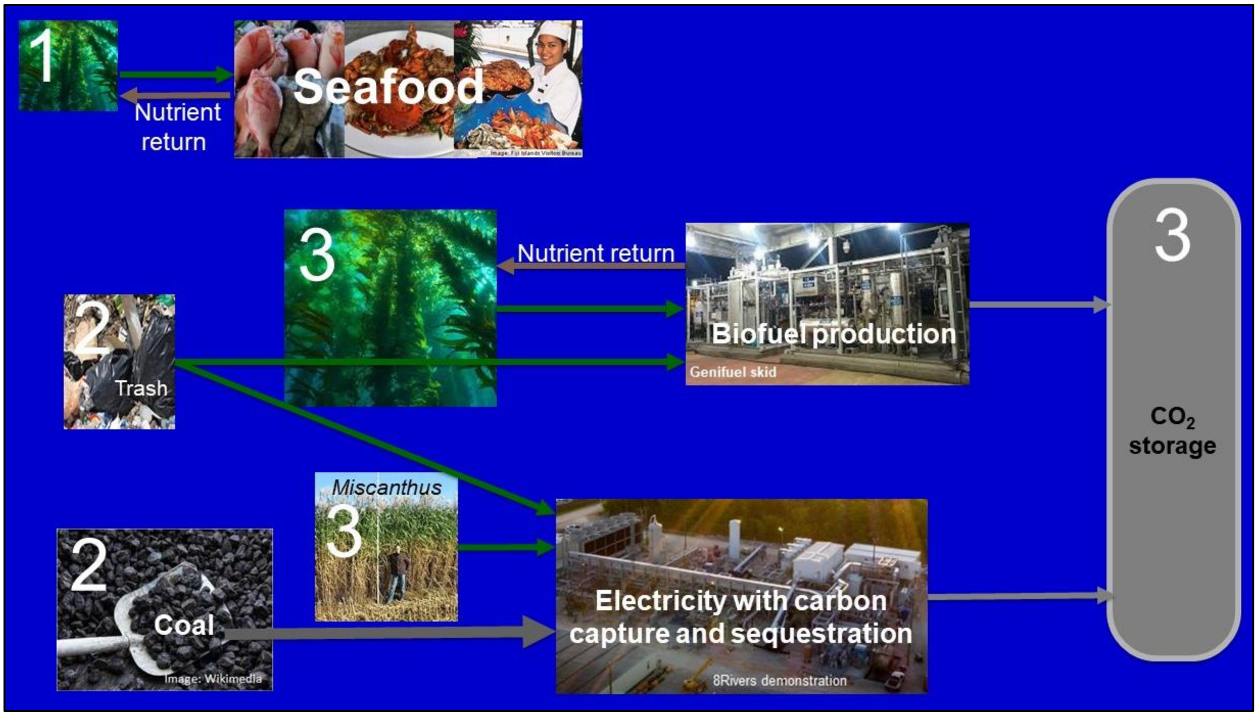
Concepts for the UN Decade of Ocean Science for Sustainable Development

Sustainable Development that supports Ocean Science
Ocean Science that supports Sustainable Development



An Information paper developed by OceanForesters

Editable version posted here

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Signatories: …

(This is an early draft welcoming more deliverables, co-authors, signatories. Signatories are people and organizations that notice some good ideas herein. Please respond to MarkCapron@OceanForesters.com)

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1. Background

The United Nations has proclaimed a Decade of Ocean Science for Sustainable Development, to be held from 2021 to 2030. Planning for the Decade includes meetings "to identify concrete deliverables and partnerships to meet the Decade's six societal objectives." The six societal objectives:

- A **clean ocean** whereby sources of pollution are identified, quantified and reduced and pollutants removed from the ocean
- A **healthy and resilient ocean** whereby marine ecosystems are mapped and protected, multiple impacts, including climate change, are measured and reduced, and provision of ocean ecosystem services is maintained
- A **predicted ocean** whereby society has the capacity to understand current and future ocean conditions, forecast their change and impact on human wellbeing and livelihoods
- A **safe ocean** whereby human communities are protected from ocean hazards and where the safety of operations at sea and on the coast is ensured
- A **sustainably harvested and productive ocean** ensuring the provision of food supply and alternative livelihoods
- A **transparent and accessible ocean** whereby all nations, stakeholders and citizens have access to ocean data and information, technologies and have the capacities to inform their decisions

2. Summary of this Document

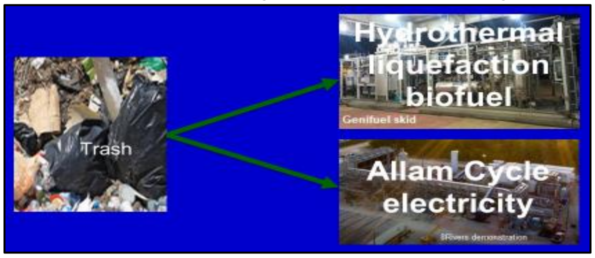
Developing Countries need "concrete deliverables" from the UN Decade of Ocean Science for Sustainable Development. This initial draft document describes seven possible deliverables that form a circular economy (cradle-to-cradle sustainability) as well as circular Development-Science-Development. The seven possible deliverables address: Seafood; Human waste resource recovery; Solid waste resource recovery; Other public health; Sustainable energy; Sustainable ocean biomass-for-energy; CO_2 sequestration; and Floating land. The document first presents an overview of the seven systems, then goes provides some examples and references for each of them. Finally, it requests additions of systems, analyses, and suggestions for targets and indicators. This is an early draft of a living document welcoming more deliverables, co-authors, and signatories. Signatories are people and organizations that notice some good ideas herein and/or want to add more. You may edit by commenting in the Forum. You also may edit the document in this folder or send email to MarkCapron@OceanForesters.com.

3. Overview of Concepts for Sustainable Development with Ocean Science

The six societal objectives are interrelated, making any "concrete deliverables" interrelated and in need of a Global Systems Approach. By way of example, tools for planning with a Systems Approach can be found at the Rockefeller Food System Vision Prize: https://www.foodsystemvisionprize.org/resources. The systems outlined below are examples of planning with a Global Systems Approach.

3.1 Food systems – Total Ecosystem Aquaculture Systems – Built reef ecosystems with nutrient recycling can provide immediate multi-species seafood and platforms for science. Science is essential for finding ways to restore and maintain healthy and productive ecosystems and biodiversity in the face of climate change, ocean acidification, and other issues. The built ecosystems can span from 0 to 200-meter seafloor depth, from sheltered to open ocean, from mangroves through seagrass, coral, macroalgae and many other species. Operating a few "Seafood-and-Science" reefs will improve the benefits of building and operating many seafood reefs. Distributed globally, seafood reefs can sustainably and economically produce a billion tonnes of seafood per year[1].

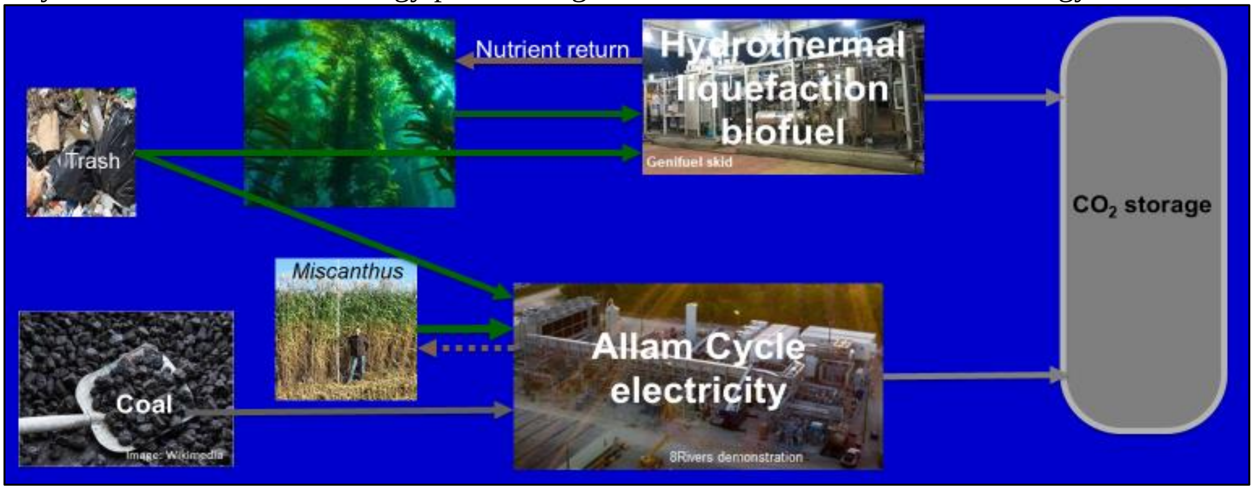
3.2 Human waste resource recovery systems – Human and livestock waste collection and recycling systems can maintain public health while recovering all the freshwater, energy, and nutrients to produce more food. When nutrients are recycled effectively, the food-waste-food circular economy should cost less than current systems for "treating" human waste. Human waste recovery can support healthy oceans and sustainable terrestrial and seafood. Human resource recovery can create healthy oceans and sustainable terrestrial and seafood.



3.3 Solid waste resource recovery systems – Solid waste collection with systems that recover resources safely, effectively with products that cover the cost of collection. Paying people for their trash would virtually eliminate future marine plastic pollution.

3.4 Other Public health systems – Replace inefficient open flame wood and charcoal cooking with clean-burning fuel or electric stoves. Replace air polluting electricity generation while increasing clean electricity generation.

3.5 Sustainable energy systems – Install multi-fuel energy systems that produce sequestration-ready CO_2. The "multi-" includes coal, natural gas, and biomass. Include ways to recycle nutrients from the energy process to grow more food and biomass-for-energy.



[1] A billion tonnes per year is 300 grams/person/day, every day for 8 billion people. The Food and Agriculture Organization estimates current seafood production is near 170 million tonnes per year.

3.6 Sustainable ocean biomass-for-energy – Gradually scale the Seafood-and-Science reefs and the Seafood-reefs with improvements in labor productivity appropriate for satisfying global demand for liquid biofuels.
3.7 CO_2 sequestration systems – Employ location-appropriate CO_2 sequestration systems for the CO_2 produced and captured during energy production.
3.8 Floating land systems – Floating land is shorthand for systems that allow people to remain in place and/or move to living on the ocean as sea levels rise.
3.9 Combined systems – Co-locate everything like at the Kalundborg Symbiosis.
3.10 Other systems – The current authors invite more systems and more authors.

Discussion: Each system has some components and/or features that are ready now and some components and/or features in need of research, development, and/or demonstration. All existing and listed systems have some climate change-induced uncertainties that could eventually cause project failure. For example, tropical aquaculture projects can be successful now, but could fail by 2050 due to warming water. Also, most off-the-shelf systems in developed countries are not particularly sustainable. For example, current wastewater treatment systems use fresh water to move "wastes" and consume energy to destroy the energy and nutrients in the wastewater.

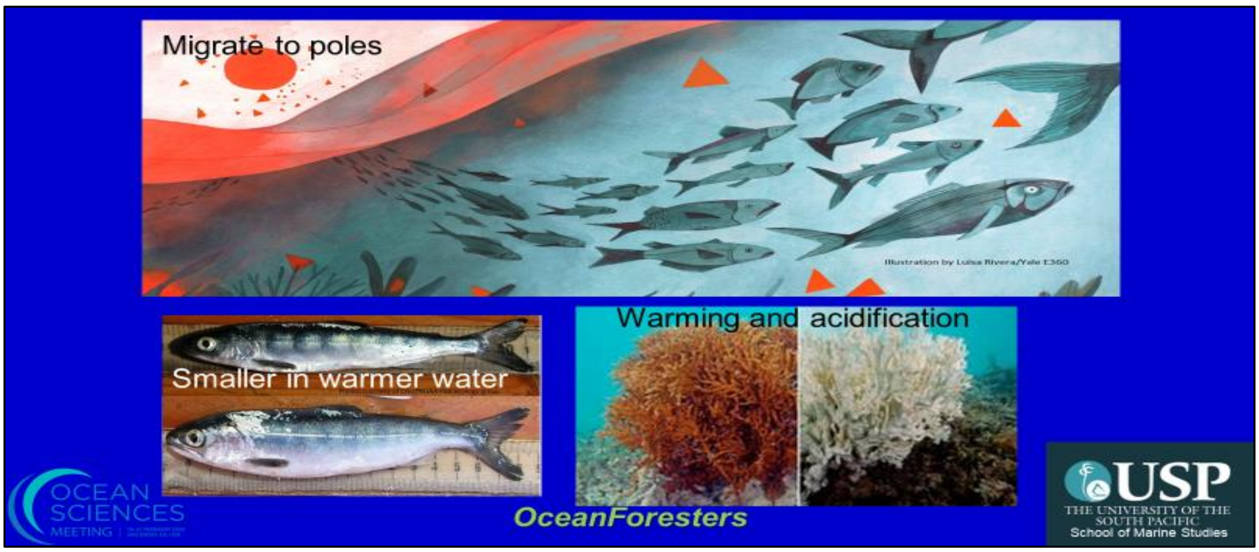
The answer to future climate change issues is full scale Ocean Science as Sustainable Development and large-scale Sustainable Development that provides infrastructure for Ocean Science. Funders should support commercial scale demonstrations of many different fully sustainable systems desired by developing countries with a guarantee: Should the demonstration fail, the funding agency replaces the failed system with a successful system. Science funders can use the infrastructure for science. For example, a floating flexible reef built for food production can be instrumented for cutting edge science. The built reef becomes "big ocean science" in the same way a supercollider is big science for nuclear physicists (except in this case food production covers the cost of building and operating the reef).

4. Examples of Needed Ocean Science and Technologies

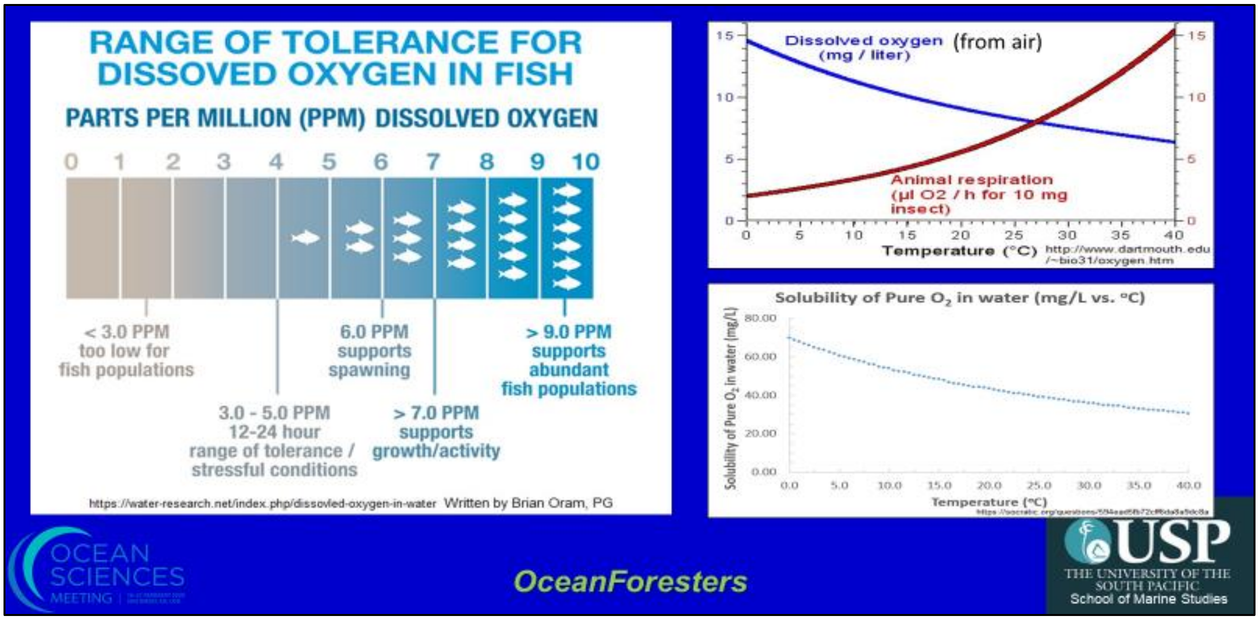
4.1 Food systems – Build on the understandings and recommendations of Hoegh-Guldberg, O., et al. 2019, particularly: "Conserving and protecting blue carbon ecosystems, … Restoration and expansion of degraded blue carbon ecosystems, … Expansion of seaweed (macroalgae) through aquaculture …". Seafood is addressed as a climate change mitigation: "There are two principal ways in which ocean-based foods can contribute significantly to climate change mitigation. One seeks to reduce the carbon footprint of ocean-derived food production. For example, changing fuel sources in vessels and technological advances in production techniques can alter the emissions associated with seafood from both wild-caught fisheries and ocean-based aquaculture. The other seeks to identify emission reductions from potentially shifting more GHG-intensive diets to those that include more GHG-friendly seafood options, if those seafood options can be provided on a sustainable basis."

Success with the "Sustainable Development" part of the UN Decade of Ocean Sciences for Sustainable Development requires addressing seafood as important development, in need of science-based adaptations. Both food and science require purpose-built new macroalgae and fauna ecosystems. OceanForesters' Total Ecosystem Aquaculture (Lucas et al. 2019, Capron et al. 2020a and 2020b) describe one such ecosystem. These are purpose-built Seafood-reefs. Some of Seafood-reefs host more science than others. Each Seafood-reef involves installing artificial substrate for the growth of plants and sea creatures supported by the engineered return of nutrients equal to the amount of nutrients removed.

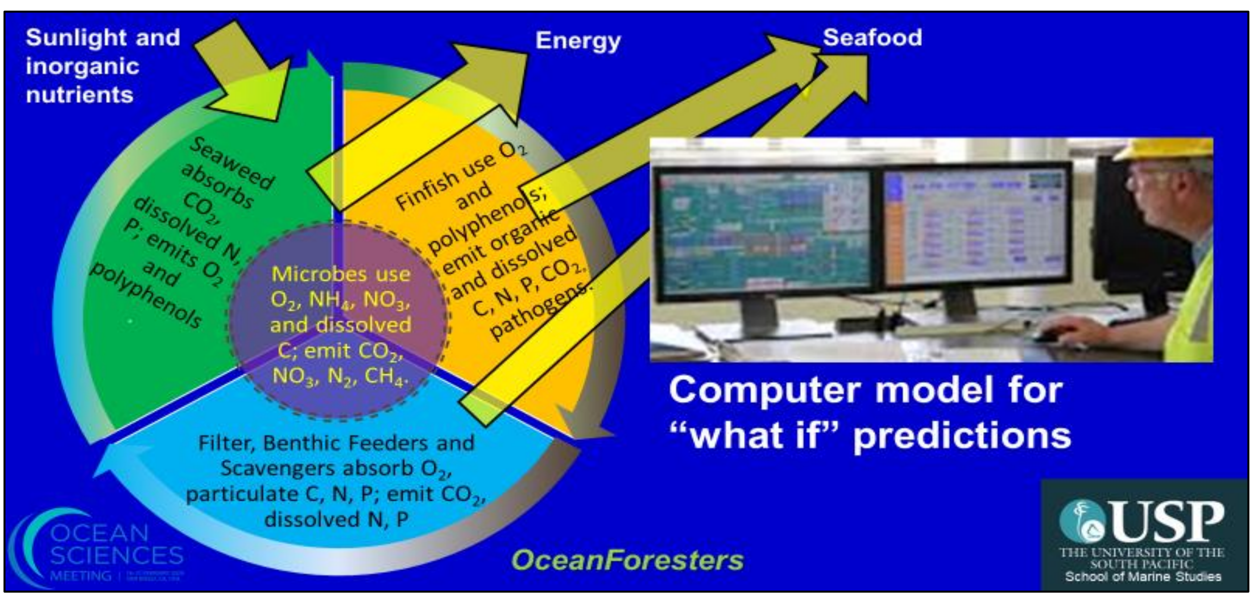
The nutrient return, planting, stocking, and harvest is managed to maintain a healthy biodiverse reef ecosystem. Tropical Pacific seafood species include: mud crab, giant clams, oysters, crabs, shrimps, lobsters, octopus, squid, sea urchins, sea cucumbers, sponges, and free-range finfish, including milkfish, perch, grouper, snapper, sea bream, and many more. Ecosystem support species (necessary but not typically harvested) include: seaweed, seagrass, mangroves, coral, worms, barnacles, snails, sea stars, anemones, microscopic creatures, bacteria, and much more.



Ocean science is essential to find ways to maintain tropical fisheries despite more issues than are shown in the pictures above. Science could include intense data gathering on the reefs with simultaneous measurements of environmental DNA in water samples and creature stomachs, automated flow cytometry, autonomous image recognition from stationary and mobile cameras, autonomous signal processing for active and passive sonar, and assorted chemistry and physical properties sensors. Much of this science data pays for itself through increased seafood production. For example, the graph at upper right in the picture below shows that dissolved oxygen concentrations drop and fish need more oxygen as waters warm. Adequate sensors may allow accurate maintenance of macroalgal oxygen production for abundant fish production even as waters warm.



The simplified diagram below hints at the complexity of total ecosystem aquaculture. Each coastal community will need a computer model with information output like shown in the picture at the right to manage their ecosystem. The model should include at least the product species plus dozens of the other species important to ecosystem health, even including bacteria.



Fear of ecosystem crashes will motivate a global organization of Ecosystem Operating Communities to fund better and better computer models. The computer models would allow "what if" for actions when anticipating events. For example: 90% of Northern California's kelp forests disappeared when sea stars died-off and sea urchin populations exploded. Kelp and abalone populations both crashed.

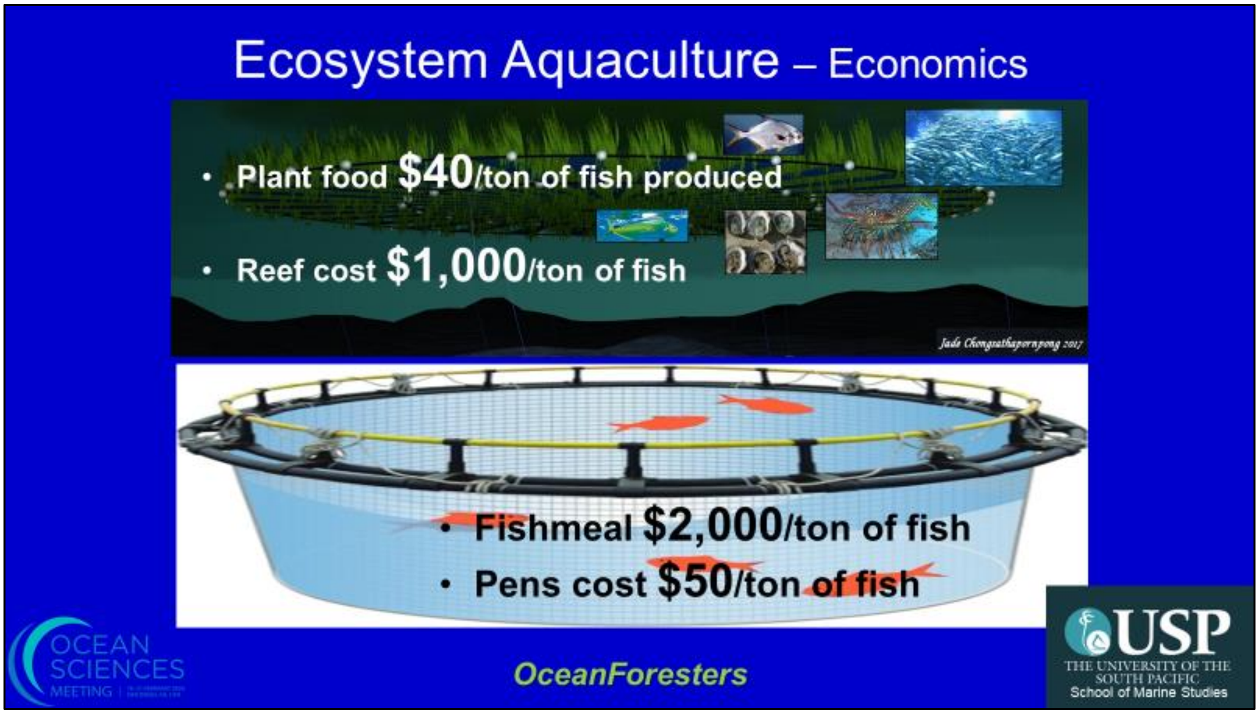
The computer helps predict the possible situation and allows trying many options, on the computer, months in advance. Do you harvest the sea urchins for sale to Japan or throw them into mangrove forests to feed mud crabs? Or do you find another community with an abundance of lobsters that you buy and stock to eat the sea urchins?

The food and science reefs are best placed along tropical coastlines of developing countries where the seafloor depth is between 0 to 200 meters. If the seafloor is less than about 30 meters, the reef is best placed where the water has an excess of nutrients and/or sediment. Laucala Bay, Fiji would be typical for this situation. Specialists at the University of the South Pacific explain applying total ecosystem aquaculture at: https://challenges.openideo.com/challenge/food-system-vision-prize/open-submission/restorative-aquaculture-sustainable-seafood-production-for-the-world.

Of the eight ocean-based entries, only the Galapagos Islands one advanced to the top 79 on 3 March 2020 (from 1,300 total entries). That entry: https://challenges.openideo.com/challenge/food-system-vision-prize/refinement/uc/comments#comments-section is a particularly good example of the social aspects of a Food Systems Vision.

In seafloor depths between about 30 to 200 meters, the purpose-built reef would be flexible, floating, and permanent. Generally, the reef's plant-growing substrate would be 3 to 10 meters deep depending on the optimum depth for the local macroalgae or seagrass. The reef might submerge to 50-meter depth, when tropical storms pass nearby. Open ocean reefs are further described in this presentation by Don Piper at the International Symposium on Stock Enhancement & Sea Ranching, November 2019. Some of the research from the AdjustaDepth project for the U.S. Department of Energy, Advanced Research Project Agency-Energy's MARINER program can expand seafood production. AdjustaDepth project deliverables are available at: https://drive.google.com/drive/folders/1uIudPOFZi1qZCXSbQq_vSZuDFmkSqio_.

Each region of the world needs a total ecosystem aquaculture research and training center for open ocean floating flexible reefs. (The nature of the structures, the storms, and the animals interacting with the structures varies.) Example locations for the first food and science open-ocean reefs include: The Bay of Thailand; the Bay of Bengal; near Tanzania and/or Madagascar; near Ghana; Costa Rica (both Caribbean and Pacific); and more. Each of these locations could showcase typical species and tropical marine ecosystems for many countries near them. (There are some non-tropical developing counties and even developed countries where food and science reefs are needed for general ocean health and adaptations for climate impacts: the Mediterranean Sea, the Baltic Sea, and the U.S. Gulf of Mexico.) Food and science reefs should be near a host university with access to seafloor, oceanographic, and nutrient conditions typical of a larger area.



The OceanForesters were part of a team funded by the US Department of Energy to find inexpensive ways to grow and harvest macroalgae-for-energy. The team, led by aquaculture experts at the University of Southern Mississippi, University of New Hampshire, University of the South Pacific and others estimated the comparative economics of total ecosystem aquaculture (TEA, free-range finfish) with penned finfish aquaculture. The graphic above shows that TEA is more like renewable electricity with a small operating cost and a larger infrastructure cost. The high cost of fishmeal and the low cost of infrastructure for penned finfish aquaculture is more like fossil fuel electricity.

The $40/ton of fish for the plant food is based on supplying nitrogen as ammonia at 1.5 times the current cost of ammonia. The cost assumes only 50% of the supplied nitrogen gets into a fish product. Our fish products include finfish, shellfish, mollusks, crustaceans, seaweed, … everything that will grow over, in, and around our floating flexible reef.

The $1,000/ton of fish for the structure is based on our techno-economic analysis prepared for the U.S. Department of Energy Advanced Research Projects Agency-Energy' MARINER program. The reef is built for 20-year service life while surviving hurricanes in 50 to 100-meter seafloor depths in the Gulf of Mexico. Sheltered locations like Laucala Bay, Fiji would be much less expensive. Some of the harvest would be exported to developed countries for values ranging from US$2,000 to US$4,000 per wet or shell-on tonne, with resulting large export revenues helping economic self-sufficiency.

Bottom line: Fish products from an open-ocean flexible floating reef will cost about half as much as products from pens. Fish products from sheltered water TEA, perhaps a fifth as products from pens.

Some of the Seafood reefs can also support full-scale simultaneous demonstrations of automated biomass-for-energy growing and harvesting systems. These might deliver biomass to the HTL process for less than US$100 per dry metric tonne (US$10 per wet tonne) with the Seafood production paying for the reef structure. Such dual purpose, food and fuel yielding ecosystems can proliferate up to the limit of the global demand for seafood.

A thousand people provide sufficient nutrients to grow about 700 wet tons of seaweed per 20-hectares of reef per year. Allowing for the difference in protein density, about half that seaweed productivity would give about 150 wet tons of non-seaweed high-value seafood. At $2 per wet kilogram, we'd have $30 million per year at the dock from one of our open-ocean 20-hectare reefs.

Related seafood production concepts that involve ocean infrastructure include:

Professor Tian Tao, Dalian Ocean University, Marine Ranching in China and Podcast: Marine ranching off China's coast.

Professor Ricardo Radulovich's Sea Farms.

Dr. Brian von Herzen's Enhancing Coastal Community Value Chains with Marine Permaculture (CVC-MPs) which is in the top 100 solutions for the crowdsourcing contest MacArthur 100&Change:2020.

Professor Thierry Chopin's Integrated Multi-Trophic Aquaculture, explained in Ecosystem-based aquaculture: We need to stop thinking about aquaculture farm as something within the limits of a few buoys or GPS coordinates on a map.

Kelp farming, described in An ecosystem approach to kelp aquaculture in the Americas and Europe.

4.2 Human waste resource recovery systems – Initially, human wastes were collected and treated as a public health measure. Diseases and parasites that kill many people are transmitted in feces and water that contacted feces: typhoid, cholera, intestinal worms, etc. Therefore, public health is the top requirement for human waste resource recovery systems, followed closely by sustainability. True sustainability requires recycling the energy, the nutrients, and the water. True sustainability is exemplified by the "wastewater treatment" industry's move to "water resource recovery." Developed countries are burdened with systems that focused on public health and "treatment." Developing countries lack of infrastructure allows quick adoption of many existing and emerging safe and sustainable human waste collection and recycling systems including:

a. The Rich Earth Institute explains the benefits and "how-to" of collecting urine. Note that a developed country (Vermont, USA) utility found that collecting, pasteurizing, and selling urine as fertilizer was less expensive than removing the ammonia nitrogen at its wastewater treatment plant.

b. Feces can also be collected safely and effectively, if careful. Feces contain substantial carbon allowing processes like anaerobic digestion or hydrothermal liquefaction (HTL) to produce biogas or biocrude oil separated from the recycle-ready nutrients. Because the HTL process can convert many plastics to biocrude and pasteurizes at 350°C, it may be particularly safe and effective for feces, medical wastes, and preventing epidemics.

c. Locations with existing collection systems and energy-intense treatment systems should consider pasteurizing the wastewater immediately downstream of screens and grinders. By using heat exchangers, pasteurizing can be accomplished with low grade (70 to 90ºC) "waste" heat from electricity production. HRS offers a heat exchanger system. PTG Water & Energy offers an integrated system of gas turbine and heat exchangers. After the waste is pasteurized, the existing treatment facilities could be converted to grow food (for animals, if not people). Options include: (1) growing filter feeders (shellfish) in the pasteurized water; (2) settling and/or filtering out the solids for consumption by black soldier fly larvae; and (3) distributing the water on agriculture and/or total ecosystem aquaculture facilities.

d. ECOLOO is a Swedish odorless water-free toilet with special bacteria that digest both urine and feces producing a pathogen-free liquid fertilizer (plus some mineral-rich solid fertilizer).

Ocean Science is essential for optimizing the distribution of nutrients on total ecosystem aquaculture systems to enhance yield, bio-diversity and sustainability. The rate of nutrient dose needs to be less than the capacity of the plants to supply dissolved oxygen to bacteria consuming the dissolved organic carbon. The plants' oxygen production will vary with sunlight. The nutrient dose rate needs to be adjusted each hour of the day and each season of the year depending on the amount of organic carbon and hour-to-hour variations in sunlight. At the same time, the rate of nutrient dose needs to support the biomass of the standing stock of plants to maintain ecosystem biodiversity. It may be important to stock (from hatchery) filter feeding shellfish and/or finfish to maintain water clarity as the bacteria consuming the organic carbon move up the food chain.

4.3 Solid waste resource recovery systems – Solid waste (aka trash) can contain paper, metal, plastic, glass, ceramics, and organics (grass clippings, food waste, animal manure, blood, mucus, etc.). Some of these materials can produce biofuels with less separation, transportation, labor, and energy cost than landfilling. The processes that could replace landfills and might generate a product with more value than the cost of collecting the trash include: incineration (to generate electricity); gasification (to generate electricity and/or liquid fuel); anaerobic digestion (to generate biogas, often followed by composting); and hydrothermal liquefaction (to generate biocrude oil, fuel gas, and CO_2 that could be captured and sequestered). (Because trash now pays a landfill disposal fee (up to $100 per wet ton, which can be $300 per dry ton), it is possible that much of that fee could be paid to the energy producing system, perhaps producing energy at no cost. Or the energy producer could pay people to collect trash.)

The system's safe handling of medical, hazardous, potentially infectious wastes is important. These wastes include blood, used syringes, used Kleenex, disposable wipes, diapers, secure no-contact containers for said wastes, secure no-contact-with-contents handling of the containers, and more.

Lombardelli et. al. (2017) "LCA Analysis of Different MSW Treatment Approaches in Light of Energy and Sustainability Perspectives" analyzed a two-path model. The dry materials (paper and plastic) were gasified and the gas used to produce electricity and heat. The wet materials (food waste, grass clippings, etc.) are anaerobically digested and then composted with the biogas producing electricity.

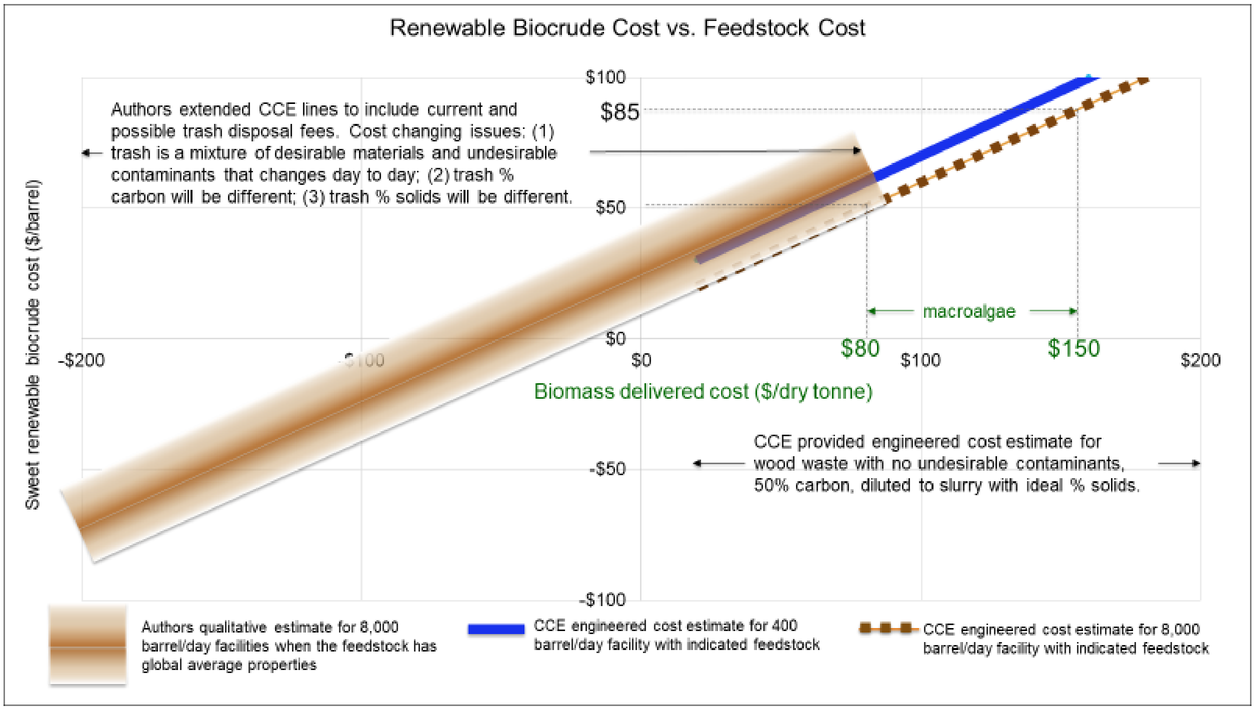
We suggest an updated version of the Lombardelli, et al. two-path model. Trash and dry biomass would replace coal for gasification in Allam Cycle electricity power plants. (Allam 2017, NET Power 2018, 8 Rivers Capital 2019). These plants produce inexpensive electricity with zero emissions and pressurized liquid CO_2, ready for sequestration. The Allam Cycle uses CO_2 as a supercritical fluid to spin the turbine. Because the exhaust fluid spins the turbine, the Allam Cycle combustion chamber does not require heat tubes. Inside the Allam Cycle combustion chamber pure oxygen, natural gas, and CO_2 (for cooling the combustion chamber) mix. The oxygen and natural gas (or gasified coal, gasified biomass, or biofuel) combust to generate heat while producing only water and more CO_2. After spinning the turbine, the CO_2 is compressed and cooled into a liquid. Any remaining water, nitrogen gas, argon gas, and other products can be recovered separately from the liquid CO_2. Sales of gases are an additional source of income.

The authors also suggest updating the wet biomass-to-energy process to include hydrothermal liquefaction (HTL) followed by anaerobic digestion (in place of anaerobic digestion followed by composting). HTL (Jiang et al. 2019, Pichach 2019) converts any blend of wet plants, paper, wax, and most plastics to bio-oil – expired juice in plastic bottles, newspaper, expired packages of meat, seaweed, microalgae, switch grass, feces, biohazard wastes in plastic – all chopped and blended together.[2] The process is similar to the way algae became oil when buried deep in the Earth. By using a combination of high temperature (350ºC, 660ºF) and pressure (200 atmospheres, 2,000 meters of water pressure, 3,000 psi) the conversion to oil is complete in about a half-hour. Because the reaction temperature is less than about 400 ºC, all the plant nutrients can be recovered and used to grow more plants.

HTL technology is almost commercial now, based on substantial research and development in many countries. Recent examples include work at the U.S. Pacific Northwest National Laboratories with U.S. Department of Energy funding (Jiang et al. 2019). Aarhus University (Denmark) has investigated using HTL to recover phosphorus and carbon from manure and sewage sludge with Horizon 2020 funding (Bruun 2019). Several companies are preparing ever larger demonstrations of HTL devices including: Genifuel (2019) (USA), Licella (Australia) with a plastic feedstock demonstration in the United Kingdom (ReNew ELP 2019),

[2] This is a comprehensive example – Paper and plastic are already "sequestered" carbon. HTL is counterproductive in that it "releases" that carbon to be burned as fuel. But HTL of trash can significantly reduce methane released from landfills and marine plastic pollution. Eventually, plastic will be based on plants, biogas, and biocrude such that the biofuel will be carbon neutral and the captured byproduct CO_2 will be carbon negative.

Steeper Energy (2019) (Denmark, Canada), and CleanCarbon Energy (Pichach 2019) (Canada).



With many HTL startups, and no commercial-scale operations yet, HTL costs are not accurately known. The solid blue and dashed brown estimate of biocrude product cost as function of feedstock cost is provided for one specific feedstock by CleanCarbon Energy (CCE). We have qualitatively extended the fuzzy brown line for trash feedstock using our qualitive understanding for how HTL costs change for different situations.

Steps to move forward to address uncertainties in both HTL and the local trash mix include: (1) Build Allam Cycle electricity plants using coal with space for a co-located HTL facility. (2) Collect both wet and dry trash by paying people to deliver the trash. (3) Sort and quantify all aspects of delivered trash. (4) Gasify the dry trash with coal while monitoring emissions (if any) and what is in the CO_2. (5) Temporarily (2 to 10 years) compost or landfill the clean wet trash while conducting design and feasibility checks on HTL processes while plastics manufacturers roll-out plastics designed for circular manufacturing with HTL. (6) Install HTL. (7) Adjust the solid waste collection system economics and technologies with Allam Cycle electricity and HTL for maximum public health benefits and minimum plastic escaping to the ocean.

Ocean science in support of self-funded[3] trash collecting systems can include:

a. Self-funded trash collection is one way to stop the flow of plastic (and other trash) into the marine environment.

[3] Funded from the former landfill disposal fees mentioned above.

b. Ocean scientists, pharmaceutical manufacturers, and plastics manufacturers need to work together to ensure that only pharmaceuticals and plastics that fulfill their intended public safety purposes while converting cleanly into energy (leaving no harmful residues in the leftover water and ash) are the feedstock for energy processes.
c. Micro- and macroalgae absorb metals and produce toxins. Ocean (and other) scientists need to quantify impacts from recycling nutrients. Other scientists need to find economical ways to recover metals and any surviving toxins from the ash and leftover water. For example, macroalgae has been shown to reduce mercury levels in the surrounding water by about 99% (Henriques et al. 2015). Most of the mercury will be contained in the ash.

4.4 Other Public health systems – Similar number for indoor cooking with traditional wood or charcoal on inefficient stoves? How about the exhaust from large ships? West et al. (2013) calculated local average marginal co-benefits of avoided mortality from current coal-electricity generation air pollution range from US$50–380 per tonne of CO_2. (US$34-260 per MWh for coal-fired electricity).

Ocean Sciences are needed in this concept when ocean-based renewable energy and clean fuel production: offshore wind, wave, tidal, biomass, thermal energy, oceanic biomass.

4.5 Sustainable energy systems – See the explanation of Allam Cycle electricity generation and HTL liquid biofuel generation from trash in Concept 4.3. Early in the decade, electricity and pure CO_2 at 100-atm pressure should be produced from dry trash and coal. Liquid biofuel and CO_2 at 1-atm is produced from trash. Later in the decade, all the CO_2 from electricity production and the byproduct CO_2 from biofuel production is sequestered. Then terrestrial biomass supplements the coal and macroalgae biomass supplements the trash. Most of the nutrients, excepting nitrogen, are recovered from the electricity production. All of the nutrients needed to grow more biomass are recovered from the liquid biofuel production.

Terrestrial and oceanic biomass energy systems are sustainable to the extent they recycle nutrients. At the temperatures of anaerobic digestion and HTL, all the nutrients needed to grow more biomass can be recovered. However, at the higher temperatures of a gasification process, all the nutrient nitrogen in the biomass is lost as nitrogen gas or oxides (but phosphorous and other minerals can be recovered in the ash). The loss of nitrogen is not insurmountable for naturally dry terrestrial biomass (such as miscanthus), which needs relatively little additional nutrient nitrogen. In addition, agriculture scientists are finding more ways to increase soil microbe nitrogen fixing.

4.6 Sustainable ocean biomass-for-energy – Oceanic biomass energy systems are built and operated on and with the same infrastructure and ocean science as the food reefs and resource recovery systems of Items 3.1, 3.2, and 3.3.

The ocean science needed for sustainable ocean biomass includes: artificial intelligence, autonomous harvesting, and human-robot systems for biomass-for-energy on the Seafood-and-Science reefs (see for example Wanuri Kahiu's (2020) vision for Kenya). Improvements in labor productivity are essential for growing a global supply of ocean-biomass-for-energy at current costs for energy. Biomass-for-energy involves handling nearly a thousand times the biomass and nutrients of growing a global supply of seafood. To compete with fossil fuels, costs of labor and energy expended growing and harvesting biomass-for-energy needs to be less than 1% that of growing and harvesting seafood.

Consider that 400,000 seafood reefs, 20-ha each, could provide a billion wet tonnes of seafood per year. Whereas 40 million such reefs are needed to provide the biomass to produce 100 million barrels of bio-oil per day (roughly 2018 global demand for oil). Biomass growth in tropical oceans can be nearly constant year-round, which minimizes the need for storing biomass. The growing and harvesting systems will move slowly to minimize energy expended. Slow movement and safety considerations preclude putting people on the equipment.

At the scale of energy production, ocean science is essential to ensure benefits of improved ocean health and biodiversity without adverse impacts. Macroalgal biomass production near 400 billion wet tonnes per year (13 billion tonnes of carbon/year) means increasing ocean net primary productivity by 26%. Currently, land net primary productivity is about 60 billion tonnes[4] of C per year on land area of 150 million km^2. Ocean production is about 50 billion tonnes[5] on 360 million km^2. That is: oceans are under-producing relative to land. That is, the additional substrate in the photic zone combined with nutrient recycling need not be "taxing" the oceans primary productivity capacity.

Forty billion dry tonnes/yr of oceanic biomass, requires cycling 1.2 billion tonnes of nitrogen per year[6] from ecosystem to energy process and back. Proportional amounts of phosphorous, potassium, iron, boron, copper, manganese, molybdenum, zinc, nickel, and other micronutrients are also cycling. HTL recovers virtually all the N as ammonia in the "leftover" water. Other nutrients are recovered in the "ash." Since recycled nutrients (such as biosolids) contain a complete array of needed micronutrients, they are also more beneficial to biomass growth than commercial fertilizer (Pan, et al. 2017; Wesseler 2019).

Ocean biomass growing and harvesting techniques are not as refined as for terrestrial biomass. There was large scale wild harvesting of kelp-for-potash off California in the 1920s by mowing the top meter of the water surface. Since then, wild harvests have been limited and kelp farming techniques have become much more complex to produce a food-quality product. Our estimates of scale and cost are based on the techno-economic analysis from nine teams awarded US$500,000 each in the U.S. Department of Energy, Advanced Research Projects Agency-Energy's MARINER[7] program.

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[4] Gough et al. 2011 "Terrestrial Primary Production: Fuel for Life."
[5] Boyd et al. 2014 "Net Primary Production in the Ocean".
[6] Dry macroalgae is about 3% N, but varies a few percent by species and for the same species seasonally.
[7] Macroalgae Research Inspiring Novel Energy Resources: https://arpa-e.energy.gov/?q=arpa-e-programs/mariner

One team proposed attached growth of temperate macroalgae (kelp) on a free-floating structure. Two of the teams proposed free-floating and "corralled" *Sargassum*. Three teams proposed attached growth of tropical macroalgae on moored structures. Three teams proposed attached growth of temperate macroalgae (kelp) on moored structures. Data from the teams that contributed suggest the potential for growing over 80 billion dry tonnes/yr. That is about twice the 42 billion dry tonnes/year needed to produce 110 million barrels of biocrude oil per day on the high biofuel pathway. Most teams determined their system at-the-dock macroalgae price (less than $160/dry tonne) would enable producing biocrude oil for less than $100/barrel. See the Supplemental Materials spreadsheet, Tab 4. Project deliverables from the AdjustaDepth project for the U.S. Department of Energy, Advanced Research Project Agency-Energy's MARINER program are available at: https://drive.google.com/drive/folders/1uIudPOFZi1qZCXSbQq_vSZuDFmkSqio_.

The MARINER program is only a tiny fraction of the effort needed on oceanic biomass-for-energy. Unlike terrestrial biomass, oceanic biomass-for-energy is early on the learning curve. Even so, ocean biomass appears to scale up much better that does terrestrial biomass for reasons including: three times the global growing area, the opportunity for harvesting food while improving biodiverse ecosystems, and no land use and freshwater impacts. While ocean biomass is not affected by droughts and floods, there will be climate change impacts from marine heat waves (which may be avoided by submerging) and ocean acidification to manage.

4.7 CO_2 sequestration systems – Long-term ocean health and productivity is best ensured by removing a few trillion tonnes of CO_2 from air and ocean within a century or so (as described in Capron et al. draft manuscript in preparation). Sequestration techniques involving ocean science include: "Geologic" sequestration in sub-seafloor oil wells, gas wells, and brine aquifers; mineralization in sub-seafloor basalt; and contained CO_2-hydrate storage on the seafloor. Every developed and developing coastal country will have physical resources appropriate for at least one of the three. Countries producing sequestration-ready CO_2 from their new energy production infrastructure will need ocean scientists and engineers to build safe and secure CO_2 sequestration infrastructure.

Ocean science with appropriate-scale demonstrations is needed to prove the permanence and decrease the costs of several CO_2 sequestering options. That is, don't put all the eggs in one basket. Develop multiple technologies. Currently leading options include: storing CO_2 in saline aquifers plus mineralization in basalt and other rocks on land and sub-seafloor. On land mineralization has been successfully demonstrated in Iceland (Gunnarsson, et al. 2018) and Wallula, WA (USA) (McGrail, et al. 2017). A sub-seafloor demonstration is just starting (Moran et al. 2019). Research is needed to bring down the cost of offshore subsea basalt which is projected at $200-$400 per ton (Kelemen et al. 2019). Another opportunity is contained CO_2-hydrate storage on the seafloor (Capron, et. al. 2013), which suggested a cost of only $16/t of CO_2.

4.8 Floating land systems – The UN Decade of Ocean Science for Sustainable Development implies many continuing and new jobs on and near the ocean. People like to live near their jobs. People would rather remain in place as sea levels rise. Minimum requirements for such locations:

a. Storm wave dampening – mangroves, living reefs, sand berms, floating breakwaters, and the like.
b. Homes on stilts, homes that float, land (with homes on it) that floats – These homes shelter people from rain, wind, and rising water during the worst combinations of storm and tide. The wave dampening system means the homes are not directly impacted by storm waves.
c. Safe and sufficient freshwater collection and storage system – One of the reasons for floating land, instead of raising individual houses is the remaining land provides more area for collecting and storing rain.
d. Robustly sustainable food production and distribution – Floating land can support terrestrial crops as saltwater ruins existing crops. Seafood reefs provide convenient, compact systems for a wide variety of seafood.
e. Robustly sustainable waste resource recovery – The systems described above safely utilize all liquid and solid wastes for productive purposes.

4.9 Combined systems – There are large resource recovery synergies by co-locating the human waste, solid waste, electricity production, biofuel production, food production, and carbon sequestration.

4.10 Other systems – The current authors invite suggestions for more systems and more co-authors.

Potential planning and analysis that could be added to this document

Improving the opportunity to exceed Sustainable Development Goals

Add more systems.

Describe how concepts 3.1 through 3.10 can be implemented to improve ocean literacy.

Each system 3.1 through 3.10 needs more discussion for how the system helps achieve the Decade's six key Societal Outcomes. Ideally, the discussion is led by developing countries to help each developing country plan the sequence of Development-Science-Development that best fits each country's issues and resources.

For each system 3.1 through 3.10 identify and quantify expected outcomes. For example, the expected outcomes for 3.1 Food Systems might be: (1) Twenty Seafood-and-Science reefs producing 60,000 tonnes of seafood per year. (2) The Seafood-and-Science reefs host $200 million per year of science projects by 2025. (3) About half the $200 million is "matching funds" represented as the value of providing ocean structures (the reefs) and reef ecosystem operations on those Seafood-reefs that host Ocean Science. (4) Seafood reefs are producing 300 million tonnes of seafood by 2030 and growing toward a billion tonnes/yr.

Each system 3.1 through 3.10 could have a table of "Targets" and "Indicators" and a table of "Examples of Actions."

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