Science Enables Abundant Food (SEAFood) with Healthy Oceans
Tropical Pacific Region, University of the South Pacific
A Proposed Programme Description for the
UN Decade of Ocean Science for Sustainable Development (2021-2030)

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Appendix A – Typical Projects
1. Executive Summary

The University of the South Pacific (USP) mission includes:

- Achieving excellence in research by addressing consequential and multidisciplinary scientific questions which appreciate the distinctiveness and richness of Pacific Island Communities (PICs), culture, environment and biodiversity.
- Contributing effectively to the sustainable use and governance of the PIC’s natural resources for the advancement, prosperity and development of the people and for the conservation of its rich biodiversity and environment.
- Preparing human resources capable of generating excellent scientific data and use such information for making informed and rational decisions based on factual evidence for the welfare of people and nature of PICs.
- Increasing the visibility of university research and to inform the public about its importance for the management and conservation of the PICs’ natural resources.
- Attracting more international students as a result of the growing reputation of USP as a centre of excellence for research and knowledge creation in Oceania.

As Lead Institution for the Tropical Pacific SEAFood with Healthy Oceans Programme, USP strives to individualize the science and development each coastal community needs for the oceans each coastal community wants. USP will organize tasks common to every community such as networking, training, research, ecosystem model development, data visualization, data standardization and data management. Accomplishments will depend on initial funding. USP has a financial accounting system and people management systems to support projects throughout its local coastal communities. By the end of Ocean Decade, USP would like to have established such robust biodiversity and seafood production that the income from seafood production can fund USP’s globally accessible research and training indefinitely.

All the member countries of the University of the South Pacific (USP) are within the Tropical Pacific Region. Other countries/communities may join the Tropical Pacific Region as USP and the other country agree.

USP and its member communities are most interested in truly sustainable aquaculture integrated with living reefs and adaptations. Adaptations are essential for continued biodiversity and seafood production over future centuries of anthropomorphic impacts: warming oceans; changing climate; ocean acidification; pollution; sediment loading; etc. USP plans a research and training centre to identify the most sustainable aquaculture for the tropical Pacific and distribute “how to” knowledge to interested communities. This may include: establishing marine protected areas and policing fisheries rules; farming macroalgae; farming shellfish; integrated multitrophic aquaculture with penned finfish; and SEAFood built-reef ecosystems.

SEAFood built-reef ecosystem, “built-reef ecosystem”, or simply “SEAFood” refers to a form of truly sustainable aquaculture that operates like a natural reef. On a natural reef, life creates the conditions for more life. The wastes of animals become nutrients for plants and other animals and multiple species thrive. Plants use sunlight (photosynthesis) to turn a small amount of nutrients into a substantial amount of food, as shown in Figure 1.
Fig. 1 – The large outer nutrient cycle shows how nutrients removed from the reef for food can be returned to the reef. The small inner circle represents nutrients’ cycles within the reef.

SEAFood built-reef ecosystems would be built outside of existing and future marine protected areas (MPAs), in areas where there is currently low biodiversity and low productivity, and even inside a dead zone or other polluted area. The new reef ecosystems include science-based adaptations to support continued biodiversity and productivity for centuries. With vastly increased seafood production on their own new reef ecosystems, built and managed to their specifications, coastal communities can more readily accept vastly increased MPAs.

Seafood income means that coastal communities, investors, and MPAs would not rely solely on tourist income. The income from seafood produced on the built reef would pay for science and poaching prevention sensors. The sensors will be on the built reef, in the hands of citizen-scientist-fishing-people, and in the MPA. Nearby MPAs would be managed for tourist income while also providing sea creature services that might not be available on the initial built reefs (spawning habitat, turtle shell cleaning stations, etc.).

Conditions for SEAFood built-reef ecosystems generally span between two extremes:

a. In sheltered shallow water with excess nutrients and sediment (Fig. 2) – Clarify the water with farmed filter feeders (shellfish, some finfish) and sediment capture (mangroves, seagrass). Increase macroalgae substrate in the photic zone. The substrate may be a mix of bamboo, rope, and nets. Where native, giant clams are both filter feeders and primary productivity.
Fig. 2 – Possible substrate supporting structures (upper left), seafood products, and ecosystem support species for the situation of shallow water and excess nutrients

b. In the open ocean, as much as 200-m seafloor depth (Fig. 3) – Install permanent flexible floating fishing reefs at the optimum depth for the desired native macroalgae, filter feeders, shellfish, and crawling sea creatures. Recycle nutrients from land (people and livestock) matching the amount on nutrients extracted from the fishing reef.

Fig. 3 – Artists’ concept of a SEAFood floating flexible fishing reef ecosystem
Expecting 2050 demand of 500 million tonnes/yr suggests the 2030 goals for both Sustainable Development and the UN Decade of Ocean Sciences for Sustainable Development should be 100 million tonnes/yr of seafood from built reefs by 2030. This amount of seafood replacing meat would save 1.5 billion tonnes/yr of CO\textsubscript{2}eq plus conserve more freshwater than the flow of the Mississippi River. The seafood would be worth about $200 billion/yr at the dock. Ten percent of ten years of income implies $200 billion may be available for ocean conservation and research to sustain ocean ecosystems through a century of climate change.

Human and livestock waste collection and recycling systems can maintain public health while recovering all 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 and livestock waste. That is, new water resource recovery systems will recover nutrients instead of using energy-intensive oxidize-the-carbon and convert-ammonia-to-nitrogen gas technologies.

2. **Recent research supporting urgency for SEAFood programme**

   September 2019 – SEAFood can employ concepts in “Harnessing global fisheries to tackle micronutrient deficiencies” to provide the most needed micronutrients locally and in an alliance of globally dispersed local coastal communities.

   April 2020 – A quote from “Rebuilding marine life” “Rebuilding fish stocks can be supported by market-based instruments, such as …the growth of truly sustainable aquaculture to reduce pressure on wild stocks.” SEAFood builds truly sustainable aquaculture while building the science to ensure true sustainability with robust biodiversity and species survival.

   September 2020 – 110 aquatic scientific societies, representing over 80,000 scientists, suggest the urgent need for SEAFood in the American Fisheries Society’s “Statement of World Aquatic Scientific Societies on the Need to Take Urgent Action Against Human-Caused Climate Change, Based on Scientific Evidence.”

   September 2020 – SEAFood is the first step in “Restoring pre-industrial CO\textsubscript{2} levels while achieving Sustainable Development Goals.” Also AGU Fall Meeting 2020 iPoster.

   September 2020 – “Half of resources in threatened species conservation plans are allocated to research and monitoring” Lead author Rachel Buxton: "In some ways, it's like we're counting the deck chairs on the Titanic.” More nuanced analogy from a discussion with Dr. Phillip Williamson – The monitoring and predictive modeling of environmental science updates our ability to avoid hazards, like providing radar to the lookouts on the Titanic and ensuring the radioed “ice ahead” warnings from other ships reach the ship’s captain. Like the Titanic, Earth lacks adequate and sufficient lifeboats. See Fig. 4. Lifeboats are needed to support ecosystems and feed/shelter people in place. Ocean SEAFood ecosystems are self-rescuing lifeboats in that seafood production can pay for monitoring, modeling, adaptation (cooling the ecosystem or increasing dissolved oxygen during heat waves), and mitigation.
3. Details of Ocean Science and Sustainable Development

3.1 Seafood Production and Science

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.”

Sustainable, eco-friendly seafoods require purpose-built new seaweed and sea animal ecosystems, as in Figure 3. OceanForesters’ Total Ecosystem Aquaculture reefs (Lucas et al. 2019, Capron et al. 2020a and 2020b) present one such ecosystem. These are purpose-built Seafood-reefs. 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.

In the tropics, throughout their pre-historic range, giant clams may be the keystone species of built-reef ecosystems and nearby natural coral reef ecosystems. Per Noe (2015), giant clams’ internal algae can provide more net primary productivity than coral or most macroalgae. Giant clams provide food for local organisms directly through their tissue and indirectly through the discharge of feces, gametes (reproductive cells), and zooxanthellae (photosynthetic algae). Noe et al. 2105 and references therein goes on to explain that giant clams control eutrophication (in areas of excess nutrients) two ways: (1) filtering large quantities of seawater, clearing the water of microalgae; and (2) assimilating inorganic nutrients. All this means tropical built-reef ecosystems could employ nutrient recycling to increase fish harvest productivity while improving the health of nearby natural coral reefs. The typical tropical built-reef might have a few hundred mature (+20 years old) giant clams and a few hundred thousand juvenile (less than 10 year old) giant clams.

Ocean science is essential to find ways to maintain tropical fisheries despite more and more urgent issues than are shown in Figure 5: (1) Flemming et al., 2020 found that embryos and adult fish when breeding are much more sensitive to warming than fish at other life stages. (2) Marine heatwaves are shifting ocean temperatures at similar scales to what is anticipated with climate change – but in much shorter time frames. The average climate change temperature shift in 2020 is about 20 kilometers per decade. Marine heat waves displace temperatures an average of 200-km in a few months (Jacox et al. 2020).

Fig. 5 – Changes in local ecosystems due to increased greenhouse gas concentrations (The debate on how and why fish size changes with warmer water is ongoing.)

Plants in the ocean may respond to heat waves the same way land plants do. McGowan et al, 2020 studied subtropical coastal ecosystems in eastern Australia. They found the optimum temperature range for photosynthesis of 24.1°C to 27.4°C. Temperatures above optimum were accompanied with rapid decline in photosynthetic production, made worse if soil water content decreases. (The response of plants in the ocean will not be dependent on soil water
content, but might be dependent on salinity, or nutrient availability, or some other parameter.

Science could include intense data gathering on the built 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 of Figure 6 shows that dissolved oxygen concentrations drop and fish need more oxygen as waters warm. Adequate sensors plus reefs may support accurate maintenance of macroalgal oxygen production for abundant fish production even as waters warm.

The simplified diagram in Figure 7 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.

Fig. 6 – Shows the double whammy of equilibrium dissolved oxygen concentrations dropping while animals need for oxygen increases as water temperature increases
Fig. 7 – A schematic of nutrient, energy, and biomass flows into, within, and out of the built reef to the left of a representation for how a model of those flows might be displayed.

USP will reduce the risk of ecosystem crashes by developing computer models for tropical Pacific built-reef ecosystems. 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. You give them urchins to feed their lobsters. They give you lobsters to eat your urchins.

Table 1 – Sketch of database with a few of the seafood species and a few of the parameters that would go into a computer model.

<table>
<thead>
<tr>
<th>Species harvested for people food</th>
<th>Giant Clam</th>
<th>Rock oysters</th>
<th>Rabbitfish</th>
<th>Giant Trevally</th>
<th>Mahi Mahi</th>
<th>Red Snapper</th>
<th>other finfish</th>
<th>Crab</th>
<th>sea urchin</th>
<th>sea cucumber</th>
<th>gastropod</th>
<th>shrimp</th>
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<td>Optimum standing biomass (tonne/ha)</td>
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</table>
Describe spawning timing (text)

Describe embryo behavior (text)

What it eats or limiting nutrients (text)

How much it eats (kg food/kg body mass/day)

How it eats, daily and seasonal variation (kg vs. time)

Dissolved oxygen consumption or production (g O₂/kg body mass/hr)

Variations in O₂ consumption or production with sunlight and temperature (g O₂ vs. light and temperature)

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<tr>
<th>Other important ecosystem species</th>
<th>Macroalgae</th>
<th>Macroalgae</th>
<th>Seagrass</th>
<th>Seagrass</th>
<th>Parrot fish</th>
<th>barnacles</th>
<th>starfish</th>
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Ideally, the model of nutrient flow, species populations, and harvests can be extended to include the interrelationships amongst food systems (e.g., production, processing, distribution, waste), health (consumption), the environment (sustainability), and public...
Every built-reef ecosystem could benchmark its environmental benefits and impacts with to-be-developed methodologies and techniques to calculate, model, and simulate these benefits and impacts. Operators of SEAFood may raise the bar for healthy food and ecosystem services. They may need new metrics so that food consumers and governments can distinguish the merits of eating wild-caught, free-range SEAFood seafood from penned aquaculture with IMTA, penned aquaculture without IMTA, etc.

The food and science reefs are best placed where there is the most urgent need for seafood and science, along tropical coastlines 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. That is, the natural situation is lacking biodiversity and productivity. Laucala Bay, Fiji would be typical for this situation. Professors at USP explain applying shallow water built-reef ecosystems in Figure 2 and at: https://challenges.openideo.com/challenge/food-system-vision-prize/open-submission/restorative-aquaculture-sustainable-seafood-production-for-the-world.

In seafloor depths between about 30 to 200 meters, the purpose-built reef would be flexible, floating, and permanent, as in Figure 3. 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-Energy’s MARINER program can expand seafood production. AdjustaDepth project deliverables are available at ResearchGate or at: https://drive.google.com/drive/folders/1uUudPOFZi1qZCXSbQq_vSZuDFmkSqio_ .

Each region of the world needs a research and training center (perhaps a Decade Collaborative Centre) near a host university with access to seafloor, oceanographic, and nutrient conditions typical of a larger area. This because the nature of the structures, the storms, and the animals interacting with the structures vary greatly between regions. 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); the Eastern Mediterranean Sea; and more. Each of these locations could showcase typical species and tropical marine ecosystems for many countries near them.

There are some non-tropical countries where food and science reefs are needed for general ocean health, adaptations for climate impacts, and/or peace. For example, nutrient recycling built-reef ecosystems in the Eastern Mediterranean Sea (which is oligotrophic, Massa et al. 2017) could create jobs for migrants and Palestinians. Built reef ecosystems would not need recycled nutrients in the dead zones, such as the Danish Baltic Sea and the outlet of the Mississippi River in the U.S. Gulf of Mexico. The area of Danish seas affected by low oxygen levels is double what it was in 2020 at about 3,300 km².

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 built reef ecosystems...
with free-range finfish relative to penned finfish aquaculture. Figure 8’s graphic shows that built reef ecosystems are 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.

**Ecosystem Aquaculture – Economics**

- Plant food $40/ton of fish produced
- Reef cost $1,000/ton of fish
- Fishmeal $2,000/ton of fish
- Pens cost $50/ton of fish

**Fig. 8 – SEAFood – Economics** Comparing the economics of seafood from built reef ecosystems with seafood from penned finfish aquaculture

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 not including operating labor in either case:** Fish products from an open-ocean flexible floating reef will cost about half as much as products from pens. Fish products from sheltered water built reef ecosystems, perhaps a fifth as much as products from pens.

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 open-ocean 20-hectare reef.
3.2 Human 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, polio, 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.” The lack of infrastructure in some countries 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 and uses less energy 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, which supports 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 90°C) “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 pasteurized water on agriculture and/or built reef ecosystems.

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).

e. Calysta makes high protein fishmeal pellets from methane. A similar process could be used to make high protein fishmeal pellets from pasteurized sewage. Either fishmeal pellets would be a good way to distribute nutrients into otherwise oligotrophic (starved for nutrients) total ecosystem aquaculture.

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. Ocean Decade Challenges Addressed

Challenge 1: Develop solutions to remove or mitigate pollution – Most (but not all) “pollution” is human urine and feces. Water resource recovery engineers are refining systems to recover and pasteurize the valuable plant nutrients and energy (carbon) in urine and feces. Any aquaculture, including purpose-built fishing reefs, is only truly sustainable by returning the plant (inorganic) nutrients that were extracted from the purpose-built reef (as protein, organic nutrients).

Challenge 2: Develop solutions to monitor, protect, manage and restore ecosystems and their biodiversity under changing environmental, social and climate conditions – For example, some fish species will leave the tropics as tropical waters become too warm to reproduce. A purpose-built reef ecosystem allows research, large-scale experiments, and rewilding. (Rewilding is bringing back native species made extinct, or rare, by humans. Perhaps giant clams near Zanzibar.) That is, many cameras coordinated with acoustic sensing and occasionally providing cooler water on hot nights. As the number of purpose-built reef systems increases, the seafood production operation would pay for sensors and actions needed to maintain biodiversity.

Challenge 3: Develop solutions to optimize the role of the ocean in sustainably feeding the world’s population under changing environmental, social and climate conditions – An additional 100 million tonnes/yr of seafood by 2030, as much as a billion tonnes/yr by 2050, but limited by demand.

Challenge 4: Develop solutions for equitable and sustainable development of the ocean economy under changing environmental, social and climate conditions – Any coastal community, no matter how lacking in existing fishing resources or currently lacking means to recover their waste resources, can have a purpose-built reef that matches their population.

Challenge 5: Build resilience to the effects of climate change across all geographies and at all scales, and to improve services including predictions for the ocean, climate and weather – In some cases, the structure is a mangrove forest, giant clams to reinforce coral reefs, or other kind of living reef. In all cases, the sensors on the living reef input to a computer ecosystem model. The reef operators use the model to predict if one species population will crash or explode based on forecasts of future conditions. That is, the reefs build resilience to the effects of climate change. Many purpose-built reefs each with many sensors will improve predictions.

Challenge 6: Enhance multi-hazard early warning services for all geophysical, ecological, biological, weather, climate and anthropogenic related ocean and coastal hazards, and mainstream community preparedness and resilience – Many purpose-built reefs each with many sensors will improve predictions. For example, some reefs could include sensors that detect seismic or volcanic activity in addition to the geophysical, ecological, biological, and weather sensors used to optimize long-term productivity with biodiversity.
Challenge 7: Ensure a sustainable ocean observing system across all ocean basins that delivers accessible, timely, and actionable data and information to all users – The data from every reef could go to the cloud, with all the measurements and units organized for data mining. As income from seafood production allows, the reef operators will come to rely on real time data. That data can be made available on the web for school children to view and listen to activity on their local reefs or distant reefs. The acoustic systems on a reef might detect and provide an alarm for unauthorized activity in the reef or in nearby marine protected areas.

Challenge 8: Through multi-stakeholder collaboration, develop a comprehensive digital representation of the ocean, including a dynamic ocean map, which provides free and open access for exploring, discovering, and visualizing past, current, and future ocean conditions in a manner relevant to diverse stakeholders – Each purpose-built reef with its sensors provides a highly detailed representation of the ocean near it with a computer ecosystem model. The model might be viewed similar to the U.S. National Ocean and Atmospheric Administration’s (NOAA) virtual ecosystem scenario viewer.

Challenge 9: Ensure comprehensive capacity development and equitable access to data, information, knowledge and technology across all aspects of ocean science and for all stakeholders – All reef systems would provide transparent public reports. In addition, philanthropic resources could provide support for online and direct interactions to share information and insights across all reefs. Philanthropies may also be needed to bring purpose-built reefs to small communities needing to sustain local food production but lacking (or not interested in) an export market.

Challenge 10: Ensure that the multiple values and services of the ocean for human wellbeing, culture, and sustainable development are widely understood, and identify and overcome barriers to behaviour change required for a step change in humanity’s relationship with the ocean – The internet allows everyone to view the output of sensors on purpose-built fishing reefs. People will see where their food comes from, when their pasteurized urine and feces combine with sunlight to produce a wealth of biodiversity, how the non-food flora and fauna are important to the ecosystem’s sustainable and robust food yields, etc. They will also see plastic and other trash, or clouds of sediment. They may see or hear people poaching from a reef or a nearby marine protected area. In short, each reef can be in everyone’s living room or pocket. Some people may edit the most interesting moments to produce ocean documentaries and the ocean equivalent of funny cat videos.

5. Achieving Decade Objectives

The goal of 100 million tonnes of seafood by 2030 implies newly built seafood reefs involving 10,000 to 100,000 local coastal communities. Built-reef seafood productivity/area depends on the nutrient recycling/area and ecosystem health. Operators (fishing people) need to track many parameters (temperature, pH, nutrient concentrations, disease, species population, individuals’ health, etc.). In addition to instruments (maintained by the operators) the fishing people will be citizen scientists with smart phones.

Each built-reef operator will use information to foresee changes in species populations (due to harvesting, heat waves, disease, …). Foreseeing changes means long-term (decades) of seafood production security. All 10,000 to 100,000 coastal communities have reason to share information and costs.
Each local community will select a governance arrangement in concert with their funding agency. Individual governance arrangements might be: local government (a community or special district); a fishing cooperative; a private company. The individual communities can collaborate for economy of scale.

1.1 Regularly assess the state of the ocean: An alliance of coastal communities can provide management software to operators that automatically produces a continuous report on the state-of-the-ocean near each built reef. The local information can be rolled up into regional summaries, or provided individually, as desired.

1.2 Promote new technology and access to it: The alliance of coastal communities can set up a program for several communities to provide resources to one community to try new technology and conduct experiments of interest to all.

1.3 Expand ocean observing systems: Each built-reef is an ocean observing platform.

1.4 Support community-led science: OceanForesters plans for local coastal communities to develop the capabilities to design, build, operate, and maintain their new reef ecosystems. They might retain outside consultants, materials, and construction equipment initially. All the knowledge (local, indigenous, and contemporary) for each built-reef will be compiled and shared. Each built-reef is likely to be unique.

1.5 Overcome barriers to diversity and promote investment: The value of seafood is such that each seafood reef should generate the income needed to pay back construction loans while increasing the quality of life in the community. The funding agencies can incentivize equity.

2.1 Comprehensive understanding of ocean-land-atmosphere-cryosphere-people: During design, construction, operation, and maintenance each built-reef provides big data to understand the ocean and interactions of ocean-land-atmosphere-cryosphere-people. The demand for built-reef seafood by 2050 might be near 500 million tonnes/year implying 50,000 to 500,000 built-reefs supplying big data.

2.2 Understanding thresholds and tipping points: Every built-reef is an instrumented experiment requiring operators to detect and communicate thresholds and tipping points. Threshold and tipping point detection is critical to sustaining seafood production and biodiversity on each built-reef.

2.3 Use historical knowledge to support SDGs: Yes! Use indigenous, historical and pre-historic knowledge while restoring the density of species that were over-fished to extinction locally: conch in the Caribbean, giant clams in the West Indian Ocean, etc.

2.4 Improve ocean models: Every built-reef needs a three dimensional model including oceanographic data, nutrient flows, multiple species (from as small as microbes to as large as whales) populations, and human actions.

2.5 Improve predictions: Collecting big data allows artificial intelligence mining the data to find correlations and improve predictions, which will benefit local adaptation, productivity, and economics.

2.6 Expand ocean-related collaboration: Local communities with similar oceanographic conditions and species can improve their productivity by sharing research and training centers. For example, the University of the South Pacific might host a research and
training center for tropical Pacific Ocean communities employing giant clams for primary productivity.

3.1 **Communicate the role of ocean science for sustainable development:** This programme promises to reach local fishing people, particularly those with indigenous knowledge. Built-reefs will be successful when the local fishing people have adjusted the design to conform to their fishing and cultural norms. Without such adjustment, failures (population crashes, reduced biodiversity) become likely.

3.2 **Open access connecting knowledge generators and users:** The OceanForesters would like the Alliance of local communities to maintain a wiki that is accessible globally. The wiki would contain and organize all the information and data from every built-reef and the associated nutrient collection and seafood distribution systems.

3.3 **Multi-stakeholder co-design and co-delivery:** The complexity of built-reef ecosystems requires interdisciplinary multi-stakeholder collaboration.

3.4 **Spatial planning for sustainable development across regions:** Built-reefs can be positioned with spatial planning across regions and scales. Note that some communities will produce only local seafood (no exporting). Some areas will produce less expensive yet higher quality seafood for local consumption and export. Regional and global spatial planning can help prevent conflicts (trade wars, monopolies) as supply eventually exceeds demand.

3.5 **Management to maintain ecosystems and adapt within community values and needs:** The built-reef ecosystem includes habitat and substrate such that the vast majority of species volunteer. Relatively few species might be farmed or stocked such as: oysters, giant clams, and conch.

3.6 **Prepared for multiple stressors and hazards:** Maintaining seafood production requires tools for preparing and adapting to stressors and hazards.

3.7 **Expand tools that integrate knowledge of ocean-related capital:** Each reef is likely to have passive acoustic sensors. Acoustic data can help track the location and quantity of species, the movements of people and larger animals, and the actions of people and larger animals. These movements and actions can be tracked in nearby boat channels and marine protected areas. The acoustic data might be matched with people’s locations and purchases.

6. **Achieving Sustainable Development Goals**

**SDG #1. No Poverty:** Ocean farming reefs are truly sustainable environmental community enterprises that create jobs especially for underserved communities. The jobs range from reef construction and maintenance to planting, nutrient collection and distribution, seafood harvesting, and seafood processing and marketing.

**SDG #2. Zero Hunger:** Ocean farming rapidly grows a variety of sustainable and protein-rich food sources. Seaweed (the primary productivity and dissolved oxygen source, not an important crop) requires neither fresh water, pesticides nor land input to grow. The primary crops are high-protein free-range finfish, shellfish such as mussels, oysters, clams, etc., as well as invertebrates, including profitable sea cucumbers and sponges. An alliance of reef operators can employ concepts in “Harnessing global fisheries to tackle micronutrient
deficiencies” to provide the most needed micronutrients locally and to share micronutrients among globally dispersed communities.

SDG #3. Good Health and Well Being: Fish and shellfish provide the healthiest source of protein, complete with micronutrients often lacking in terrestrial crops from depleted soils. In addition, seaweed (and creatures on its food chain) contains high amounts of iodine, potassium, magnesium, calcium and iron, as well as vitamins, antioxidants, phytonutrients, amino acids, omega-3 fats and fiber.

SDG #5. Gender Equality: Ocean farming enterprises can focus on training and advancing women as an economic development tool that serves the immediate family and ripples out to the community and nation. There are women-run co-operatives farming seaweed and adding value to the harvest. A built reef ecosystem would be a step up to higher income for existing seaweed (or fishing) co-operatives.

SDG #6. Clean Water and Sanitation: Coastal communities will come to value recovering the carbon and nutrients that had, in concentrated form, spread disease and overwhelmed local ecosystems. The productivity of built reef ecosystems depends on building human and animal waste collection systems that will pasteurize wastes and use them to fertilize seaweed forests. Replacing 100 million tonnes/yr of the current about 300 million tonnes/yr of meat production with 100 million tonnes of seafood, saves about 600 million acre-feet/yr of freshwater (800 km³/yr, 30,000 m³/sec). For perspective, the average flow of the Mississippi River is about 20,000 m³/sec.

SDG #8. Decent Work and Economic Growth: A permanent built reef ecosystem provides permanent quality jobs in ocean forestry. “Ocean forestry” is a more accurate term than “farming” because the reefs avoid mono- or duo-cultures. The reefs produce diverse income streams including: finfish, shellfish, crabs, snails, sea cucumbers, urchins, lobster. Managing the many product species and the ecosystem support species is like forestry that includes flora and fauna. (Seaweed harvests should be limited because of its low value and to avoid putting seaweed farmers out of business.) The quantity of jobs is only limited by the availability of suitable ocean area and recyclable nutrients. That means reefs could be built to provide permanent jobs for and recycle the nutrients from refugees and migrants.

SDG #10. Reduced Inequalities: A built reef ecosystem is a “new industry” for each community. As a new industry, the first built reefs lack an entrenched hierarchy of inequalities. The funding agencies can insist the new organizations structure for merit-based promotions and equal opportunity. The income from reef operations can fund education for everyone (online classes to improve one’s certification level). Each reef has a wide range of manual, shop, and desk jobs from lifting nets full of fish, to maintaining sensors and communications, to maintaining the reef structure, to maintaining the fishing equipment, to processing the catch, to using the computer model when identifying how much of each species to catch that week.

SDG #11. Sustainable Cities and Communities: Cities and communities move toward sustainability when their food supply completes the nutrient cycle.

SDG #13. Climate Action: Built reef ecosystem seafood can scale to meet global high-protein food demand in 2050 even to displacing all meat and current seafood production. Any decrease in meat production would free-up land that is currently producing meat or grain

Contents  Tropical Pacific SEAFood Programme, Rajesh.Prasad@USP.ac.fj  MarkCapron@OceanForesters.org  18
for meat for other uses: grain for people, biomass-for-energy, permanent carbon-sequesterining forests (or at least an end to deforestation). People whose livelihood depend on deforestation could become ocean foresters.

Mass weighted average meat GHG impact is about 17 tonnes of CO$_{2eq}$ per tonne of meat (Ritchie & Roser 2019; Poore & Nemecek 2018). Seafood GHG impact is about three tonnes of CO$_{2eq}$ per tonne of seafood (including both wild-caught and aquaculture) (MacLeod et al. 2020; Parker et al. 2018). A business-as-usual increase in both meat and seafood production would mean 13 billion tonnes of CO$_{2eq}$. Continuing 2018 meat and seafood production levels and adding a half billion tonnes of built reef seafood would total eight billion tonnes of CO$_{2eq}$, a savings of five billion tonnes of CO$_{2eq}$. Although the macroalgae could be harvested for energy production, that is not within the SEAFood Programme.

**SDG #14. Life Below Water:** “Rebuilding marine life” suggests that, “Rebuilding fish stocks can be supported by market-based instruments, such as …the growth of truly sustainable aquaculture to reduce pressure on wild stocks.” This program can move beyond truly sustainable aquaculture to the aquatic version of rewilding. Rewilding is returning species to areas where humans caused their extinction: wolves, grizzlies, bison, and beaver to the U.S.; bison to Europe. Aquatic rewilding could include giant clams, seagrass, dugongs, sea turtles, clams, oysters, etc. restored over their pre-human range at their pre-human density.

Ocean waters around seaweed ecosystems have measurably lower acidity, which helps crustaceans and sea life of all kinds. In fact, submerged plants can facilitate the formation of calcium carbonate minerals, which are transported down current, buffering pH wherever they go (Jianzhong Su et al., 2020). Ocean reef ecosystem operators should manage to increase biodiversity because doing so should offer the most long-term and robust seafood production. Good management requires a calibrated computer model of nutrient flows, species populations, the effect of species populations on other species, the effects of changing temperature and ocean chemistry on species populations, etc. The model needs to cover a range of species sizes from virus to whale. (These points require substantial science.)

Scaling built-reef ecosystems allows more marine protected areas. 200,000 to 300,000 km$^2$ of floating flexible reef structures with total ecosystem aquaculture could produce a billion tonnes of seafood per year. A billion tonnes is 5 times current seafood production. Including space between reef structures to avoid overlapping mooring lines, they might occupy 1.5 million km$^2$ of continental shelf with seafloor depth less than 200 meters. That is about 13% of the 11 million km$^2$ of 0 to 200-m deep continental shelf that Gentry et al. (2017) found potentially suitable for fish and shellfish aquaculture. If all the non-indigenous ocean fishing and aquaculture were on floating flexible reef ecosystems, the entire deep ocean (deeper than about 200-m) and 87% of continental shelves (less than 200-m seafloor depth) could become marine protected areas or reserved for indigenous fishing.

Built reef ecosystems will diversify monitoring and maintenance funding for marine protected areas. The coastal community fishes the built reef for food and income. Most built-reefs will have acoustic sensing systems to detect poachers and monitor fish populations. The sensors on the built-reefs can detect poachers in nearby marine protected
areas. When economic recessions or pandemics drop tourist income, the local community can survive on the built reef and still detect unauthorized activities in the marine protected areas.

**SDG #15. Life on Land:** The demand for meat, grain, and terrestrial plant biofuel is driving deforestation and overdrawing aquifers. Built reef ecosystem seafood can scale to meet global high-protein food demand in 2050 even to replacing all meat and current seafood production. Replacing 100 million tonnes/yr of the current about 300 million tonnes/yr of meat production with 100 million tonnes of seafood, saves about 600 million acre-feet/yr of freshwater (800 km$^3$/yr, 30,000 m$^3$/sec). For perspective, the average flow of the Mississippi River is about 20,000 m$^3$/sec.

**Other SDGs:** While directly addressing the above eleven SDGs, ocean forests indirectly support the other five Goals by creating sound economic and social foundations so that everyone can participate in and gain from (4) Quality Education, (7) Affordable and Clean Energy, (9) Industry, Innovation and Infrastructure, (12) Responsible Consumption and Production, (16) Peace, Justice and Strong Institutions, and (17) Partnerships for the Goals.

7. **Knowledge uptake, data sharing, partnerships, capacity development, diversity, local and indigenous knowledge**

The local coastal community and its indigenous knowledge holders should design and operate their built reef ecosystem to suit local the local natural ecosystem, their ways of fishing, and their preferences for organizing. The only intrusion should be an understanding that funding depends on equalizing opportunities for everyone in the community. The local community must become “invested” in adapting the science to fit their resources. When communities are involved in the planning, they find ways to make the development successful. Development that is not planned by the community can be detrimental. See Saini, A. and Singh S.J., “The Aid Tsunami” Scientific American April 2020 for an example of adverse “help.”

Scientists and engineers mentoring and coaching the local organizations will strive to leave the local reef-operating organizations with the skills to add more reefs independent of the initial scientists and engineers.

Likewise, scientists conducting research on built reef ecosystems will strive to leave the local organization with the skills to continue and expand research topics independently. Scientists might: (1) purchase data that the local organization gathers for its purposes; (2) pay for maintenance services, power, and communication connections on additional sensors; (3) work with the community to conduct research without affecting seafood production; (4) coordinate research with yield-enhancing experiments conducted by the local operator (submerge to cool, changing details of recycled nutrient distribution, and the like); and (5) offer to pay for difference in profit losses between the experiment reefs and the control reefs.

Resource providers (funding and in-kind) should find a funding mechanism that: (1) leaves the local community owning the built reef outright within 15 years; (2) does not saddle the local community with debt, should revenue minus expense be inadequate to repay; (3) collects more than the initial funding where revenue minus expense allows. Particularly in least developed countries, the lack of product transportation infrastructure may limit export
revenue. The lack of export revenue may hamper purchasing some of the materials needed to maintain the structures.

8. **Lead Institution and Partners** (as of 14 November 2020)

1. Lead Institution: The University of the South Pacific
2. Type: University
3. Lead Institution physical address: [_address]
4. Contact person: Dr. Rajesh Prasad
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*Note the Ocean Decade Submission form requests listing partners by institution. “6. Partner details (for each partner please list Institution name, contact details including address & email and role of partner)” However, we can include partners who prefer to be listed as individuals.*

Dr. Flower Msuya is the founder and leader of the [Zanzibar Seaweed Cluster Initiative](https://www.wiomsa.org) (ZaSCI), Tanzania. The ZaSCI started with women farming seaweed. Dr. Msuya, with funds from WIOMSA [www.wiomsa.org](https://www.wiomsa.org) researched on a new way to farm seaweed in deep (cooler) water and then with help from [Sea PoWer](https://www.seapower.org) implemented the new method. She also led ZaSCI into processing seaweed into 50 value-added products and placing fish traps in the seaweed farm.

Seadling is a social and environmental impact seaweed biotechnology based in SE Asia that enhances the productivity of community-led seaweed farming and produces high-value seaweed nutritional products. Seadling seedlings are proven to grow faster with higher yields and greater disease resistance than those currently used.

Luke Dallafior and Tricia Grant of Garrison Force are:

a. Supporting funding Blue Economy projects throughout Southeast Asia. Projects with the benefits of a Nutrient Recycling Seafood-Science Programme are particularly desirable. Technologies of interest, in addition to seafood: marine plant and algae extracts; ocean based alternative energy; blue carbon initiatives and ocean environmental analysis; and monitoring and data systems. Abundant Ocean Ventures will provide seed and growth capital for companies and technologies important to a sustainable blue economy.

b. Arranging projects in Bali, Indonesia that fit within a Nutrient Recycling Seafood-Science Programme. The projects will support mindful and synergistic ocean-based business ecosystems for coastal people throughout Indonesia. The projects can be scaled on a regional or global basis.
Miguel Hoffman is the Founder of RAMA (Rescate al Medio Ambiente) [Environmental Rescue], a non-governmental organization of El Salvador. RAMA believes that our blue planet requires blue solutions to the most pressing crises of our epoch: environmental degradation, climate change and deep, institutionalized poverty. RAMA will help organize SEAFood projects (both sheltered and open ocean versions) as well as projects clearing El Salvador’s freshwater lakes and rivers of their hyacinth infestations.

Lloyd's Register Foundation is a UK charity established in 2012. They have identified seven pressing challenges within their mission to protect the safety of life and property. Two challenges are particularly important for an Ocean Decade Nutrient Recycling Seafood-Science Programme: safety at sea and safety of food.

OceanForesters: Mark E. Capron, Professional Engineer (P.E.), Jim R. Stewart PhD, Mohammed A. Hasan P.E., Don Piper, Graham Harris, Martin Sherman, and Jill Santos are core OceanForesters. OceanForesters, a California corporation, is a private sector stakeholder with the mission of coaching, mentoring, consulting, and supporting local coastal communities to design, build, and operate the permanent built-reef ecosystems they desire.

Dr. Mohammad Badran is an active independent researcher with diverse knowledge of Red Sea Environmental management and Professor Mohammad al Zibdah is a manager of an experimental aquaculture unit for the University of Jordan in Aqaba. Their interest is in tackling challenges of nutrient recycling while protecting the coastal environment and enhancing biological productivity of the (oligotrophic) ecosystems near and in the nutrient-sensitive coral reef habitats in the Gulf of Aqaba and wider Red Sea.

Dr. Kevin Hopkins, Professor of Aquaculture at the University of Hawaii, Hilo teaches aquaculture engineering, fisheries science, and water quality analysis. His research interests include business aspects of aquaculture and the application of fisheries and ecological models. He has been the primary organizer of the Marine Agronomy Group.

Dr. Reginald Blaylock is the Assistant Director of the Thad Cochran Marine Aquaculture Center, University of Southern Mississippi, USA. His research interests include aquaculture, marine stock enhancement, factors affecting susceptibility to diseases and parasites, and ecological and epidemiological patterns in diseases and their use in the study and management of fisheries.

Scott James is an Associate Professor in the Department of Geosciences, Baylor University, Texas, USA. His research interest is the intersection of water and energy, which includes modeling and optimizing macroalgae growth.

Dr. Kurt Rosentrater is an Associate Professor at Iowa State University. He teaches courses in food and process engineering as well as economic and environmental assessment. His research program uses life cycle assessment and techno-economic analysis for a variety of bio-based systems and processes.

Rae Fuhrman runs Stingray Sensing, a boutique restorative aquaculture consulting firm and tech start-up based in California. By developing responsible oceanographic monitoring requirements along with the equipment to achieve real-time monitoring of regenerative marine farms, large-scale cultivation of beneficial and harvestable ecosystems becomes possible.
AquaDam manufactures water-filled tubes that can be as large as 3 meters high. The tubes can be used in ocean structures, for movable on-land aquaculture or hatchery ponds, and as levees to contain floods.

Chris Webb, CEO of AI Control Technologies, Mississippi, USA. AiCT makes remote and precise buoyancy control electronics and AI software for aquaculture. Precise buoyancy control allows submerging to avoid parasites, avoid storms (less damage to crop or structure), and avoid impeding endangered species. Also, lobster (and other) traps could be deployed and retrieved electronically under a flexible floating fishing reef without having to pass through the reef.

9. Area of similar ecology

USP’s tropical Pacific SEAFood with Healthy Oceans Programme shares a key species, giant clams with a larger region. Giant clams are a keystone primary productivity species, perhaps more important than macroalgae for producing food and oxygen within its native area. See Figure 9.

Projects within the giant clam area are described in Appendix A.

Fig. 9 – A map of the geographic extent of giant clams from Othman et al. 2010
References:


Jianzhong Su et al. Chesapeake Bay acidification buffered by spatially decoupled carbonate mineral cycling, Nature Geoscience (2020). DOI: 10.1038/s41561-020-0584-3


Appendix A

Typical Projects for the tropical West Pacific and Indian Oceans

The tropical West Pacific and Indian Oceans are likely to have somewhat similar SEAFood built-reef ecosystems. This is because the area is home to a possible key primary producing species, giant clams. See main document map Figure 9. Giant clams, like coral, contain significant symbiotic algae. Neo et al. (2015) provides details.

Table 2 in Neo et al (2015 shows individual’s natural population densities can range from 36 to 909,000 per hectare. The latter density is mostly juvenile clams producing the highest biomass (on the table) of 238 kg/ha/yr dry weight. This means that we might expect to harvest about 2 tonnes/ha/yr wet weight of all species in the ecosystem (with nutrient conditions similar to Fangatau and Tatakoto atolls). The productivity/area might be substantially improved when nutrients equal to those extracted are returned to the ecosystem. Even with only background nutrients, a 20-ha ecosystem would produce $80,000/ha/yr with seafood worth $2/kg at the dock. The 500-m diameter circle of Figure A1 encloses 20-ha. With ample nutrients and more photosynthetic species, productivity can be over ten times higher.

OceanForesters research with the U.S. Department of Energy Advanced Research Projects Agency-Energy’s MARINER program suggests macroalgae productivity with optimum nutrients could be between 300 to 1,000 tonnes/ha/yr wet weight of all harvested species.

The easiest way to recycle nutrients to a SEAFood ecosystem is to locate it where people are placing too many nutrients. This is the situation for the University of the South Pacific’s project in Laucala Bay. The challenge becomes installing and managing the filter feeders, macroalgae, and giant clams to maintain dissolved oxygen for a healthy ecosystem.

When an area has less-than-optimal nutrients, the easiest way to recycle nutrients is to collect and pasteurize people’s urine. Pasteurization requires only 55°C for 2 hours. (Or longer times and higher temperatures when dealing with more problematic materials.) All the urine from 100 people could in theory convert to 10 tonnes/year of wet shell-on blend of all harvested species (finfish, shellfish, seaweed, mollusks, etc.). Actual production will be much less, perhaps less than half. When recycling nutrients to a seaweed monoculture, 100 people’s urine could theoretically add 20 wet tonnes/yr to the crop.

When preserving or restoring coral reef ecosystems, SEAFood can emphasize giant clams for primary productivity and filtering (water clarity). That is, the aerial view could resemble Figure A1, but with less seaweed. The growth of native macroalgae, recycling of inorganic nutrients, distribution of inorganic nutrients should be managed such that increased seafood productivity is compatible with healthy nearby coral reef ecosystems.

When coral is not a concern, such as over a muddy or sandy seafloor, farmed and volunteer macroalgae can be the key primary productivity. This especially when recycling substantial inorganic nutrients. The plan could resemble Figure A1, but with more seaweed.

Only the primary producers are shown in Figure A1. The ring of seaweed around the circle filled with giant clams may be useful to define the boundary of the fished SEAFood ecosystem. Hopefully, the host country’s laws and culture will acknowledge that all the species, biomass, and shell mass inside the ring belong to the people who built (seeded) and maintain the SEAFood ecosystem. Most of the ecosystem biomass will volunteer. Many “planted” or “stocked” species
will be managed to become self-seeding, such as giant clams. Much of the SEAFood ecosystem may spread downstream.

Managing and harvesting the SEAFood ecosystem is more like forestry than farming. There are many harvested species. A species is harvested before its population boom threatens a crash of that species or the ecosystem. All species are harvested in moderation, sparing especially individuals with the largest reproductive capacity. A one-species example – A few giant clams (the survivors of heat waves and other stressors) are allowed to age until their reproductivity declines. Most giant clams become food for other creatures. Science includes genetic testing to find those young giant clams susceptible to heat waves. Some of them might be harvested and sold when heat waves are predicted.

Fig. A1 – Concept plan of a SEAFood ecosystem in shallow water where giant clams are native (Structures, giant clams, and seaweed inside the ring are not to scale.)

Growing seaweed monocrops (sometimes with shellfish) is becoming a hot topic. See the Seaweed Manifesto and the MARINER Program. Seaweed production via large farming operations could depress prices, although some hope for carbon fees. In a built-reef ecosystem, seaweed may be more valuable for ecosystem services such as: dissolved oxygen, in-situ food for other species, shelter, and reproductive habitat than when harvested.

Where seafloor depth is greater than about 20 meters, flexible floating reef structures become necessary to support macroalgae and symbiotic algae in the photic zone.
The University of the South Pacific
Science Enables Abundant Food (SEAFood) with Healthy Oceans
Laucala Bay Training and Research Center
Dr. Rajesh Prasad¹, University of the South Pacific, Fiji, with the OceanForesters²

Fig. A2 – Locations of project components

Summary: The University of the South Pacific’s (USP) member and associate countries³ need a research and training center. The shallow sheltered water center locations are shown in Figure A2. Eventually, research and training can be expanded to the open ocean. Fiji is mentioned in Gentry et al. (2017) for its abundance of open ocean area with less than 200-m seafloor depth.

Need: Most urgently, island nations that relied on tourism for jobs and subsistence have had to relax fishing management rules. People need to feed themselves during the pandemic. Over the not-so-long term island nations and their coastal ecosystems are vulnerable to the impacts of climate change which are exacerbating the issues of food security, poverty, land shortages as populations increase, declining wild fisheries, and pollution, especially in their sheltered bays and lagoons.

SEAFood with Healthy Oceans: The Tropical Pacific SEAFood Training and Research Center would be based at the USP Suva campus and would provide students from across the Pacific examples of SEAFood facilities.

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SEAFood involves establishing a complete ecosystem that cycles ‘waste’ nutrients into increased seafood production, while cleaning up pollution and restoring the natural environment.

Candidate species for fisheries restoration include: giant clams, oysters, mussels, conch, abalone, mud crabs, lobsters, sea cucumbers, sea urchins, sponges, herbivore finfish, filter-feeding finfish, predatory finfish, and more. Supporting species needed to maintain a robust ecosystem and improve yield include: seaweeds, seagrass, mangroves, epiphytes, and many tiny sea creatures. USP and OceanForesters will seek indigenous ocean knowledge to help ensure a robust ecosystem.

Why Laucala Bay: Laucala Bay, adjacent to the USP campus, will provide an excellent demonstration and teaching site, since it presents an extreme example of the excess nutrient issues found in many countries. (See Figure 2 in the main document.) The water is clouded with sediment from the rivers and microalgae growth from the Kinoya Sewage Treatment Plant outfall and fecal coliform. supplying a million or so filter feeders (oysters, mussels, clams, giant clams, plus volunteer filter feeding finfish) along with planting mangroves and perhaps seagrass will clarify the water. The shellfish and finfish can thrive when they are near underwater plants. Plants raise pH (and thus locally reverse ocean acidification) and increase oxygen levels. The plants can thrive when the water is clarified (they are not covered by sediment).

Laucala Bay is also ideal because giant clams are native, the seafloor is less than 15 meters deep, and its natural condition is coral reef. Giant clams have symbiotic algae, like coral. That is, they are both a nutrient absorbing plant and a filter feeding animal. They are the ideal keystone species for SEAFood projects that can also restore coral reef ecosystems. Giant clams are native throughout the eastern tropical Pacific and Indian Oceans. (See Figure 9 in the main document.)

Dr. Prasad and OceanForesters are currently designing a trial combining USP labor with $5,000 from OceanForesters for materials. The trial might quantify giant clam performance:

a. How many logs of fecal coliform removal the shellfish accomplish? (You can adjust the flow-thru rate proportional to the shellfish’s filtering rate. If funds allow, check for other wastewater borne microbes.)

b. Do the giant clams absorb nitrate and ammonia/urea from the water? (They might get all the N their symbiotic algae need from digesting organic N the clams filter out of the water. If they do not remove inorganic N from the water, we can arrange the ecosystem to feed them microalgae.)

c. If funds allow, check for a daytime dissolved oxygen and pH increase, perhaps night-time dissolved oxygen and pH decrease.

Self-Sustaining: Eventually, income from seafood sales can be used to expand and sustain USP’s Research and Training Center. Many island nations will install SEAFood projects for both local consumption (reducing imports) and export income, improving their diet and economies and increasing resilience to climate issues.

Open Ocean Future: Fiji is one of three places singled out in Gentry et al. (2017) for its large area of seafloor that is less than 200 meters deep. Open ocean SEAFood structures around Fiji would be in water at least 50 meters deep. The macroalgae and giant clams would normally be near the ocean surface, but would submerge during typhoons.

Funding and Governance: Training and proof-of-concept research can start with as little as US$5,000 for materials. Any amount up to about US$2 million over a few years can be leveraged into a first-rate SEAFood Training and Research Center. The reef and mangrove ecosystems, along
with seafood yield data and calibrated fisheries models, could provide collateral for bank loans to expand a SEAFood business.

USP and OceanForesters would like the Laucala Bay SEAFood business to fit the Fijian culture and UN Sustainable Development Goals. This means involving USP’s social and business departments plus all the stakeholders around Laucala Bay.

OceanForesters’ bio-ecological-engineering analysis suggests the Laucala Bay SEAFood business could have US$10 million/yr net revenue after full expansion (five to ten years). That is, the Laucala Bay business should have ample revenue to fund USP’s Laucala Bay Training and Research Center. The business would fund the Center because the business needs trained employees and knowledge to manage the SEAFood operations for robust biodiversity and yields.

**Long Range Benefits:** With minimal initial foundational funding, students trained at the Fiji Center can bring this profitable system to the open ocean and sheltered water of many countries across the Pacific, helping them to remain self-sufficient in seafood, while some of them generate income from surplus international sales. The micronutrients in seafood will improve the diets and health of thousands of people. Thousands of hectares of mangrove restoration will not only improve water quality but also protect islands against tropical storms. The income will give them more options to adapt to sea level rise.

The following projects are outside USP’s tropical Pacific region. USP and its coastal communities will be networking outside their area. Features in these projects may be adopted in the tropical Pacific.
The Zanzibar Seaweed & SEAFood Cluster Initiative
Dr. Flower Msuya⁴ and the OceanForesters²

The warming ocean forces the Zanzibar Seaweed Cluster Initiative (ZaSCI) to move operations a few kilometers offshore. The ideal seafloor depth of 6 to 10 meters of rarely too warm. The red circled area in Figure A3 includes mud, sand, and coral reef seafloors with maximum depth near 80 meters. The offshore move requires boats. Boats are expensive, which means the operation must earn more per year and more per boat trip. Needing boats is one of the reasons ZaSCI is already trapping fish that visit their seaweed farming operation.

ZaSCI plans to add the SEAFood ecosystem depicted in Figure A1 to its current seaweed farming operation. The planned SEAFood operating area (red circle in Figure A3) contains all three conditions allowing them to adjust between mostly seaweed and shellfish to mostly giant clams.

ZaSCI will start pasteurized urine recycling with 20 people using techniques refined at the Rich Earth Institute. Twenty people should boost monocrop seaweed production about 2 tonnes/yr or sea creature production about 1 tonne/yr.

The Institute of Marine Sciences will coordinate research activities on the ZaSCI SEAFood ecosystems. The minimum participation of ZaSCI members would be as citizen scientists and sensor maintenance. ZaSCI needs science to develop the full ecosystem model with operator interface mentioned in the main document.

⁴ Founder and leader of the Zanzibar Seaweed Cluster Initiative (ZaSCI), Tanzania
Malaysia and Indonesia SEAFood Projects
Dr. Simon Davis\(^5\) and the OceanForesters\(^2\)

\textit{Seadling} has strong relations with four seaweed farming communities:
- Kota Belud and Semporna, Sabah, Malaysia

Dr. Davis feels that seaweed farmers in the indicated communities may be interested in participating in the Ocean Decade. Their minimum participation would be as citizen scientists and sensor maintenance while conducting their current seaweed farming operations. Their science could include testing \textit{Seadling}’s seaweed seedlings for:
- Sustained production of high-value seaweed nutritional products through marine heat waves.
- Continued and further improved robust disease resistance through changing ocean conditions.
- Increased local day and night dissolved oxygen and pH by seaweed species and breeding.

Some of these communities may elect to transition their seaweed farming operations to SEAFood ecosystems. Doing so implies building their capacity to conduct the science needed to personalize SEAFood ecosystem model.

\textit{It would be nice to know the seafloor bottom type (mud, sand, coral reef), approximate seafloor depth typical for the existing seaweed farming operations. Also, are they finding warmer water is driving them to deeper water? Or are the \textit{Seadling} seaweed seedlings tolerating heat so they can stay in shallow water?}

\textit{This write-up would be more like the USP write-up, if the University of Malaysia is considering being a Regional Lead Institution for Malaysia and Indonesia (and perhaps other areas?). Each region can shrink or expand in coordination with more or less institutions wanting to be a Regional Lead.}

\textbf{Seadling’s Expanded Seaweed Hatcheries Project}
Dr. Simon Davis\(^5\) and the OceanForesters\(^2\)

Seaweeds used in farming need to adapt to warming and other changing conditions. Or the seaweed farmers will need to move farther offshore. Seaweeds cannot migrate fast enough when marine heat waves can cause migrations of finfish a hundred kilometers in a few months, Jacox et al. (2020). See the \textcolor{blue}{urgency discussion} for more issues needing directed evolution and the lifeboat analogy.

\textit{Seadling} will provide adaptions by expanding breeding and hatchery operations with: more science and more hatchery locations.

\(^5\) Founder and Managing Director of \textit{Seadling}.