Ocean Seaweed Forests Profitably Remove and Safely Store 2 Trillion Tons of CO_2

Explanations of MS Project Timeline Categories

1. Integrated coastal defense

1a. Refine grow-harvest w-living shorelines

A living shoreline is a natural breakwater such as a coral reef, mangrove forest, a sandbar covered with mussels or oyster, seagrass anchoring sand, etc. Humans need living and artificial shorelines in order to keep living on low-lying islands and coasts as sea level rises. (Avoid mass migrations.) U.S. Army Corps of Engineers, "The living shoreline piece is a part of what we're pushing as a nonstructural, nature-based method that is a lot less costly," said Lt. Gen. Thomas Bostick. This is not a new concept, in 2015, New York Harbor received a $60 million federal grant to build a self-rising oyster breakwater.

In the long-term, growing and harvesting seaweed is essential for coral and mollusk living shorelines by preventing coastal ocean acidification and hypoxia around the living shorelines. These threats were summarized in last April's West Coast Ocean Acidification and Hypoxia Science Panel report. Marine Protected Areas are no help for hypoxia or ocean acidification. The report's Recommendation 2 asks for ways to remove CO_2 from seawater. Our Ocean Forester Project would do so by cultivating and harvesting vast amounts of CO_2-sucking marine plants (seaweed and seagrass) while maintaining biodiversity.

Warmer oceans may be killing mangroves on Australia's north coast. Same for kelp on Australia's west coast. Warming water also causes coral to reject its symbiotic algae. However, integrated seaweed ecosystems with living shorelines can be adapted to future water conditions.

Humanity has many examples of living shorelines and many examples of growing and harvesting seaweed. The combination requires refining of synergistic relationships such that the products from the ocean forest substantially pay for the coastal resilience of living and artificial shorelines in a virtuous spiral: the ocean forest/living shoreline creates jobs; people want to live near their jobs; people adapt their shelter to stay (or even extend out) above rising seas.

1b. Develop initial coastal nutrient management

Humanity's current seaweed growing operations generally use the ambient nutrients. And there are plenty of shores with excess (relative to pre-human conditions) nutrients. Many coasts have ocean dead zones where a burst of nutrients from land cause a microalgae bloom. When the microalgae eventually die, they sink. Bacteria consuming the dead algae also consume all the oxygen in the water, killing any oxygen-breathing sea creatures in the area. This is known as an ocean deadzone. In deadzone areas "initial coastal nutrient management" is using seaweed grow-harvest to remove the excess nutrients along with the excess CO_2.

Most coastal water does not have sufficient nutrients to grow enough seaweed to remove sufficient CO_2 to reduce ocean acidification adequately. We may need ten times the ambient nutrient supply (actually the same nutrients cycled and recycled quickly) to remove 2 trillion tons of CO_2 within a lifetime. Hopefully, a trial seaweed growing operation in Puget Sound will quantify the situation.

Our goal is to distribute just enough nutrients at the just the right time of the year to keep the seaweed growing (and absorbing CO_2) while never too much at the wrong time which could trigger a microalgae bloom. We may need to build fertilizer distribution systems into our living shorelines. Ocean Foresters hope we can manage nutrients distributed as high-protein pellets to fish swimming freely in the ocean forest. The fish would distribute ammonia and phosphates naturally.

1c. Refine coastal defense governance

Developed countries generally have some form of coastal planning, but spread among several agencies. The agencies, with limited resources, are trying without success to balance the interests of coastal dwellers, coastal tourists, commercial and recreational fishing, and sustaining the ecosystem. These existing organizations need to coalesce into city-size Coastal Resilience and Restoration Districts that are adequately funded to develop and implement comprehensive integrated sustainable coastal defense balancing the competing interests.

In developing countries, villages may form Coastal Resilience and Restoration Cooperatives.

Issues for coastal defense governance also include apportioning costs and benefits between the resilience (living shoreline and floating dwelling) infrastructure and the restoration (ocean chemistry and food/energy production). Can the district/cooperative obtain income for its other operations from fish raised inside the ocean forest, but caught outside the ocean forest?

1d. Deploy integrated coastal defense, food/water

Food is worth more ($/lb or €/kg) than is energy. The global food situation may be more urgent than the global climate change situation as the earth will have more people, hopefully peaking below 10 billion near 2050. All 10 billion are demanding developed country foods. Meanwhile, issues involving freshwater exacerbated by climate change plague terrestrial agriculture: heat and droughts withering crops; floods drowning crops; uncertainties about what crop to plant; groundwater depletion; and the like.

Therefore, we expect the best economic return from Coastal Resilience and Restoration organizations to be from food production. Coastal ocean food production will be stepping in to pick up the slack in countries with inconsistent or declining agricultural freshwater supply.

1e. Deploy integrated coastal defense, energy

As we refine "Complete resource recovery" and grow ocean forests beyond the demand for food, some coastal forests can gradually transition to energy production.

Autonomous equipment will be important (especially in developed countries) to enable the desired "loose" management of ocean forests. Loose management is intended to encourage biodiversity with many creatures cycling through the forest. The autonomous equipment allows humanity to harvest exactly the species and age of species which balances the needs of the forest with the need for human food. This ultimately helps ensure the forest is not decimated by a single disease or change of climate.

2. Complete resource recovery

2a. Develop complete resource recovery

Ocean forests rely on complete resource recovery. The mass of nutrients cycling from water to seaweed to food/energy will be many times current global artificial ammonia production. Plus, seaweed needs other elements to grow in addition to nitrogen. People think the ocean has plenty of phosphate. But the amount of seaweed growing in ocean forests will deplete the ocean's phosphate, if the phosphate is not returned to the forest. The same for sulfur, iron, and many trace elements. Humanity needs the nutrients embodied in its wastes beneficially returned to ocean forests and terrestrial agriculture, not eutrophying Earth's water.

Current wastewater and municipal solid waste systems dispose of "wastes". In nature, everything becomes food for something else. Humanity is working back to this natural cycle with efforts to reuse, repurpose, and recycle. The Ocean Foresters are bullish on a combination of hydrothermal liquefaction (HTL) with other processes. Those other processes include anaerobic digestion of leftover carbon in the water effluent, mining the ash (ore) of the left over solid product, concentrating ammonia from the leftover water product, making high-protein fish pellets from the C, N, and P in the water effluent, and reusing the pasteurized water.

Humanity may be well served to continue improving the other processes for more complete resource recovery. Anaerobic digestion produces a 60:40 biogas of methane:CO_2, but leaves substantial carbon and nutrients in a difficult to concentrate form (inside bacterial cells). Higher temperature processes such as incineration, pyrolysis, or the more electrical energy productive form of supercritical oxidation, convert the nitrogen (from protein, ammonia, or nitrate) in the feedstock into nitrogen gas (N_2, 80% of air). It is better to recover all the organic N as ammonia than to destroy it and then use fossil fuels to make artificial ammonia.

2b. Deploy resource recovery in developed countries

Emerging resource recovery systems need a tipping fee for economic viability. Therefore, they are being developed using "waste" feedstocks, like biosolids from wastewater treatment plants and food waste. Developed countries will pay resource recovery facilities $30 to $160/wet ton to take their "wastes" in order to save money relative to other disposal costs. As more resource recovery facilities are built and refined, the cost of operation will decrease with economy of scale. As earth runs out of mined resources (or pollution carrying capacity) the market for recovered products will improve. Eventually, resource recovery facilities will be paying for biomass in order to keep making biofuel, metals, and commercial grade fertilizers.

2c. Deploy resource recovery in developing country situations

HTL can recover energy from many plastics, making it an ideal process (other than its technical complexity) for refugee camps, rapidly growing cities, and places with unsanitary conditions. At a refugee camp, each family could have a private plastic bag lined toilet. A medical facility could encase biohazard waste in plastic bags. New arrivals could immediately have a private restroom not needing flushing water. Every day or two, all wet wastes, mixed with plastic (like diapers) or non-flushable wipes, are picked up by cart. The bags of "waste" may be tossed into the HTL process without anyone ever coming into contact with the "wastes." Income from the recovered products helps pay for the operation.

The benefits of preventing the spread of disease (cholera, Ebola, etc.) to local water systems and not flushing with water, ripple through the water distribution and ecosystems.

2d. Deploy resource recovery for biofuels

HTL works on any wet biomass, even mixed with plastic. This feature allows much more flexibility in seaweed grow-harvest techniques than is possible when cultivating a kelp mono-culture for salad food or even fermentation into ethanol. Much of this deployment task will be devoted to reducing the energy consumption and labor of the grow-harvest arrangements.

2e. Deploy resource recovery for mining

Many plants accumulate metals and toxins (nickel, cobalt, mercury, arsenic, dioxin, …). When the plants are feedstock for HTL, the metals are concentrated in the "ash". The ash becomes ore. Many of our "wastes" contain metals which can be recovered. Areas of earth are plagued with polluted water which could be cleaned by growing plants, if the plants are processed through a complete resource recovery process.

3. Grow and sell food w/o freshwater

3a. Deploy initial food with living shorelines

Humanity is farming seaweed and mollusks for food and other uses. These existing techniques are ready for integration with coastal defense. A certain amount of "just do it" will immediately increase the supply of raw products for subsequent development efforts.

Food production provides immediate greenhouse gas (GHG) and freshwater offsets. Environmental Working Group (EWG) calculates the GHG per kg of food are approximately the same from chicken, canned wild-caught tuna and farmed salmon. All of which are much lower GHG/kg than pig or beef. The sea creatures will consume less water per kilogram of protein than does chicken, pig, or beef. Sea vegetables can have a similar edge in GHGs and a huge advantage not needing freshwater. Sea starches and animal feed would also have lower GHG emissions and freshwater use.

In the long-term, replacing fossil fuels will require so many macroalgal forests that the production of fish sufficient to provide 0.5 kg of fish and sea vegetables per person per day for 10 billion people becomes almost an “incidental” by-product.

3b. Develop and market food-chain products

Food-chain products can be thought of as a “forestry” approach to Integrated Multi-Trophic Aquaculture (IMTA). For example, sea urchins may eat the seaweed. The best urchins would be sold for human consumption. The lower quality urchins become food for lobsters, crab, and fish which in turn become people food. The emissions from free-range creatures in the food chain become well-distributed fertilizer to grow more seaweed. Possible food chains include: seaweed leaf slime (emission to prevent creatures from attaching)-bacteria-mollusks; seaweed-abalone; seaweed-HTL-protein pellets-fish-seaweed fertilizer-seaweed; etc.

3c. Develop and market pharmaceuticals and chemicals

Seaweeds are producing pharmaceuticals and chemicals. Humanity can do more.

It is likely that pharmaceutical and chemical production will leave substantial “waste” material which can become a bulk food, or energy/fertilizer, or energy/protein pellets, or direct food-chain products.

Concentrated CO_2 might be considered a chemical product used for artificial photosynthesis, employ bacteria needing pure CO_2 (without competing bacteria) at room temperature and other microalgae-to-energy systems.

3d. Develop and market bulk food products

Bulk food products include: seaweed feed (for livestock and fish); seaweed flour; KelpButter (a take-off from Plumpy’Nut); and healthy snacks of 3D printed seaweed jerky (fried dulse tastes like bacon). The current bulk product from seaweed is alginate, a food additive.

For this to happen, humanity needs to ensure people and terrestrial animals can digest the seaweed product and will want to eat it. There are Scottish sheep adapted to eat only seaweed. Perhaps probiotics should be included in the seaweed product.

3e. Refine coastal defense systems for the new products

The new products will grow best with new conditions (or the same conditions in a different location). Conditions at each location are subject to changing climate (water temperature, storm frequency, depth). Existing and future coastal defense systems will need modification.

3f. Deploy food production

Climate Change, ocean chemistry, and sea level rise will be impacting different coastlines with differing urgencies. Humanity can use this to stage deploying improvements in the economics of coastal defense.

As we deploy this refined coastal defense with its ocean forests and living shorelines, humanity must keep the forest management "loose". Loose means biodiverse with many creatures cycling through the forest, just as if humans did not exist. Humanity must grow and harvest a lot of seaweed to remove CO2 and keep living shorelines viable. Humanity can allow creatures to eat the seaweed and other creatures to eat those creatures.

4. **Open ocean energy w-food/water**

4a. Develop open ocean energy w-food/water

A February 2016 workshop by ARPA-E (US Department of Energy's Advanced Research Projects Agency – Energy) identified nutrient supply as an important limiting issue for large scale seaweed-to-energy. Consider, if the nutrients are arriving to a stationary ocean forest on an ocean current, the seaweed on the downstream side of the current will be nutrient starved. Of if the seaweed forest is drifting in an ocean gyre, it would quickly run out of nutrients. Possible techniques to address the nutrient distribution issues include: floating "teabags" of anaerobic digestion residues; slow-release teabags of ammonia and phosphate from resource recovery (this concentrated fertilizer might have been recovered from terrestrial "wastes" or ocean deadzones); protein pellets from the resource recovery process with fish distributing the nutrients as feces; etc. Loosely managed means the forest is arranged to allow biodiversity.

Other issues include grow-harvest techniques requiring very little energy. Or techniques using ambient wave, wind, solar PV, and thermal energy. Systems like the Ocean Cleanup plastic harvesting system, where the seaweed and debris migrate to collection points, are needed.

Of course the main question is economics. Ocean Foresters believe the complete resource recovery approach will help create additional products to improve the economics. Things like seaweed and plastic debris harvested and processed as one, removing mercury, mining seawater for magnesium and uranium, etc.

4b. Deploy open ocean energy w-food/water

About 5% of the world's ocean surface would be needed for a "loosely" managed ocean forest to grow 600 quadrillion btu of energy. Since most of humanity's food needs will be met with the coastal defense systems, most of the ocean could become a marine sanctuary.

5. Integrated carbon storage systems

5a. Develop integrated carbon storage systems

The Ocean Foresters would like to see an in-situ test of CO_2 storage as contained hydrate on seafloor. It appears to have the advantages of: no contact with the environment; stability (no possibility of sudden release); easily monitored and repaired; nearly unlimited rate of storage; an unlimited safe total volume of storage; an inexpensive in-situ pre-planned trial with competent partners; and reasonable economy.

The Ocean Foresters would also like to see work improving the economics of olivine carbon capture. Olivine in water reacts with dissolved CO_2 to make rock. Others have already suggested using olivine on the coast where wave energy and biology can speed the reaction while reducing ocean acidity.

The Ocean Foresters are happy to work with any carbon use and storage techniques with some observations:

- When storing whole plants, minimize storing the nutrients needed to grow more plants (i.e. less wood in structures, plants sunk or buried, biochar after high-temp loss of organic N, etc.)
- Consider replacing funding carbon capture at fossil fueled power plants with funding seaweed carbon capture, as long as the seaweed capture has better overall economic benefits.
- Consider building any new power plants with the Allam Cycle. The Allam Cycle's use of supercritical fluids appears to make BECCS much more practical. If the BECCS fuel is HTL-derived bio-oil and biogas, Ocean Foresters would have already recovered the fertilizer.
- Geologic storage injects CO_2 deep into the Earth's crust where it exists as a supercritical fluid until it dissolves in salty water and eventually (hopefully) reacts to form rock. While it is obvious CO_2, methane, and oil have been safely contained for geologic time scales, humanity cannot be sure how any one location will behave when CO_2 is injected. Also, the storage sites are not empty voids. Water must be displaced as the CO_2 is injected (not unlike injecting the wastes from fracking operations). The need for the water to move, without causing earthquakes, limits the safe rate of injection. Dr. Steve Bryant's One Stop Carbon Solution (Scientific American 309, 72 - 77 (2013) is an example of a closed-loop system that injects CO_2 into hot brine brought to the surface from deep underground that could make CO_2 storage economical by providing geothermal energy and methane for fuel.

Most of humanity's carbon storage development funding is going for the exhaust of coal-fired power plants followed by "geologic" storage. In the short-term the CO_2 is used to extract more oil (like a dry cleaning fluid) from old oil wells, a process termed enhanced oil recovery (EOR). Perhaps oil companies should fully fund research on geologic storage while governments shift funding from geologic storage to a more diversified portfolio of carbon storage options, including seafloor container storage.

5b. Deploy integrated carbon storage systems

Humanity need not wait on large scale trials of alternate carbon storage systems. Use the carbon emissions from existing power plants now.