral losses, perhaps 3-5m tonnes/yr might do the job. This is achievable for a relatively modest cost. Fertilising all the world’s iron-deficient oceans might require several times that amount of fertiliser. However, the rewards could be more than commensurately great if catastrophic global warming were thereby prevented.

### Coating the Husks

Rice husk wall thickness averages around 60μm, whilst by one study 50% of red mud mineral particles are less than 10μm in diameter. For the purposes of calculation it is assumed that the mineral particles all have a diameter of 5μm and that the lignin particles are produced or comminuted to have a diameter of around 3μm. Even when melted, the lignin particles are unlikely to flatten out much on their substrates because of surface tension and viscosity. The lignin particles will tend to attach themselves randomly over the substrate surface. They will be made to coat the husk to, perhaps, 67% of its surface area. This would provide good attachment for impinging mineral particles, whilst minimising lignin usage and ensuring that most of the pores in the husk are sealed, and new pores and voids created in the ‘sintered’ material, in order to provide additional long-term buoyancy, as do the gas bubbles in pumice stone. To facilitate a durable attachment, the fertiliser mineral particles may, but hopefully won’t, need first to be cleaned of soluble material, such as sodium hydroxide from the alumina process and sodium bicarbonate or carbonate resulting from the combination of sodium hydroxide and atmospheric carbon dioxide.

In order to maximise the buoyancy of the coated husks, and thereby to maximise the amount of fertiliser that can be carried by each husk, it is important that more tiny air pockets also be formed in the sintered coating. This can be done by building up layers of mineral, using just above the minimal amount of lignin adhesive to connect them. However, as more layers would probably progressively weaken the unit’s integrity, there will be a limit to these. Three layers of each may be the practical maximum achievable. Each successive layer can be added progressively as each husk (flattened or otherwise) sinks in the tower. The second layer of lignin might be made to cover only 50% of its bumpy substrate, whilst the third lignin layer might only cover 33%. This should still be sufficient to allow reasonably close-packing and adhesion of the final mineral coating. Using red mud with coarser grades, or with these separated out, might suggest reducing the number of layers of it to one or two, with the fine grade stuck to, or on top of, the coarse one to provide a longer release period overall, and so that an initial burst of iron fertilisation from the finer particles was followed up with a much slower, maintenance-level release rate from the coarser material.

As coated husks, flakes will cool as they descend, it may be necessary to apply extra warming so that new mineral will continue to adhere to their surfaces. Possibly the best method to do this will be to pre-heat the mineral dust in its hoppers to temperatures of perhaps 2500C or higher as found necessary.

Tiny air pockets would be formed at the husk surface and in the voids between adjacent particles of lignin and mineral. The volumetric composition of the coating of the husk might thus be arranged to be about 30:43:27, air to mineral to lignin. Allowing that perhaps half of the voids might fill with seawater by capillary action, the bulk density of the coating would then be around 1.9 g/cm3. Estimating that the average coating depth on the inner and outer surfaces of each husk is 12μm when compressed and that the average thickness of the husk wall is 60μm, this leads to the density of a coated husk being around 0.8 g/cm3. As this is well below the density of seawater, it allows considerable leeway for effects such as assembly compression, mineral and manufacturing variation, further water intrusion, mis-estimation, and the attachment of relatively dense diatoms, before the assembly becomes so dense that it sinks, thereby reducing its fertilisation effect.

### Flake Buoyancy

Besides the accretion of diatoms, algae and other plankton on the disseminated flakes, small marine species may lay and attach their eggs onto or inside the flakes. These have been known to sink large objects, such as palm fronds. Temporary rafts of flakes might be even more subject to such encrustation, as well as attachment by organisms with dense shells. As both eggs and these are typically slightly more dense than seawater, there is the possibility that enough of them adhering might cause some flakes to sink. Once flakes had sunk deep enough to compress the air pockets inside them, there would be less chance of their remaining nutrients being incorporated into biomass, though each would tend to become a usefully-fast transporter of carbon to the bottom. However on balance, should the likelihood of a significant portion of the flakes sinking because of these effects, then it may be worthwhile to decrease their manufactured density. The density of flakes that have passed through the digestive system of different species should also be investigated, to try and ensure that these, or comminuted particles of them, returned to the surface to do more good.

### Maintaining Husk Separation

As each husk capsule (really a canoe-shaped half capsule or its/their flattened equivalent) accumulates more lignin and more mineral particles, it becomes heavier and therefore sinks faster in the tower. Husks that have not accumulated much extra mass tend to stay longer in the zone where they are able to accumulate more mass. This effect tends to ensure that most husks end up well-coated for each layer. As husks accumulate more non-sticky mineral and cool, they become desirably less adhesive to each other.

### Agglomerations

Overlarge agglomerations of husks or flakes may be filtered off and broken up prior to storage.

### Silo Siting

The giant, temporary storage silos for both husks and flakes might advantageously be constructed to fill the lower part of a small valley or excavation, thus requiring little more than tilted roofing and flooring. Alternatively, the storage silos might be sited between two existing structures, likewise to save on construction cost. Such locations would also help prevent damage or loss by strong winds.

### Excess Production

It is to be noted that most rice mills store rough rice (that includes the husk) and process it daily. At least, that is the practice in the USA. However, should the supply of fertiliser husks outstrip demand at times, or there be better market value for the alternative husk products discussed below, then the fertiliser-coated husks, or just the husks and lignin binder, might be transformed into particle board, bollards, or load-bearing beams and columns. This process can be done by reheating and compressing accumulations of coated husks, possibly with the addition of some lignin dust. Because of its weather, fungal and pest resistant qualities, and formability, the material might also be used for external cladding and put to outdoor and marine uses. Eventual disposal of the products would cause no harmful pollution, although they would degrade only rather slowly.

To construct these products, the preferably still-warm flakes would need to be heated further before being dusted with additional lignin and compressed into the desired forms (extrusion might well prove to be too difficult for all but large items). Cutting the products might require tungsten carbide or diamond-tipped blades, because of the hardness of the minerals enclosed. Husk plus lignin material only would not be so obdurate and might be cut with either saws, rotating or vibrating knives, or by lasers.

### Navigation

Satellite pictures, combined with those of a ship-launched, unpiloted air vehicle (UAV) or drone, would help the navigator determine where next to guide the ship, so that the crew could most effectively fertilise the entire gyre or area. For unstaffed vehicles, this task might be performed remotely, probably using satellite pictures and communications.

### Monitoring

Fertilising-ships’ crews, scientists, and independent monitors would use sensors to monitor the situation in, below, and around the armada, gyre or plume of flakes. Powered submersible buoys with communication capabilities, floating with the current and wind and keeping alongside the flakes, would monitor and report the situation, even in bad weather.

### Delivery by USMV

Fertiliser delivery by bulk carrier may eventually be partly or wholly replaced by a customised means that is able to operate under all conditions, and more economically. This will likely be by Unstaffed Submersible Marine Vessels (USMV). Each of these could take the form of a giant rubber bladder enclosing an aqueous slurry of mineralised husks. Power for the vessels would probably be provided by fuel cells charging batteries that powered motors, sensors, and communications. The vessels would be submarine-shaped and have an internal spine, ballast, fuel, compressed gas tanks, pumps, motors, and air-filled swim bladders. To keep them reasonably rigid, even when empty, they might also have skin-mounted lengthwise ribbing, that is possibly water-inflatable to provide rigidity. The bladders would be constructed in bright, warning colours. Extendable masts might also carry warning flags, beacons, riding lights, sirens, aerials, video links and sensors, as well as the air intakes and exhausts for the fuel cells. In very bad weather or conditions they could submerge below the level of wave action, ships and icebergs.

Instead of delivery being air-blown from a ship, the flakes would be immersed in, and pumped out with, a solution of iron sulphate and other nutritive salts, whose composition is designed for two purposes: to further nutriate the microorganisms and, in concentrated form, to act as a chemical deterrent to damage or attack on the vessel by marine organisms, from seaweed to barnacles, from sharks to killer whales, to seals, walruses, narwhales, penguins and seabirds. Most of the solution might be produced cheaply by the leaching action of acids or chelating agents on iron-rich encapsulated landfills (with reclamation of any evolved hydrogen and other gases). The solution might also be produced economically by depositing iron-rich scrap into tanks of low-grade acids, possibly those derived from power plant and combustion emissions. When necessary, the acidic fluid might be neutralised with plant-nutritive ammonia. Another option would be for the solution to be in the form of treated, but still highly-nutriated, sewage or industrial effluent, though this might be more valuable when used on land.

When the vessel was spraying out the flakes for fertilisation purposes, the spray would first massively be diluted with seawater before it hit the sea surface, in order to avoid harming marine life by its concentration. A small volume of the concentrated solution, with flakes filtered out, could be restricted to the immediate surroundings of the vessel for its own protection.

Even when submerged, the USMV would still be able to pump out flake slurry into the ocean via buoyant hoses. The slurry in the hoses would also be heavily diluted with seawater before its release to avoid harm to marine life. Each vessel might periodically be replenished, on station, by delivery ships or by long-distance, remotely-controlled, mother-vessel USMVs.

### Some Possible Indirect Effects of USMVs

As with many other fixed or floating platforms in the sea, low-lying USMVs would tend to be colonised by a variety of lifeforms, either temporarily or permanently. Even though larger waves would tend to break over each USMV, seals and penguins might use them as resting places and as refuges from predators. The claws, teeth and beaks of these and their predators might damage the fabric of a USMV unless it were made thick or otherwise resistant to such attack. Seabirds and migratory species might use them either as resting places or even as (precarious) nesting sites. As a result, deposits of guano might accumulate on the tops of USMVs until washed away by storms. Despite the deterrent effect of possible releases of concentrated iron sulphate solution, barnacles, macroalgae in eventual marine forests with their own ecosystems might attach themselves to each USMV. It may be necessary to add ingredients to the fabric of the envelope of each USMV to make it tough, unpalatable, slippery and non-fouling.

None of these indirect effects would appear to cause insuperable problems to the operation of the USMVs, though they might somewhat reduce their effective lifetime and streamlining, whilst making a small contribution to biodiversity.

### Fertilising the High Seas Economically

Should a bulk ship that transports the minerals and distributes the flake fertiliser retain part of its fertiliser cargo after the initial distribution in a specific region, then it might distribute the remainder over a varying route back to the port where it collects the mineral (typically the red mud) and/or to the port where it offloads the mineral and collects a new load of fertiliser flake. By varying these routes, a much larger area of the high seas might be fertilised, and re-fertilised as required, reasonably economically.

Should credits or funding to nationally-flagged ships, nations or corporations fertilising the high seas be difficult to arrange, then ships contracted by the UNFCCC, UNEP or United Nations Food and Agriculture Organization (FAO) might be a reasonable alternative. Funds for such activity might be sourced from a per wet tonne levy (per aquatic type?) placed by the International Maritime Organisation (IMO) or UN Security Council on aquatic biomass taken from the high seas.

### Fish Catch Transportation

Fishing fleets will often use a mother ship to aggregate, sort, freeze, transport and possibly process the fish catches of a fleet of catcher vessels. It may be both feasible and advantageous to take advantage of return voyages by the bulk ships that deliver the fertiliser to the ocean, to take back part of the catch with them.

A way this might be engineered would be for the mother ship to place each fish species caught in an insulated, bar- and/or colour-coded, standardised, plastic container, perhaps of roughly the size and shape of a large, domestic fridge, though perhaps somewhat taller. Each container would be attached to two, short, branching cables off a main cable holding perhaps three containers by spring-loaded metal ring clips. The clips would be located diagonally opposite on two of the top corners of the container. Main cables could be joined lengthwise to form a long chain. Such a chain, with its attached containers of fish, could be pulled through the water from one ship to another over whatever distance was required for safety. A similar means could be used to unload the containers at port. Heavy insulation would ensure that the fish remained frozen for the short journeys, even those in tropical waters.

The bulk ship would have one or more powered wheels hanging from tethered cables, each of which wheel rim at its lowest part would grip the main cable and help pull it into the hold through the hatch. Mariners would lay each string of three containers lengthwise in the hold, fore and aft of the space immediately beneath the hold and on top of, or adjacent to, previously laid strings, preferably those of the same species. The reverse process would extract selected strings for delivery at a given port or for transhipment to another vessel. A cable-pull operation might operate out of each hold.

For quality control and pricing purposes, each sealed and uniquely identified container would have attached inside it an instrument that recorded its temperature log and possibly details of its GPS log, catcher and mother vessel, fish species, size distribution, health, biomass weight, and processing details. These details might be able to be extracted electronically without opening the container.

Empty fish containers for return to the mother ships might need to be stacked and secured on deck, around the hatch covers of the bulk ships. The empty containers would be transferred to the mother ships or catchers by the same method, possibly at the same time as filled containers came the other way.

### Whales and fishes

As the mineral-encrusted husks floating on the surface would probably not be palatable, it is expected that whales and fishes would soon learn to avoid consuming them. Consumed in small amounts, the husks, lignin, and mineral particles would probably have little deleterious effect upon these organisms’ digestions.

Whilst it is likely that any small fish nibbling a flake will find both its mineral and its lignin content unpalatable, it cannot be ruled out that slightly larger fish would not consume several flakes whole and that the indigestible components of them could interfere with either their digestion or their buoyancy. Such could result in them becoming less fit. Even should this happen during early ocean trials, darwinistic competition should, in a few generations, ensure that the survivors no longer made such mistakes. The digestive tracts of larger marine species and seabirds should ensure that the flakes pass harmlessly through their guts. However, with many seabirds, the grinding action of the small stones in their crops would probably mean that the exiting, well-comminuted flake mineral content would all be immediately available to phytoplankton and filter feeders, rather than lasting on the ocean surface for months more.

Crustaceans including krill, molluscs, larvae, and small fish would probably find the drifting formations of husks to be both an inviting and a nutritious environment. In turn, these species would attract larger fish to forage there, making the fertilised plume an attractive fishing ground for seabirds, penguins, predatory fish, seals, whales, and humans. The flakes would probably be small enough to pass through the mesh of nets designed to catch fish larger than anchovies, though care might need to be taken to avoid concentrating the flakes. In this sense, the armadas of flakes could act as re-usable bait or burley fish attractant to attract schools of passing fish to be harvested. Of course, if much of the global ocean were sparsely covered in flake, there would be less concentration of marine life in just a few favoured regions.

Scientists have suggested that fertilising the Southern Ocean with iron has the potential to restore its ecosystem. Krill numbers have declined dramatically there, partly due to whaling and overfishing, partly because whales played a crucial role in keeping the waters fertilised with the iron in their buoyant faeces (Smetacek, 2012) and partly because of cumulative iron and phosphate removal by humans in our fish catches. Should krill numbers be restored with our flake-borne fertiliser, then whale numbers should grow faster (harpooners allowing) until there are enough to help keep the ocean as abundant with life, as it used to be.

It is of relevance to note that, because of the economics of prey-catching, the higher the density of prey, the less energy is typically required to locate and catch it (Markels, 1995). Thus, within limits, the higher the density of phytoplankton that can be achieved with fertilisation, the greater will tend to be the productivity of every level above them in the food chain, including that of human fishers.

### Temporal Food Chain Effects

Whilst some beneficial effects of fertilising nutrient-deficient oceanic areas by this means will probably not be observed for months or years, the main beneficial effects on long-lived, slow-maturing species, such as tuna and whales (in the absence of predation by humans), will not be manifested in terms of substantially-increasing populations of mature adults for some fifteen to fifty years. However, the effects should be evident from Antarctic krill and squid population increases some three to four years after widespread ocean fertilisation has commenced (commencement being in early Spring) and fertilisation’s on-going and effective maintenance has occurred. This forecast derives from the concatenated estimations: that it may take a month before the ultra-slow release fertiliser has suffused the top, and most productive ten metres depth, of the water column; that phytoplankton and plankton build-up may take another month; that krill build-up may take yet fifteen more months; and that squid build-up will require two full, growing and reproducing seasons after that. Allowing some overlap of these concatenating processes, the main effect on increasing oceanic biomass and increased carbon flux towards the deep, cold ocean sediments is likely to be observed only some three to five years after widespread fertilisation commences. A similar elapsed time is likely to be required before the fertilisation of nutrient-deficient temperate and tropical waters results in commercially valuable small-fish stocks, such as anchovies, sardines and herring, increasing there substantially. Stocks of medium-sized fish, such as mackerel and salmon, might take another three years, and large, long-lived species still longer.

### Aquaculture in Areas of National Jurisdiction

Many nations claim, or are acknowledged by international law to possess or have rights over, areas of ocean suited to ocean fertilisation. Australia alone has acknow-ledged marine jurisdiction over twelve million square kilometres of ocean, and that is exclusive of most of its claimed Antarctic waters. With similar Antarctic EEZ exclusions, the United States, France and Russia have even larger jurisdictional waters, whilst Indonesia, Canada, the UK, NZ, Japan, Brazil, Portugal, Chile, and Mexico have very substantial holdings. Some other island nations also have extensive areas of ocean under their jurisdiction. It is quite possible that some of these nations, particularly small ones threatened by sea-level rise and dependent upon fishing royalties, will be prepared to license ocean fertilisation and aquaculture rights over some of these areas, and perhaps even over moving plumes of fertilised water that are within their jurisdiction. Alternatively, nation states may decide to perform the fertilisation and monitoring themselves, gaining the revenue for this by issuing fishing quotas. These quotas are often termed ITQs, or individual transferable quotas. They may be purchased by commercial fishers, though sometimes only for a single, or a few, fish species.

It seems less likely that, beyond jurisdictional waters, the benefit of increases in the quantities of pelagic or wide-roaming fish species could be garnered exclusively by those funding the fertilisation activity, though such species caught within their jurisdictional waters should still benefit them.

### Funnels, Eddies and Whirlpools

It has recently been established that there are five giant funnels, eddies, or slow whirlpools, on average about 100km in diameter, in the Southern Ocean. Perhaps seven more have recently been discovered in the South Atlantic. These all carry carbon dioxide-rich water down into the ocean depths for thousands of years. These may be useful locations in which to begin site fertilisation activity that is substantially for biosequestration, as any sinking biomass would therefore be conducted more rapidly away from zones of high metabolic activity and much of the acidic CO2 in the surface water would be neutralised and biosequestered before it descended.

### Patent Protection and Extent

Aspects of intellectual property protection will need to be determined. Patent attorney advice suggests that the fertilisation method is likely to be patentable. However, I have decided that all this potentially valuable intellectual property shall be public property as far as these related papers describe them for the first time. The inventions are intended to be available free to all, in perpetuity, as creative commons property. It is hoped that inventions building on these will similarly be made open source so that we may more quickly and efficiently control runaway environmental threats.

### Surface Warming

It is yet to be determined what is the optimal density for fertiliser flakes to be distributed and renewed in each ocean area and by season. Should they optimally on average cover perhaps 0.2% of the sea surface in an area, then the increase in the albedo caused by both the increase in free-floating or swimming microorganisms near the surface, and those that colonised the flakes, might be significant enough to elevate the temperature of the sea surface and its evaporation rate somewhat, whilst probably decreasing that of the layers for some 100m below the surface. In cold waters, this surface elevation just might be sufficient enough to increase biomass productivity and generally extend the prime, growing season. In warm waters, particularly calm ones, the change in productivity might go either way or cause the local species either to acclimate to the new conditions, to evolve, to relocate or to decline. It is even conceivable that the shading and dappling caused by the flakes might have beneficial effects similar to those provided by terrestrial shade and greenhouses, and by beneficial flashing-light effects that cause phytoplankton to utilise solar energy more efficiently.

The presence of the sun-warmed flakes and plankton would cause the top few centimetres of sea surface to warm more than it would if more of the sunlight were allowed to penetrate deep into the water. This would tend to cool, or heat less, the lower layers and would cause increased evaporation at the surface, resulting in increased cloud formation and increased rainfall downwind. Of course any surface warming effect might well be more than wholly offset by the parallel albedo and carbon sequestration effects. At first sight, such changes would appear to give a net beneficial effect. However, they should be subject to both modelling in advance and field trials in order to confirm these suppositions.

### Albedo Effects

In the Google Group *Ocean albedo modification*, an independent researcher using pixel brightness as a rough surrogate for albedo has calculated from photographs of algal blooms that a bloom increases the mean ocean reflection from 10.6% to 36.7%, a mean difference of around 26%. Much of this additional reflection would be in the green band, because those frequencies are reflected most by chlorophyll-containing organisms, but some would reflect white light from shell-building marine organisms. Estimating the annually averaged insolation in the Southern Ocean as 100W/m2, it amounts to a solar flux modification of 26W/m2 or a 1W/m2 contribution spread across all oceans, as the Southern Ocean is in area only 20.3Mkm2 compared to the world oceanic area of 510Mkm2. Now, we know that approximately 40% of the global ocean area is seriously nutrient deficient and that the averaged insolation of the world is 170W/m2. Hence, if all deficient areas were made nutrient-sufficient, the contribution to increased albedo might be around 18W/m2, which is considerably more than is the current anthropogenic global forcing of ~1.7W/m2. Even if only a third of this potential additional solar reflection were achieved by ocean flake fertilisation over the next fifteen years, the contribution to reducing global warming by this effect alone could be 6W/m2, or 3.5 times that currently being caused by anthropogenic forcing. However, because there would not be dense blooms (because of predation in a balanced ecosystem), but only substantial increases in marine biomass, the effect might be just 1.5 times the effect of anthropogenic forcing. As there is always the chance that even such a significant reduction in solar energy absorbed by the world might be overwhelmed by causes such as positive feedback resulting from other global warming determinants, it is well that the oceanic albedo could be ramped up substantially, should such undesirable events threaten or begin to occur, as some have already done.

For the past three centuries, the global albedo in the visible spectrum has been undergoing major anthropogenic modification by means of: desertification of land & sea, land clearance, loss of sea and glacial ice, lake shrinkage, land salination, snow darkening, eutrophication, plastic waste, stratospheric sulphate aerosols from burning dirty fossil fuels, peatlands and forests, road and city growth, particulate and gaseous emissions – some, but not all of these, serving to increase albedo. However, the mixed effect of these has been overshadowed by retention in the infra-red spectrum of heat, caused by major increases in greenhouse gases. Together, these effects have caused weather patterns to change, albeit in complex and not well understood ways. Better modelling is required to understand the complex effects of these and other processes.

Care will needs be taken that widespread ocean fertilisation has net positive effects. Fortunately, there are likely to be fewer adverse regional effects the more globally disperse is the fertilisation – and the 40% of under-nutriated ocean areas are well-dispersed around the globe. This is likely, as a general increase in albedo should have fewer and less-intense local and regional effects than would be caused by only local or regional changes in albedo and their effects upon neighbouring regions. Fewer adverse regional effects and improved global effects should also mean less litigation and diminished tension and conflict amongst neighbours.

There should be exceptions made to such general dispersal of oceanic flake fertiliser, as modelling should be able to show us where fertilisation might best be used to offset current, regionally-adverse effects of decreasing albedo and of increasing extreme weather events. Examples of these might be: to use fertilisation’s albedo effect (including that of additional cloud formation via increased DMS production) to offset the loss of high-albedo sea ice, and at the same time to cool the over-warming water near the poles; also to mitigate the increasing temperature of surface waters, where this contributes to hurricane intensity, by increasing marine cloud and ocean brightening (these effects overwhelming that of the flakes solar-warming the top several centimetres). An example of where fertilisation should be avoided is where it could adversely affect coral reefs due to excessive and smothering algal production, even though it might help reduce coral bleaching. In such cases, fertilisation should only take place sufficiently upwind or up-current that predation, fishing, dispersal and sinking are able to reduce algal concentrations sufficiently that they do not hurt the coral, prior to the plume reaching the reef. By this means, the water could be both cooled and reasonably-well clarified before it reaches coral reefs. Note, that it may also be the case that the algal species flowing onto coral reefs from such fertilisation may not typically be those that are particularly dangerous to corals, indeed they may well help to feed the coral polyps. Species likely to be dangerous to coral are those that form dense algal mats. Generation of these may be partly avoided by the careful choice of the fertiliser mix and distribution site.

### Net Cooling Effect of Changes in Greenhouse Gas Concentrations and Albedo

The additional phytoplankton produced by ocean fertilisation does not only reduce the oceanic and atmospheric concentrations of the greenhouse gas (GHG) carbon dioxide, but it also probably increases the concentrations of water vapour, methane and nitrous oxide (N2O), all potent GHGs, whilst increasing global albedo by means of elevated oceanic chlorophyll content, cloud cover and brightness, and DMS-derived sulphate aerosols. Although most oceanic methane is produced by methanogens from sedimentary biomass under anoxic and sulphate-depleted conditions, some of it will eventually find its way into the atmosphere. Nitrous oxide is generated from decaying biomass in the Nitrogen Cycle in the part of the cycle called denitrification. Some of this gas also finds its way into the atmosphere, where it has a residence time of around 120 years and also contributes to global warming. Its effect is over 300 times that of the same amount of carbon dioxide. The amount produced by the oceans is relatively minor, being only about 20% that produced by the total from soils, fertilisers, cattle, feedlots, industry, fossil fuel and biomass burning (unless increasing methane clathrate melting as a result of global warming reverses these proportions). Nonetheless, its contribution to global warming will become more significant when ocean fertilisation increases the amount of phytoplankton in the ocean, probably by many times. Fortunately, modelling and tests should confirm that the global warming effect of the extra methane, nitrous oxide and water vapour in the atmosphere, caused indirectly by ocean fertilisation, will be many times offset by the parallel changes to global albedo increase and to atmospheric carbon dioxide reduction.

The temperature effects of increasing cloud cover depend upon their coverage, density and type or altitude. Critical also is the degree of mixing amongst atmospheric layers. In *Nature (2014)*, Sherwood et al. report that whilst low cloud cover gives a net cooling effect via its reflectivity, increases in mid- and high cloud cover has a net warming effect because of its longwave (heat) absorption. Thus, our system that provides greatly increased ocean surface and low cloud reflectivity, whilst little in the way of extra high cloud absorption, may have the best of both worlds.

### Methods, Effects and Costs of Increasing Global Albedo

Compared to other methods of changing the world’s albedo, such as by stratospheric sulphate aerosol injection or space shields & mirrors, using phytoplankton to do this is much less risky. Furthermore, using buoyant flakes to nutriate phytoplankton in order to ‘paint’ the nutrient-deficient oceans emerald green from their typical dark blue and to initiate marine cloud brightening, are methods likely to be both more cost-effective and natural than is, for instance, painting roads and roofs white.

The DMSP produced (~1Gt/yr) and released by varieties of marine organisms, chiefly macroalgae, diatoms, dinoflagellates and haptophytes, is transformed into DMS. In turn, a portion of this (Johnston (2015) in *Science* reports that the amount is in excess of 0.01Gt/yr) finds its way into the atmosphere where it is oxidised, from whence it nucleates ice, snow, fog and rain. The first three of these serve to extend and brighten marine clouds, particularly when their nucleators are located at altitudes and in regions where there is excess water vapour. Such nucleation also may serve to reduce or retard the formation of larger water droplets and the heavier ice particulates. In turn, this may well serve to delay their precipitation, thereby allowing time for the prevailing winds to carry the marine clouds over land. Marine Cloud Brightening (MCB) may thus be an important driver of increased terrestrial snowpack and rainfall, whilst at the same time tending beneficially to reduce the damaging severity of extreme precipitation. Due to the high albedo of marine clouds and their prevalence, they will also be a major contributor to reflecting solar energy away from the planet, and hence of cooling it.

Global albedo may also be increased by at least three new or variant methods: polar oceanic glaciation by means of pumping seawater onto sea ice to thicken it maximally by means of semi-submersible wind turbine power to create linked, ice shield arrays; increasing ocean surface albedo by introducing to it long-lived, fluidic oscillator-produced nanobubbles and microbubbles whose longevity may be increased still further with benign surfactants; and by providing nucleating nanodroplets of saltwater from similarly-produced, but bursting, microbubbles issuing from saltwater-suffused diffusers located on the trailing edges of ship-towed, boomerang-shaped aerostats at the most suitable, cloud-nucleating altitude, the seawater being pumped up the hollow, towing cable by a series of electrically-powered micropumps in the cable, the lightly pressurised and warm gas being taken from the ship’s engine exhaust, after cycloning to remove its particulates. Any acidic content of the exhaust gas, dissolving rapidly in the microbubbles’ seawater, would tend to increase the nucleating power of the nanodroplets, whilst removing it from the atmosphere and thereby alleviating the need for separate, and costly, ship-borne exhaust scrubbing.

### Replacing Nutrients

An argument can be made that this form of oceanic fertiliser supplementation is not so much interfering with the environment as it is simply replacing the nutritive elements that humans have removed, and continue to remove, from the oceans over the past thousand years in the form of fish, whale, mollusc, crustacean, and algal harvest. Such unsustainable activity has already reduced many marine populations down to a small fraction of what there were only three hundred years ago. Ocean flake fertilisation, done carefully, should actually improve global sustainability and biodiversity.

Whilst it may be the case that a substantial fraction of these nutrients have been returned to the sea via sewage, this has typically been delivered to coastal waters. These have thus become over-nutriated, resulting in eutrophication and dead zones, whilst the remote ocean areas have become increasingly denuded of some key nutrients, including iron, silica and phosphate. Implementing flake fertilisation should help to make these remote waters highly productive.

### Methane Clathrates

It may be objected by some, that increasing the carbon flux to the deep, cold-ocean sediments by means of such ocean fertilisation could have deleterious effects upon some forms of benthic life there. This could well happen, because increasingly hypoxic conditions might well result because aerobic bacteria and other organisms consume a portion of the extra carbonaceous material, thereby exhausting much of what little oxygen is made available there by ocean currents, mixing, diffusion and down-welling. Now, hypoxic or even anoxic conditions are desirable if carbon is to be biosequestered for long periods. After all, the sapropelic (organic ooze deriving from marine snow) deposits that form some aquatic sediments and derive from subsurface oxygen deficiency give rise to oil source rocks that biosequestrate carbon for millennia. Hence, this hypoxic change would simply be returning the benthic environment, and its correspondingly-strong carbon flux, to that which pertained some 300 years ago, before humans began removing large numbers of whales, seals, squid, fish and krill from polar seas. Moreover, it is archaean methanogenic microorganisms that have continued, from Carboniferous times, to convert carbonaceous sediments resulting from carbon fluxes into the vast deposits of methane clathrates, natural gas, oil and coal that are to be found around the world, so it can hardly be claimed that this is an unnatural process, or one that inflicts unduly harmful effects on biodiversity. Finally, and to clinch the debate, it is a very poor argument to say that the rest of terrestrial life, including humankind and our very Civilisation, together with all other marine life, should be gravely imperilled or even completely destroyed, to benefit some sparse, oxygen-loving life-forms in some cold, abyssal depths.

### Precautionary Principle

Following the precautionary principle, considerable care and attention is required in putting this concept into operation. The first precaution to be taken is that there be transparency, extensive scientific monitoring and public reporting of modelling results, experiments, pilots, effects, risks and outcomes. The second is that there be parallel research and development to model and improve the entire process at every stage. The third is that no initial use of the technology should extend to more than a few percent of any single and distinct marine ecology. The fourth is that for each later scale-up, none should be greater than one or two orders of magnitude (ten to a hundred-fold) more than its immediate predecessor, preferably around ten to thirtyfold.

In addition, there should be close attention paid to a few, likely or possible side-effects of implementing the concept, harmful, neutral and beneficial. These would include the possibilities: that fertiliser minerals containing a significant proportion of aluminium hydroxide, metal ore at toxic concentration when dissolved and diluted, or other substance that might, even in the resulting very dilute concentration in the sea, adversely affect certain species, without there being greater, off-setting benefits; that herbicide, pesticide and fungicide residues on the husks might be harmful to some marine species even at similar high dilution in the sea; that flakes, plankton and DMS might well cause substantial increments in probably beneficial albedo; and that the mineral types and application regimes might require modification, both by site and by season to enhance the net benefit. Should red mud not have net positive effects, then laterite, ironstone or other cheap and iron-rich rock or benign waste material might be used instead.

Regarding husk contamination by anthropogenic organic chemicals, not only are the concentrations of these likely to be reduced to innocuous levels by dilution in seawater, but the processes that occur to transform the husks into nutritive flakes are such that many of these chemicals are likely to be rendered innocuous by chemical transformation or binding. The processes include: exposure of the diaphanous raw husks to steam and concentrated solar or infra red radiation, followed by further heating to around 2200C; and partial contact with highly alkaline red mud. Should these not be sufficient to mitigate harmful downstream effects, then the raw husks might also be pre-treated with one or more of intense UV-light, ozone, or other passivating agent. Should ozone be selected, then its production might derive from the upcoming generation of low-power, high-efficiency ozone plasma microreactors.

To make the whole concept come together will require the collaborative efforts of scientists, engineers, funding agencies, journalists, diplomats, policy-makers, legislators, leaders, entrepreneurial industry, governmental organisations, NGOs, and the mobilisation of supportive public opinion from around the world. Fortunately, major net benefits are ascribable to virtually everyone under this concept, as well as to this, our home planet.

*Author and inventor: William S. Clarke, CEO Winwick Business Solutions P/L.*