More Economical Living Reefs that Provide Shore Protection,
Habitat Restoration, and Sustainable Seafood
Consider Artificial Reef Plan comment at
Innovating Sustainable Shore and Marine Ecosystems

Communities need innovation funding

Coastal communities in the U.S. will spend $10s to $100s of billions, in aggregate, between 2030 and 2060 on shore protection and sustaining marine ecosystems, if they use traditional[1] systems. Costs might be halved while marine ecosystems are restored and preserved, if communities can combine the two issues in one project and be supported to employ innovative solutions.

Appendix A – **Structures combining shore protection and sustainable seafood**

Appendix B – **Marine ecosystems, ocean ranching, and suitable systems research**

Appendix C – **Local issues in MA, NC, SC, FL, TX, and CA**

Appendix D – **Kelp Forest economics with California Ocean Ranching Ecosystem (CORE)**

Appendix E – **US East & Gulf Coast economics with California Ocean Ranching Ecosystem (CORE)**

Appendix F – **Beach-focused managed retreat**

Appendix G – **Quick shore protection and best management practices**

Multi-purpose reef economics

Typical continental U.S. costs for beach nourishment range from $500,000 to $5 million per mile per year. The economic value of beach tourism is $40 million to $800 million per mile of beach per year ($6 million to $120 million of taxes generated). Both total value and tax income are currently larger than the cost of beach nourishment.

But, beach nourishment costs will increase per a 2024 Nature study: "Consequently, the annual volume of sand required for beach nourishment could triple by 2050, increasing from the present-day amount of ~1,200 to ~3,700 cubic meters per year per kilometer. However, the associated cost for this nourishment will grow five times, exacerbating several coastal communities' economic and logistical pressures." That is, those paying $5 million/mile/yr now should plan for $25 million/mile/yr in a few decades.

Beach nourishment has an opportunity cost – It does nothing to sustain local seafood productivity and marine biodiversity through centuries of climate change.

Table 1 shows a range of annual savings on beach nourishment costs, insurance costs, annual income from sustainable seafood. The value of ecosystem services has to be calculated for each location, but it is significant, as presented in this graphic from the Ocean Conservancy. In addition, the increased tourism and surfing values are location-specific. The bottom line is the breakeven value shown in the table. If the $/mile of breakwater/reef is less than the bottom line present value of total savings, the community saves money with the breakwater/reef. Traditional breakwaters are made with large rock or concrete armor costing $50 to $75 million/mile. Some innovative wave-reducing bio-supporting reefs should cost less than half that of traditional breakwaters, as shown below.

[1] Traditional systems include artificial reefs or breakwaters consisting of large rocks or concrete shapes.

Table 1 – Estimates of the present values of reduced need for beach nourishment and increased sustainable seafood production.
(Red numbers are "selectable" values that would be adjusted to the local situation.)

Annual beach nourishment cost w/o breakwater/reef [1]	$/mile/yr	$500,000	$5,000,000	$500,000	$5,000,000
Increased interval between beach nourishments [2]	factor of	2	2	8	8
Annual savings on beach nourishments with breakwater/reef	$/mile/yr	$250,000	$2,500,000	$437,500	$4,375,000
Annual insurance savings with breakwater/reef[3]	$/mile/yr	$300,000	$700,000	$300,000	$700,000
Annual improved sustainable seafood income with breakwater reef [4,5]	$/mile/yr	$1,000,000	$2,300,000	$1,000,000	$2,300,000
Breakeven value of breakwater/reef, 4% annual interest over 50 years, rounded [6]	**$/mile**	**$33,000,000**	**$120,000,000**	**$37,000,000**	**$160,000,000**

[1] Pick your community's projected annual cost for shore protection between 2030 and 2060. Include the cost of beach nourishment, seawalls, living reefs, raising buildings, managed retreat, etc. Current $0.5 to $5 million/mile/year costs are expected to be $2.5 to $13 million/mile/year in a couple of decades.

[2] Select the desired amount of wave energy attenuation. A 50% reduction in wave energy may double the interval between beach nourishing projects. A 90% reduction might multiply the interval by 8 times.

[3] Identify your community's insurance cost per mile and Zone. For example, Palm Beach, Florida, beachfront premiums are about $1 million/mile/yr. Downgrade from danger Zone VE to Zone AE (waves 1.5 to 3 feet high) for a 30% premium reduction. Downgrade from Zone VE to Standard AE (waves less than 1.5 feet) for 70% premium reduction.

[4] Estimating sustainable seafood income requires research on the local marine present and future ecology. Numbers shown are estimated based on the research on Net Primary Productivity in Southern California summarized in Appendix D. This row (or additional rows) could include other components of ecosystem services, such as: tourism, recreation, aesthetic, surfing, clean water, and spiritual (such as tribal traditions) benefits; plus carbon sequestration (all of which need to be calculated for each location).

[5] Multi-purpose reefs can provide more ecosystem benefits relative to beach nourishment than commercial seafood including improved surf break, SCUBA diving and snorkeling interest, recreational fishing, biodiversity, spiritual (such as tribal traditions), carbon sequestration, etc. (all of which need to be calculated for each location).

[6] The design life of each breakwater reef should be much longer than the economic life, perhaps over a hundred years. That might include a few moves to adjust for sea-level rise. Engineers can select an interest rate and economic life applied to all alternatives considered for a location.

Appendix A – Structures combining shore protection and sustainable seafood

Coastal communities need their infrastructure to support coastal resources for property protection, recreation, tourism, and sustainable seafood. Adaptations should be selected for the lowest total life-cycle cost of sustaining the benefits described in Appendices A-D through these examples and future unanticipated disasters:

a. Storms and associated waves are becoming more intense. What used to be a 100-year storm in 1950 had already become roughly a few-year to few-decade event by 2020, and is projected to become roughly a 2- to 15-year event by 2050. Every major storm requires major beach replenishment.
b. Calming ocean waves can prevent erosion and protect structures, allowing a few more decades for raising infrastructure before managed retreat becomes the only option.

Breakwater/reefs – Living reefs are colonies of coral, oysters, and/or mussels. In most cases, sea life needs a foundation to attach to and grow on. The foundation can be an existing coral reef, rocks, or any breakwater/reef.

Innovative breakwater/reef systems

a) Microbially Induced Calcite Precipitation for beach stabilization and Dellanera Reef.
b) MIT's concrete interacting foil wall is transformative with its (20^+) drag coefficient permeable wall of interacting concrete foils. It maximizes peak horizontal wave force.
c) Thin metal foil artificial reefs, such as COILReef™, are fundamentally transformative using defense-in-depth to spread and balance wave forces over wavelengths of structure.
d) US Defense Advanced Research Projects Agency (DARPA) developed reefs – University of Hawaii reef, University of Miami X-Reefs, Rutgers' oyster-based reef use special concrete shapes that support coral or oyster growth to increase size and self-repair over time. The Louisiana Wave Attenuating Device, is similar in concept to some of the DARPA reefs.
e) These reefs are not thought of as breakwaters, but could attenuate waves if deployed in significant quantities: The University of Louisiana tested Wave Robber, IntelliReefs, Natrx, Printera and other 3-D printed concrete variations, Reef Balls, Sea Cave® Reef Unit. Octo-cylinders, Figure A1, may be attached to breakwater reefs or embedded in the seafloor.

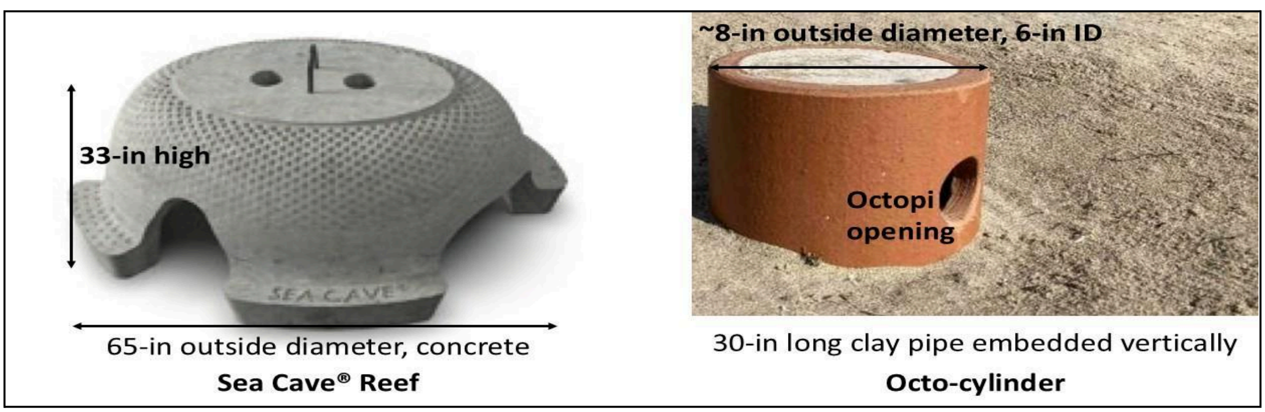

Figure A1 – Sea Cave Reef Unit and Octo-Cylinder Habitat Module

Traditional breakwaters

Traditionally, breakwaters have been constructed of large rocks and concrete modules, such as tetrapods. The larger the wave, the larger and denser the rock or concrete module needed to resist movement.

Living reef foundation engineering and research needs

All of the listed innovative breakwater/reef systems listed on Page 3 require hydrodynamic analysis, structural engineering, and wave tank testing for the local conditions and local oceanographic effects, which will affect the local marine ecosystem and recreation. Some, such as microbially induced calcite formation and those relying on coral or oyster growth may require more laboratory or in-ocean research to establish their long-term viability. All require a few years of in-ocean operation to learn how well and how to sustain the local marine ecosystem through centuries of climate change.

More details on one thin[2] metal foil artificial reef – COILReef™ [3]

Thin metal foil artificial reefs are not just an incremental improvement — they are fundamentally transformative. Research on them can show how to reduce future costs and annual sand replenishment needs by a factor of 2 to 20. For example, COILReef™, Figures A2-A10, is an inexpensive example of thin metal foils. COILReef is adaptable to produce any desired wave attenuation from 10 to 95% by mimicking a coral barrier reef, while supporting seagrass beds and other habitat within or behind the structure. It can be a storm wave filter, reducing the largest waves while leaving small waves to carry mud offshore. It can also provide an attached growth surface for coral, kelp, and other seaweeds. It can have eye bolts for attaching ropes for farming kelp, *Gracilaria*[4], mussels, etc. It can even be designed to produce precisely desired surf breaks to optimize the surfing experience.

Figure A2 – COILReef Wave-Attenuation and Habitat Structure

[2] "Thin" includes 1 mm thick, standard road guardrail 12-gauge (2.67 mm), and up to a half inch (12 mm) thick for roll-forming.
[3] US Patent 11,248,356 B2
[4] In temperate kelp ecosystems like New England, California, and Peru, TURF members could "plant" *Gracilaria* on ropes a month before the water becomes too warm for kelp.

The cost of the COILReef™, to be found after research and *in situ* trials, is estimated to range from $27 million/mile to $70 million/mile. Each COILReef™ design can be tailored for the desired savings listed in Table 1, seafood incomes, funding availability, and budget capacity of the local coastal community.

Concept sketches of thin metal foil artificial reefs (showing design flexibility)

Thin foil reefs can be any shape and orientation, either straight or circular. Figures A3 and A4 show straight coils, which are perpendicular to the beach.

Figure A3 – AI-generated sketch showing scale and wave attenuation of COILReef[5]

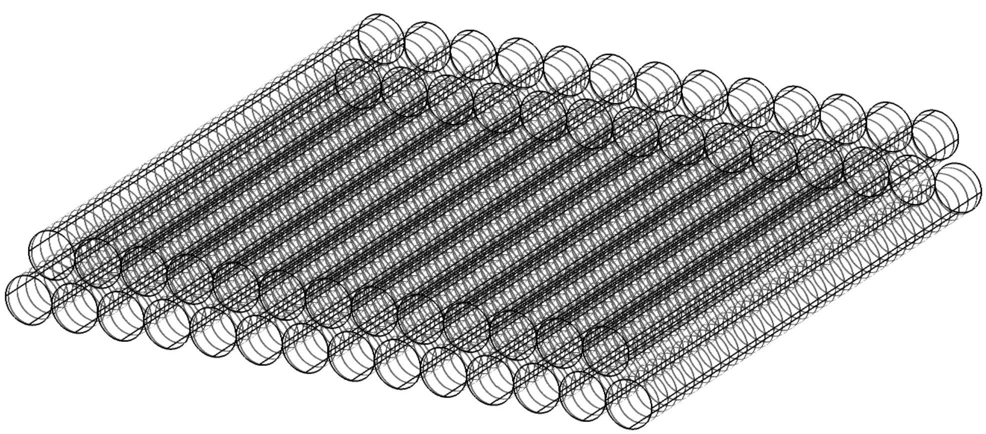

Figure A4 – Example of COILReef™ "Field" that is 100x100 meters[6]

[5] This sketch lacks the roll-formed longitudinal ribs at the top, sides, and bottom, which make the coils into a rigid structure and can make net-zero horizontal force when the coil is at least half a wavelength long. The ribs will leave openings for large sea creatures.

[6] The structure can be 2 to 50 meters high with relatively little economic penalty, compared to rock or concrete reefs. The footprint of each module depends on the available construction area.

Round donut or toroidal shapes, Figure A5, show promise for wave energy dissipation for waves with seasonal directional variation.

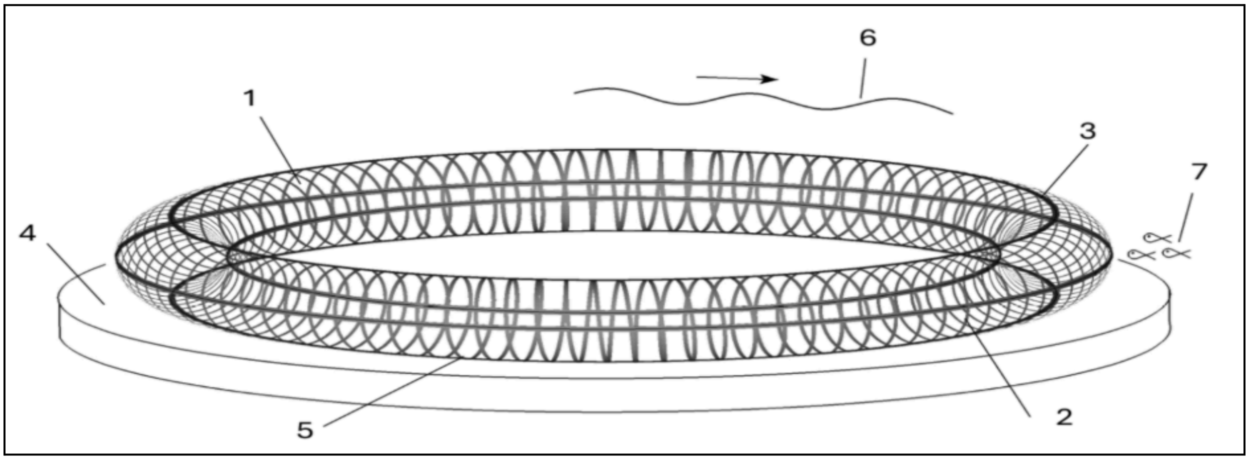

Figure A5 – Concept sketch of a wave attenuating habitat reef

In Figure A5:

1 and **2** are the coil. **3** is the top longitudinal rib. **4** is the seafloor.
5 is the bottom longitudinal rib. The outer diameter and inner diameter ribs are not numbered. **6** is the ocean surface with a wave traveling left to right over the torus.
7 is sea life.

The COILReef described in Figures A6-A11 is optimized for the largest possible seafood growing area. It uses all straight sections with coils perpendicular to shore. COILReef can be either titanium or impressed current cathodic protected (ICCP) steel[7]. ICCP can precipitate a protective layer of calcium carbonate on the steel, with the proven chemistry of Biorock. COILReef does not rely on the precipitated mineral for structural strength, only for sea life compatibility.

The lightweight, open nature of COILReef allows less expensive construction methods than any existing reef system (such as those mentioned on page 3). The two strut shapes are roll-formed. That is, a ribbon of metal passes through a roll-forming machine to become either a coil or a longitudinal rib. Roll-forming is a cost-effective process for making long structural shapes like road guardrails and roof gutters. The continuous length of coil or rib is limited only by the length of the metal ribbon on one roll. Initially, the coil is like a huge slinky. When the ribs are connected to the coil at every intersection, the structure becomes quite rigid, like a spaceframe.

COILReef attenuates waves in the same manner as a coral reef. That is, each component (or each coral) experiences a fraction of the wave force and attenuates a fraction of the wave's energy. In Figure A5, the one (structurally connected, 3,000 meters from ocean-side to beach-side) COILReef interacts with 20 waves simultaneously. The wavelengths shown are for a 15-second wave at the indicated depth.

The coil and the longitudinal ribs are roll-formed to most any cross-section shape, radius, and skew. For example, the smallest standard radius for road guardrail is 3 feet. The coil and ribs could be rolled in a factory and assembled on site. Or the roll-forming machine and rolls of

[7] Initially we recommend starting with titanium for ease of installation, zero operating cost, and likely zero maintenance cost.

titanium or plain steel could be set up on the beach or nearby port. Full-size reefs can be mass-produced under controlled conditions and floated hundreds of miles to where needed. After decades of use, they could be refloated and moved to a new location as needed.

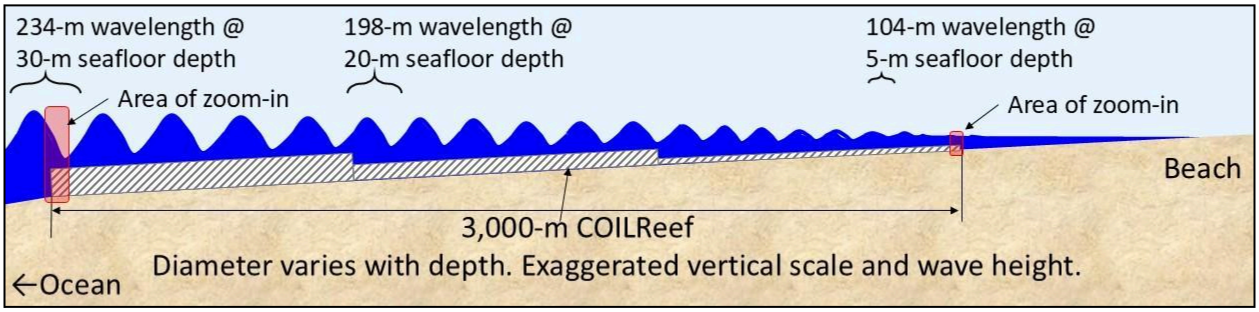

Figure A6 – Side overview (elevation) showing the full extent of the living reef foundation

A 6-m (20-ft) high wave has 16 mega Joules (4.4 kWh) of energy in its wavelength per meter (3.3 ft) of crest length. (Crest length is parallel to shore.) Trying to attenuate all that energy in the first 10 meters (33 ft) of coil would apply about 8 metric tons of force per meter of wave crest on the coil. That would be 160 tons of force on the 20-m diameter coil.

However, the pictured COILReef can be configured to remove only $^{1}/_{300}{}^{th}$ of the wave's energy in each 10-m length. Perfect force distribution would mean only 27 kg (60 lb) of force per meter of wave crest or 0.5 tons of force on each 20-m diameter coil. Dispersing the forces allows the wave attenuating structure to cover a large area at relatively low cost, while removing 95% of the wave energy. Large areas also receive a large amount of sunlight, which powers net primary productivity throughout the system.

Some locations or foil designs may require added weight and/or shovel anchors to resist sliding or local lifting, shown in Figures A7 and A11. With shovel anchors and added weight, COILReef could attenuate tsunami waves. The structure could be designed to absorb energy by "plowing" the seafloor without other structural failure.

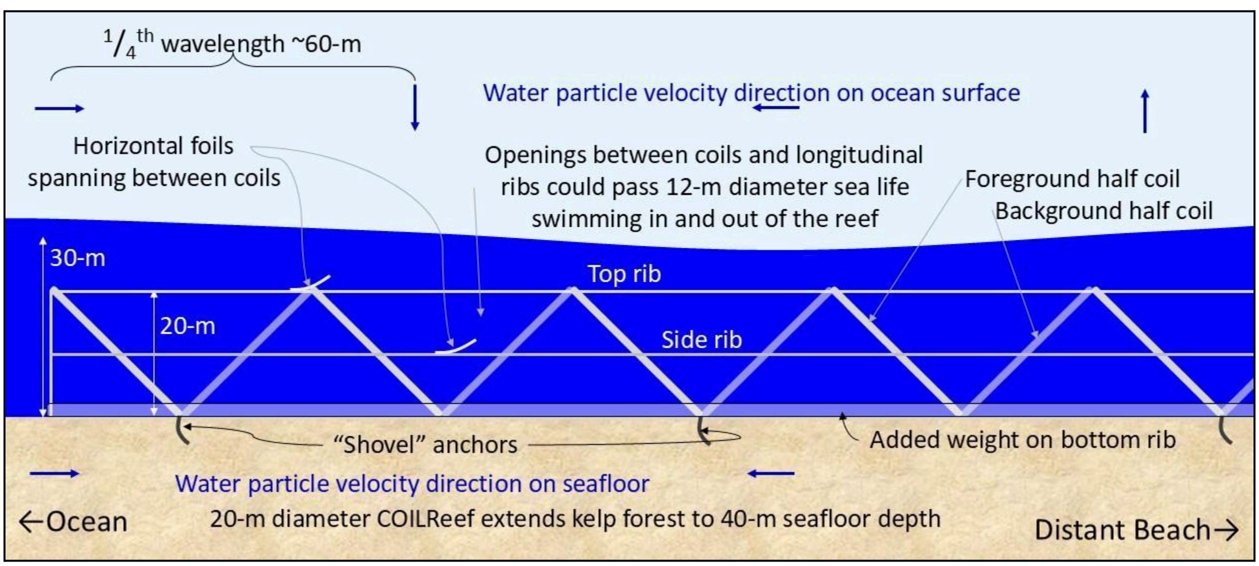

Figure A7 – Side view zoom-in on deep water edge

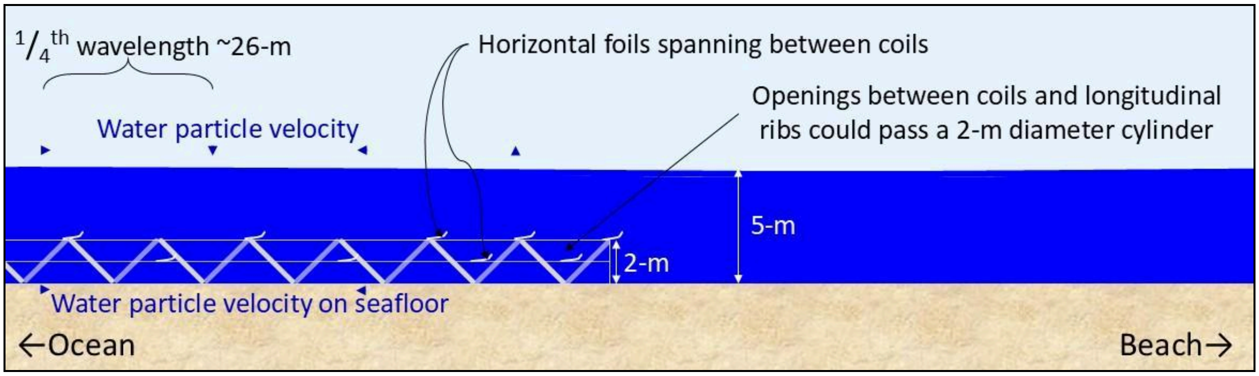

Figure A8 – Side view zoom-in on shallow water (near beach)

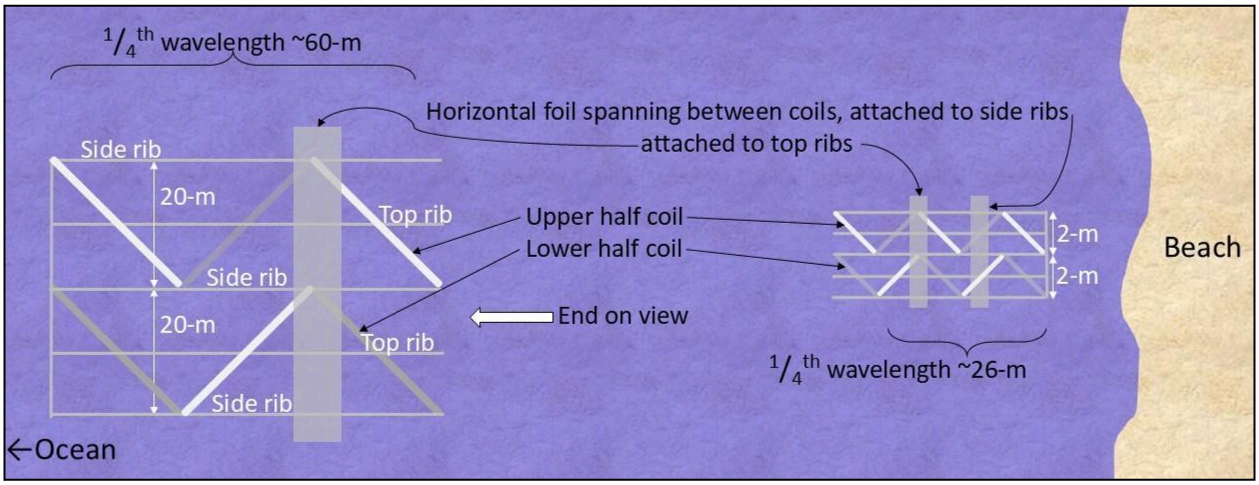

Figure A9 – Aerial zoom-in on deep (ocean-side) and shallow (beach-side)

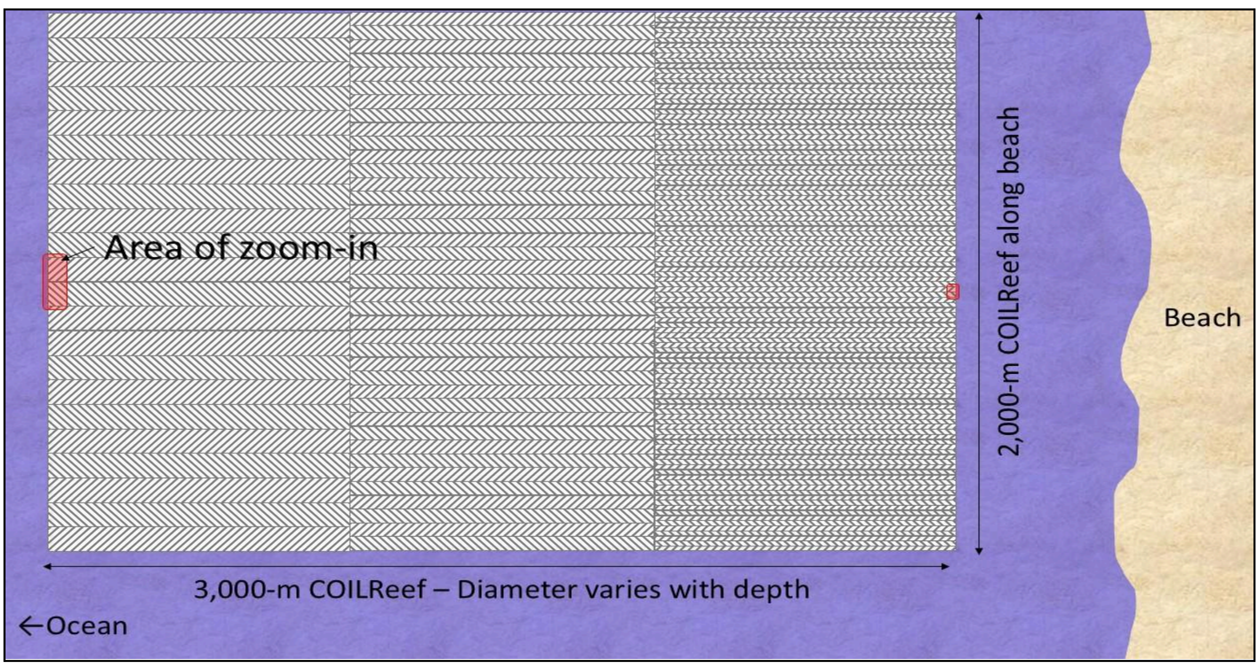

Figure A10 – Aerial overview showing possible area of living reef foundation

Figure A11 shows arch tie horizontal foils and impressed current cathodic protection (ICCP) anodes. Arch ties are structurally useful for preventing the coil from being squashed or stretched vertically. When employing ICCP, the steel will be the electrically conductive cathode. The anode would be specially coated titanium. The required voltage is determined by the desired amps and the distance of electron travel through seawater. Extending the anode through the center of every coil will minimize the required electrical energy.

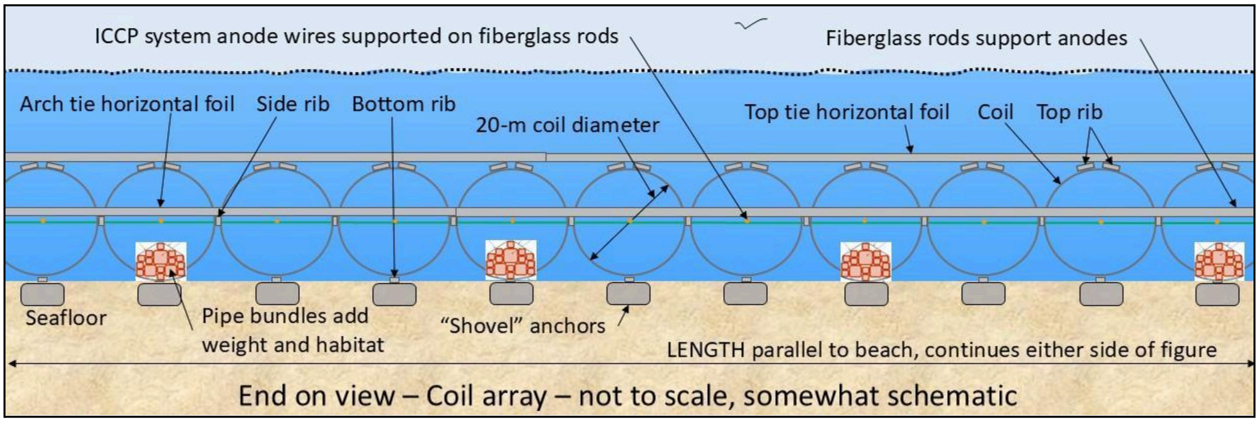

Figure A11 – End on zoom-in facing toward ocean

Particularly for smaller COILReef arrays, which are not spreading the wave forces over more than half a wavelength, added weight may be necessary. Bundles of vitrified clay pipe, as in Figures A11 and A12, are ideal because they provide excellent habitat and added weight.

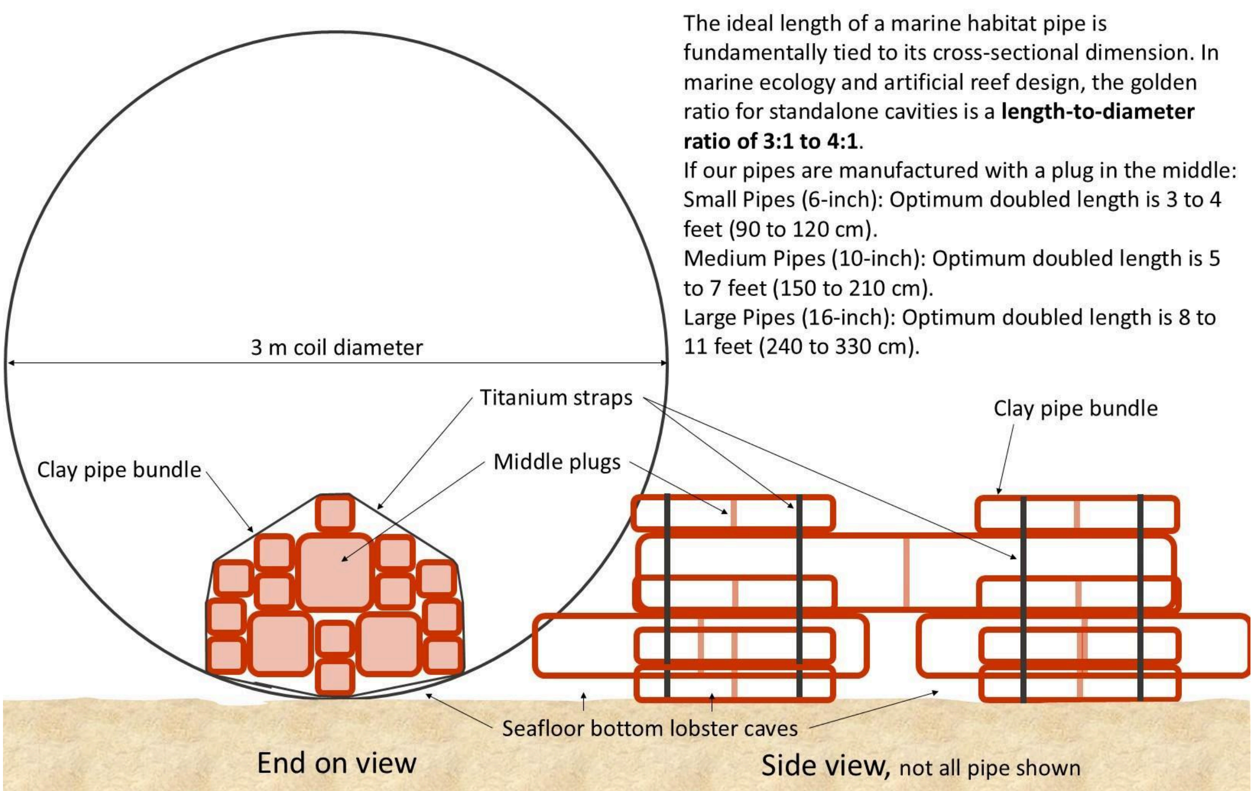

Figure A12 – Views of a typical rectangular clay pipe bundle

Rectangular pipe is useful in different sizes for different species because:

a) Many cryptic marine invertebrates (like rock crabs, octopuses, and juvenile lobsters) prefer 90-degree tight corners. Right-angle corners allow small creatures to wedge their bodies tightly into a crevice, shielding themselves from predators on two sides simultaneously.
b) Lobsters prefer actual seafloor for trenching and a large low-ceiling area for congregating.
c) An eel in a square pipe can wedge its muscular tail tightly into the 90-degree corner, locking its body in place so it can strike out and roll with maximum kinetic force.

Location design features for all artificial reefs (any intertidal or subtidal structure)

Each community should find the lowest net life-cycle cost governance and management systems to support their sea life through centuries of warming waters, migrating species, sudden diseases, invading ecosystem-destroying species, ocean acidification, and increasing storm intensity. The research could include:

a) Forming species-specific habitats with the titanium – In addition to hydrodynamic, strength, and stiffness design, we can optimize the titanium coils and ribs for sea life. For example: the coil and rib cross-sections can form 4 to 6-inch diameter "caves" at every intersection for octopi, crabs, finfish, lobster, etc. During roll-forming, the titanium surface can be textured and 12-mm diameter holes punched in patterns. The texture and holes support strong mechanical attachments for coral, kelp holdfasts, oysters, mussels, barnacles, giant clams, algae, etc.
b) Seafloor footprint: What is the optimum lower rib placement for maximum secondary productivity? Unlike boulders and large concrete shapes, the sand under the reef continues supporting native species such as squid, flatfish, sharks, rays, sand crabs, halibut, clams, scallops, sand dollars, sea cucumbers, tubeworms, etc. Combining sandy seafloor ecosystems directly under the net primary productivity may provide more net secondary productivity than does a rocky seafloor ecosystem.
c) Marine mammals and sea turtles – What is the minimum opening size between coils and between ribs that dolphins, sea elephants, and sea turtles can easily swim through? Will whales use the reefs to scrape off barnacles?
d) Supporting coral reef ecosystems – In areas where coral has bleached and won't recover, algae adapted to warmer water could grow on the titanium or calcium carbonate-coated steel. Algae in the complex shelter-providing shape might support the coral reef ecosystem species that can stay in the warmer water.
e) Migrating species – Is the seafood and marine biodiversity productivity cost-effective when growing kelp and other ocean plants on top of a COILReef in the cool deep water? Deeper water is cooler, even on the ocean surface, than shallower water. Kelp and other cool-water sea plants need sunlight and cannot grow when the water is too deep.
f) Seagrass – Is seagrass, seafood, and marine biodiversity productivity cost-effective in the additional low-wave-energy area with cooler and cleaner seawater?
g) Coastal marine ecosystem model development – Instrument the test beds to collect high-frequency ecological and oceanographic data, potentially including:
    - Acoustic sensors arranged to triangulate the source location of sounds in real time and trigger other sensors.

- eDNA automated sampling coupled to current sensors to predict a “cone of origination” for particles in the sample. Sample at pre-selected times and occasionally when triggered by visual or acoustic stimuli, when the DNA related to that stimulus is expected in the eDNA sample.
- Stereo camera video monitoring with species, size, and distance identification tied into the acoustic and e-DNA sensors.
- Fisher and ocean-farmer observations.
- Nutrient, temperature, isolation, light, and current sensors.
- New sensors and autonomous systems for new issues, for example, to “sniff out” and remove invasive species, determine if some plants prioritize reaching reproductive maturity versus reaching “normal” size in warmer water, and not-yet-identified issues.

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Appendix B – Marine ecosystems, ocean ranching, and local research

Coastal communities need their infrastructure and coastal resources for protection, recreation, tourism, trade, sustainable seafood, etc. Adaptations should be selected for the lowest total life-cycle cost of sustaining the benefits described in Appendices A-D even through the examples below and future unanticipated disasters:

a. Ocean warming is causing a (2024-continuing) shift from kelp to turf algae in the Gulf of Maine. California's giant kelp was decimated when sea star wasting disease allowed sea urchin populations to explode and then become zombies wandering kelp barrens.
b. Ocean warming caused an 85% decline in oysters, clams, and scallops from Maine to North Carolina between 1980 and 2010.
c. Oyster farmers along the US East Coast are battling Sudden Unusual Mortality Syndrome, which can wipe out 75% of a crop within weeks.
d. Apalachicola Bay, Florida oyster collapse of 2013 due to reduced freshwater (drought worsened by climate change) and overharvesting (during the drought).
e. Snow crab populations crashed in the Gulf of Alaska when a marine heat wave sped up their metabolism, causing mass starvation.
f. Intertidal sea life was cooked to death in June 2021 by an atmospheric heat wave in the Pacific Northwest.
g. Harmful invasive species, similar to those threatening California's marine ecosystems, such as European Green Crab, Asian Shore Crab, Watersipora (a colonial invertebrate), Sargassum horneri (Devil Weed/Asian Sargassum), Caulacanthus okamurae (Asian Turf Alga), and Caulerpa spp., are taking over. As many are warm-water or warm-tolerant species, warming seas will favor them over native kelps and red algae. Some are toxic to and avoided by native grazers, posing extreme danger.

Ocean Ranching

The disasters mentioned above suggest simple "no-take zones" or "marine protected areas" may no longer be effective or sustainable. Coastal communities may need "ocean ranching", which uses a portion of the income from fishing and ocean farming to maintain the marine ecosystem. Ocean ranchers would be marine conservationists, fishers, farmers, and citizen scientists motivated by their desire for sustainable fisheries and ocean farms. Ocean ranching might be implemented within a Territorial Use Rights Fishery (TURF). TURFs limit fishing and shellfish/crustacean harvesting from a specific area to the TURF members, who agree to contribute a portion of their revenue and/or labor to maintain and protect their TURF.

Ocean ranchers are motivated to be proactive. Potential 'chores' include: removing invasive species; removing turf algae; farming *Graclaria* a few months before the water becomes too warm for kelp; replacing sea urchin predators as needed; restoring ecosystems by helping beneficial warmer-adapted species migrate north; farming mussels to improve water quality and also feed sea cucumbers, sea urchins, rock scallops, oysters, sandworms, sponges, flatfish, and rockfish; and supporting the development of coastal marine ecosystem computer models to inform their harvesting and other actions.

Purpose and expected outcome of local research

1. Purpose – Determine the economics of combining shore protection and ocean ranching for different shore protection and/or habitat restoration systems. Appendix C lists several such systems.
   Expected outcome – Increased revenue and biodiversity while maintaining healthy oceans and protecting shores through centuries of climate change.
2. Purpose – Determine the most cost-effective techniques and tools for sustainable harvesting while increasing biodiversity and net secondary productivity through centuries of climate change with ocean ranching.
   Expected outcome – U.S. sustainable coastal seafood production increases many-fold, with the seafood income paying for maintenance of the ecosystem. That is, seafood revenue funds the removal of invasive species and prevents or responds to marine ecology disasters using the tested techniques and tools.
3. Purpose – Determine the most cost-effective techniques and sensors for monitoring hundreds of species populations and ocean parameters on ocean ranches.
   Expected outcome – Ocean ranchers can afford accurate monitoring for effective long-term management, with their data continually improving their coastal ecosystem model.
4. Purpose – Develop and refine coastal ecosystem computer models involving hundreds of species populations and ocean parameters.
   Expected outcome – The model's predictive "event" alarms and "what if" simulations help ocean ranchers avoid ecosystem crashes that can cost hundreds of times the cost of developing the model. That is, all stakeholders can use the computer model to:
   - Predict, detect, and locate invasive species.
   - Predict and identify optimal pro-active responses to marine heatwaves or sudden population shifts.
   - Recommend weekly harvest amounts that sustain biodiversity and biomass.
   - Replace today's coarse management tools with precision, predictive, and adaptive management.
   - Align conservation and fishing communities around shared, data-driven decisions.

For example, determining the economics of combining shore protection and ocean ranching would involve identifying the expected ranges for each ecosystem:

- **$/amount of wave-energy attenuation** per unit distance of shoreline produced by each shore protection system and its attached biological growth.
- **$/area/year** of sustainable seafood production as a function of the cost of the related infrastructure.
- **Capital and maintenance costs** of the infrastructure, expressed as $/area, and related to their expected seafood production.
- **Variability in seafood production** driven by environmental conditions such as currents, wave size, nutrient flux, grazer density, predator density, ENSO cycles, marine heatwaves, and ocean acidification.

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Appendix C – Examples of Local issues in Massachusetts, North Carolina, South Carolina, Florida, Texas, and California

Nantucket, Massachusetts

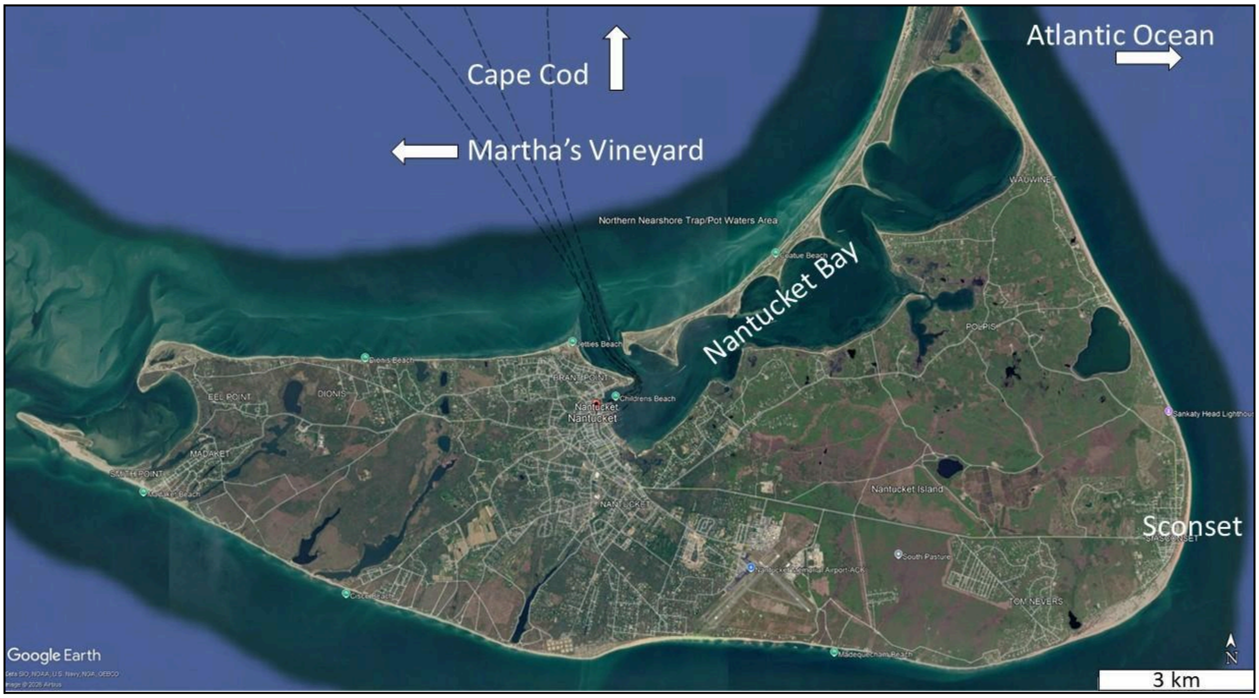

Figure C1 – Google Earth view of Nantucket

The Nantucket Coastal Resilience Plan includes $830-$930 million spent over 5 to 15 years. The work includes about $300 million for sand and shoreline management, maintaining sand dunes to protect utilities, living shorelines, and managed retreat programs.

Homeowners on Nantucket are spending about $20 million on private erosion mitigation. Litigation and fees add to the cost of private efforts.

Nantucket's eelgrass and bay scallops have declined and will disappear. The decline and future extinction is due to excess plant nutrients and warming water. Heatwaves have caused massive die-offs even in areas with improved water quality.

Nantucket's Sole Source Aquifer is recharged by rainfall and snowmelt falling on the island's permeable glacial sand and gravel. The aquifer is a few hundred feet thick and extends for miles underneath the seafloor. Still, it may become important to maintain the island's elevated permeable surface area as insurance against droughts and rising seas and for future retreat.

Nantucket benefits from the suggested research and/or pilot installations described in the Appendices:

a) Structural – A permanent artificial coral barrier reef can attenuate wave energy to extend sand replenishment intervals from years to decades. It can also be cost-effective to protect infrastructure by storing sand for occasional forepassing (moving sand from accumulating to eroding areas) to other areas.
b) Ecological – Select barrier reefs create low wave energy beaches to support seagrass and bay scallops with ocean water quality and temperatures.

Nags Head, North Carolina

Figure C2 – Google Earth view of Nags Head

The 2019 Center for Climate Integrity report, "High Tide Tax: The Price to Protect Coastal Communities from Rising Seas," estimated that Nags Head, NC, would need at least $424.1 million for minimalist seawalls. The seawalls would be ineffective (not preventing wave damage) against more than 1-year storm surge on top of the 2019 projection for sea level in 2040.

Beach nourishment costs about $30 million every 6 to 8 years, but are expected to double by 2050. Beach nourishment costs 2030 -2060 could be $200 million, and continuing.

Litigation concerning public access to the renewed beach between the renewed high tide line and vegetation has slowed some beach nourishment projects.

Nags Head's sound-side eelgrass is being "pinched" toward extinction with shallow water too warm and deeper water too murky for light penetration. Eelgrass supports scallops and shrimp. Sea turtles and seabirds would benefit from a more stable beach and sand dunes. Marine mammals and finfish should benefit from an artificial coral reef.

Nags Head benefits from the suggested research and/or pilot installations described in the Appendices:

a) Structural – A permanent artificial coral barrier reef can attenuate wave energy to extend sand replenishment intervals from years to decades. It can also be cost-effective to protect infrastructure by storing sand for occasional forepassing to other areas.
b) Ecological – Select Atlantic-side barrier reefs create low wave energy and stable beaches. The stable beaches support sea turtles and seabirds. The low wave energy supports seagrass, scallops, and shrimp. The coral-reef mimicking reef should support marine mammals and finfish.

Isle of Palms, South Carolina

Figure C3 – Google Earth view of Isle of Palms

The City of Isle of the Palms relies on beach nourishment. The 2026 project will place 2.5 million cubic yards of sand for about $32 million. City consultants suggest similar-sized projects will be needed every 8 to 10 years. Unit costs are expected to increase, resulting in an average annual cost of $6 million. There are occasional legal battles involving a few $100 thousand in civil penalties for illegal armoring.

Species in the sound (Gray Bay) are struggling with warmer water and excess nutrients, with increasing harmful algae blooms. Affected species include oysters, cordgrass, blue crabs, shrimp, red drum, and speckled trout. An adjustable barrier reef might be tuned to migrate much of the sound ecosystem to the ocean-side. Research should focus on attenuating waves just enough to support seagrass but not so much as to harm sea turtles or other life in the existing ecosystem.

Isle of Palms benefits from the suggested research and/or pilot installations described in the Appendices:

a) Structural – A permanent artificial coral barrier reef can attenuate wave energy to extend sand replenishment intervals from years to decades. It can also be cost-effective to protect infrastructure by storing sand for occasional forepassing to other areas.
b) Ecological – Select Atlantic-side barrier reefs create low wave energy and stable beaches. The stable beaches support sea turtles and seabirds. The low wave energy supports seagrass, scallops, and shrimp. The coral-reef mimicking reef should support marine mammals and finfish.

Palm Beach, Florida

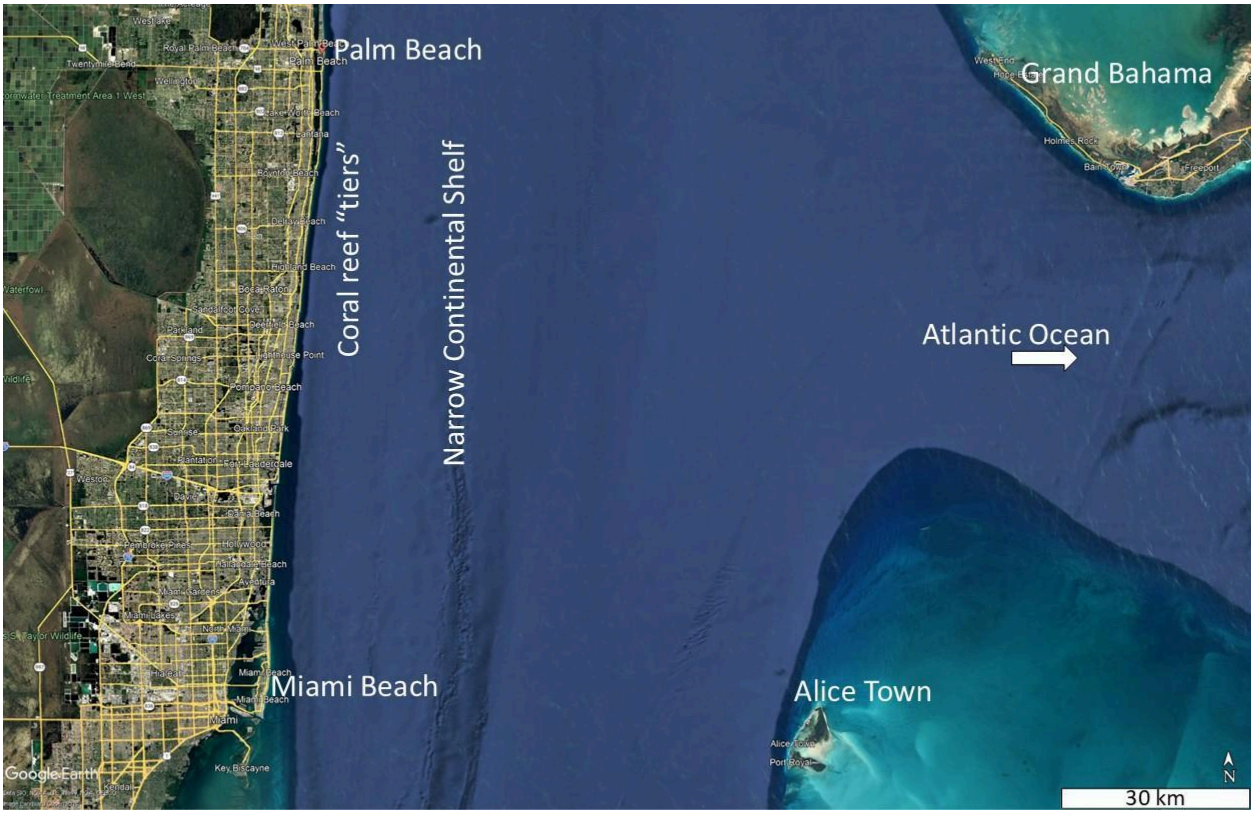

Figure C4 – Google Earth view of Palm Beach

50-year cost projections for beach nourishment, dune restoration, and sand forepassing for communities around Palm Beach are as high as $2.5 billion ($50 million per year).

Palm Beach communities are experiencing red tide (harmful algae blooms) and sargassum washing up on shore. The sargassum fouls beaches, costing $billion in tourism cancellations. Ocean conditions support coral reefs off Palm Beach, and hard surfaces are rapidly colonized by corals. However, the existing reefs are too deep for significant storm wave attenuation.

Palm Beach benefits from the suggested research and/or pilot installations described in the Appendices:

a) Structural – A permanent artificial coral barrier reef can attenuate wave energy to extend sand replenishment intervals from years to decades. It can also be cost-effective to protect infrastructure by storing sand for occasional forepassing to other areas.
b) Ecological – A thin metal reef, explained in Appendix A, relatively inexpensively mimics a coral reef and can provide up to 95% wave attenuation, and perhaps sargassum capture, even with 20 m seafloor depth.
c) Both – Research and pilots are needed to optimize trade-offs between cost, wave attenuation, sargassum trapping, and benefiting species, including corals, sea turtles, finfish of all sizes, lobster, seagrass meadows, and shallow reefs.

Texas Gulf Coast

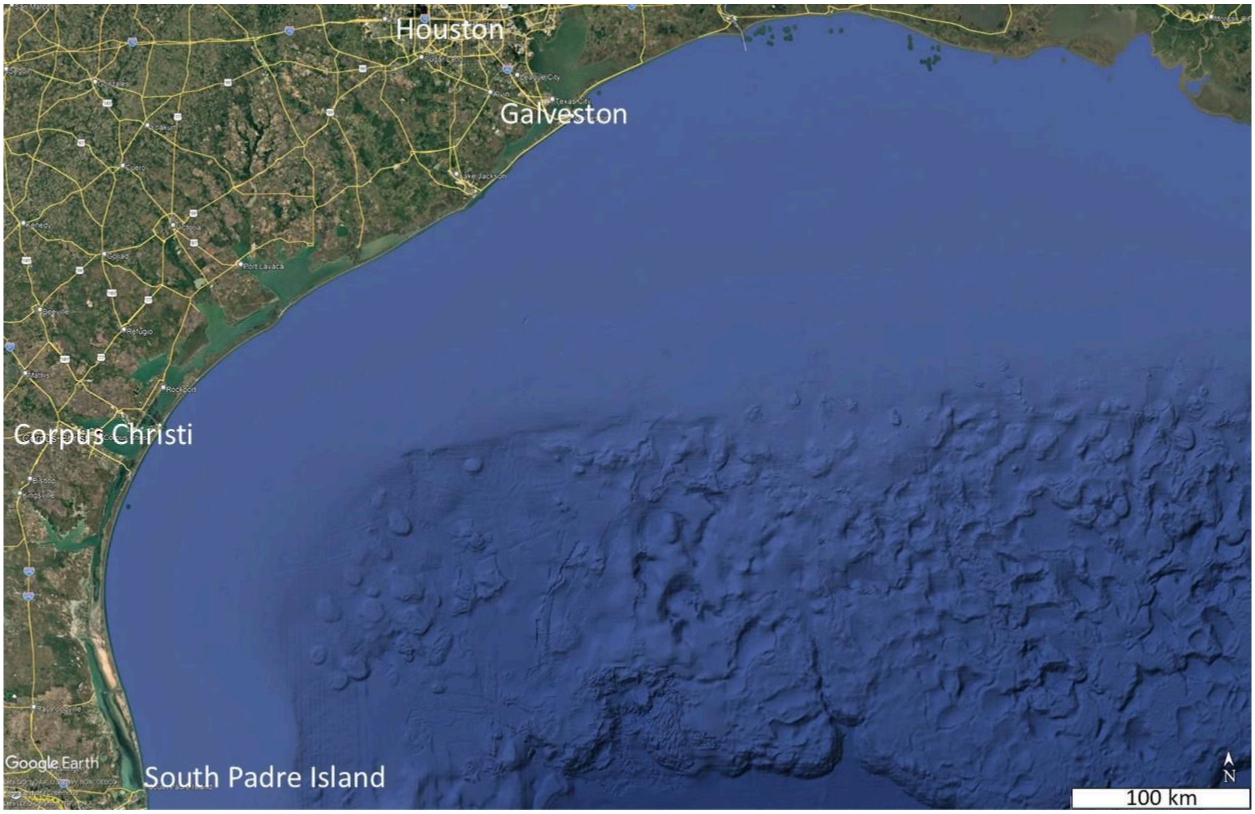

Figure C5 – Google Earth view of 340 miles of Texas coast

The U.S. federal government, the State of Texas, and communities along the Texas coast expect to spend about $110 million every year nourishing beaches and sand dunes between 2030 and 2060. They might need to spend more if sand becomes less available.

Texas beaches are experiencing local sargassum washing up on shore. Sargassum cleanup costs near $3 million per year are manageable, and tourism losses are acceptable. Texas' red tides (harmful algae blooms) are also less frequent than Florida's.

Texas bay seagrass ecosystems are being "pinched" toward extinction with shallow water too warm and hypoxic, while deeper (cooler) water is too murky for light penetration. Metabolic rates of crustaceans and fish increase, requiring them to eat and breathe more.

Texas benefits from the suggested research and/or pilot installations described in the Appendices:

a) Structural – A permanent artificial barrier reef can attenuate wave energy to extend sand replenishment intervals from years to decades.
b) Ecological – A thin metal reef, explained in Appendix A, relatively inexpensively mimics a coral reef that can be tuned as a "storm filter". A storm filter reduces the largest waves (less erosion) while leaving small waves to carry mud offshore.
c) Both – Research and pilots are needed to optimize trade-offs between cost, wave attenuation, benefitting species, including sea turtles, finfish at all ages, crabs, lobster, seagrass, mangroves, and potentially harmed species adapted to high-energy beaches.

California

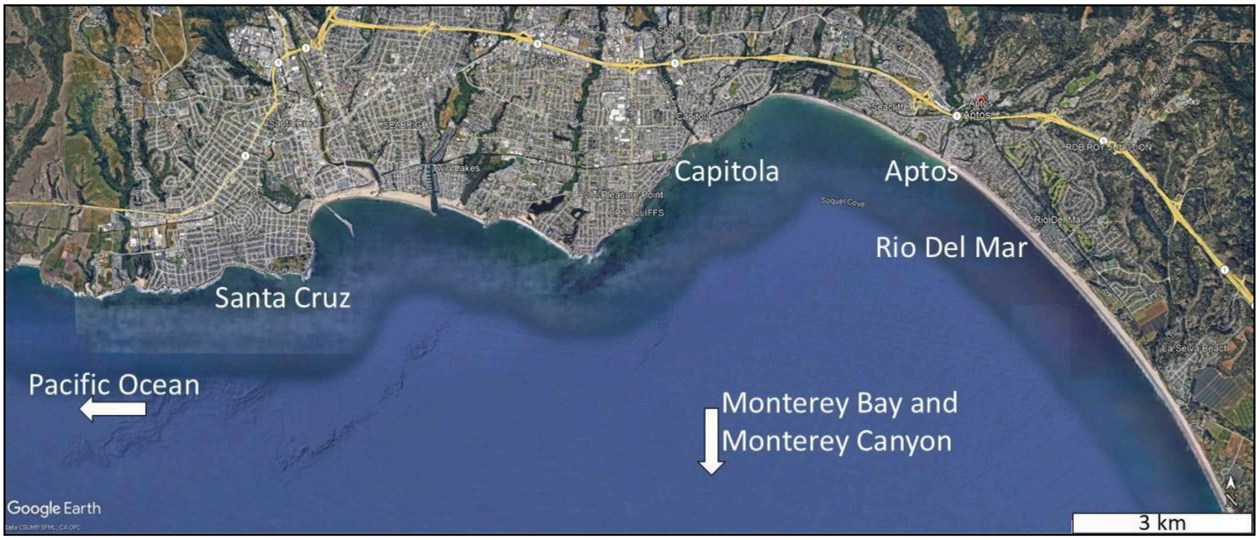

Figure C7 – Google Earth view of Aptos – Santa Cruz

These coastal California communities have identified the need for several $hundred million in aggregate for coastal erosion protection over the next thirty years – Oceanside, San Clemente, Broad Beach Geologic Hazard Abatement District (BBGHAD), Aptos – Santa Cruz, and Pacifica.

Relative to the U.S. East and Gulf coasts, the California coast is steep with beaches close to the deep water of the continental shelf. The East and Gulf coasts have reserves of sand in ancient riverbeds. California's sand falls down subsea canyons. For example, every year, 400,000 cubic yards fall into Monterey Canyon, and a million cubic yards fall into Mugu Canyon[8]. The lack of inexpensive, acceptable-quality sand drives litigation with shorefront property owners wanting armor and the community wanting beaches via managed retreat with some armor to protect public property such as water resource recovery facilities.

California's kelp forests have been decimated by large waves, zombie sea urchins, invasive species, and warming water.

California benefits from the suggested research and/or pilot installations described in the Appendices:

a) Structural – A permanent artificial barrier reef can attenuate wave energy such that the natural sand supply can accumulate. The barrier reef might start near the subsea canyon "sink" with some forepassing while the reef is extended to the river, a sand "source".
b) Ecological – A thin metal reef, explained in Appendix A, can distribute wave attenuation over a large area, provide stronger kelp holdfast attachments, and support kelp growing where the seafloor is normally too deep. (Deeper water is cooler). Larger areas support more primary production, which supports a healthy marine ecosystem.
c) Both – Research and pilots are needed to optimize trade-offs between cost, wave attenuation, benefitting species, including kelp, finfish at all ages, lobster, abalone, shellfish, and urchins. Back to first page.

[8] A million cubic yards is a box of sand 3 miles along the beach, 50 yards wide, and 9 feet high.

Appendix D – Kelp forest economics with California Ocean Ranching Ecosystem (CORE)

On the US West Coast and the US Northeast Coast net primary productivity is from giant kelp. A mid-canopy attached growth macroalgae, such as *Gracilaria* can replace kelp's primary productivity when the seawater becomes too warm for giant kelp. Hence, West Coast artificial reefs maximize biodiversity, federal funding, and CORE income by maximizing the area (and depth) exposed to sunlight for giant kelp and providing adequate larger species-specific habitat. Also, designed for current and future mid-canopy substitutes for giant kelp.

Coastal communities need their infrastructure and coastal resources for recreation, tourism, trade, and sustainable seafood. Adaptations should be selected for the lowest total life-cycle cost of sustaining the three areas described in Appendices A-D through these examples and future unanticipated disasters:

a. Conservation through adaptation with livelihoods addresses the same events as for habitat restoration and maintaining biodiversity while promoting equity and inclusion.
b. Most sea life is maturing at smaller sizes in warmer water. That is less mass for the same number of fish and less value for each fish. It might also mean fewer or smaller eggs per spawning event.
c. Sustainable seafood offers a practical way to confront worsening freshwater scarcity. Climate change is driving more frequent droughts, "thirst waves," and destructive floods. With less freshwater available, land agriculture faces mounting pressure. Seafood, by contrast, produces food with seawater and requires no desalination. That is, increased sustainable seafood production complements land-based agriculture and reduces freshwater demand for agriculture.

California ocean ranching economics

Other locations may have data like the Santa Barbara Coastal Long Term Ecological Research (SBC LTER) program, which is gathering data on giant kelp forest ecosystems. Figure D1 shows its locations and the El Estero Water Resource Center (El Estero) outfall. NPP data from SBC LTER: Reef: Long-term experiment: Taxon-specific seasonal net primary production (NPP) for macroalgae can be used to estimate future sustainable seafood production. NPP_season_gC_m2_day was converted to total NPP as metric tons/ha/qtr. The analysis used only the control TREATMENT data (the other treatments removed giant kelp). The understory species NPP excluded data on species codes MAPY and MPJ, both listed as Macrocystis pyrifera. The giant kelp species is only the MAPY NPP.

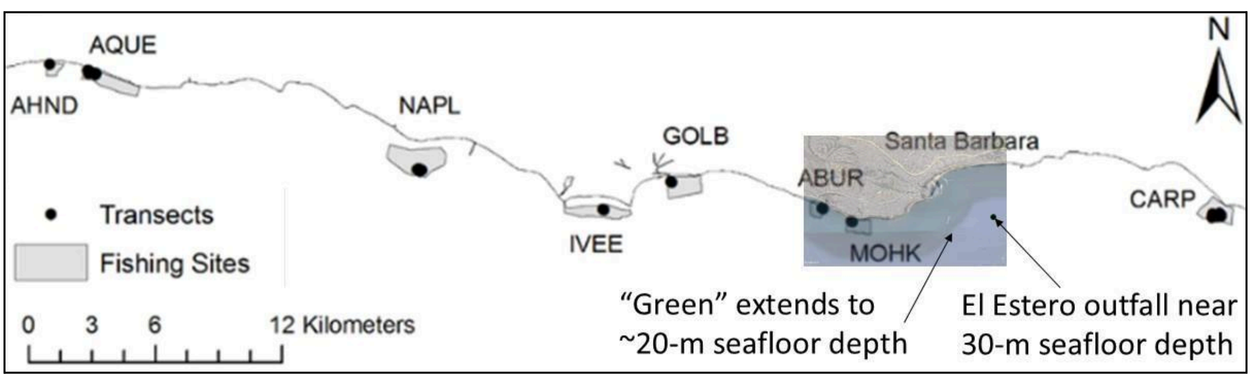

Figure D1 – SBC LTER kelp forest locations AQUE, ABUR, MOHK and the El Estero outfall

AQUE (Arroyo Quemado) – Giant kelp averaged 26 dry metric tons of Net Primary Productivity per hectare per year (NPP/ha/yr, 1-ha is 2.5 acres or 1.9 football fields or 1.4 soccer fields). Understory species averaged 10 dry metric tons of NPP/ha/yr. See Figure D2. Continuous bedrock, high rugosity, strong upwelling, and high habitat complexity should support the highest biodiversity, strongest kelp forests, and most stable ecological conditions.

MOHK (Mohawk) – Giant kelp averaged 78 dry metric tons of NPP/ha/yr. Understory species averaged 11 dry metric tons of NPP/ha/yr. See Figure D3.
Intermediate substrate, complexity, and oceanographic conditions should result in moderate biodiversity and kelp persistence.

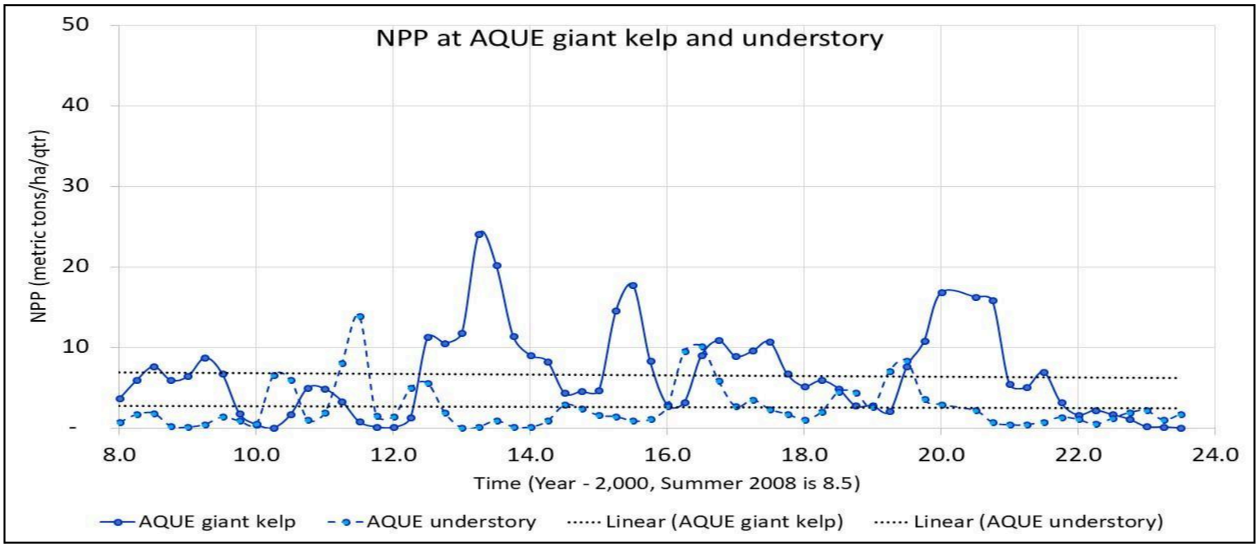

Figure D2 – Quarterly giant kelp and understory macroalgae NPP at AQUE

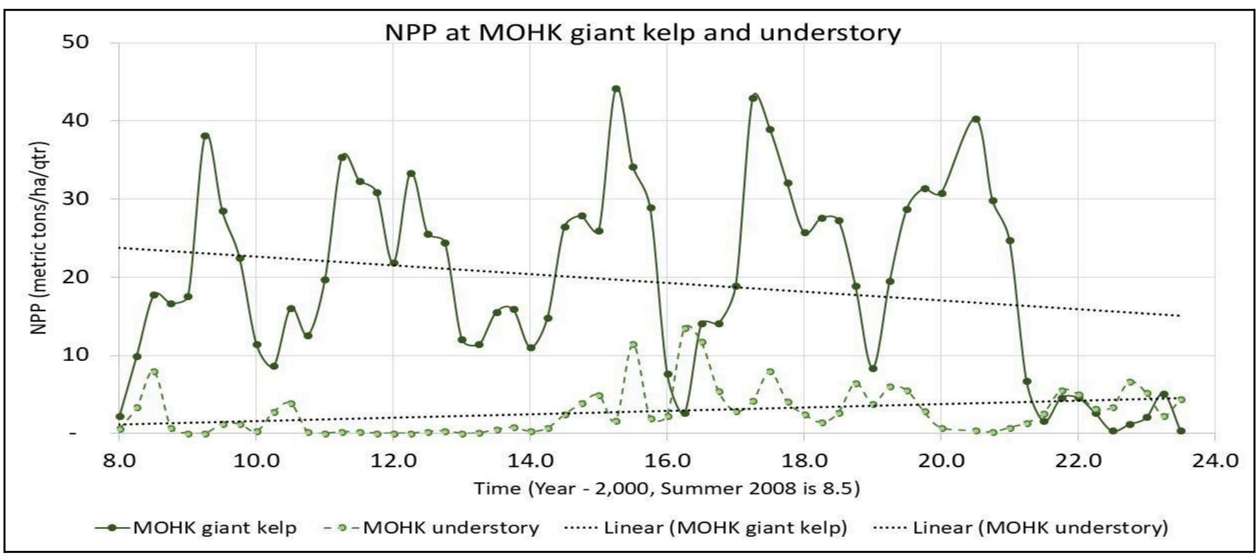

Figure D3 – Quarterly giant kelp and understory macroalgae NPP at MOHK

Note: By far the highest NPP is at **MOHK**, which has intermediate substrate and oceanographic conditions. MOHK is also the closest to the plant nutrients supplied via El Estero's outfall. El Estero nutrient supply is roughly equivalent to 40 dry metric tons of macroalgae per year over 1,000 ha (10 km^2).

AQUE has the best and least human-disturbed habitat. The fact that NPP at AQUE is close to zero for years at a time confirms that some (science-proven) intervention will be required to maintain California's coastal ocean biomass and biodiversity.

ABUR (Arroyo Burro) – Giant kelp NPP averaged 20% of the AQUE average. The ABUR site is somewhat better than a sandy seafloor. It had a patchy reef structure, low rugosity (a measure of complexity), weak upwelling influence, and high sand scour with low biodiversity.

Economic potential of California ocean ranching ecosystems

Table D1 converts the 22-year average of Net Primary Productivity (NPP) from each ecosystem into the average expected value at the dock from sustainable fishing of that ecosystem.

A shore protection system and/or an NPP restoration system might provide habitat from 5 to 30-m seafloor depth. Giant kelp grows with undiminished NPP out to 20-m seafloor depth, because they access sunlight near the ocean surface. Giant kelp could grow in greater-than-30-m seafloor depth if the shore protection or restoration system included hard substrate at less-than-20-m depth.

Table D1 –NPP converted to the possible sustainable seafood value

Parameter	kelp forest→	**AQUE giant kelp**	**MOHK giant kelp**	**AQUE & MOHK understory**
Average annual dry net primary productivity (NPP)	dry metric tons /ha/yr	26	78	11
Conversion factor from dry kelp mass to wet mass of sea creatures	% dry	25%	25%	25%
Transfer efficiency to 1st trophic level	%	14%	14%	14%
1st level secondary production	metric tons /ha/yr	15	44	6
Transfer efficiency to 2nd trophic level	%	9%	9%	9%
2nd level secondary production	metric tons /ha/yr	1.3	3.9	0.6
Average sustainable harvest rate (varies widely with lower rates for longer lived and slower maturing species)	%	40%	40%	40%
Value of seafood at the dock with average of $7.50/kg (caught within 3 miles of shore)	**$/ha/yr**	**$48,000**	**$140,000**	**$20,000**

For Southern California beaches, the distance for 5 to 30-m depth change is commonly 3-4 kilometers (2-2.5 miles). This means each kilometer of shore could support 30 hectares (60 football fields) of ecosystem. A mile would support 48-ha of ecosystem. Therefore, each mile of coast could sustainably produce about 48 ha x $48,000/ha/yr = $2.3 million per year/mile of coast of seafood at the AQUE giant kelp rate, $6.9 million at the MOHK giant kelp rate or $1 million per year/mile at the understory rate.

Note the SBC LTER-derived values don't include sustainable ocean farming and ranching activities such as farming Mediterranean mussels; increasing native California mussels for their increase in other seafood production; removing invasives (like weeding a garden); scallop farming; planting species able to handle anticipated water temperatures; stocking species with radio frequency identification (RFID) chips for ranching of abalone and other valuable but slow growing species; providing birthing caves for lobster; and more innovations.

As oceans warm, more heat-tolerant plants fill in each TURF starting from near shore (warmest water) and following the giant kelp's move to deeper (cooler) waters. California has native marine plants that provide almost as much NPP as giant kelp in water too warm for giant kelp: *Stephanocystis osmundacea* (Sea fern, up to 2-m tall, 3-5 year individual plant life); *Cystoseira* (0.5-2-m tall, 3-10 years for the holdfast); and red algal turfs (2-15-cm turf height, mats are effectively perennial persisting 5-20 years. All these support grazers including urchins, abalone, snails, amphipods, and isopods. Amphipods and isopods are critical food for many finfish.

There are about 55-70 miles (90-113 kilometers) of sandy beach shoreline within city limits between San Diego and Santa Barbara. That implies potential sustainable seafood income between $50 million (understory rate on 55 miles) and $480 million/year (MOHK giant kelp rate on 70 miles). Currently, commercial fishing less than 3 miles from shore between San Diego and Santa Barbara generates about $40 million to $55 million per year with a mass-averaged value of $7.5 to $9.5/kg. Ocean ranching is likely to derive most of its income from current shallow zone species: California Spiny Lobster, Red Sea Urchin, and California Halibut.

Where and how to start California ocean ranching ecosystems (CORE)

Each community might start by protecting their Water Resource Recovery Facilities (aka Wastewater Treatment Plants). These are usually near the shore at the lowest point in the community. Much water resource recovery infrastructure and all its foundations are below ground level. That means that attenuating waves now to prevent local shore erosion will be less expensive than modifications to continue operations while flooded and much less expensive than moving the Water Resource Recovery Facility to higher ground before 2100 (or later). Even if the facility is moved, the wave attenuation system remains essential to protect remaining infrastructure, such as major sewer lines and a large pump station. California's Coastal Commission and Water Resources Control Board want the facilities protected from coastal erosion to prevent wastewater spills.

Another reason to start near the Water Resource Recovery facility is that the steady supply of plant nutrients will support consistently higher NPP.

Each project will balance costs and benefits for two objectives: 1) prevent soil erosion from storm waves near the water resource facility and 2) produce sufficient seafood to cover the cost of maintaining marine biodiversity and biomass through centuries of climate change and other issues.

Erosion prevention can be accomplished with typical community outreach and stakeholder engagement. Maintaining marine biodiversity and sustained seafood production requires finding fishers, ocean farmers, and ocean conservationists willing to invest in and work with ocean ranching.

Appendix E – US East & Gulf Coast economics with California Ocean Ranching Ecosystem (CORE)[9]

The US Gulf Coast and the US Southeast Coast open ocean net primary productivity is from pelagic phytoplankton drifting by in the water column. The CORE reef is covered with a thick carpet of sponges, barnacles, and bivalves, creating complex micro-topography that shelters billions of tiny mobile invertebrates (amphipods, isopods, and crabs). Hence, US Gulf and East Coast artificial reefs maximize biodiversity, federal funding, and CORE income with an open structure that allows the maximum volume of seawater to flow past its surface area.

COILReef, described in Appendix A, can have titanium coils 2 to 100 feet in diameter. The invertebrate-covered coils (see Figure A2) will feed baitfish. The baitfish will feed pelagic fish. When the reef reaches into the photic zone, it should develop a thick bio-carpet of invertebrates such that resident fish show faster growth rates, higher body fat and/or lower natural mortality than the no-reef situation. That is, with proper design and employing CORE management principles, the artificial reef will increase total fish production. Thus it is not merely a Fish Attracting Device (FAD).

COILReef could be designed to restore fish of local concern, including:

- American Lobster and Atlantic Cod off Maine and Massachusetts
- Striped Bass and Blue Crab off Virginia and North Carolina
- Grouper, Snapper, Drum and Shark off South Carolina, Florida, and Texas

A normally submerged COILReef is uniquely capable of attenuating waves during storm surge. This because it can be designed for "defense in depth". Figure A5 in Appendix A shows waves moving over 3,000 meters of COILReef. The coils and associated foils are designed to extract about 1/300th of the original (ocean side) wave energy for every 10 meters of wave travel over the reef. That is, a large area reef that is more likely to increase fish is also well-suited to the US East and Gulf Coasts due to their high storm surge during hurricanes.

To be clear – on the US Gulf and East Coasts, one could design COILReef with these wave attenuation features:

1) The reef is fully submerged at low tide.
2) Design the coils and associated foils to attenuate waves during storm surge and high tide, even with hurricane winds over several wavelengths as close to the beach as possible.
3) Consider planting seagrass between the reef and the beach because the reef will be attenuating better than 95% of wave energy except during strong hurricanes.

The University of Miami's SUSTAIN Laboratory can test wind-wave-current performance of a model artificial reef that is 30 feet cross-shore length (ocean side to beach side) and 20 feet along-shore width at 1:100 scale. (Full scale would be 3,000 feet by 2,000 feet.

Consider sending a comment like that at Innovating Sustainable Shore and Marine Ecosystems to your state's agencies, non-profits, and communities interested in marine conservation, shore protection, fishing, and ocean farming.

[9] Use your own state or nation for the first letter to make your own acronym.

Appendix F – Beach-focused managed retreat

Many coastal communities would like to preserve public access to wide beaches as long as possible while sea-level rises. Employing beach-widening hard structures could be considered beach-focused managed retreat. Hard structures create winners and losers because sand moves. Sand moves along the beach, onto the beach and up into sand dunes, or out to deeper water. On California's coast, sand moves generally from a river source to a subsea canyon sink. For example, sand from several sources moves south along the Santa Barbara Littoral Cell[10] south. On average, about 1 million cubic yards of sand are permanently lost down the Mugu Submarine Canyon each year.

The US East and Gulf Coasts don't have subsea canyons extending into the shallow, nearshore surf zone. But they do have sand "sinks". From North Carolina's *Report on the Effects of Hard Structures on Sandy, Open-Ocean Coastlines*: "Along the NC open-ocean coastline, which is largely made up of barriers, relatively high-energy waves play a stronger role in shaping and shifting the landscape than do tidal currents, leading to long stretches of continuous alongshore sand transport, interrupted by relatively widely spaced tidal inlets. In addition to the cross-shore and alongshore processes described above in Section 1a, the tidal inlets and associated shoals in NC tend to act as "sand sinks," meaning they are depositional environments where sand collects and is therefore effectively removed from the beach/dune system (Fitzgerald, 1988)."

All the communities of each littoral cell could agree on the type of retreat planned for each stretch of coast: beach-focus managed retreat; facilities-removal managed retreat; or unmanaged retreat.

Figure 10 (shown below) of North Carolina's *Report on the Effects of Hard Structures on Sandy, Open-Ocean Coastlines* can teach us how to apply the lessons in the *Report*:

1. Artificial reefs (that attenuate waves) will slow sand movement and/or store sand. Zoom in on the left side of "2006" to see the salients[11] extending toward the breakwater reefs. The width of the beach in the beach-focused managed retreat is relatively uniform.
2. By 2016, the protected beach on the left is somewhat wider, the unmanaged retreat area has eroded and sand is being stored on the far right.
3. In 2025, two tombolos at the left of the protected beach are blocking sand flow. With sand flow blocked, the protected beach may be shrinking slightly. The unmanaged retreat area is further eroded and more sand is stored on the far right. Wind, wave, and sea level conditions change. Traditional breakwater reefs of rock or concrete cannot be moved or removed easily to suit the new conditions.

The fix – COILReefs' wave attenuation can be precisely adjusted such that an array of COILReefs along the shore can slow sand movement with small salients and no tombolo. If conditions change, a previously-situated deadweight-anchored COILReef can be floated (straight up using large vibrators to minimize lifting seafloor and sea life). Once floating, it can be moved a little (or a lot) and sunk to prevent tombolo formation. The biologic compatibility of the old and new locations limits the maximum movement distance.

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[10] Patsch and Griggs, "Development of Sand Budgets for California's Major Littoral Cells" (2007) at ucsc.edu.

[11] Coastal engineers carefully place artificial reefs to control which of these features forms. If a reef is placed too close to the shore, a **tombolo** will form and block natural longshore sediment transport. To prevent this and safely trap sand to rebuild a beach, engineers usually aim to form a **salient** instead.

Figure 10. Presque Isle in 2006, 2016 and 2025 (top to bottom), showing continued, progressive erosion along the eastern end of the peninsula, downdrift of the field of breakwaters (Google Earth). The yellow curve in each image shows the shoreline position in 2006.

Appendix G – Quick shore protection and best management practices

The draft California Artificial Reef Program Plan (CARP Plan) is out for review. All comments must be received by September 4, 2026, by 5 pm. The draft CARP Plan explains that structures built for shore protection are not artificial reefs and will need permitting through the California Coastal Commission as hard shore-protection structures.

Quick timeline with COILReef

COILReef can have the primary purpose of restoring or creating marine habitat as an artificial reef. COILReef is a living reef foundation that might support the local marine ecosystem through centuries of climate change, if properly managed.

COILReef can also have the primary purpose of shore protection. A single COILReef can blend habitat and protection at any ratio desired.

A COILReef pilot (or modules of a full-size unit) might be installed in one day, managed for months or decades, and moved or removed in one day. One-day moves make pilot reefs eligible for a temporary research permit and essential for accurate permitting, environmental documentation, and performance prediction. There is no reason to calculate the environmental issues (sea life's ability to hang on, species symbiotic relationships, heat transfer, etc.), the amount of wave energy attenuation, the forces on each component of the structure, the anchoring, or the economics.

Tasks toward installing a full-size COILReef	Aug26-Jun27		Jul27-Jun28		Jul28-Jun29		Jul29-Jun30	
Agency approves engineer with sub-consultants, public information campaign, temporary research permit awarded, pilot reef installed (e.g. for tourists during '28 Olympics)								
Pilot reef monitored, public visits (citizen scientists) encouraged, full-size design completed, ecosystem management planned, construction and monitoring/management funding secured								
Environmental document approved, permits granted, reef constructed and installed, ecosystem maintenance starts (e.g. attract 2030 or future Ocean Science Meetings?)								

Because COILReef pilots can be mass-produced at a port and easily shipped, communities might coordinate to trial different primary purposes and different long-term management funding. Potential approaches are described below.

Reef A, control, is designed for maximum biodiversity with no commercial or recreational fishing or ocean farming and no active management. It is a strictly hands-off marine protected area, except for monitoring.

Reef B, active management, is identical to Reef A but with active management by scientists. The primary objective of active management is to cost-effectively sustain the community's marine ecosystem through decades, even centuries of climate change. Active management includes removing invasive turf algae, pre-emptively adjusting species populations during disease outbreaks (such as preventing an explosion in the sea urchin populations that devour all the kelp and then become zombies), planting warm-water-tolerant ocean plants before kelp dies off during a marine heat wave, etc.

Reef C, active management funded by mariculture, is structurally identical to Reefs A and B, but allows commercial fishing and ocean farming as a trial of the governance for a California Ocean Ranching Ecosystem (CORE). CORE objectives include: 1) sustain the community's marine ecosystem through centuries of climate change, and 2) income from harvesting more than pays for the necessary active management. The CORE team could collaboratively "compete" with the scientists' active management team of Reef B, to see who can most cost-effectively sustain the community's marine ecosystem through centuries of climate change.

Reef D, mobile, is designed to move seasonally, such as to deeper and cooler water when marine heat waves threaten. It could be managed like any of Reefs A-C.

Reef E, surfing, is designed to optimize a locally desired surf break, perhaps a plunging point break for waves larger than 6 feet. It would also have big habitat benefits (although perhaps less than reefs that are optimized for habitat benefits), while also providing the desired amount of wave attenuation. It could be managed like any of Reefs A-C.