Sweetening the Waters

The Feasibility and Efficacy of Measures to Protect Washington's Marine Resources from Ocean Acidification

By Eric Scigliano

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An analysis commissioned by the Global Ocean Health Program, a joint project of the National Fisheries Conservation Center and the Sustainable Fisheries Partnership, to assist the Washington State Blue Ribbon Panel on Ocean Acidification and citizens seeking options to tackle the problem.

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CONTENTS

Since there are countless ways to go wrong but only a very few ways to do right, our best chance to deal successfully with our contemporary problems and those of the future is to learn from the success stories of our times.

– Rene Dubos

PREFACE

Sweetening the Waters examines a wide, though hardly inclusive, range of ways to address ocean acidification, considering their potential feasibility, efficacy, benefits, and consequences. Only in the last few years has ocean acidification been recognized as an unwelcome fact of life in the Pacific Northwest. It has already taken a toll on the shellfish industry and, very likely, on a broad spectrum of marine species. But much can still be done to prevent it from getting far worse, and to reduce the consequences to Washington's—and the world's—seafood supplies and marine ecosystems.

This report assesses a selection of measures to reduce harm. They fall into three distinct "buckets."

- **ADAPTATION –** Easing some of the symptoms and consequences of acidification rather than the causes. One example: monitoring water chemistry at a shellfish hatchery in order to avoid "corrosive" water that kills oyster larvae or to treat the water in a hatchery tank.
- **MITIGATION –** Reducing acidifying pollution. This amounts to tackling the root cause in order to prevent increasingly severe future consequences, or at least ease them.
- **REMEDIATION –** Restoring healthier chemical conditions in water or seabed areas that are already acidified.

Sweetening the Waters was commissioned by the Global Ocean Health Program, a joint initiative of the Sustainable Fisheries Partnership and the National Fisheries Conservation Center. The findings presented here helped inform deliberations of Washington's Blue Ribbon Panel on Ocean Acidification. The panel was appointed by Gov. Christine Gregoire in February 2012 as part of the Washington Shellfish Initiative, becoming the nation's first state-based effort to confront acidification. This report is now offered to citizens and leaders who need to evaluate the tools they can use to protect shellfish and other marine resources and ecosystems from this emerging threat.

This review of the tools shows that means do exist to reduce harm and protect marine resources from acidification, but the toolkit needs further development. To date, the only proven *adaptation* strategy —the reason the West Coast still has a thriving shellfish industry—merely protects shellfish larvae within hatchery tanks. Careful field trials and experiments are needed to extend this modest "umbrella." To conserve vulnerable marine organisms and ecosystems, especially along the Northwest's outer coast, we must continue to develop and refine methods to reduce the consequences of changing ocean chemistry even as we work to curtail its causes.

Ocean acidification is driven by some of modern society's biggest waste streams, chiefly carbon dioxide from the burning of coal, oil and gas. This impact is aggravated in some coastal waters by runoff charged with nitrogen and other nutrient wastes. Tools for reducing pollution are rapidly evolving, and some methods already have strong track records.

Harm that cannot be prevented can often be reduced. Again, a wide range of options exists for reducing and remediating impacts of acidification, especially for shellfish. Still, in the long run, the best defense—and for much of the sea, the only one—is prevention. The root causes of acidification are in human hands. The choice is ours.

— Brad Warren, Director
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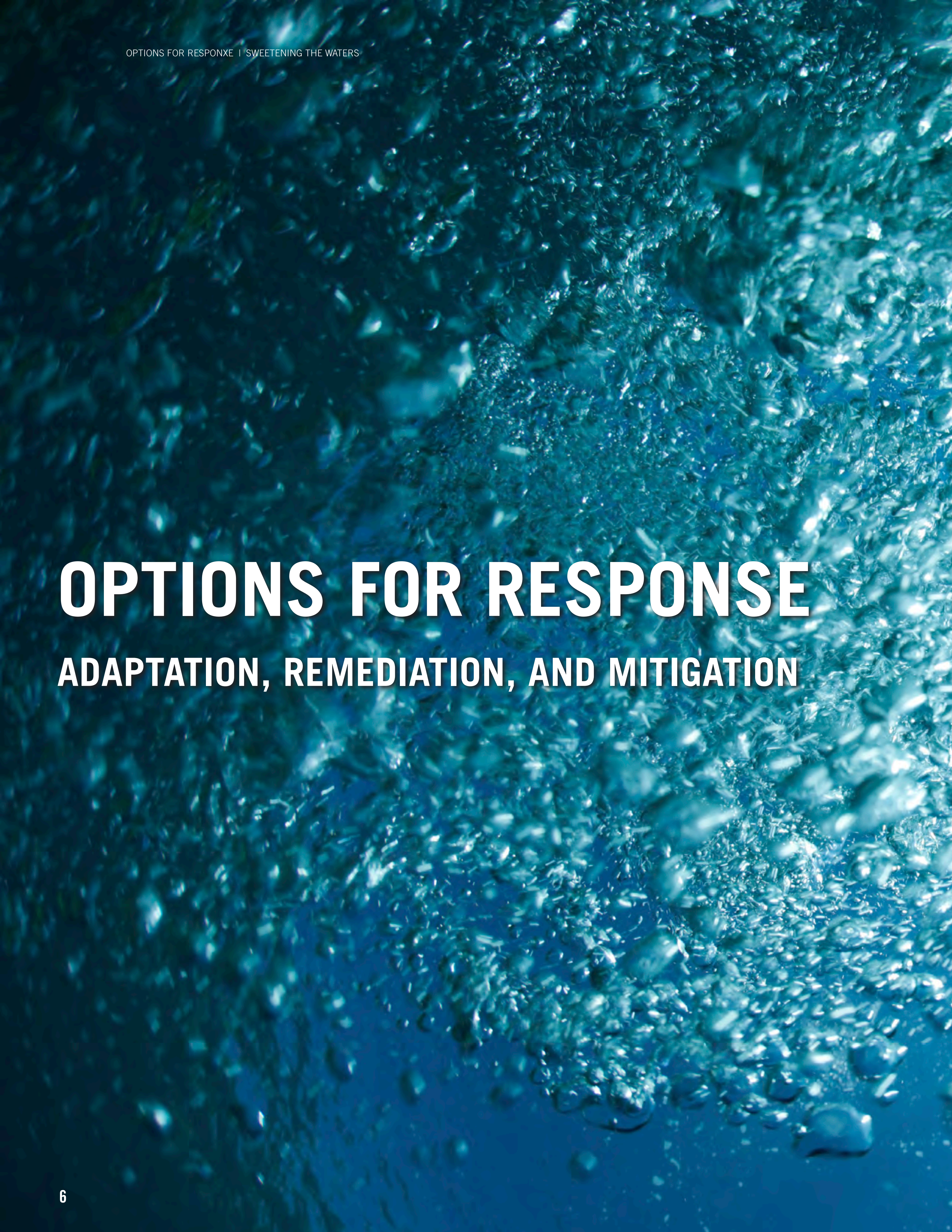


OPTIONS FOR RESPONSE

ADAPTATION, REMEDIATION, AND MITIGATION

This report investigates the feasibility and efficacy of three categories of action for addressing acidification in Washington's marine waters. The selection of measures examined here is meant to suggest, not exhaust, the range of options available for:

- **ADAPTING SHELLFISH PRODUCTION SYSTEMS TO PROTECT VULNERABLE LARVAE FROM CHANGING WATER CHEMISTRY.**
- **REMEDIATING ACIDIFIED CONDITIONS IN WATERS AND SEDIMENTS TO PROTECT BOTH WILD AND CULTIVATED SPECIES.** Strategies explored here range from highly local to regional-scale (and more speculative) measures to restore healthy chemistry. These include relatively well-established approaches such as buffering sediments in shellfish beds with recycled shell hash, cultivating seagrass to protect nearby larvae by absorbing CO_2, and a review of available estimates of the potential to remediate larger areas by cultivating and harvesting macroalgae in offshore waters.
- **MITIGATING THE ANTHROPOGENIC WASTE STREAMS THAT DRIVE ACIDIFICATION.** These include airborne emissions of carbon dioxide and other gases that can mix into seawater and change its chemistry, and terrestrial runoff that can carry nitrogen wastes and organic carbon into downstream waters, fueling algae blooms that soon decompose, depleting oxygen and releasing more CO_2 into the water. This section concentrates on terrestrial runoff, where local action may have potential to deliver more immediate local benefits, but it also evaluates several low-cost strategies for reducing atmospheric emissions that may contribute to local acidification.

These examinations are, of course, based on current knowledge and experience, which in many cases are woefully incomplete. Methods of adaptation, remediation and mitigation are evolving rapidly. Evaluating their feasibility and efficacy will require experiments and field trials, a number of which the Blue Ribbon Panel recommends in its own report.

In confronting a daunting challenge like ocean acidification, the first move is often the hardest. It helps to start by reviewing the tools at hand. This report is meant to offer a first, and necessarily preliminary, look at what those tools can do. As the first effort of its kind, Washington's initiative—starting with the launch of Governor Gregoire's Blue Ribbon Panel on Ocean Acidification and continuing into the implementation of measures to tackle the problem—is being closely watched around the country and around the world. Governor Gregoire famously summed up the responsibility and the opportunity that come with this mission in a single word. When asked what a small state like Washington could do about a global problem such as ocean acidification, she replied: "Lead."

Governor Christine Gregoire announced plans for a Blue Ribbon Panel on Ocean Acidification in December 2011. It is the first such state initiative in the nation. *Photo: Eric Swenson.*

Adaptation

So far only one proven adaptation strategy has been found: monitoring in order to protect larvae from corrosive waters. Research is also underway on potential to selectively breed oysters that might be more tolerant to acidification.

Sustaining monitoring at shellfish hatcheries and breeding beds

Combined monitoring of seawater chemistry and larval condition is a crucial survival tool for shellfish producers in the Pacific Northwest. Since it began in 2010, real-time monitoring of pH, pCO_2, salinity, temperature, and dissolved oxygen in intake water has saved Northwest shellfish hatcheries and the Pacific Coast oyster industry from collapse. It has enabled the hatcheries to draw water at those times and depths that are least by "corrosive" to shellfish larvae, and to buffer the water to improve larval survival when required. This monitoring continues at the Whiskey Creek, Taylor Shellfish Farms, and Lummi hatcheries and at three Willapa Bay sites. As of this writing (November 2012), the federal and foundation funding that supports this monitoring will be exhausted by early 2013. Without monitoring, the West Coast oyster industry would once again face collapse, and production of Manila clams, geoducks, and other shellfish might also be threatened, together with those species' economic and water-purifying benefits. Alan Barton, who coordinates the shellfish industry's monitoring program, calculates that $166,000 a year would sustain the current program, while providing improved calibration and technical support.

Monitoring was essential to restoring production at Washington and Oregon hatcheries that lost up to 80% of their oyster larvae from 2005 to 2009. Here Benoit Eudeline checks the seawater being drawn from Dabob Bay. *Photo: Eric Swenson*

Breeding OA-resistant strains of vulnerable marine species

Selective breeding shows some promise as a strategy to increase the resilience of certain shellfish species. Preliminary findings suggest some strains may have greater resistance to low-pH waters. But many questions remain: How much resistance can be achieved? Will such breeding undermine the traits that breeders have traditionally sought, such as rapid growth and increased meat fill? Will it lead to higher feed requirements or oxygen demand?

Large-scale experiments are needed to achieve rapid progress and evaluate risk factors. But funding for such efforts has been limited and erratic; a key industry resource, the Molluscan Broodstock Program at Oregon State University ran out of funds last winter and attempted, unsuccessfully, to delegate its functions to a private developer. Four Northwest oyster hatcheries/growers are endeavoring to pool their resources and continue at least some of that work.

Remediation

Because plants absorb carbon dioxide, phytoremediation has been suggested as a potential strategy to ease acidification. There are indications that shellfish may sometimes improve conditions for some seagrasses and macroalgae. Meanwhile, research on the East Coast has showed that restoring shucked shells to clam beds can restore healthier chemistry in acidified sediments, improving larval survival. The chemical effects of shell restoration among Pacific Northwest species are presumed to be similar, and detailed field trials could help maximize benefits and define best practices. Multitrophic culture practices and coastal conservation practices that increase wetland carbon storage may also play a role. Whether large-scale cultivation and removal of marine macroalgae could soak up enough carbon to ease acidification along the Northwest outer coast is a more speculative question, but a preliminary assessment of that potential is offered here.

Cultivating seagrass and shellfish together to help protect both and counteract acidification of local waters.

Seagrass, sequestering superstar

Seagrasses are undersung champions of carbon sequestration; the top meter of soil in seagrass meadows contains more than 50 times the biomass of the plants themselves, an estimated 4.2 to 8.4 quadrillion metric tons of carbon worldwide.[1,2] Even considered as entire communities, including the animals and other organisms that live among the grasses, 83 percent of seagrass meadows studied in the tropical Indo-Pacific, from Fiji to Kenya, were found to be net autotrophic—that is, they take up more carbon for photosynthesis than they release through respiration. These meadows can raise nearby saturation levels of aragonite, the form of calcium carbonate larval bivalves use to build their shells, by up to 14 percent, and raise pH by up to .38—in effect doubling the level of alkalinity. This seems especially impressive when one considers that the average pH of the global ocean has fallen by just .1 since the dawn of the industrial era.[3]

One report from the Pacific Northwest National Laboratory suggests that currents transport much of this impounded carbon to offshore depths, where it is then sequestered. It does not offer any data supporting this apparent seaward transport nor explain the processes enabling it, which the

Marsh on Willapa Bay. Marshes can sequester large amounts of carbon deep in the mud substrate, which may improve conditions for some larval shellfish above.

Seagrass and CO_2: the phenolic factor

Hope that rising carbon dioxide levels will fuel more seagrass growth, partially sequestering that CO_2 , may be dampened by a surprising recent finding regarding seagrass metabolism and chemistry. When atmospheric CO_2 levels rise, many terrestrial plants produce more phenolics, chemicals that serve as antimicrobials and to deter grazers, make the plants less digestible, screen out ultraviolet radiation, and, in the case of the phenolic lignin, provide structural strength—in short, to make the plants more resilient as climate and other conditions change. A study of seagrasses growing beside a natural CO_2 vent off the Italian island of Vulcano and under artificial CO_2 enrichment in Chesapeake Bay found that they did indeed grow faster as CO_2 levels rose and pH fell. But they suffered a "dramatic loss" of phenol production, potentially leaving them more vulnerable to threats ranging from slime mold-like pathogens to grazing fish, geese, and sea urchins.[11]

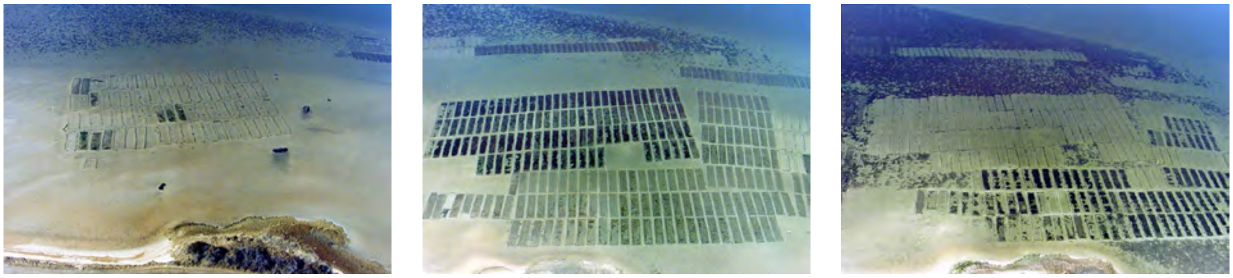
report notes is "a controversial subject."[4] Such transport has, however, been documented in other regions of the world, where "many photographs of the deep-sea floor reveal seagrass detritus, indicating that an abundance of seagrass detritus reaches these depths."[5]

Seagrasses also facilitate the dissolution of calcium carbonate from sediments into the water column, effectively transforming acidifying CO_2 into calcifying carbonate; the denser the seagrass, the more carbonate gets released.[6] This raises the water's pH, makes more carbonate available to shell-building organisms, and counteracts (to an undetermined degree) the rise in dissolved CO_2.[7]

Furthermore, in many coastal ecosystems seagrasses and other aquatic plants, together with oyster reefs, play an important role in denitrification—sequestering nitrogen that otherwise could fuel eutrophying algal blooms, which contribute to acidification. One 2011 study found that, at then-current values for nutrient trading credits, these habitats removed nearly $3,000 worth of nitrogen per acre each year, nearly twice as much as intertidal flats, seven times as much as subtidal flasts, and 20 percent more than saltwater marsh.[8]

Rising CO_2 boosts the growth of seagrasses, as long as they get enough light.[9] But rising levels of carbon, and of nitrogen and other nutrient runoffs, also stimulate the growth of suspended microalgae and of epiphytes that grow on seagrass. Both block the light the grass needs for photosynthesis. Suspended sediments block even more light, especially along erosive, sediment-rich littorals like Puget Sound.[10]

Recognition of these benefits, and of the importance of seagrass meadows as nurseries and habitats for many marine species, has come late. Seagrass is considered one of earth's most threatened ecosystems.[12] Many of Washington's meadows have lately expanded, but they're still well short of their historic range; just 49,000 acres remain of the prevailing eelgrass (*Zostera marina*) in the Salish Sea.[13] Future sea-level rises may move the narrow window of shallow-water transparency in which seagrass thrives. In some estuaries, the loss of coastal marshes, which act as pollutant sponges, and the inundation of upland areas will cause new influxes of suffocating nutrients and sediments.[14] This gives Washington and its various aquatic stakeholders an additional incentive to sustain their commitment to preserving existing seagrass meadows and reducing the erosion and runoff that threaten them.



Left: Clam beds in formerly barren sand substrate in Cherrystone Creek, Virginia, soon after planting. **Center:** One year later, after additional planting and colonization of the original beds by eelgrass. **Right:** After two years and harvesting of the initial beds. Note how eelgrass has spread in the surrounding substrate. *Courtesy William M. Peirson.*

Upstream eelgrass, coral's best friend?

Eelgrass also appears to benefit tropical corals, which like many shellfish larvae depend on aragonite for calcification; an analysis of 64 data sets on Indo-Pacific reefs found that adjacent, upstream seagrass meadows could boost the corals' calcification rates by 4 to 18 percent.[24]

Eelgrass meadows are one of the the most efficient carbon removal mechanisms on Earth. Unfortunately seagrass-rich estuaries are rapidly disappearing under the pressure of development. *Photo: NOAA*

Shellfish benefits to seagrass

Researchers have long hypothesized, and shellfish-industry advocates have long contended, that filter-feeding bivalves promote seagrass by removing light-blocking microalgae and sediments. Recent experiments with eastern oysters (*Crassostrea virginica*) and hard clams (a.k.a. quahogs, *Mercenaria mercenaria*) support these claims.[15]

This is just part of the complex (and generally mutually beneficial) relationship between seagrass and shellfish and of the suite of ecosystem services that shellfish provide.[16] Hard clams and Gulf mussels don't merely remove light-blocking phytoplankton; they convert a large portion of what they ingest into buried nutrients that the seagrass can exploit.[17][18] The bivalves excrete nitrogen- and phosphorus-rich feces and pseudo-feces into the substrate, which the seagrasses then take up. This process also works to remove nitrogen from the aquatic system altogether. The shellfish ingest biologically active nitrate and excrete ammonia, which soil microbes metabolize, releasing harmless elemental nitrogen that rises into the atmosphere.[19]

On the Atlantic coast, oyster reefs can serve as underwater breakwaters, reducing the destructive scouring of seagrass beds and salt marshes by storms.[20] It might be useful to examine whether oyster beds provide similar services on the Pacific coast, which lacks similar reefs. Clam beds may also help stabilize the substrate, providing a more secure growing surface and allowing more seagrass seeds to sprout and take root. Clam growers in Virginia have observed eelgrass growing at an accelerated pace first on and then around their clam beds. The initial and perhaps primary impetus to this growth appears to be the nets stretched over the clam beds, which anchor the substrate and reduce sand migration. Improved water clarity kicks in as the clams suck down plankton and sediments.[21]

Seagrass-shellfish synergies

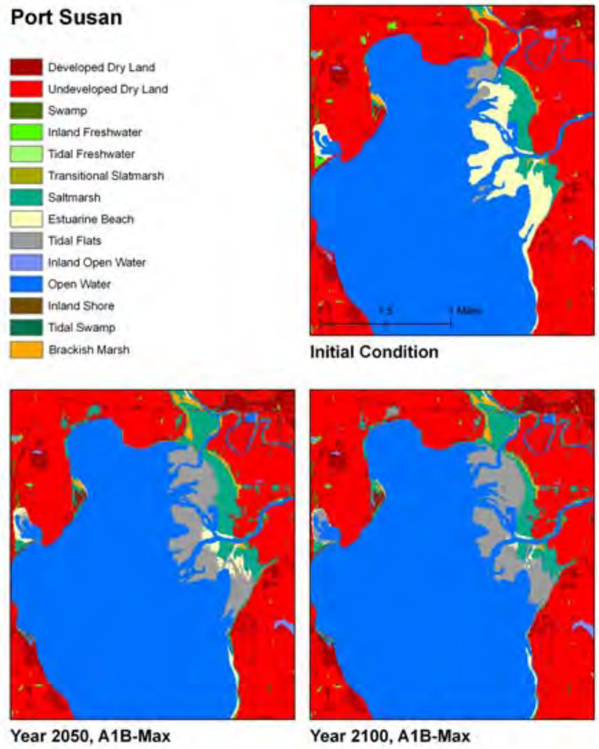
In shallow bays, this effect can be both a blessing and a curse. Eelgrass-rich Netarts Bay undergoes dramatic daily shifts in acidity and pCO_2 as the seagrass, together with other photosynthesizers, takes up incoming upwelled carbon by day and then respires it away at night. The Whiskey Creek Shellfish Hatchery's operators time their water intakes, avoiding high-CO_2, low-pH water in the morning and drawing in late afternoon after the eelgrass (together with phytoplankton and macroalgae) has done its photosynthetic work. This, in combination with buffering, has enabled the hatchery to regain much of its lost oyster-larvae production. But it complicates the operation and cuts into productivity; manager Alan Barton dreads autumn, when the upwellings recede and the eelgrass dies back and rots, releasing a surge of carbon.[22]

On a smaller, more controlled scale, however, seagrass may provide mitigation consistent enough to help shellfish larvae survive. North American research has so far concentrated on shellfish's benefits for seagrass, but that imbalance may soon be corrected. Scientists in North Carolina who've been investigating the nutrient contribution of clams to seagrass beds are now conducting early trials of the effects of seagrass on Eastern oysters.[23] After observing apparent benefits in the field, shellfish growers have begun experimenting with shellfish-seagrass co-culture.

Like all ecological relationships, however, the seagrass/shellfish match depends on species and circumstances and is not always mutually beneficial. At the Banc d'Arguin on France's Arcachon Bay, populations of the cockle *Cerastoderma* edule declined as the seagrass *Zostera noltii* spread.[25] In local trials, adding clams and oysters to gaps between meadows did not affect seagrass colonization.[26] Geoduck (*Panopea generosa*) culture appeared to first encourage, then eradicate eelgrass on a Samish Bay plot where no eelgrass had grown before. The eelgrass colonized the plot after Taylor Shellfish began growing geoducks there. But then matted macroalgae infested the protective mesh covering the geoducks tubes, blocking the sunlight the eelgrass needed for photosynthesis, and increased tidal scour washed away both the eelgrass and much of the carbon-trapping sediment beneath. After the harvest and removal of the tubes and mesh, sediment levels recovered and eelgrass began recolonizing the area.[27]

This episode does not show that geoduck culture and eelgrass habitat are incompatible, as some critics of the industry have suggested. It may suggest the opposite, since eelgrass did not grow on the site until the geoducks were planted and resumed growing after they were harvested.[28] But it also suggests that the relationship between the two is complex and incompletely understood, and it may be helpful to test alternative methods or techniques of geoduck culture that might better retain sediments, protect eelgrass, and sustain its carbon-capturing contribution.

These interactions among grasses and bivalves, and their potential benefit for both shellfish production and carbon sequestration, are a promising field for study and the development of sound practices in the Northwest. Research so far has concentrated on the Atlantic coast. Investigations here in the Northwest might quantify any potential carbon-storage and other benefits from integrated cultivation in Pacific habitats and determine the best conditions for it. Local shellfish growers would then be better able to weigh the costs and benefits of incorporating seagrass in and around their beds, for the sake of their own harvests and for the wider imperative of sequestering carbon. This sedimentary sequestration may be further rewarded with emissions credits if and when a trading system comes on line in Washington.



Projected inundation, Port Susan, from "Sea-Level Rise and Coastal Habitats in the Pacific Northwest," National Wildlife Federation.

Given rising seas, could future inundations be used to create new salt marshes and seagrass meadows, providing shellfish habitat and carbon storage?

Future sea-level rises may create new seagrass habitat; they will likely create extensive saltwater marshes, which are also efficient carbon sinks and filters for pollutants, nutrients, and sediments.[29] In many estuaries—notably Port Susan, Padilla Bay, and Skagit Bay—what are now beaches will become tideflats, and extensive freshwater marshes and dry land will give way to tideflats and, especially, saltwater marshes.[30]

These changes foretell threats to saltwater habitat and water quality, with the loss of the filtering capacity of extensive wetland "sponges." But they also present what could be an opportunity to replace or augment the carbon storage and other environmental services provided by today's coastal wetlands. Eelgrass meadows and salt marshes both tend to be more tenacious impounders of carbon than diked meadows and freshwater marshes, thanks in large part to the fact that, when the tides wash over them, they deposit sediments that bury and contain dead plants and other organic detritus.[31] A comparison of two neighboring tidal marshes on Grays Harbor, one of which had been diked for 50-plus

years while the other was still open to the tides, tells the story. In the diked marsh, the concentration of buried carbon fell off sharply five centimeters below the ground and petered out after nine. The undiked marsh's soils were loaded with evenly distributed carbon down to 30 centimeters.[32]

New and restored marshes can build up these carbon reserves quickly. Within 10 years of being created, a new salt marsh on the Chehalis River had accumulated carbon levels comparable to those in an existing marsh nearby. Eelgrass may sequester carbon even faster; within two years, the carbon levels of the soils in two experimental tanks planted with eelgrass matched or surpassed those in four reference beds (while still lagging behind seven other natural beds).[33]

Breaching dikes to create saltwater habitats is a well-established conservation practice. It may also be a useful way to prepare for sea-level changes in the future. The Nisqually Delta is a much-lauded regional and national model of what such efforts can achieve. This three-decade-long cooperative effort by scientists, citizens, state and federal agencies, the Nisqually Tribe, and Ducks Unlimited and other conservation groups has restored more than 900 acres of salt marsh and 35 miles of tidal sloughs.[34] To the north, the Tulalip Tribes plan to open up about 400 diked acres, mostly freshwater marsh, at Ebey Slough on the Snohomish Delta to create new habitat for juvenile salmon. These efforts may also afford useful insights for future saltwater habitat restorations and re-creations.

Choose sites carefully

Restoring eelgrass is a difficult, uncertain process, costing from $100,000 to $1 million per acre according to one 1998 study.[35] Several reviews of planting and transplantation efforts around Puget Sound have found only poor to moderate success; one found just 13 percent of efforts to be unequivocally successful.[36] Another West Coast attempt offers a cautionary example. In the 1980s Richard Zimmerman, a leading eelgrass expert, supervised plantings in Parsons Slough, an arm of Elkhorn Slough at the head of Monterey Bay. All eventually failed, and recent introductions by the slough's managers also appear to be failing.[37] But biologist Kamille Hammerstrom, who helped perform the Elkhorn restoration, notes that strong currents, poor water clarity, and excessive depth hampered it from the start. Careful siting, informed by past experience, may avoid such hazards.[38]

A backhoe works to bring the dike down to marsh level and open a channel for tidewaters to flow into the marsh at Port Susan Bay, Washington.
Photo: Nature Conservancy. Copyright: Marlin Greene/OneEarthImages

Can recycling seashells help recruit larvae to oyster beds, and give consumers to a way to protect their favorite shellfish?

Oyster growers and gatherers have long noted that putting seashells back in the water helps oyster populations thrive, and in doing so they have probably been inadvertently reducing local harm from acidification without even knowing it. They have used old shells because these make the best kulch for new oysters to anchor to.[39] Sometimes, however, the growers noticed that scattering shells seemed to bring clams and oysters back, even to anoxic sediments where nothing would grow, and wondered if some other process was at work.[40] Bob Rheault, oysterman and president of the East Coast Shellfish Growers Association, recalls how, after losing hundreds of thousands of dollars' worth of clams in a mysterious die-off, he dumped the shells on a lifeless, anoxic patch of his Rhode Island leasehold—"black mayonnaise"—and was amazed to discover that "clams grew there just like they used to."[41]

What they had observed was a basic process of ocean chemistry at work. The shells of mollusks and other marine invertebrates are composed of calcium carbonate, which the organisms extract from seawater. When these shells dissolve, they release this carbonate, raising both carbonate saturation and alkalinity in the surrounding waters and sediments. The level of calcium carbonate—in particular of aragonite, the especially soluble form of calcium carbonate that bivalve larvae use—is essential to their survival.

Scientists have confirmed that bivalve shells—preferably broken or ground up, since they otherwise take several years to dissolve—can buffer sediments acidified by nutrient runoffs and decomposing phytoplankton, causing many more juvenile clams to settle and survive there.[42] In field trials in Maine, an acre of acidified sediment buffered with ground shell "hash" had recruited and sustained nearly 600 juvenile clams after five weeks. By contrast, the number of young clams in nearby unbuffered sediment topped out at a little over 200 per acre.[43]

Mountains of bivalves have come from Washington's prolific Willapa Bay. Research from Maine suggests that returning some of the shucked shell material to nursery areas might give tiny young oysters a better place to land, by buffering acidified conditions on the seafloor. These mounds are in South Bend, Washington, known widely as the "Oyster Capital of the World." *Photo: Brad Warren.*

Shell may also provide chemical cues, attracting young clams and other bivalves. Its remediative value seems to lie in more than simple buffering and calcium carbonate input. The Maine researchers tried spreading reagent-grade calcium carbonate instead. It proved less effective, even with heavier and heavier doses.[44]

Recruiting clams, oysters, and citizens

Since the 1980s, shellfish growers, public agencies, and volunteers on the East Coast have undertaken a number of shell collection and deposition campaigns to restore depleted oyster beds.[45] One, the year-old Martha's Vineyard Shell Collection Project, has closed an egregiously wasteful broken loop. The island's growers would import hundreds of yards of shell from the mainland while its restaurants tossed theirs into dumpsters bound for an off-island landfill. Volunteers collect the shells daily from the most prolific restaurants and from drop boxes at recycling stations. It cost $6,000 to launch the Vineyard shell project and operate it in its first season.[46]

The Pacific Shellfish Institute is working with restaurant partners to establish a similar shell collection program here. This would complement plans to restore native Olympic oyster beds that were destroyed decades ago by overharvesting, pulp mill effluent, and other pollution. The Washington Department of Fish and Wildlife has targeted 19 historic Puget Sound beds for restoration. The Puget Sound Restoration Fund, which is spearheading the effort, seeks to seed 100 acres initially, out of some 10,000 original acres.[47]

The logistics are complex, and the transport equation not as favorable on Washington's sprawling coastline as on compact Martha's Vineyard. Each acre of local sediment requires from 100 to (in soft muck) 400 cubic yards of kulch. Collecting from restaurants and consumers would save the $25 a cubic yard it costs to buy shells. But trucking them to a site where their smell would not offend, storing them for a year or more to eliminate potentially infectious tissues, hauling them again and spreading them on the beds, and securing permits from various state and federal agencies to do so might cost $50 a yard.[48]

For now, there's a shell surplus on the local market.[49] But that surplus may shrink or vanish as oyster restoration takes root here. On the Atlantic side, where restoration has been under way for decades, "shell is quickly becoming a limiting resource for all the oyster restoration projects," says East Coast Shellfish Growers Association executive director Bob Rheault.

Shell collection can serve another valuable purpose: to enroll businesses and citizens (as volunteers and as conscientious consumers) in marine conservation. Enlisting them in hands-on remediation and restoration can educate them about acidification and all the personal choices that contribute to it, and instill a sense of ownership and stewardship over Washington's waters. The research in Maine suggests that many local tidelands might also benefit from applications of shell hash[50] (It must, of course, be applied judiciously. The ground shell can prevent kelp and other seaweeds, which require suitably firm or weighty holdfasts, from anchoring, so shell should not applied where they may grow. It might also impede shorebirds' foraging.)

Carbon, kelp, and sea otters

Not all unintended consequences are malign. Conserving predators at the top of a food web can restore carbon-sequestering plant resources at the base. The recovery of sea otters, once nearly hunted to extinction along North America's Pacific Coast, has triggered the explosive recovery of formerly depleted kelp forests. The reason: Sea otters prey voraciously on sea urchins, which graze voraciously on kelp when otters are absent. When otters are present the urchins tend to hide in rocky fissures and eat kelp detritus, and the kelp flourishes. A recent study attempts to calculate the indirect contribution otters thus make to carbon sequestration, and finds it sizable: With otters, kelp achieves more than 12 times as much biomass as without. This translates to between 4.4 and 8.7 billion additional grams of carbon storage across the otters' northern habitat, from Vancouver Island to the Western Aleutians, worth $205 to $408 million on the European Carbon Exchange.[51]

At least one important local burrowing bivalve may be more susceptible to acidification than previously thought. Geoducks were previously believed to be relatively impervious to acidification. But young geoducks began showing pitted, even perforated shells at Taylor's Dabob Bay hatchery, which draws deeper, cooler (and lower-pH) water for them. Taylor Shellfish biologist Benoit Eudeline says the hatchery now buffers the water used in the geoducks' larval and second phases, and once again gets good survival. As for spreading crushed shell in exposed bays, he predicts, "Ultimately, we're going to have to do that."

Can growing and harvesting macroalgae remediate coastal eutrophication and corrosive oceanic upwellings?

The seaweed solution

Macroalgae are prodigious photosynthesizers and consumers of carbon dioxide, nitrogen, and phosphorus. The largest species, the giant bladder kelp (*Macrocystis pyrifera*), found further south along the Pacific Coast, is one of the fastest-growing organisms on earth, adding up to two feet in a day and 150 in a single season.

But kelp grows only in certain limited conditions: a narrow band of water depth where enough light can penetrate to enable photosynthesis—typically less than 20 meters in murky Puget Sound—along only about nine percent of Washington's coast. It needs active water movement, ample nutrients, and rocky substrate to cling to.

Growing seaweed on suspended nets or lines can extend this range. As early as 1968, researchers concluded, and successful transplantation efforts seemed to confirm, that cultivation could supplement Southern California's rich kelp beds, but commercial development did not follow.[52] In Japan and neighboring countries, however, a centuries-old tradition of seaweed farming spawned a major 20th-century industry. By 2004, seaweed harvests, more than 90 percent of them cultivated, totaled $6.8 billion worldwide.[53] Most were in Asia, but cultivation has spread to Canada, the United States, South Africa, Chile, and several European countries. More than 80 percent of seaweed harvests by value still go to food, with retail dry prices for some varieties surpassing $30 a pound. But seaweeds also supply other high-value products—

Until 2005 when it moved operations to Scotland, Kelco Inc. used vessels such as this one to "mow" the top of the canopy of giant bladder kelp off Chula Vista, California. The vessels could harvest and carry up to 550 metric tons per day. *Photo: Dr. Ray Lewis*

America's once and (maybe) future seaweed industry

During World War I, giant kelp supplied a lucrative extractive industry in Chula Vista, California, where the Hercules Powder Company, a DuPont spin-off, harvested up to eight tons of kelp a day to produce potash and (via fermentation) acetone, essential for munitions.[54] Industrial-scale kelp harvesting revived in California in 1928 and continued until 2005, though it was in later years restricted to "grazing" within four feet of the surface in order to preserve the beds. The dominant harvesting firm, ISP Alginates, constrained by regulations, finally decamped to Scotland.[55]

In 1978, the U.S. Department of Energy's Aquatic Species Program began investigating offshore seaweed cultivation as a source of biomass for methane production. But some early trials foundered in stormy waters, and in the early '80s DOE opted to concentrate its limited aquatic-species funding on producing biodiesel economically from microalgae (a goal that has revived in recent years with a surge of venture capital). In 1996, DOE narrowed its biofuel sights further, to ethanol production from terrestrial crops, and shut down the Aquatic Species Program.[56]

In the 1980s investors attempted to grow edible nori (*Porphyra* sp.) in Puget Sound, as well as *Macrocystis* and *Nerocystis* kelp for herring-roe harvest, but met unbreakable resistance from shoreline property owners.[57] The fact that culinary seaweed processing is highly labor-intensive has also inhibited development in America.

In recent years, however, algal aquaculture has revived on several other American coasts. Operations in California, Oregon, and Hawaii grow kelp and red algae species such as dulse , usually in tanks, to feed commercial abalone stocks and reintroduced, endangered pinto abalone. Others in Hawaii and British Columbia grow edible seaweeds in both tanks and open waters.[58] In Maine, the East Coast's first commercial algaculture operation, Ocean Approved, began growing kelp for sale to restaurants and the Whole Foods chain two years ago.

The kelp forests along the West Coast of the United States are the most extensive underwater forests in the world. Some forms of kelp reach 200 feet in length. *Photo: Dr. Mark Carr*

carrageenan, agar, pharmaceutical and cosmetic ingredients, iodine supplements—as well as fertilizer and fish and animal feed. Some contain small shares of natural marine oils—the vaunted omega-3 fatty acids—that may substitute for forage-fish sources, relieving pressure on anchovy and other stocks. Taken together, these revenue sources and others suggest opportunities for multiple benefits.

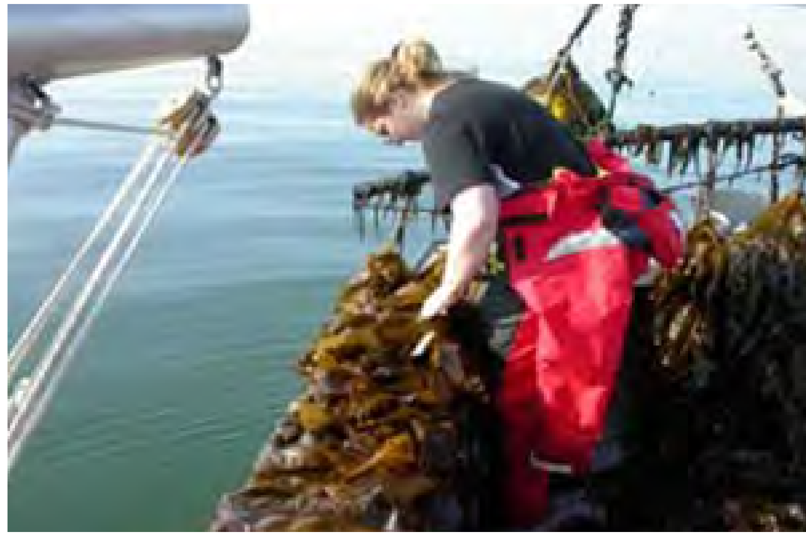
IMTA presents new opportunities, and difficulties

Macroalgae and finfish have been widely hailed as natural partners for integrated multitrophic aquaculture (IMTA) and shellfish can complement both of them, separately and together). From South Africa and Chile to Portugal, British Columbia, and the Kitsap Peninsula, aquaculturalists use kelp and other macroalgae as biofilters to capture the excretions of salmon, turbot, sea bass, and other species.[59] The seaweed also replaces some of the oxygen consumed by concentrated pen and tank populations.

Many studies chart the success of such multitrophic ménages and attempt to calculate the potential for much larger biofiltration benefits from seaweed cultivation. According to one, seaweeds can remove up to 90 percent of the nutrients discharged from an intensive fish farm.[60] At NOAA's Manchester, Washington, experimental station, a small Seattle-based firm, Sol-Sea, grows the red alga *Chondracanthus exasperatus* (a.k.a. Turkish towel) to produce specialized cosmetics. It runs effluent from tank-raised Pacific halibut (*Hippoglossus stenolepsis*) and black cod (*Anoplopoma fimbria*) through 1,200-gallon tanks, each containing some 110 pounds of algae grown on a 21-day cycle.

Initial tests by University of Washington researchers found that the *Chondracanthus* removed about 90 percent of the nitrogen in the halibut effluent water.[61] Sol-Sea has reported that the alga also doubles its medium's oxygen content and removes 85 percent of its carbon dioxide.[62] The company is now considering adding California sea cucumbers (*Parastichopus californicus*) to eat unwanted algae growing along the sides of its tanks.

But growing macroalgae at industrial scale in tanks may be more difficult than it looks. The Whiskey Creek Shellfish Hatchery, which grows large quantities of microalgae to feed its oyster larvae, considered using *Ulva* (sea lettuce) to



Feeding the wastes of one species to speed the growth of other species is at the heart of integrated multi-trophic aquaculture. Converting waste streams into profit is a double winner. Here a kelp line is checked in an operation that combines, fish, shellfish, and seaweed. *Photo: Thierry Chopin*

remove carbon dioxide from its intake water, and even raised an initial batch. But it decided not to proceed. "It's pretty difficult on our scale," says Whiskey Creek proprietor Sue Cudd. "You need enough sun, and have to manage a whole other biological system—microalgae is just in batches, but you'd have to keep this going continuously. It's possible, but we haven't figured out how to maintain it."[63]

Algal treatment, from dairy to coastal scale.

Algal remediation is also used to treat municipal waste and has been studied for the treatment of dairy waste. Its efficacy is well established, but cost remains a concern. One study found that using an algal turf scrubber, a relatively simple, highly effective system modeled on the multi-species algal communities in coral reefs, in combination with anaerobic digestion to treat manure slurry would consume about nine-tenths of average dairy profits.[64] But this estimate did not consider potential compensation from nutrient credits or government subsidies, revenues from the algae harvested, or savings in the (substantial) costs of hauling and disposing of the manure. These savings are the main benefit for the dairy farmers participating with the Tulalip Tribes in the Qualco biodigester.[65]

Microalgae are more widely used than macroalgae for waste cleanup in contained vessels. But macroalgae are more much more easily strained from the water than micro, and unlike micro they

can be grown and harvested in open waters. This has opened up new potential venues for algal remediation on a much larger scale.

Ocean Approved founder Paul Dobbins says one Maine sewer district is considering using his kelp for biofiltration.[66] University of Connecticut researchers are incubating Grassilaria red algae and ribbed mussels for planting at the confluence of the polluted Bronx and East Rivers in New York, as a trial for large-scale bioremediation in Long Island Sound.[67] (The seaweed consumes inorganic nitrogen; the mussels, organic waste.)

Cultivated shellfish and seaweed already play substantial roles as carbon and nutrient sinks in China, home to three-quarters of the world's mariculture. Its cultured shellfish and seaweed took up an estimated 3.8 million tons of carbon per year in the decade to 2008[68] (and probably more in the years since, given the rapid growth of Chinese aquaculture). At least 1.2 million tons of this carbon was subsequently harvested, 340,000 tons in the form of seaweed. Most of the rest was seashell; macroalgae make up only about one-eighth of Chinese mariculture by weight but contain a higher share of carbon, 20 to 35 percent of dry weight, than does shell.

In Northern China, the kelp *Saccharina* (a.k.a. *Laminaria*) *japonica* Aresch. has been grown for many years to remediate pollution from extensive scallop cultivation.[69] One Chinese researcher argues that large-scale cultivation of this and certain other seaweed species could correct massive eutrophication problems along the country's entire coastline, impounding excessive nitrogen and phosphorus as well as carbon dioxide.[70]

Saccharina (or *Laminaria*) *japonica* is an edible kelp enjoyed throughout East Asia, where it is grown extensively on ropes. It is an extraordinary biofilter, removing land-based toxic pollutants that cause eutrophication and also sequestering carbon from the atmosphere. *Photo: connect.innovateuk.org*

Can large-scale, off-shore kelp cultivation protect Northwest coastal waters from corrosive upwelling?

The Chinese experience suggests an interesting, if admittedly speculative question: What could be achieved through algal remediation of ocean acidification along the North American West Coast? How much seaweed cultivation would it take to counter the corrosive upwelling that aggravates acidification along this coast in spring and summer? This geoengineering thought experiment requires first a calculation—a very tentative one—of the scale of those upwellings and their carbon content, based on data from several NOAA sources:[71]

In 2008 Richard Feely and his colleagues, in their seminal *Science* paper revealing upwelling of corrosive, high-CO_2 waters onto the Northeast Pacific continental shelf, estimated that these upwellings contain about 31 micromols (μmol) per kilogram of water.[72] The NOAA Pacific Fisheries Environmental Laboratory in Pacific Grove, California, compiles monthly and six-hourly indices of upwelling volumes at various points along the coast.[73] These have been used here to derive a rough estimate of the average upwelling rate at 48° N, the approximate latitude of LaPush on Washington's ocean coast, during the six midyear months of active upwelling: 50 cubic meters of water per second per 100 meters of shoreline.

Based on this estimate and several established measures:

1 mol carbon = 12 g

1 μmol carbon = 12 g x 1^{-6} = .000012 g

31 μmol C per .1kg = .00372g / kg

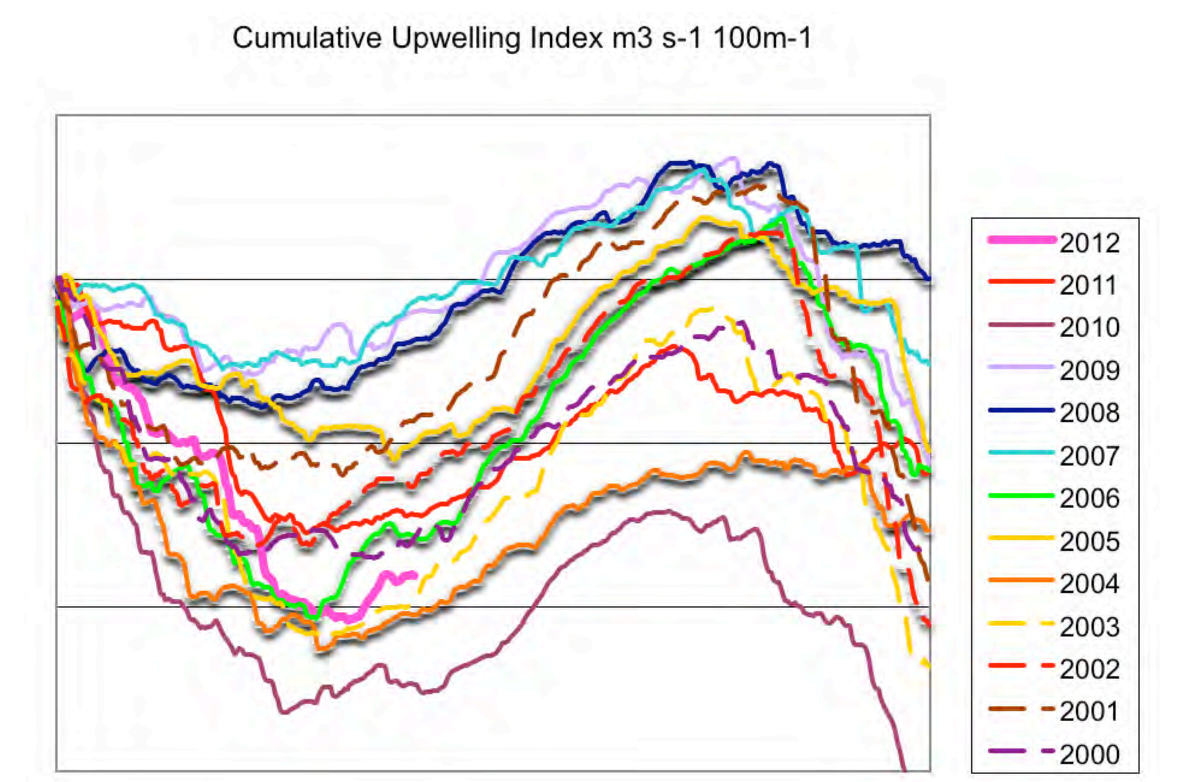
Seawater = ~1030 kg/m^3

50 m^3/s = ~51,500 kg/s (/100m)

.00372g x 51,500 = 191.5g or .0001915 tonnes of carbon per second per 100m of shoreline

.0001915 tonnes x 31,556,926 seconds x .5 [for 6 months of active upwelling] = 3021.6 t C/y/100m or 30,216 t/km

Kelp is 28% carbon by dry weight.



Cumulative upwellings, NE Pacific, 2000-2012. Source: National Marine Fisheries Service.

So one would have to harvest about 108,000 tonnes of dry seaweed per kilometer per year to remove all the upwelled anthropogenic carbon and lower the aragonite saturation level by 50m.

To take a more specific case: In 2011 (a year of relatively low upwelling), the average upwelling rate at Newport, Oregon (45° N), one would have needed to harvest about 62,000 tonnes of dry seaweed per year per kilometer of shoreline to remove all upwelled anthropogenic carbon. This would effectively reclaim near-surface waters for some vulnerable shelled larvae by eliminating corrosive conditions. Iin technical terms, it would lower the aragonite saturation horizon by 50m).

Recent studies posit that seaweed cultivation could produce 1,000 to 5,000 tons a year per square kilometer of open ocean.[74] At those rates, and positing one kilometer as the optimal field depth for intercepting upwelled carbon, we could grow less than a tenth of the seaweed required to remediate all the anthropogenic carbon upwelled off the Washington coast.

Nevertheless, the gap may not be so wide, for several reasons:

- Removing all the anthropogenic carbon from upwelling, the assumed benchmark, is an extremely ambitious standard—a rollback to preindustrial levels of carbon dioxide, something nearly no climate crusader imagines for atmospheric emissions. It is also probably much more than is needed to stop corrosive upwelling from reaching the shallows. How much that would be is a subject for further study, and any such calculation would have to take account of mixing.[75]
- Cumulative upwelling volumes on Washington's coast were not as readily accessible as the Oregon data, but upwellings there tend to be substantially weaker than those off Oregon. To judge by hourly samples, the volume at 48° N may be as much as 50 percent lower than that at 45° N. (On the other hand, 2011 volume at 45° N was 26 percent below the 40-year average, so an upward adjustment would also be necessary to ensure sufficient carbon capture in other years.)
- That production estimate is fairly conservative, reflecting the incipient state of open-ocean cultivation. A recent analysis from the Pacific Northwest National Laboratory notes, "Advances in macroalgal cultivation technol-

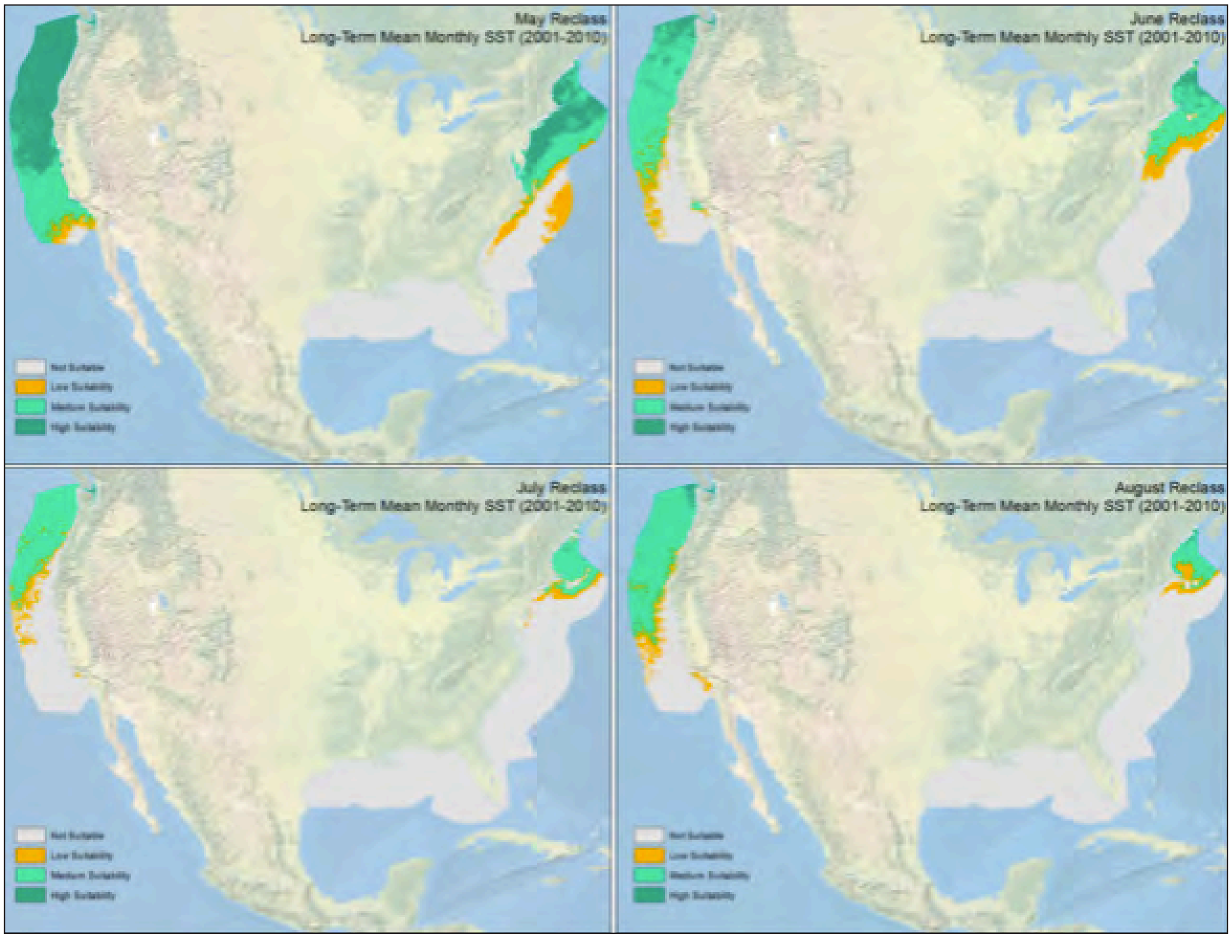


Figure 17. General suitability maps for kelp growth as a function of temperature in the U.S. EEZ off the East and West coasts of the United States using temperature suitability rules. Maps are shown for months of January to December (top left to bottom right). Legend: *Not Suitable – white*; Low Suitability – orange; Medium Suitability – aquamarine; High Suitability – green. From Roesijadi et al., "Techno-Economic Feasibility Analysis of Offshore Seaweed Farming for Bioenergy and Biobased Products," PNNL Report PNWD-3931 (2008).

ogy could potentially increase production from three to 10-fold with a corresponding decrease in the area needed for cultivation to meet specified production goals."[76]

» The Washington coast may be able to achieve better-than-average production rates, thanks to optimal temperature conditions for *Macrocystis*[77] and the region's nutrifying, carbon-rich upwelling system. Elsewhere, open-ocean seaweed growers might need to pump up nutrient-rich deep water to feed their crops—a measure that could be prohibitively expensive, as well as technically difficult in strong currents.[78] The Northwest's upwelling cycle serves up the goods at the optimal time for seaweed production: The April-to-September upwellings coincide with kelp's growing season.

All this is highly speculative—an initial rough guess at a question that calls for much more data, concerning a strategy that would have to cross many pitfalls and hurdles, both known and unknown, before it could be implemented. But options to remediate the Northwest coast's corrosive upwellings are scarce, so even a long shot is worth some examination.

The biofuel double-play

Unlike seagrass, algae do not root and bury carbon in the soil, and many (including bull kelp) are short-lived. When they decompose, a sizable but as yet unmeasured share of the carbon they consume may be borne down and sequestered in the deep ocean (at least until it returns in upwellings). The rest must be harvested to prevent its returning straightaway into circulation. The millions of tons of kelp that would be grown in any meaningful coastal remediation program would dwarf current world seaweed production (somewhere above 1.6 million tons). What to do with it?

Will microalgae keep pace with rising CO_2 ?

Single-celled microalgae grow and reproduce fast, within a matter of hours, prompting hopes that they will adapt quickly to changing ocean chemistry and ramp up their photosynthesis to exploit, and at least partly consume, the additional CO_2. Some scientists and entrepreneurs have even proposed seeding the open ocean with iron, a growth-limiting nutrient, to accelerate this process.

But recent experiments in Canada and Scotland suggest that microalgae may not respond in such a simple, bullish way to more carbon dioxide. About 1,000 generations of the green alga *Chlamydomas* raised at high CO_2 levels failed to develop characteristic adaptations. Some lines did crank up their metabolisms, with more rapid photosynthesis and respiration, but rather than growing larger on this enriched diet actually showed reduced cell size.[86] Some did not respond at all. Populations growing in CO_2-rich natural springs followed a similar pattern.[87] Whether macroalgae such as kelp also would is a question for further study.

Algae is the world's most productive source of biomass for fuel production and also one of the most nutritious organisms in nature. The 30.000 species of microalgae are a virtually untapped resource with fewer than 10 in commercial production. *Photo: Aeon Bio Group*

A proposal is already on the table, independent of ocean-remediation considerations. To meet the objectives of the Energy and Security Act of 2007, the U.S. Department of Energy set a target of producing 44 million dry tons of biomass feedstock by 2012 and 130 million—about as much as all the grain now grown for ethanol—by 2017. Macroalgae offer a number of advantages as a feedstock:

- Extremely rapid growth, thanks to photosynthetic rates two to four times as high as those of terrestrial plants.
- High sugar content.[79]
- None or very little of the nonconvertible lignin that complicates fuel production from wood waste and other terrestrial sources.
- Much less impact on land use and freshwater resources than terrestrial crops.
- No diversion of food crops (in the U.S.).
- Ample available room, apparently: Meeting that 250 million-ton goal with an average production of 2,960 tons per square kilometer would require 84,500 k^2 of sea space—just 0.7 percent of the United States' 200-nautical-mile Extended Economic Zone. Cultivating 0.3 percent of the ocean's surface (about one million 250-acre algae farms) could produce one billion tons of biomass—a fifth as much as is now harvested from all terrestrial sources, which exploit 24 percent of earth's land surface.[80]
- Habitat created, rather than lost as in terrestrial agriculture. As long as they are located in deep enough water to avoid shading the substrate, floating seaweed nets or pens might have minimal negative impacts. They could become rich feeding grounds, shelters, and nurseries for many different fishes, crustaceans, and other animals.
- Various higher-value products that could be extracted before fermentation or biodigestion, though production on such a scale might soon glut the market for wakame, agar, or iodine. The mineral nitrogen and phosphorus remaining after fuel extraction could replace some 30 percent of the nitrogen fertilizer now used worldwide, further displacing fossil-fuel consumption.[81]
- Opportunities for integrated multitrophic aquaculture. Open-ocean finfish (and perhaps even shellfish) cultivation could add further value and fertilizer, with fewer impacts than inshore aquaculture and ready remediation of emissions.

When we actually start farming the sea for food and fuel, macroalgae will be a major crop. They grow far faster than terrestrial plants and are even more effective at carbon sequestration and bioremediation. Products made from kelp include food, supplements, pharmaceuticals, biomedical staples, cosmetics, fertilizer, and industrial products such as paper coatings, adhesives, dyes, and gels. *Photo: CNN.*

Many challenges and unanswered questions remain, however:

» Conflicts with other marine uses. Maine's small kelp farms are minimally disruptive and nearly invisible. Their lines are suspended seven feet below the surface from the same buoys as the ubiquitous lobster traps, so small boats can pass over. But fishing and larger vessels are excluded, as they would be from much wider areas under industrial cultivation. Fewer such conflicts would likely arise off Washington than off other, more heavily used coasts.

» Engineering challenges in scaling up nets or lines that can survive storms and currents, especially on this turbulent coast. But finfish aquaculture and offshore oil drilling and wind farms, plus the failed efforts in the '80s, provide a wealth of pertinent experience.

» Potential conflicts with marine mammal habitat and migration paths.

» New permitting and regulatory structures. Legal protocols to protect what would be substantial private investments in the EEZ are not yet in place.[82]

» Fuel consumption, for harvesting and other operations. Any large-scale ocean activity entails a lot of it.

» A philosophical choice. Some climate analysts and activists contend that burning any carbon-emitting fuel is unconscionable, and that biofuels will merely supplement, not replace, fossil fuels. Others argue that fuel-burning will continue regardless, so it's worth minimizing its impacts. The climate- and ocean chemistry-tempering value of algal ethanol and butanol, as of any biofuel, depends on their displacing rather than augmenting oil, gas, and coal burning, and on policies that ensure such displacement

The series of macroalgal studies and analyses by Battelle researchers at the U.S. Department

of Energy's Pacific Northwest National Laboratory (PNNL) from 2008 to 2011 found strong initial indications of economic and environmental feasibility: "Open ocean seaweed farming has, in principle, inherent advantages over terrestrial biofuels systems," one concluded.[83] Those prospects took a leap forward in January 2012 when a cover story in *Science* announced that Bio Architecture, a Berkeley-based biotech firm with backing from DuPont, the U.S. Department of Energy, and Norway's Statoil, had engineered microbes that could convert alginate and other previously resistant polysaccharides in seaweed directly to ethanol[84]—which seems a much more efficient process than the biodigestion for methane envisioned in the PNNL studies.[85] That would make kelp a very rich energy source.

Nevertheless, DOE had already opted not to continue the multiyear National Macroalgal Project at PNNL and to concentrate instead on microalgal biofuel (where much venture capital has also gone). Microalgae are deemed more alluring because, despite persistent cost and productivity issues and the large land areas production would require, they yield a higher-value feedstock (oil) and grow in more controlled, confined conditions—and because of the difficulties in processing seaweed and fermenting those polysacchyrides.

Mitigation

Tackling the root causes of ocean acidification in the Northwest means controlling pollution. Global emissions of CO_2 are the primary cause. However, other acidifying air emissions also contribute to the problem, and runoff that contains nutrients and organic carbon can further aggravate acidification. When these substances flow into coastal waters, they can stimulate phytoplankton blooms that then die and rot, releasing yet more acidifying CO_2. While efforts to reduce global emissions have so far proved frustrating, many local and regional pollution control measures have demonstrated records of success.

Can more be done to control agricultural nutrients?

The nutrient challenge

In much of the Puget Sound Basin, especially in shallow bays and estuaries, contaminated runoff and nutrient discharges, which lead to eutrophication, contribute to acidification, hypoxia, and depletion of the "building blocks" in seawater (especially carbonate) that shellfish use to create their shells.

Rivers transport 54 percent of the dissolved inorganic nitrogen flowing into Washington's inland seas.[88] Most of this nitrogen, together with a large quotient of phosphorus, comes from manure and other fertilizers, the leading anthropogenic source after wastewater treatment plants of nutrient pollution. In some heavily agricultural watersheds, agriculture is the largest source of nutrients.[89]

These impacts reflect in part the heavy manure load in the Puget Sound Basin. In some counties manure supply exceeds the capacity of all the existing farm and pastureland to absorb nitrogen and/or phosphorus at agronomic rates.[90] Such oversupply exerts pressure on farmers to spread manure thickly and at times when the ground cannot absorb nutrients, such as winter, when the ground is frozen or saturated and heavy rains wash away nutrients. In Washington, only dairy farmers are prohibited from spreading manure in winter.

The opposite economic incentive pertains when landowners apply expensive synthetic fertilizers. But even here the regrettable watchword is "The more the better," in the words of Snohomish over-fertilization of crops (to say nothing of lawns) has been documented throughout the developed world.[91]

The environmental costs of lawn care are high and include the energy required to manufacture, distribute, and run mowers, blowers, and other equipment; their emissions; contamination and runoff from fertilizers and herbicides; and water depletion. *Photo: Home Wizards*

Healthy estuaries are critical to humans and animals. They are the nurseries for many marine species and nurture the food web; provide food to support commercial and sport fishing; treat waste and runoff, maintaining water quality; and protect coastal areas from natural hazards. *Photo: Washington Department of Ecology.*

At the same time, most manure and fertilizer sources are subject to far less regulation and oversight than nutrient point sources such as sewage plants. In Washington, concentrated animal feeding operations (CAFOs) fall under the NPDES requirements of the U.S. Clean Water Act, but crop growers and non-CAFO livestock operations are considered nonpoint sources, hence exempt. (They do still fall under Washington state ground and surface water regulations,[92] but these lack permitting and inspection requirements, relying largely on complaint-driven enforcement.)

Varying levels of regulation

Washington requires that registered dairies prepare manure management plans—menus of best management practices tailored to individual sites—and test their soils before applying nutrients. It inspects them every 18 months to ensure that they follow these plans. The results have been impressive; between the enactment of the Dairy Nutrient Management Act in 1998 and the enrollment of the last dairies in 2003, fecal coliform levels in five Nooksack River tributaries with heavy dairy concentrations fell by 90-plus percent, far exceeding projections.[93]

King County requires such plans of other livestock keepers and also sets (fairly permissive) standards for the space required per animal.[94] But the state places no such requirements on non-dairy livestock and crop producers. As a result, dairy farmers complain that while they correct their downstream impacts, egregious practices continue, sometimes across the fence, on small beef, horse, and other livestock operations.[95] Many close observers of Western Washington agriculture affirm that claim.[96]

Because beef and other non-dairy livestock operations tend to be smaller than dairies, as well as exempt from regulation, their stock numbers are somewhat elusive and probably undercounted in federal farm surveys. But those numbers total well over 100,000 animals in the Puget Sound Basin.[97] Livestock numbers may be growing with the arrival of inexperienced new stock keepers, so-called "hobby farmers," startup growers of organic and specialty crops, and other new farmers fulfilling long-cherished dreams of breeding horses or operating boarding stables. Unlike traditional farmers, these newcomers do not benefit from generations of family experience, and they are often naïve about the effects of their animals' wastes.[98]

Cooperation and its limitations

Cooperation is widely preferred to coercion and confrontation, by regulators as well as by those regulated. Conservation agents strive to enlist farmers, both rookies and veterans, in watershed protection. Those in Snohomish and Whatcom counties are even experimenting with new social marketing tools, with support from the Department of Ecology.

Peer-to-peer cooperation is an emergent trend in conservation management. In one celebrated example, cattlemen in Eastern Washington's Whitman County have joined together to monitor bacterial levels in streams flowing through their ranches, after receiving training in the same techniques used by Ecology inspectors. The findings have afforded some vindication, says Whitman County agricultural agent Steve Van Vleet. "On some places with cattle, the water's more contaminated coming in than going out."

But the Whitman effort also reveals the limits of voluntary cooperation. Only about half the local cattlemen—perhaps the better actors—have participated. And, says Van Vleet, they were moved to do so only after Ecology threatened enforcement action because of high fecal colliform levels.

Snohomish Conservation District planner Bobbi Lindemulder voices the calculation she sees farmers make when faced with additional costs to manage their wastes: "'If there's no implication [of consequences], especially in this economy, why would I do it?' We can use a stronger regulatory backstop than we have now." Nothing concentrates a landowner's mind like the prospect of getting fined in the morning.

Would it possible, and would it be useful, to require that all livestock operators manage their waste flows as dairies do?

Several states require that other livestock keepers prepare and follow the sort of manure management plans that Washington requires only of dairy farmers.[99] Maine was one of the first, beginning in 1998. It requires that any farm keeping livestock weighing more than 25 tons (about 40 dairy or 60 beef cattle) or importing more than 100 tons of manure submit a nutrient management plan covering synthetic fertilizers as well as manure, including site-specific setbacks from all watercourses. Holders must file new plans every five years and update them annually.

Other states set even lower thresholds for obligatory nutrient management plans:[100]

» **KENTUCKY:** Ten acres in agriculture or forestry. Plans must include state-mandated best practices.

» **MARYLAND:** Eight head of stock or $2,500 annual farm income. Certified nutrient management consultants must prepare plans, with partial reimbursement or free consultation from the state.

» **DELAWARE:** Ten acres or eight head of stock.

» **CALIFORNIA:** All dischargers, including nonpoint dischargers such as farms, must obtain pollution permits.

Such regulation, if it's implemented in fact as well as on paper, does not come cheap. Maryland spends about $2 million a year preparing, overseeing, and updating plans for about 7,000 farms covering 1.2 million acres (most in the fragile Chesapeake watershed), inspecting 500 to 600 a year, and (rarely) waging enforcement actions.[101] Washington has many more farms, about 39,300, but a large share might fall below any regulatory size threshold.

As a result, enforcement of these plans is commonly underfunded and often weak, and violations tend to be resolved by consultation rather than citations. But participation in at least some states' plans is surprisingly strong; in Maryland 99 percent of eligible farms had both filed and updated their plans as of 2009, a decade after the system was launched.[102]

Compliance in Maine has been "pretty good," says Mark Hedrich, the Maine Department of Agriculture's nutrient management coordinator. "Everyone seemed to accept it. They realized it was to their benefit, to save money on excess fertilizer and avoid getting sued, having [the Department of Environmental Protection] come after them—or us." Some 750 farmers have filed plans so far. Hedrich's office handles more than 300 complaints about manure operations each year; most are resolved with site visits and enforcement actions are "very rare."[103]

Substantive compliance comes harder than procedural, however. Maryland officials found that 69 percent of 400 farms inspected on-site were actually in compliance with their plans. Some cheating—over-reporting crop yields to justify high spread rates, keeping double books—may be inevitable, even among professional consultants.[104]

Nevertheless, agricultural pollution is a relative bright spot in the generally bleak picture of non-point-source pollution in the Chesapeake watershed. From 2001 to 2010, nitrogen runoff from Maryland's farms declined by a third and phosphorus runoff by 16 percent. Stormwater pollution levels meanwhile remained flat, and nitrogen pollution from septic tanks rose by 36 percent.[105] Case studies of four farms in Virginia found that

One recent study found that by adopting nutrient management plans, several farmers reduced their nitrogen losses by 23 to 45 percent and raised their net income by up to $7,249 per acre. *Photo: Farmland Report.*

Capturing runoff while providing water for crops, a swale winds through hay fields near northern Puget Sound. *Photo: Brad Warren.*

by adopting nutrient management plans, they reduced their nitrogen losses by 23 to 45 percent per acre and raised their net income by $395 to $7,249.[106] Similar savings have accrued in other venues. As far back as the 1980s, Iowa corn farmers who undertook nutrient planning were able to reduce their fertilizer usage by more than 10 percent, with no loss of yield. Minnesota corn farmers achieved two to three times more fertilizer savings than their Iowa counterparts.[107]

Farmers know best

Such savings, together with runoff reductions, seem to be most pronounced when farmers themselves—with suitable training—execute their own nutrient plans. A Maryland study found that "farmers preparing plans for their own operations almost always recommended decreases and virtually never recommended increases" in manure and fertilizer levels. Extension agents and trained farmers designing plans for other farmers recommended decreases more often than increases but usually advised no change at all in fertilizer regimens. Fertilizer dealers recommended increases somewhat more often than those groups did, and independent crop consultants even more often; they were the only cohort to recommend increases more often than decreases.[108]

Findings like these point up the importance of enlisting and empowering farmers in any campaign to control runoff, while giving them the tools to manage their nutrients scientifically. Nutrient plans' effectiveness may ultimately lie in the openings they create for cooperation and consultation between landowners and agencies—with the stick of enforcement looming in the background and the carrot of compensation (from NRCS and, often, state conservation funds) dangling in front.

"Everyone should have a management plan" regardless of size, says Whatcom Conservation District manager George Boggs. He avows that preparing them would not overly burden his small staff, even though Whatcom County has some 1,300 small farms. "We could do one a day, using a checklist." That's the easy part, however." Then there has to be someone who can enforce it."

Waste = profits for farmers and tribes

“Any time you can take a waste stream and turn it into a value stream, you’ve done something extremely positive,” says Qualco Systems Manager Andy Werkhoven of Werkhoven Dairy. In 2003, the 4,100-member Tulalip Tribes formed a partnership with local dairy farmers to pipe their cows’ waste to an anaerobic digester that captures methane to generate electricity. The digester is owned by the Tulalips and produces enough electricity (which it sells to Puget Sound Energy) to serve 300 homes. Qualco Systems earn roughly $25,000 per month in electricity sales and $35,000 per month in tipping fees for the waste it uses. *Photos: Indian Country Today Media Network and Qualco Energy.*

Would training, testing, and certifying fertilizer applicators prevent over-fertilization?

Commercial applicators exert an outsized influence on how much manure and fertilizer are spread on Washington’s soils and how much nutrient excess winds up in Washington’s waters. In Whatcom County, home to the state’s largest dairy herds and correspondingly large manure resources, these applicators cover about one-half of all acres treated.[109]

Washington requires that pesticide applicators and septic-system installers and inspectors be tested, certified, and licensed.[110] It does not impose any such standards on manure and fertilizer applicators; anyone with a truck and a spreader can enter the business.

Other states have taken a similar hands-off stance, but that is starting to change. As of last January, Indiana requires that anyone applying agricultural fertilizer or manure for hire be trained, tested, and certified in agronomic nutrient standards and application procedures or work under an operator who is. The state also offers a course in proper application. The same requirement holds for anyone applying more than 10 cubic yards of manure from a CAFO to his own farm in a year.[111] In January 2013, Maryland will impose a similar requirement on both landowners and for-hire spreaders treating more than five acres and extend it to lawn care professionals and other commercial fertilizer applicators. It will also enforce a number of other standards for lawns: no fertilizer application in winter or when the ground is frozen, limits on nitrogen applied per acre, no phosphorus application except on new or damaged lawns or when indicated by a soil test.[112] Delaware has adopted similar measures.

In Washington, rules taking effect in 2013 require that fertilizer containing phosphorus be labeled for use only on new or damaged lawns or when a soil test justifies it. Otherwise the state does not specify how fertilizer may be applied or who may apply it. To do so might draw resistance from commercial applicators and lawn-care operators. But some farmers and other landowners might welcome professional standards and accountability, to protect their fields from over-spreading and themselves from liability for the consequences, and to demonstrate their commitment to safe nutrient practices. The Indiana Farm Bureau supported testing and licensing.[113]

Indiana expected to test about 2,000 manure applicators initially but has already certified 3,000. It was able to do so at modest expense, using its pesticide rules as a template and using existing staff to design an original exam and vet it in a “stringent” peer process.[114]

The Hoosier State does not require that professional applicators obtain insurance or bonding to ensure performance, but it may consider doing so in the future. It opted against another measure suggested here by the Washington Conservation Commission’s Ron Shultz—to have owners and commercial spreaders enter any planned applications into a central database. “With that, we could

monitor cumulative impacts by multiple applicators—if we see a lot of people doing it in one watershed, maybe we should go out and do spot checks."[115] Indiana's applicators contended that that would be too onerous, so instead they must record all applications and make the records available for two years.[116]

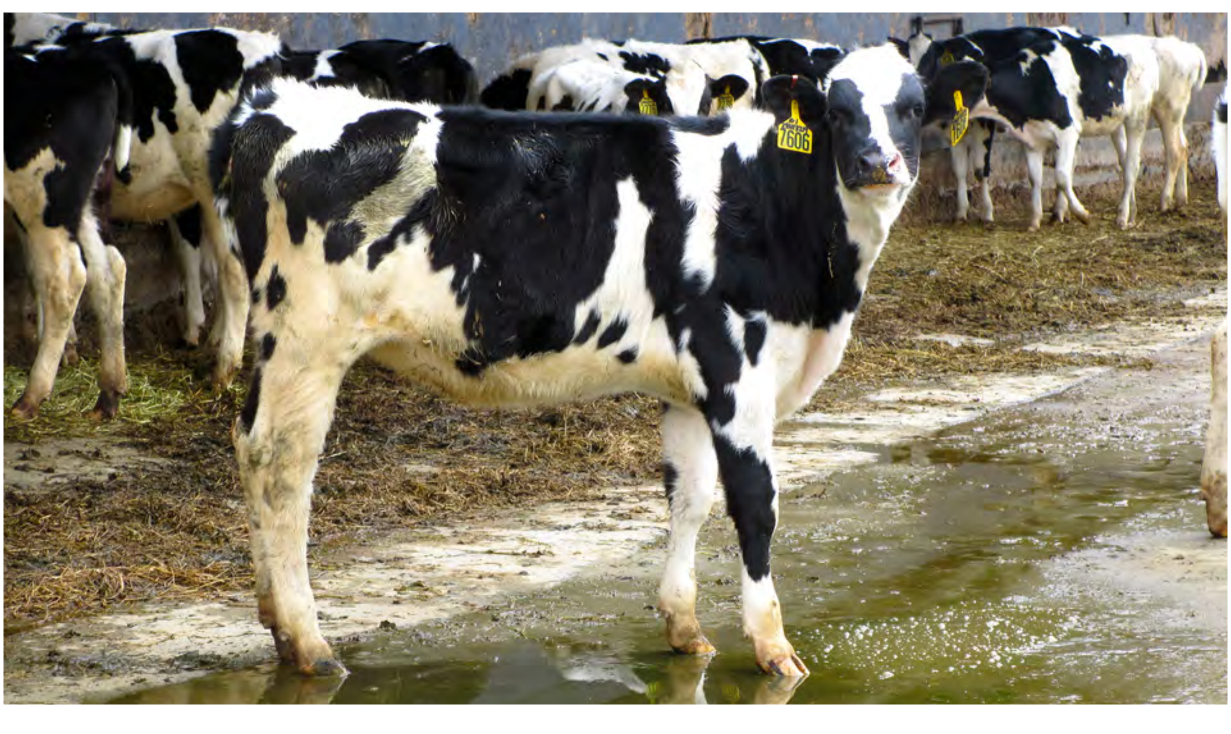
Could nutrient credit trading work in Washington?

Nutrient trading credits are the perennial next big thing in pollution control. Trading schemes enable point sources facing costly infrastructure upgrades—typically wastewater treatment plants and municipalities struggling with combined sewer overflows—to purchase credits for less expensive, more efficient nonpoint-source reductions, typically in agricultural inputs. Cap-and-trade regimes have achieved substantial impact reductions—sometimes far surpassing projections—in various forms of pollution and other inadvertent consequences of production. Examples deep cuts in North Pacific fisheries bycatch, CO_2 emissions (notably in the Regional Greenhouse Gas Initiative undertaken by 10 Northeastern states), and NOx and SO_2 emissions. Water quality is considered one of the most promising fields, together with CO_2, for such employing trading credits.[117] One study of the Chesapeake Bay watershed calculates that offsetting additional stormwater and sewage outflows with cheaper reductions in agricultural releases could save 80 percent of the cost to remediate them.[118]

A few nutrient trading schemes have achieved significant cost savings. Boulder, Colorado, met its total maximum daily load limit and saved $3 to 7 million on extra treatment plant upgrades by funding $1.4 million in stream restoration.[119] Seventy-nine Connecticut treatment plants operating under a common permit mixed and matched 31 nitrogen removal projects and reduced their collective releases into Long Island Sound by 15,500 pounds per day, or more than 2,800 tons per year, with a subsequent shrinkage of hypoxic areas—all at an estimated capital cost savings of $200 million.[120]

Nevertheless, despite strong EPA support for the approach, nutrient credit trading has been slow to catch on around the country—even on the Chesapeake, where the opportunities may be greatest. Maryland's efforts were hampered by the "lack of a regulatory driver"—i.e., a system-wide total maximum daily load (TMDL), says John Rhoderick, who manages those efforts at the Maryland Department of Agriculture. With the adoption of a TMDL in late 2010, work is now proceeding. So far Maryland has certified only two farmers as eligible to sell nutrient credits, with seven more certifications in process, while spending more than $200,000 a year on its certification program.[121]

In some areas, dairy operations have made strides to protect downstream waters from their wastes, while eutrophying pollution from septic systems and stormwater overflow is unchecked or even increasing. *Photo: Brad Warren.*



Nutrient credit trading has been even slower to come to Washington. Ecology has explored potential trading on the Chehalis, Puyallup, Yakima, and Spokane rivers but failed to find or make suitable matches—sometimes for lack of eligible nonpoint credit sources, sometimes for lack of willing purchasers, and sometimes for lack of suitable caps to motivate deals. TMDLs, if stringent enough, can provide this motivation.

Can California greenhouse-gas offset credits support local nutrient-reduction projects?

Starting in January 2013 under California's AB 32 cap-and-trade system, utilities and heavy industries such as cement plants are subject to increasingly stringent emissions caps but can offset up to 8 percent of their emissions by purchasing credits for qualifying carbon sequestration and emission reductions elsewhere. Approved measures include two that might serve not only to remove or sequester carbon but to prevent eutrophying nutrient releases into Washington waters: "urban forest" plantings[122] and methane-capturing manure management systems; i.e., biodigesters.[123]

These credits would provide revenues for projects with both global climate and local anti-acidification benefits, possibly making additional projects financially viable and reducing total nutrient loads. Exchange credits have worked in a wide range of climate, pollution, and fisheries fields to achieve environmental goals more effectively and less expensively. The Qualco Energy Bio-Gas Project in the Snohomish basin and the phytoremediation undertaken by various stakeholders in Coupeville are two local examples of the kinds of projects that might be eligible to produce credits for California's offset market.

However, John Battaglia, who tracks offset credits at Evolution Markets, a leading California-based environmental markets broker, cautions that no urban forestry credits have yet been proposed in the state, and "there's a general perception that offsets just aren't viable there." Urban forestry doesn't deliver enough carbon mitigation for the money.[124] However, if it also delivers locally focused water-quality and shellfish-protection benefits, as at Coupeville, that equation may improve.

The California market for biodigester credits promises to be more robust—and highly competitive. "Standards are pretty rigorous," says Evolution Markets vice president Ben Rees, and many projects are seeking accreditation.[125]

Rush-hour traffic in Seattle produces a measurable spike in carbon dioxide emissions. Options to reduce vehicle use are gaining traction in the city. *Photo credit: Wikimedia Commons.*

Reducing transportation-related emissions of greenhouse gases

Nationwide, electric generation is the largest source of greenhouse gas emissions; in 2008, 70 percent was produced by burning fossil fuels (48 percent from coal, 21 percent from natural gas,[126] and one percent from natural gas).[127] Transportation accounts for only about one-quarter of U.S. GHG emissions.[128] These ratios are neatly reversed in Washington, thanks to abundant hydropower resources (29 percent of the national total). In 2008, hydro supplied 70 percent of the state's electricity and fossil fuels just 17 percent, near-evenly divided between coal and gas.[129] By default, transportation, which relies largely on fossil fuels, accounts for nearly 45 percent of Washington's greenhouse gas emissions.

This means that the biggest savings in emissions are to be had not by, say, switching from coal-fired power plants to lower-emission natural gas or non-emitting wind and solar generation, but by changes in the ways we get around. These changes can be broadly classified under three strategies:

MODE SWITCHING. Shifting travel and, especially, commuting from high-emission, resource-inefficient modes that confer personal convenience by externalizing costs (air travel and single-

Washington State Total Annual GHG Emissions (MMtCO2e) Million Metric Tons CO2e	1990	2000	2005	2006	2007	2008
Electricity, Net Consumption-based	16.9	23.3	18.9	18.1	19.4	19.1
Coal	16.8	17.4	15.2	14.7	15.2	15.1
Natural Gas	0.1	5.3	3.6	3.3	4.1	3.9
Petroleum	0.0	0.6	0.0	0.1	0.1	0.1
Biomass and Waste (CH4 and N2O)	0.0	0.0	0.0	0.0	0.0	0.0
Residential/Commercial/Industrial (RCI)	18.6	20.3	19.7	20.4	20.7	21.0
Coal	0.6	0.3	0.1	0.2	0.3	0.3
Natural Gas	8.6	11.3	10.4	10.8	11.3	11.3
Oil	9.1	8.5	9.0	9.1	8.9	9.2
Wood (CH4 and N2O)	0.2	0.2	0.2	0.2	0.2	0.2
Transportation	39.0	46.7	44.9	46.2	48.3	45.3
Onroad Gasoline	20.7	24.7	24.2	24.2	24.3	23.6
Onroad Diesel	4.1	7.6	7.0	9.1	9.2	9.2
Marine Vessels	3.8	3.7	3.9	3.7	4.7	3.2
Jet Fuel and Aviation Gasoline	9.0	9.9	7.8	7.5	8.3	7.8
Rail	0.8	0.3	1.3	1.0	1.2	0.9
Natural Gas, LPG	0.6	0.6	0.7	0.6	0.7	0.7
Fossil Fuel Industry	0.5	0.7	0.8	0.8	0.7	0.7
Natural Gas Industry(CH4)	0.5	0.6	0.7	0.7	0.7	0.7
Coal Mining (CH4)	0.0	0.1	0.1	0.0	0.0	0.0
Oil Industry (CH4)	0.0	0.0	0.0	0.0	0.0	0.0
Industrial Processes	9.6	10.0	4.1	5.3	5.1	5.6
Cement Manufacture (CO2)	0.2	0.5	0.5	0.5	0.6	0.4
Aluminum Production (CO2, PFC)	8.3	7.4	1.0	2.1	1.8	2.2
Limestone and Dolomite Use (CO2)	0.0	0.0	0.0	0.0	0.0	0.0
Soda Ash	0.1	0.1	0.1	0.1	0.1	0.1
ODS Substitutes (HFC, PFC and SF6)	0.0	1.6	2.1	2.2	2.3	2.5
Semiconductor Manufacturing (HFC, PFC, SF6)	0.0	0.1	0.1	0.1	0.1	0.1
Electric Power T&D (SF6)	0.9	0.4	0.3	0.3	0.3	0.3
Waste Management	2.4	3.2	3.7	3.8	3.8	3.9
Solid Waste Management	1.9	2.7	3.0	3.1	3.2	3.3
Wastewater Management	0.5	0.6	0.6	0.6	0.7	0.7
Agriculture	5.9	6.1	6.3	6.3	5.9	5.9
Enteric Fermentation	2.3	2.2	2.2	2.3	2.3	2.3
Manure Management	0.7	1.0	1.0	1.0	1.0	1.0
Agriculture Soils	2.9	2.9	3.1	3.1	2.7	2.7
Total Gross Emissions (third decimal rounding)	**92.9**	**110.3**	**98.2**	**100.7**	**104.0**	**101.1**

Source: Washington Department of Ecology (2010), Washington State Greenhouse Gas Emissions Inventory 1990-2008. https://fortress.wa.gov/ecy/publications/publications/1002046.pdf

occupancy motor vehicles) to more efficient, lower (or no-) emission modes such as bicycling, walking, and carpooling to bus, rail, and water transit. Such strategies are often freighted with ancillary goals that may elicit funding and political support but compromise the transportation mission, such as the use of light rail and streetcar lines as agents of redevelopment in cities such as Seattle. They may entail large infrastructure investments, with their own carbon contributions and other impacts. (Steel and cement production is a significant source of greenhouse gases, and roadway runoff contributes eutrophying and toxic water pollutants.)

The issues surrounding such strategies are often complex and contentious; witness the efforts to build an urban rail system in Seattle and intercity high-speed rail in California. They are explored in many other venues and are beyond the scope of this report.

Less attention goes to measures with lower investment but potentially high cost/reward ratios, intended to induce, support, and reward behavioral changes among commuters and travelers. Examples include telecommuting, proximate commuting (facilitating job swaps within businesses and agencies with multiple sites so employees can work closer to home), bicycle lanes and paths, and zoning to encourage neighborhood retail so residents can shop on foot. This section will explore one emerging example that recently came before, but did not pass, the Washington Legislature—pay-as-you-drive automobile insurance.

MILEAGE-EFFICIENCYIMPROVEMENTS, ALTERNATIVE FUELS, AND ALTERNATIVE PROPULSION SYSTEMS.
Such approaches implicitly concede that private motor vehicles still afford unsurpassed personal convenience in most American communities, and a large share of consumers remain devoted to or dependent on them. These strategies include ludicrously simple measures. In 2008, candidate Barack Obama was widely mocked for suggesting that filling America's car tires to proper pressure would offset the oil that could be gained by reopening its coasts to offshore drilling (as President Obama would later do)—not to mention improve tire wear and driving safety. In fact, he was right,[130] and service stations could do much to help if they stopped discouraging motorists from checking and filling their tires by charging for air.[131]

Otherwise, incremental improvements in engine efficiency and auto body lightening and streamlining continue and will receive additional impetus from rising federal fuel-mileage requirements. Biofuels have entered the mainstream (and, in the case of ethanol, every American gas tank). But first-generation biofuels remain dogged by environmental and food-diversion concerns, and stubbornly high costs hinder the development of algal, cellulosic, and other second-generation fuels.

Biofuels don't eliminate tailpipe emissions; they merely substitute fresh, replantable hydrocarbons for irreplaceable, deeply stored hydrocarbons (together with the impacts of growing, harvesting, processing, and transporting those hydrocarbons). A wider field of innovation focuses on replacing hydrocarbon burning and the internal combustion engine altogether. Gas-electric hybrids such as the Prius and Insight mark a transitional stage, which will likely yield to all-electric vehicles if current limits on range and charging opportunities can be raised.

Electric vehicles are an especially interesting prospect in hydro-rich Washington, with its relatively low electric rates—especially since they can be charged at night, when usage is low. (Hydro, unlike wind and solar power, operates all the time,

At Port Townsend-based Cape Cleare Fishery, low-carbon transport is business as usual. Rick Oltman and his crew pedal 200-pound loads of salmon to market on bicycles. *Photo: Brad Warren.*

Electric vehicle charging station at Fauntleroy ferry terminal in Seattle. Advocates say building more of these could help to reduce Washington's largest source of emissions: driving. *Photo: Brad Warren.*

once reservoir capacity is filled; wind and solar operate when the elements, not demand, dictate.)

This is not exactly a free midnight snack; storage in car batteries is not necessarily the only option for power that would otherwise go unused in Washington. Northwest utilities sell much of their transient surpluses to other states, which may help displace some dirty coal power. For example, in 2011, Seattle City Light sold surplus power worth $103 million—13 percent of its total operating revenues—on the short-term wholesale market.[132] But electric vehicles and other systems for converting fixed electrical generation to mobile motor power can help fill out and smooth demand.

Charging time and range, as well as the high cost of lithium batteries, remain big challenges for electric vehicle makers and barriers to widespread adoption. At least two promising solutions are just entering the market. Tesla, the maker of high-powered, high-priced electric roadsters, recently began deploying solar-powered "Supercharger" stations it says can charge its Model S sedan for 150 miles of driving in a half-hour (versus three to five hours on ordinary current, depending on connector).[133] Israel-based Better Place offers even faster service by supplanting the charging model with "swap and go" switching stations, which it has begun deploying in Israel, Denmark, and the Netherlands (three compact countries with high gasoline taxes, well-suited as testbeds).[134] Members swap out depleted battery packs for precharged ones in the time it takes to fill a gas tank.

Some inventors and entrepreneurs are dumping batteries entirely for other mobile energy-storage technologies. Hydrogen fuel cells, which release energy by combining stored hydrogen and ambient oxygen in a non-combustion chemical reaction, are the perennial great clear, colorless, odorless hope of alternative motoring. They offer ranges and refill speeds comparable to conventional combustion engines. But they are much more expensive than even lithium batteries and have fewer charging stations. Hydrogen is also hard to handle and store and potentially explosive (remember the *Hindenburg*). And while fuel cells do not produce the noxious pollutants that come (albeit in much smaller quantities) with burning hydrocarbons, they do emit carbon dioxide as well as water.

Not so air itself, nor the element that makes up 78 percent of it, nitrogen. Liquefied at just a little over 200 degrees Celsius using an electric-powered heat exchanger, nitrogen becomes highly compressed. When it's brought back to ambient

Cutting emissions and fuel costs and helping the ocean

Seattle-based Erling Skaar, a trained engineer and longtime Bering Sea crabber, has poured his retirement into creating and commercializing a super-efficient on-board generator to save fuel and minimize carbon emissions. His GenTech Global device taps unused momentum from the main propulsion engine, optimizes its load, and integrates with fuel meters to eliminate more than 80% of the fuel normally consumed to run pumps and equipment on board. Savings for an eight-day fishing trip can top $2,500.

Says Skaar: "Especially given what we have learned about ocean acidification, we need to dedicate ourselves to reducing carbon emissions and urge others to do the same, within and outside the seafood industry."

Skaar points to the computer brains of the system that lets it run regardless of RPM. *Photo: Eric Swenson.*

temperature—i.e., when it boils—it expands nearly 700 times. The result is a potentially powerful neo-steam engine with an energy density comparable to that of lithium batteries, though far less than that of hydrocarbons, with inert, ubiquitous, elemental nitrogen wafting from the tailpipe.

Liquid nitrogen shares some of the disadvantages of batteries, It stores and returns only about half the energy used to produce it, and vehicles running on it would have a similar limited driving range. So far there are no roadside nitrogen-refill stations.

If and when they arrive, however, they'll be as speedy as gas stations. And though it requires suitable thermal insulation, liquid nitrogen is much easier to handle than elusive hydrogen or combustible, toxic hydrocarbons. With no high-temperature combustion, a nitrogen engine doesn't need heavy, heat-proof metal; plastics or light alloys will do. By one estimate, it will cost about half as much as a comparable lithium-battery system.[135]

The idea is hardly new. The first crude liquid-air car was built it 1899, just a few years after air was first liquefied. It vanished after a few years, but the idea rekindled repeatedly over the next century.[136] During that period, liquid nitrogen powered U2s and other rockets. But one hurdle remained to inexpensive mass application: the costly heat exchanger and multi-stage process required to vaporize the liquid nitrogen quickly.

Now that barrier may have been overcome with a simpler, cheaper design by a British engineer named Peter Dearman. It injects the liquid nitrogen into a mix of water and an antifreeze, achieving the desired gaseous expansion at ambient temperature.[137] If this approach scales up and pans out, early adopters may get a special bonus. For now, liquid nitrogen is surprisingly inexpensive—about 50 cents a gallon, plus the cost of a tank, if required, which can be significantly more—because it is produced as a byproduct of liquid oxygen, which is used in steelmaking and other industrial processes.

That would likely change, should "nitro cool" cars catch on. Other pitfalls may appear in the road to mass production and adoption. But this seems a technology that will receive more attention.

PAY-AS-YOU-DRIVE AUTOMOBILE INSURANCE. Traditional mileage-based pay-as-you-drive (PAYD) automobile insurance prices premiums according to miles driven. A bill authorizing it passed Washington's Senate in 2011 but did not clear the House. "Usage-based" schemes monitor and adjust for driving habits as well; one failed to pass in the 2012 session.

PAYD rewards motorists for driving less. It may thus reduce automotive use and emissions, resultant climate and acidification impacts, and deliver ancillary benefits: reduced congestion, collisions, and release of brake-pad metals, engine fluids, and other road waste harmful to water quality.[138]

Some elements of PAYD have been offered in 34 U.S. states. Israel, Japan, the United Kingdom, and the Netherlands employ more robust versions. A Brookings Institution study calculates that enrolling all motorists nationwide would reduce total driving by eight percent, oil consumption by four percent, and CO_2 emissions by two percent.[139] In actual trials in Minnesota, pay-per-mile drivers reduced their weekend driving by 8.1 percent, weekday off-peak by 3.3 percent, and weekday peak driving (which has the greatest pollution and congestion effects) by 6.6 percent.[140] These short-term effects may be amplified with longer use and habituation.

PAYD would require changes in state insurance law and administrative procedures but no new programs. It costs the Insurance Commissioner's Office about $100,000 to adopt rules, complete new filings, and train volunteers to answer consumer questions and complaints about a measure such as this.[141] The Brookings study calculates that two-thirds of drivers would save money—$270 on average—under PAYD; high-mileage drivers would pay more.

Trains, trucks, and ships: What's the right engine for the job?

TRAINS: Diesel-powered locomotives have traditionally wasted large quantities of fuel and emitted correspondingly large quantities of carbon dioxide and nitrogen oxides, even when they're not moving. That's because they continue idling their big engines to provide heat, electricity, refrigeration, and other stationary services and to avoid lengthy startups when it's time to move again. The impacts are far from trivial. A switcher locomotive idling 75 percent of the time consumes 27 percent of its fuel and emits 25 percent of its NOx while still, and unregulated locomotives accounted for some five percent of total U.S. NOx emissions.[142] While idling for several thousand hours each year, the average switchyard locomotive burns more than 16,000 tons of diesel fuel and emits more than 180 tons of CO_2, three tons of NO_x, and 200 pounds of cancer-causing particulates.[143] Residents of yardside neighborhoods such as Seattle's Interbay testify to the local impacts.

In response, the EPA has since 2002 required that all new and newly overhauled locomotives meet strict NOx, carbon monoxide, hydrocarbon, and particulate emission limits; these limits were tightened in 2005. Rail operators can meet the NO_x standards by adjusting combustion settings—which, however, burns more fuel—or by the officially preferred approach of installing small auxiliary engines to operate idling systems, including electric heaters to warm the main engines' oil for rapid startup.

These auxiliaries burn only a tenth to a fifth as much fuel as idling main engines, which can now be shut off while in the yard.[144] This confers significant cost as well as emission savings, with payback periods variously estimated at two to five years. Nevertheless, cash-strapped railroads operating on thin margins often defer incurring the upfront costs of installing auxiliary engines. Jurisdictions here and elsewhere have attempted

Nationwide, trucks and trains burn billions of gallons of fuel and emit millions of tons of CO_2 while standing still. Local governments often encourage operators to cut costs and pollution by providing plug-in facilities or offering incentives to install efficient small auxiliary generators. *Photo: Don Wilson/Port of Seattle.*

to overcome this resistance with various incentives, from emission trading credits to outright grants to purchase APUs.[145]

TRUCKS: The half-million long-haul trucks in the United States spend substantial time—an estimated six to eight hours a day, 300 days a year—stopped and, commonly, idling while drivers rest, burning up to a gallon an hour of fuel. The result: some 1.2 billion gallons of fuel burned and 11 million tons of CO_2 and 150,000 tons of NO_x emitted each year.[146] As on trains, auxiliary power units dramatically reduce these emissions, but other technologies can reduce on-site emissions even more or eliminate them entirely:

» **Truck stop electrification**, a.k.a. truck electrified parking, provides current to parked trucks, which must have AC-powered heating, cooling, and ventilation to use it.

» **Advanced truck stop electrification** goes beyond electrical outlets, connecting truck cabs to a central HVAC system. This is less efficient than onboard electric appliances but serves trucks that don't have their own.

» **Battery-powered systems** provide emission-free on-board amenities anywhere, not just at truck stops. These advantages must be balanced against the additional weight, which adds to fuel consumption. The Kenworth Truck Company of Renton has developed an onboard battery pack good for 10 hours of idling, as well as a hydrid diesel-electric drive system with regenerative braking.[147] Rooftop solar collectors might harvest more emission-free power to help power engines by day and battery-operated systems at night.

DIESEL-POWERED BOATS AND SHIPS suffer from the opposite mismatch between engine scale and task at hand. Marine operators preceded railroads and truckers in installing smaller auxiliary power units to run their onboard systems while in port. But these APUs continue to power electrical generators while under way—less efficiently than if the generators could run off the powerful main engines. A Seattle firm, Gen-Tech Global, has devised a system to do just that, via a hydraulic generator and precise, proprietary controller to maintain constant flow into the generator and voltage from it.[148] Monitoring of its performance by Seattle's FloScan Instrument Company found that, even as it assumed the redundant auxiliary motors' duties and powered the Gen-Tech system, the main engine's fuel consumption rose only slightly. At some engine speeds it actually fell. The net reduction in NO_x emissions was 45 to 50 percent.[149]

How much can fuel flow monitoring save in consumption and emissions, on the sea and on the highway?

FloScan and other fuel-monitoring technologies have enabled maritime operators to save significant quantities of fuel by letting them know how much they burn (and, in the case of FloScan, how much NO_x they emit) at various speeds. In 2002, Washington State Ferries concluded after monitoring flow on one of its Seattle-Bainbridge boats that it could save at least one million gallons a year on that route alone—1,500 gallons per vessel per day, nearly 6 percent of the total fuel tab for its 29-vessel system—simply by slowing from 18 to 16 knots.[150]

Commercial fishing, an extremely fuel-intensive activity that is not as subject to schedule pressures as ferry services, might especially benefit from such technology. A Seattle-based crab boat skipper (the son, it should be noted, of Gen-Tech's founder) uses a FloScan meter and GenTech's system together to regulate engine speed and optimize fuel efficiency. Combined, these approaches allow him to trim fuel consumption from 42 to 23 gallons an hour, sacrificing just a half knot in cruising speed.[151]

On land, attentive drivers of the Toyota Prius already know how informative (and surprising) such data can be from watching readings on their instant fuel consumption displays vary from less than 10 to more than 100 miles per gallon. These monitors, pioneered on the Prius, are now included in most new cars. Federal research determined that they lead drivers to refine their driving habits and "attain significantly greater fuel economy"; one previous study found a 16 percent improvement.[152]

Millions of drivers of older cars not so equipped might likewise benefit from consumption monitors. At least one employed in the federal study, the PLX Kiwi, can be easily retrofitted to post-1995 models that have standard OB-II onboard diagnostic ports.[153] Its retail price, about $300, seems a high barrier for consumers other than hypermilers and other aficionados. But from the public view it may still present an attractive cost-benefit ratio compared to hybrid and electric vehicles and other publicly subsidized measures for reducing fuel consumption and emissions.

Tax credits or other inducements could encourage the wider adoption of fuel consumption monitors and perhaps spur innovation and competition in the field.

The devices' value is only as good as the attention motorists pay to them. But those who choose to install them, rather than receiving them automatically, may heed them more.

Measuring and, if necessary, monitoring airborne NOx and SOx inputs in Puget Sound.

Combustion-produced nitrogen oxides and sulfur dioxide are important acidifying agents in many fresh and coastal waters, exerting as much as half the impact of anthropogenic CO_2 in coastal areas worldwide.[171] Maritime activity generates an outsized share of these pollutants, including 33 percent of the sulfur dioxide emitted in King, Pierce, Kitsap, and Snohomish Counties and 83 percent in the South Sound and Olympic counties.[172] Many of these emissions are carried overland by the prevailing west winds. But not all; these compounds are deposited on the surface much more rapidly than CO_2. How many enter Puget Sound waters, and how do they affect its chemistry and biota? No one knows; these inputs are not monitored.

Can creative partnerships reduce emissions and nutrient loading from point sources, with offsetting savings and revenues?

Peer-to-peer cooperation and multi-sector partnerships can muster diverse resources, ideas, volunteer energies, innovative technologies, and political capital to achieve results that elude conventional regulatory approaches (though the threat of regulation and enforcement are often necessary goads). These partnerships can take many forms, including cooperation between industrial firms or municipalities in Combined Heat and Power (CHP) projects, which capture waste heat from one facility for use or conversion in another,[154] and biogas capture projects.

Some projects achieve high returns on investment as well as emissions reductions, largely through avoided energy or disposal costs. Corning reported a 100 to 200 percent return on CHP and similar efficiency investments. The Tulalip Tribes' Qualco Energy biodigester project has enfranchised farmers in habitat protection, turning adversaries into cleanup partners.

Daryl Williams of the Tulalip Tribes played a key role in developing the tribe's dairy digester project with farmers in the Snohomish Valley. Biogas from manure powers this generator, producing electricity for sale while reducing farmers' waste hauling costs and cutting both air emissions and runoff of acidifying wastes to downstream waters. *Photo: Brad Warren.*

Does anaerobic digestion of manure and food waste actually reduce nutrient loads or just repackage them?

Anaerobic digestion is an old technology that's gaining new interest and investment as a solution to the growing waste problems engendered by concentrated livestock operations (in particular, dairies) in Washington and other states. Biodigestion uses microbial fermentation in sealed tanks, followed by mechanical or heat-driven separation, to turn animal and food waste into three usable materials:

Biogas, about 60 percent methane and 40 percent carbon dioxide with traces of other gases such as sulfur dioxide. In this country, biogas is commonly burned to generate electricity and to heat the digestion tanks themselves, but it can also be refined and added to the natural gas stream. In the developing world, where small, even family-scale digesters are increasingly common, the gas is used for cooking in place of kerosene, wood, and charcoal.

Nutrient-rich slurry, sometimes called "liquor," which can be applied as fertilizer.

Dry, fibrous solids that are used as livestock bedding or garden soil amendment, similar to peat moss. These solids can also be burned in coal-fired power plants, displacing coal consumption.[155]

Critics of biodigestion note that it does not reduce, much less eliminate, nitrogen or phosphorus wastes. This is literally true—biodigestion merely extracts gases formed of oxygen, hydrogen, and carbon. But the subsequent mechanical separation

impounds some of the nitrogen and phosphorus in the dry fiber, removing them from the waste stream. Biodigestion itself converts organically bound nitrogen into readily assimilated ammonium, making it more available to crops and less prone to build up in and eventually leach out of soils.[156] Some studies have found higher nitrogen availability and crop yield in soils treated with post-digestion slurry rather than raw manure. One found no difference in nitrogen uptake or yield between digested and raw slurry but concluded that this still evinces more efficient nitrogen use with digested slurry, since it contains less nitrogen than the raw.[157]

Anaerobic digestion kills pathogens, producing cleaner, safer, and potentially higher-value materials for various uses. And it captures methane—a greenhouse gas about 21 times more potent than carbon dioxide—that is released to the atmosphere when manure is spread directly on cropland and food wastes rot in landfills and other uncontained sites.

Researchers and dairy operators are developing and testing various techniques for further stripping polluting nutrients from the post-digestion products. The DeRuyter Dairy in Sunnyside, Washington, uses settling and screening to inexpensively remove about half the phosphorus from its effluent, for sale as fertilizer.[158] This method does little to remove nitrogen, but since phosphorus is a more acute, and more stringently regulated, agent of algal blooms and eutrophication, it seems a significant low-cost improvement.

Struvite formation is a technology used to more thoroughly remove phosphorus from wastewater that is now being considered for post-digester effluent. Struvite is a magnesium-phosphate crystal that may have high value as a slow-acting fertilizer because it contains equal quantities of phosphorus and nitrogen. It is produced by adding various minerals to the effluent in a crystallization reactor. One Washington study characterizes struvite formation as an "emerging commercially viable P removal and recovery process." But that same study's *pro forma* calculations tell a very different story: Even assuming struvite prices rise as the market grows, the chemicals needed to make it will vastly exceed the revenues to be recovered—by a factor of 25 in the near future, declining merely to a factor of six in 30 years. And this doesn't consider capital and electricity costs for the reactor.[159]

Struvite aside, the economics of biodigesters are more promising, but they aren't simple. They depend on a number of variables, including site and access costs, renewable energy subsidies, local costs for other modes of waste disposal, and the feedstocks used. Because animal digestion has already removed much of the energy from manure, it is a relatively unproductive biogas source; silage and food wastes can generate 10 to 40 times as

Urban runoff can fuel acidification and oxygen depletion, once the overfed algae begin to decay in the shallows. Here muddy green waters show heavy influence from development along the eastern shore of San Francisco Bay. *Photo: Brad Warren*

Planting poplars to protect mussels

In a neat switch, a promising local experiment in phytoremediation—using trees to filter sewage effluent instead of discharging it into an important shellfish-growing cove—derives from techniques developed to keep clean water out of landfills. There, fast-growing trees such as poplar and cottonwood are planted atop the dumps to take up water and wick it away by transpiration.[166] In one Georgia trial, a tree cap reportedly performed better than a conventional clay cap at about half the estimated cost.[167]

Now Whidbey Island shellfish growers, conservationists, the City of Coupeville, and an Iowa-based phytoremediation firm have joined in a project testing the capacity of poplars and willows planted in engineered absorbent soils to capture the nutrients in the untreated runoff and the city's treated sewage effluent.[168] If it works, the cleaned water will then be used to irrigate the nearby Ebey's Prairie agricultural reserve. And mussel crops in Penn Cove will be protected from the effluent's eutrophying and acidifying (and potentially pathogenic) effects.[169]

Fast-growing, thirsty poplars are now widely used to control runoff. They also absorb nitrogen wastes that can harm water quality and contribute to acidification downstream. *Photo: Brad Warren.*

much biogas.[160] Britain's National Non-Food Crops Centre has found that while a 50-50 mix of manure slurry and plant matter is optimal in commercial-scale digesters, "even a modest amount of crop material…can increase its energy output ten-fold for only three times the capital cost."[161] The NNFCC concludes that, with U.K. energy subsidies, efficient digesters can return 10 to 15 percent a year and pay back their capital costs in as little as five to seven years.[162]

In Western Washington, tipping fees—what food-processing operations pay to dispose of their waste—and avoided costs for manure disposal are essential, even primary, to the digesters' economic viability. Generating 450 kilowatts, the Tulalip Tribes' Qualco project yields about $20,000 a month in electricity sales—and $35,000 in tipping fees for food wastes.[163] At $660,000 a year, the project would seem to offer a generous return on its capital cost of $3.7 million, 70 percent of it from federally backed renewable-energy bonds, the rest from federal grants and tribal funds. Qualco has not yet realized several other prospective revenue streams, from energy credits and sales of the fiber and nutrient-rich effluent. And its Tulalip operators also realize another non-monetized pay-off from the project: by diverting nutrients that would otherwise wash into the Snohomish Delta, they protect their cherished salmon fishery.

Brothers Daryl and Kevin Maas operate three digesters in Western Washington under the corporate moniker Farm Power Northwest; they are building two more in Oregon. Farm Power has reported profits and even paid investors a small divided two years after starting its generators.[164] "We've got markets for most of the liquids and fiber" separated after digestion, says Daryl Maas. The dry fiber, about 40 cubic yards per digester per day, brings $10 a yard, mainly for use as dairy bedding—completing the circle from barn floor back to barn floor. Farm Power and Washington State University researchers are meanwhile working on methods to separate more nutrients from the liquor.[165] If they can purify the effluent enough to discharge it as water, this will save significant transport expense and yield a higher-value fertilizer.

Biodigestion has not yet achieved all its hoped-for pollution reductions or economic gains. But those may now be in sight, and the benefits so far are substantial.

Could low-cost nutrient-flux monitoring technologies and programs manage multiple small load sources?

"You can't manage what you can't measure," said the statistician and manufacturing-process guru W. Edwards Deming. Small nonpoint sources

compose a large portion of the total nutrient load in many riverine and estuarine systems in Washington. Low-cost sensors and electronic reporting systems tracking nutrient loading from small sources would make it possible to manage sources that are individually minor but collectively important, including those affecting shellfish-growing estuaries. Investigations by WSU researchers have established one model. Ecology's and others' existing monitoring programs might provide useful baseline data on site selection and design for new experiments, input on sensor specifications, capabilities to evaluate new sensors via A-B comparison with existing equipment, and information-reporting infrastructure (e.g., a web platform for data).

Enlisting resource users and potential polluters as citizen monitors.

Cooperative monitoring can augment agency capabilities, enlist resource users and potential pollution generators in conservation efforts, identify elusive emission sources, clarify responsibility, and obviate costly, divisive enforcement and court actions. Widespread monitoring has worked to achieve these goals in the West Coast and Alaska trawler fleets, among other fisheries. Whitman County ranchers monitor their streams' fecal coliform levels according to state standards in order to ensure (and prove) they are not polluting.[170] Such citizen monitoring is not entirely voluntary; it's typically done to forestall more intrusive regulation or enforcement. But it can be a force multiplier and cost saver, achieving public goals with private labor.

Can stimulating plankton growth with iron sequester carbon after all?

In the 1990s, ocean iron fertilization, or OIF, was briefly the great hoped-for cure for climate change. Then it devolved into something somewhere between a laughing-stock, a nightmare scenario, and a fable of geoengineering hubris. Now the idea is seeing a resurgence.

The logic behind OIF is simple: Plants need iron to carry on photosynthesis. Because it's so insoluble in water, iron is in short supply in much of the Pacific and Southern Oceans, making it a limiting factor for phytoplankton growth. Seed the seas with iron sulfate and you'll get CO_2-gobbling blooms of phytoplankton—in particular of desirable diatoms, which unlike other microalgae form heavy silica cell walls that sink when they perish. So, the hypothesis goes, the diatoms will die and sink to the frigid depths or get eaten by zooplankton that will get eaten by fish that will get eaten by fish, etc.—some of whose feces and remains will likewise sink to the depths, there to stay sequestered for decades or centuries.

A dozen trials showed that spreading iron can indeed stimulate plankton blooms, but they failed to show that the resulting biomass sank to and stayed on the ocean bottom. Scientists and environmentalists meanwhile warned of the potential consequences from such meddling with the ocean system:[173]

- A plankton boom might nourish a boom in fish and other desirable species higher up the food chain—or an eruption of unwanted jellyfish or cyanobacteria (the source of "toxic algal blooms"), suppressing the useful species.
- Rotting plankton masses suspended at middle depths might produce anoxic "dead zones."
- The artificially stimulated blooms would deplete not only carbon dioxide but other nutrients, possibly disrupting the marine food chain far downstream.
- At shallower depths, they would shade kelp, corals, and other sunlight-dependent communities.
- Dark algal blooms absorb more solar radiation than open water, warming both the water and the atmosphere above and counteracting the intended greenhouse reduction.
- Warmer water holds less carbon dioxide and mixes less with the cooler water below, reducing its ability to absorb CO_2 from the air.
- Slowly decomposing in the low-oxygen depths, the plankton detritus could release methane or nitrous oxide, which are much more potent greenhouse gases than CO_2.
- By the opposite token, the plankton at the surface could release dimethylsulfide, which stimulates the production of heat-shielding clouds.

In 2007, the international organization regulating ocean dumping instituted a moratorium on commercial iron fertilization projects; the UN Convention on Biodiversity passed a broader moratorium on geoengineering projects. Several commercial operators who hoped to sell carbon

credits for deep-sea sequestration went out of business.

In November 2012, one of them came roaring back into the headlines. Russ George, the flamboyant founder of the since-shuttered OIF firm Planktos, had ignited heated controversy, and helped provoke the moratoria, when he attempted to fertilize waters off the Galapagos and Canary Islands. Now he spread about 100 tons of iron sulfate—five times as much as in any previous OIF experiment—off Haida Gwai, British Columbia's Queen Charlotte Islands. According to various news reports, George either persuaded[174] or was recruited[175] by the native Haida Salmon Restoration Corporation to undertake the dumping.

The Haida hoped to boost the dwindling salmon stocks on which they depend; George suggested they could also recover the $2.5 million they put up for the effort by selling carbon credits, though given the controversy surrounding the project it seemed doubtful that even voluntary buyers would want them. The Haida have since backed off from invoking carbon credits; they and their sympathizers say the proof of the measure will likely be in the size of the sockeye salmon run in two years, when this year's small fry return to spawn. Even if it's a bumper run, however, proving causality will be difficult or impossible in the absence of experimental controls.

Scientists in the field swiftly denounced this uncontrolled iron dumping, charging that it violated both international moratoria to little useful scientific end. Some of those same scientists, however, cheered another iron fertilization trial reported three months earlier in *Nature:* the European Iron Fertilization Experiment (EIFEX), which spread seven tons of iron sulfate in an eddy of the Southern Ocean in 2004. Its authors, led by Victor Smetacek of the Alfred Wegener Institute for Polar and Marine Research, made some bold claims: Not only had EIFEX stimulated a big diatom bloom, as previous attempts had done; unlike its predecessors, it had managed to track the sinking diatoms into the depths. They concluded "that at least half the bloom biomass sank far below a depth of 1,000 metres and that a substantial portion is likely to have reached the sea floor. Thus, iron-fertilized diatom blooms may sequester carbon for timescales of centuries in ocean bottom water and for longer in the sediments."[176]

In an accompanying article, Ken O. Buesseler of the Woods Hole Institution, one of the scientists denouncing Russ George's iron dumping, saluted this as "the first time that [deep-ocean sinking of fertilized algae] has been convincingly observed."[177]

Nevertheless, the evidence for this deep sinking is complex and perhaps tenuous. The authors themselves note that it depends on "multiple lines of evidence…each with important uncertainties," which they believe add up to a conclusive whole. Much of this evidence is contained in online supplementary materials or has not yet been published. The conclusion of deep sinking and sequestration is inferred from the amounts of carbon exported from the surface layers and from readings at intermediate depths. The authors concede that their controls—measuring stations outside the iron-seeded patch—were "not ideal." Some showed plankton and chemical readings similar to those in the test patch, raising questions as to whether this natural, unseeded outer bloom might have been the source of the detritus found in the depths.[178]

POPULAR SCIENCE *10-17-2012*

Rogue geoengineer dumps 100 tons of iron off Canada's west coast

The very idea of geoengineering—large-scale tampering with the planet's natural climatological or geological systems to produce a desired effect—is brazen enough, but doing so in violation of two UN conventions is flat-out ballsy. That's the word we would use to describe California businessman Russ George who in July dumped more than 100 tons of iron sulfate into the Pacific in an effort to capture carbon from the air and sink it to the depths of the ocean. http://www.popsci.com/science/article/2012-10/rogue-geoengineer-dumps-100-tons-iron-canadas-west-coast

If iron-fertilized diatoms did sink to the desired depth, their carbon would not be permanently sequestered. Eventually—in a matter of decades at 1,000 meters depth in the Southern Ocean, centuries at the sea bottom—it would well back up the surface.

OIF's proponents argue that that would be enough; it would buy us time to mend our carbon-spewing ways. But a more immediate

and potentially decisive limitation threatens the strategy. Supplying the iron needed to grow as much microalgae as possible means that growth will be constrained by the next essential nutrient to run out. In some waters that might be nitrogen or phosphorus; hence removing them from the waste stream prevents eutrophication. At the test site, as in much of the ocean, it appears to be silicate.

A review of earlier iron fertilization trials found that both fertilization and natural conditions could deplete silicate even while nitrate supplies waited to be consumed, causing blooms to decline.[179] The diatoms produced in the South Ocean iron seeding took up only about 6 percent of the nitrate available in the top mixing layer of water. (Because this layer was deep, to 100 meters, this still represents a substantial amount of biomass, hence of carbon taken up.)[180] However, they took up two-thirds of the available silicic acid (the form of silicate present, which diatoms use to build their shells). Additional iron seeding, as envisioned under geoengineering strategies, might soon deplete the silicon available.

Indeed, this is exactly what happened in a 2009 iron-seeding effort also led by Victor Smetacek. This joint Indo-German project, dubbed Lohafex, spread six metric tons of iron across 300 square kilometers inside another Antarctic eddy. This stimulated a bloom, not of diatoms but of another phytoplankton variety lacking diatoms' protective glass shells. "Diatoms could not grow in the Lohafex experiment because previous, natural blooms had already extracted all the silicic acid," the Wegener Institute reported. Copepods swiftly ate up the bloom and were eaten in turn by larger zooplankton. "As a result, only a modest amount of carbon sank out of the surface layer by the end of the experiment." The conclusion: "Since the silicic acid content in the northern half of the Southern Ocean is low, iron fertilization in this vast region will not result in removal of significant amounts of CO_2 from the atmosphere."[181]

It will still result in blooms of competing phytoplankton, notably cyanobacteria (a.k.a. blue-green algae), that thrive on iron and do not need silicon. But cyanobacteria do not sink as diatoms do, and they produce cyanotoxins that can be deadly to both marine and human life. Even if more benign blooms result and get eaten, digested, and excreted, much of the resulting detritus will disperse on the currents and get recycled into the food chain rather than sinking to the bottom.

Whole-lake experiments, in which water conditions can be more readily manipulated and measured than in the open ocean, demonstrate the silicate-mediated, seesaw swing between diatoms and cyanobacteria.[182] In one Michigan lake, stirring up the water column to distribute silicate and other nutrients produced ample blooms of diatoms, until the diatoms depleted the silicate and crashed themselves.[183]

In a small, contained system, it might be possible to add enough silicate to sustain a bloom. But diatoms require silicate in greater quantity than they do iron—3,429 times as much by weight, Charles Miller calculates. "Shipping and spreading a few hundreds or thousands of tons of iron ore dust or some acid-soluble iron compound (e.g., iron sulfate) is possible and could be done at enormous expense for large sectors of the Southern Ocean. It is not possible to ship enough silicate to make it worth bothering."[184] Furthermore, Miller notes, grinding silicon dioxide (i.e., sand or quartz) finely enough to dissolve is energy-intensive, adding to the cost—and much of it may sink rather than dissolving anyway.

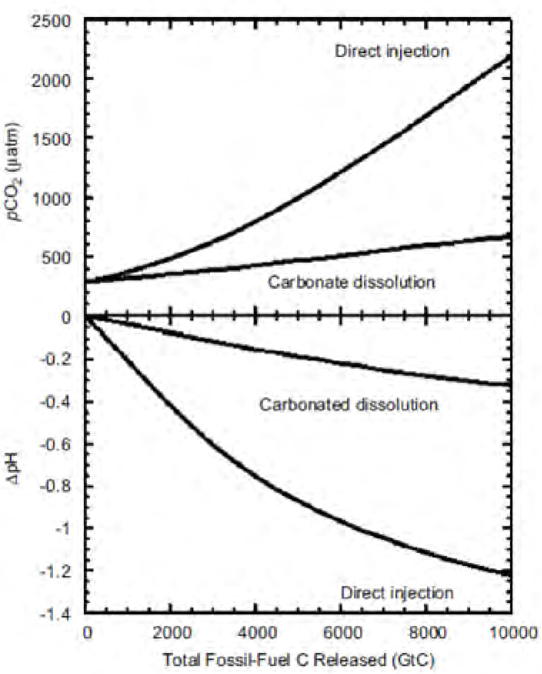
No one in the scientific community (as opposed to "rogue geoengineer"[185] Russ George) seems to argue that ocean iron fertilization is ready for commercial implementation yet. Many believe that it deserves and demands more ocean trials, especially following the EIFEX results. At some point they will have to consider more than the iron in the diatoms' diet—and reconsider not just the desirability but the feasibility of stimulating sinking plankton blooms.

Accelerated carbonate weathering works in principle, but what about in Washington?

Accelerated carbonate dissolution, a.k.a. weathering, is a geoengineering strategy that promises rare dual benefits, to remove and sequester anthropogenic carbon dioxide that would otherwise go into the atmosphere and to increase alkalinity and carbon saturation in marine waters, at least on a local scale. The idea was proposed in its dual aspect by 1999 by Ken Caldeira, who around the same time coined the term "ocean acidification," and Greg Rau, who has continued to develop it since.[186] It is a souped-up variation on other proposals to speed up the natural drawdown of CO_2 by the weathering of carbonate and silicate rocks such as limestone, dolomite, olivine, and serpentine—a major carbon sink.

In nature these minerals react slowly with CO_2, releasing their constituent metals (such as calcium, iron, and magnesium) and producing bicarbonate and, in the case of silicaceous rocks, silicic acid. One proposed approach is to simply dump limestone into subsurface waters, which are more acidic than surface waters and undersaturated with calcium carbonate. Others propose speeding this process via fine milling or high heat. Dutch researchers contend that such energy-intensive interventions aren't necessary, at least in the case of olivine. Coarsely milled, spread in coastal waters, and subjected to tidal jostling, it will begin breaking down, capturing CO_2, in just days.[187]

Rau and his colleagues propose using this weathering to remediate CO_2 emissions from gas-fired power plants and mitigate ocean acidification. Flue gases would be passed through ground-up limestone and water—ideally seawater, in order to obtain the large quantities needed at low cost—



Comparison of the effects on atmospheric CO_2 content (top panel) and on deep-ocean pH (bottom panel) 1000 years after the injection of the specified quantities of either molecular CO_2 or carbonate dissolution effluent into the deep-ocean (mean depth: 1950 m). If the ocean's anthropogenic carbon capacity were determined by the amount of CO_2 that would shift ocean pH by 0.3 units, then the carbonate dissolution technique would increase the ocean's capacity by roughly a factor of six. With the direct-injection method, for large amounts of anthropogenic CO_2 released, over 45% of the injected CO_2 is in the atmosphere after 1000 years. With the carbonate dissolution method, less than 15% of the initially released CO_2 degasses to the atmosphere. (From Rau et al., "Reducing energy-related CO2 emissions using accelerated weathering of limestone.")

which would then be released into marine waters. The bicarbonate thus produced would sequester carbon in the waters, or be taken up by organisms to form shells.

In laboratory trials, this process removed up to 97 percent of the CO_2 in simulated flue gas and retained up to 85 percent of it in simulated seawater.[188] Whether it could achieve anything like these results in practice is another matter; questions of scalability, the effects on the process of other pieces in the sea's chemical puzzle, and impacts on marine life still loom. Those last impacts would seem to be beneficial, at least up to a point.

The big issue for feasibility is cost. Rau and his colleagues note that waste fines (powder), representing more than 20 percent of U.S. crushed limestone production, could provide a free or inexpensive source of calcium carbonate.[189] Federal sources report that limestone dust and fines do have market value.[190] Either way, they amount to more than 300 million tons a year,[191] enough to mitigate more than 100 million tons of carbon dioxide—perhaps 10 to 20 percent of U.S. point–source emissions.[192]

Rau et al. recommend that the process be employed at smokestacks sited on the seacoast, because of the large volumes of water required, and near limestone quarries and crushing plants, since transporting the stone would be the largest cost. Thus sited, they contend, it could mitigate CO_2 for as little as $3 to $4 a metric ton—much less than many other mitigation techniques, with the added marine benefits of de-acidification and improved carbonate saturation.

Any such economies would be realized on a small scale in Washington, however; this state is not blessed with such a confluence of siting conditions. According to a U.S. Geologic Service map, only one Washington county, Grays Harbor, produces crushed stone.[193] There are extensive limestone beds and three active quarries (one of them quite large) in Northeastern Washington but just one small gas-fired power plant, in Spokane Valley. Western Washington has many gas-fired plants, including five in coastal communities, and one coal plant. But it has only two permitted lime quarries, in the interior of Whatcom County. It once had many more[194]—witness Concrete in Skagit County and Lime Kiln Point on San Juan Island—but its limestone deposits have since been largely mined out.[195]

Accelerated weathering seems a promising concept, especially when coupled with marine car-

Sustainable management practices keep forests growing at a higher rate over a potentially longer period, providing net carbon sequestration benefits. The EPA estimates forests sequester about 10% of the carbon dioxide released in the U.S. *Photo: National Park Service*

bonate mitigation. It may be ready to move from the laboratory to real-world trials. But however much Washington's waters might benefit from such efforts, the economics don't favor them here as much as in other states.

Preserving carbon-sequestering land uses, especially forests.

Many different land uses and natural habitats provide significant carbon sequestration via photosynthesis—nature's own carbon-removal mechanism—and storage in soils and plant mass. Washington is richly supplied with some of the most efficient natural storage systems on earth: saltmarshes, seagrass beds, and, especially, the dense conifer forests of the state's wet west side.

Nationwide, forest, grass, and agricultural lands are estimated to sequester up to 18 percent of U.S. carbon emissions. This share is probably even higher in Washington, with its especially efficient forest and wetland carbon sinks, and conscientious land use and preservation may increase it substantially. For example, thanks in large part to the cutting restrictions implemented under the 1996 Northwest Forest Plan, by 2050 the amount of carbon stored in living trees on Northwest national forest timberlands is projected to rise to 64 to 71 metric tons per acre, nearly double the levels of the 1970s. Meanwhile, carbon storage in live trees on Northwest private timberlands continued to decline until 2000 but then began to level off at about 26 metric tons per acre; it's projected to recover to 1970 levels, about 32 metric tons per acre, by 2050.[196]

This storage continues even after trees are harvested for use in long-lasting building materials. Such use can yield significant emissions reductions relative to other materials. For example, using appropriate wood products in place of steel studs, concrete slab floors, and concrete-and-stucco walls can eliminate two to nearly four pounds of CO_2 emissions per pound of wood fiber used. Replacing steel floor joists with engineered wood product I-joists saves 10 pounds of CO_2 per pound of wood fiber.[197]

Carbon sequestration and storage levels in various land uses and habitats

Sources: Congressional Budget Office, The Potential for Carbon Sequestration in the United States, 2007 (*http://www.cbo.gov/sites/default/files/cbofiles/ftpdocs/86xx/doc8624/09-12-carbonsequestration.pdf*), and others as noted.

Land use/ ecosystem type	Rate of carbon sequestration, metric tons per acre per year	Carbon storage, metric tons per acre	Period of sequestration until saturation (assuming no disturbance/interruption)
Unharvested forest	0.6 – 2.6 (highest is PNW Douglas fir forest)[198]	465 per acre (nationwide average) 1,179 per acre (PNW Douglas fir)[199]	90 – 120+ years. Sequestration is most rapid in the third through seventh decades of Douglas fir life cycle.[200]
Managed forest harvested on 30-year rotation	0.3 – 2.1	203 at start of regrowth 256 at end of rotation (not including carbon sequestered in lumber and other harvested wood products)[201]	Saturation not reached. Life cycle of lumber used in building, 80+ years.
Cropland Added sequestration using no till/low till "conservation farming"	0.2 – 0.3[203] 0.4 – 0.6 credited by the Chicago Climate Exchange (CCX)[204]	56 – 120 (U.S. average, 80 mt/acre)	15 – 20 years[202]
Pasture and rangeland	1 mt/acre credited by the CCX for new grassland plantings[205]	73 – 159 (U.S. average, 113 mt/acre)	25 – 50 years[206]
Salt marsh All marshes and swamps	.07 – 7 4.49[208]	 312[209]	50+ years[207]
Seagrass meadows	0.38[210] 0.2 – .7[211]	6.5 to 257 (global median, 57 mt/acre)[212]	2+ years (perhaps with ongoing transport of sequestered carbon to deeper waters)[213]
Nonforest residential land	0.24 (in Maryland)[214]	7.2 (in Maryland)[215]	

Current U.S. carbon sinks, in million metric tons (tg)

Forest 922 Tg

Cropland 10 (15.6 Tg in established cropland, minus 5.9 Tg carbon emissions from other lands converted to crops)

Grassland 32 Tg

Source: U.S. Environmental Protection Agency (2012), Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2010.

Areas occupied by various land uses and habitats in Washington state

Forest: 21.8 million acres[216]

Timberland: 16.9 million acres

Agriculture: 15.1 million acres (2007)[217]

Cultivated crops: 5.4 million acres

Noncultivated crops: 1.1 million acres

Conservation Reserved Program land: 1.2 million acres

Pastureland: 1.1 million acres

Rangeland: 5.9 million acres

Wetlands, including saltmarshes: 938,000 acres[218]

Aquatic lands: 1.5 million acres

Eelgrass meadows: ~ 40,000 acres

Developed land: 2.3 million acres

Representative carbon sequestration rates and saturation periods for key agricultural & forestry practices

Source: U.S. Environmental Protection Agency. This chart does not include any associated changes in emissions of methane (CH4), nitrous oxide (N2O), or fossil CO2.

Activity	**Representative carbon sequestration rate in U.S.** (Metric tons of C per acre per year)	**Time over which sequestration may occur before saturating** (Assuming no disturbance, harvest or interruption of practice)	**References**
Afforestation a)	0.6 – 2.6 b)	90 – 120+ years	Birdsey 1996[219]
Reforestation c)	0.3 – 2.1 d)	90 – 120+ years	Birdsey 1996
Changes in forest management	0.6 – 0.8 e)	Saturation does not necessarily occur if wood products are included in accounting and C flows continuously into products.	Row 1996
	0.2 f)		IPCC 2000[220]
Conservation or riparian buffers	0.1 – 0.3 g)	Not calculated	Lal et al. 1999[221]
Conversion from conventional to reduced tillage	0.2 – 0.3 h)	15 – 20 years	West and Post 2002[222]
	0.2 i)	25 – 50 years	Lal et al. 1999
Changes in grazing land management	0.02 – 0.5 j)	25 – 50 years	Follet et al. 2001[223]
Biofuel substitutes for fossil fuels	1.3 – 1.5 k)	Saturation does not occur if fossil fuel emissions are continuously offset	Lal et al. 1999

a) Values are for average management of forest established on previous cropland or pasture.

b) Values calculated over 120-year period. Low value is for spruce-fir forest type in Lake States; high value for Douglas fir on Pacific Coast. Soil carbon accumulation included in estimate.

c) Values are for average management of forest established after clearcut harvest.

d) Values calculated over 120-year period. Low value is for Douglas fir in Rocky Mountains; high value for Douglas Fir on Pacific Coast. No accumulation in soil carbon is assumed.

e) Select examples, calculated over 100 years. Low value represents change from 25-year to 50-year rotation for loblolly pines in Southeast; high value is change in management regime for Douglas fir in Pacific Northwest. Carbon in wood products included in calculations.

f) Forest management here encompasses regeneration, fertilization, choice of species and reduced forest degradation. Average estimate here is not specific to U.S., but averaged over developed countries.

g) Assuming that carbon sequestration rates are same as average rates for lands under USDA Conservation Reserve Program.

h) Estimates include only conversion from conventional to no-till for all cropping systems except wheat-fallow systems, which may not produce net carbon gains. Changes in other greenhouse gases not included.

i) Assuming that average carbon sequestration rates are same for conversion from conventional till to no-till, mulch till or ridge till. Estimates of changes in other greenhouse gases not included.

j) See Improve/Intensify Management section in Table 16.1 of Follett et al. (2001). Low end is improvement of rangeland management; high end is changes in grazing management on pasture, where soil organic carbon is enhanced through manure additions. Flux changes in other greenhouse gases not included.

k) Assumes growth of short-rotation woody crops and herbaceous energy crops, and that burning this biomass offsets 65-75% of fossil fuel in CO2 emissions. Changes in other greenhouse gases not included.

CONCLUSION

Sweetening the Waters reports on a selection of measures for dealing with ocean acidification and its causes. These tools range from proven to promising to speculative, and in a few cases even risky. Field trials and experiments in Washington are already beginning to establish sound practices and protocols for managing resources that are vulnerable to this human-caused change in marine chemistry.

It is true that, working in isolation, Washington would have little chance to achieve deep reductions in the world's carbon dioxide emissions. However, the state and its citizens have stepped up to define and refine methods to reduce local acidifying pollution, prevent the consequences that can be prevented, and heal the damage that can be healed. Facing the "spear point" of ocean acidification, shellfish hatcheries along the Pacific Coast have developed the first viable methods for adapting seafood production systems to cope (for now) with acidifying waters. The Blue Ribbon Panel has recommended strategies to begin expanding this modest toolkit, aiming to help conserve vulnerable resources and ecosystems along the coast from an increasingly corrosive ocean. As the first mover, Washington can set an example by continuing to identify, test, and prove methods to understand and combat the causes and consequences of ocean acidification. By doing so, the state strengthens its standing to urge other governments to join this effort, both domestically and worldwide. In short, as Governor Gregoire put it, Washington can lead.

ENDNOTES

[1] These deposits compose a global carbon sink at least as large, and possibly twice as large, as those provided by mangroves and saltwater marshes together. James W. Fourqurean, Carlos M. Duarte, Hilary Kennedy, Núria Marbà, Marianne Holmer, Miguel Angel Mateo, Eugenia T. Apostolaki, Gary A. Kendrick, Dorte Krause-Jensen, Karen J. McGlathery, and Oscar Serrano (2012). "Seagrass ecosystems as a globally significant carbon stock." *Nature Geoscience* 5(7):505-9.

[2] Unlike algal seaweeds such as kelp, seagrasses are true flowering plants that root—deeply—in the substrate; two-thirds of the carbon in living seagrass is buried in its roots and rhizomes, Seagrasses, mangroves, and saltwater marshes together contain nearly half the carbon buried in marine sediments worldwide, though they cover less than 0.2 percent of those sediments, C. M. Duarte, J. J. Middelburg, and N. Caraco (2005). "Major role of marine vegetation in the oceanic carbon cycle." *Biogeosciences* 2, 1-8.

[3] Richard K.F. Unsworth, Catherine J. Collier, Gideon M. Harrison, and Len J. McKenzie (2012). "Tropical Seagrass Meadows Modify Seawater Carbon Chemistry: Implications for Coral Reefs Impacted by Ocean Acidification." *Environmental Research Letters* 7 (2012) 024026.

[4] "We have observed large quantities [of benthic carbon] in deep portions of Puget Sound and in open water offshore of Washington. This indicates that these systems export large quantities of carbon to deeper locations where it may be buried or otherwise sequestered." Ronald Thom, Susan L. Blanton, Dana L. Woodruff, Gregory D. Williams, and Amy B. Borde (n.d., post-2000). "Carbon Sinks in Nearshore Marine Vegetated Ecosystems." Pacific Northwest National Laboratory, Marine Sciences Laboratory. www.netl.doe.gov/publications/proceedings/01/carbon_seq/5c5.pdf

[5] Kenneth L. Heck, Jr. et al. (2008). "Trophic Transfers from Seagrass Meadows Subsidize Diverse Marine and Terrestrial Consumers." *Ecosystems* 11: 1198-1210.

[6] One of the two main drivers of carbonate dissolution is oxygen pumping into the sediments by seagrass. David J. Burdige, Xinping Hu, and Richard C. Zimmerman (2010). "The widespread occurrence of coupled carbonate dissolution/reprecipitation in surface sediments on the Bahamas Bank." *American Journal of Science*, Vol. 310, 492–521.

[7] Burdige, Zimmerman, and Hu (2008). "Rates of carbonate dissolution in permeable sediments estimated from pore-water profiles: The role of sea grasses." *Limnology and Oceanography* 53(2), 549–565.

[8] M.F. Pieler and A.R. Smyth, Piehler (2011). "Habitat-specific distinctions in estuarine denitrification affect both ecosystem function and services." *Ecosphere* 2:art12. http://dx.doi.org/10.1890/ES10-00082.1

[9] Piping in industrial flue gas with a carbon dioxide content comparable to that anticipated in the atmosphere of 2100 significantly boosts the growth of eelgrass (Zostera marina L.) in full light conditions, especially the growth of the underground roots and rhizomes that store carbon. But the gas has no effect under limited light (Palacios and Zimmerman 2007).

[10] In Dumas Bay, north of Tacoma, sediments suppress seagrass more thoroughly than microalgae does (Zimmerman 2001). The same situation prevails in San Francisco Bay and, probably, in many other parts of South Puget Sound (Richard Zimmerman, pers. comm., May 2012).

[11] Thomas Arnold, Christopher Mealey, Hannah Leahey, A. Whitman Miller, Jason M. Hall-Spencer, Marco Milazzo, Kelly Maers (2012). "Ocean Acidification and the Loss of Phenolic Substances in Marine Plants." *PLoS ONE* 7(4): e35107.

[12] Seagrass meadows worldwide are declining as fast as mangrove forests and faster than coral reefs and tropical rainforests; more than 35 percent have been lost since 1980 (Waycott et al. 2009).

[13] Dowty et al., 2005.

[14] Patty Glick, Jonathan Clough, and Brad Nunley (2007). *Sea-level Rise and Coastal Habitats in the Pacific Northwest: An Analysis for Puget Sound, Southwestern Washington, and Northwestern Oregon.* National Wildlife Federation. http://www.nwf.org/~/media/PDFs/Global-Warming/Reports/PacificNWSeaLevelRise.pdf?dmc=1&ts=20121123T0436051581

[15] The bivalves significantly reduced phytoplankton levels stimulated by high nutrient inputs and increased light penetration; the highest concentrations significantly increased seagrass growth (Wall et al. 2008, 2011). Earlier experiments found that the presence of the Gulf Coast mussel Modilous americanus reduced the epiphyte load on the seagrass Thalassia testudinum (Peterson and Heck 2001). The mussels appear to consume the epiphytes' free-floating propagules before they can attach to the seagrass, and provide shelter for small snails and amphipods that graze on the epiphytes.

[16] Loren D. Coen and Raymond E. Grizzle, 2007. "The Importance of Habitat Created by Molluscan Shellfish to Managed Species along the Atlantic Coast of the United States," ASMFC Habitat Management Series #8.

[17] Charles C. Wall, Bradley J. Peterson, and Christopher J. Gobler (2011). "The Growth of Estuarine Resources (*Zostera marina, Mercenaria mercenaria, Crassostrea virginica, Argopecten irradians, Cyprinodon variegates*) in Response to Nutrient Loading and Enhanced Suspension Feeding by Adult Shellfish." *Estuaries and Coasts* Vol. 34, No. 6.

[18] Wall et al. 2008; Peterson and Heck 1999, 2001.

[19] Hauke Kite-Powell, Porter Hoagland, Di Jin, Dror Angel, Heidi Clark, Kevin Kroeger, 2006. *Mitigating the Effects of Excess Nutrients in Coastal Waters through Bivalve Aquaculture and Harvesting.* Final project report, submitted to the Cooperative Institute for Coastal and Estuarine Environmental Technology.

[20] Coen and Grizzle 2007.

[21] William M. Peirson, pers. comm., May 2012.

[22] Alan Barton, pers. comm., May 2012.

[23] Joel Fodrie, pers. comm., May 2012.

[24] Unsworth et al. 2012.

[25] V. Tu Do, Xavier de Montaudouin, Nicolas Lavesque, Hugues Blanchet, and Hervé Guyard. "Seagrass colonization: Knock-on effects on zoobenthic community, populations and individual health." *Estuarine, Coastal and Shelf Science*, Volume 95, Issue 4, p. 458-469.

[26] Jennifer Ruesink, pers. comm., May 2012.

[27] Jennifer Ruesink and Micah Horwith (2012). "Resilience of Soft-Sediment Communities after Geoduck Harvest in Samish Bay, Washington." In *Geoduck Aquaculture Research Program: Interim Progress Report October 1, 2010, through September 30, 2011.* Washington Sea Grant.

[28] Bill Dewey and Jennifer Ruesink, pers. comm., May 2012.

[29] Such projections are however variable and provisional. On the Washington, Oregon, and Northern California coasts, tectonic land lift will partly or

entirely counteract the effects of rising sea level. The National Academy of Sciences, in a recent report, forecasts a mean sea level rise at Seattle of 69 cm by 2100, consistent with an earlier IPCC report—amidst a possible range of 10 to 143 cm. (NAS Board on Earth Sciences and Resources and Ocean Studies Board, Division on Earth and Life Studies, 2012. *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future.*)

[30] This effect will be especially pronounced in the Snohomish Delta if the dikes now containing its pastures and freshwater marshes are removed. Assuming a sea-level rise of 27 inches by 2100 (in accordance with modeling by the Intergovernmental Panel on Climate Change), saltwater marsh will grow by 7,548 percent, to 5,528 acres, through the conversion of freshwater marsh, swamp, and dry land. More than 4,000 acres of new tideflats will appear (Glick et al., 2008). Because many dikes along the Snohomish were constructed from wood waste and other degradable materials during Everett's "Milltown" days, they may be especially ripe for reconsideration and possible removal or replacement.

[31] Thom et al, "Carbon Sinks."

[32] Ibid.

[33] Ibid.

[34] U.S. Environmental Protection Agency, "Nisqually Estuary restoration wins national award for coastal protection." Press release, Dec. 2, 2011.

[35] Fonseca, M.S., W.J. Kenworthy, and G.W. Thayer (1998). "Guidelines for the conservation and restoration of seagrasses in the United States and adjacent waters." NOAA Coastal Ocean Program Decision Analysis Series No. 12.

[36] Thomas F. Mumford, Jr. (2007). *Kelp and Eelgrass in Puget Sound.* Washington Department of Natural Resources Aquatic Resources Division Technical Report 2007-05.

Stamey, M.T. (2004). *An analysis of eelgrass transplantation performance in Puget Sound, WA. 1990-2000.* MA thesis, University of Washington School of Marine Affairs.

[37] Sherry Palacios (2010). *Eelgrass: factors that control distribution and abundance in Pacific Coast estuaries and a case study of Elkhorn Slough, California.* Elkhorn Slough Technical Report Series 2010:2.

[38] Richard Zimmerman and Kamille Hammerstrom, pers. comm.

[39] "Historically they've been using oyster shell to make firmer ground for many, many years. Now they're thinking, hmm, how much is due to buffering?" (Benoit Eudeline, biologist, Taylor Shellfish, pers. comm.)

[40] Mark A. Green, George G. Waldbusser, Shannon L. Reilly, Karla Emerson, and Scott O'Donnell (2009). "Death by dissolution: Sediment saturation state as a mortality factor for juvenile bivalves." *Limnology and Oceanography* 54:4, 1037–1047.

[41] Bob Rheault, pers. comm.

[42] Kraeuter, J. N., M. J. Kennish, J. Dobarro, S. R. Fegley, and G. E. Fimlin. "Rehabilitation of the northern quahog (hard clam) (Mercenaria mercenaria) habitats by shelling—11 years in Barnegat Bay, New Jersey." *Journal of Shellfish Research* 22: 61–67, 2009. Green et al. 2009.

[43] George Waldbusser and Mark Green (2011). "Juvenile Marine Bivalves within Corrosive Sediments: How Do (Or Don't) They Do It?" Presentation to the American Fisheries Society Meeting, Sept. 7, 2011.

[44] Right up to the point where the carbonate powder formed an oxygen-proof seal atop the sediment, allowing anaerobic bacteria to grow and emit toxic hydrogen sulfide. (George Waldbusser, pers. comm.)

[45] Large-scale shell collection and deposition jumpstarted the revival of Connecticut's oyster industry (Bob Rheault, pers. comm.).

[46] The shells provide substrate and buffering on clam and oyster beds afflicted with nutrient runoffs and anoxic mud. In its first season the projected collected about three tons (four cubic yards), up to a third of the shells discarded on Martha's Vineyard. Some restaurants even run the shells through their dishwashers for easier storage. (Rick Karney and Jesse Kanozak, Martha's Vineyard Shellfish Group, pers. comm.)

[47] Betsy Peabody, Pacific Shellfish Institute president, pers. comm.

[48] Ibid.

[49] Local growers use less shell since the market shifted from preshucked to higher-value oysters on the half shell. Instead of letting oysters cluster atop whole kulch—no good for raw bars—Taylor Shellfish grinds shells down to small grains that only one larva can anchor onto, ensuring neat, separate specimens. Shells have piled up at its Canadian farms, with no place to use them. (Bill Dewey, pers. comm.)

[50] Mark Green, the lead researcher in Maine, is now trying to launch a statewide shell-collection program there. He says the equipment required is fairly simple: a road-surface roller can crush substantial quantities of shell, and a spreader used to salt roads in winter broadcasts the hash from a boat.

[51] Christopher C Wilmers, James A Estes, Matthew Edwards, Kristin L Laidre, and Brenda Konar (2012). "Do trophic cascades affect the storage and flux of atmospheric carbon? An analysis of sea otters and kelp forests." *Frontiers of Ecology and the Environment* 2012; doi:10.1890/110176.

[52] Wheeler J. North and Michael Neushul (1968). "A Note on the Possibilities of Large-Scale Cultivation of Macrocystis," in *Utilization of Kelp-Bed Resources in Southern California*, ed. by Wheeler J. North and Carl J. Hubb. State of California Resources Agency Department of Fish and Game.

[53] FAO 2008, Rosesjadi et al. 2008

[54] This yielded more than 20 thousand metric tonnes of cordite, filling most of the British Navy's needs for this smokeless gunpowder. (Rosesijadi et al. 2008.)

[55] California Department of Fish and Game (2020). "Review of selected California fisheries for 2009: coastal pelagic finfish, market squid, red abalone, Dungeness crab, Pacific herring, groundfish/nearshore livefish, highly migratory species, kelp, California halibut, and sandbasses." *Fisheries Review*, CalCOFI Rep., Vol. 51. http://calcofi.org/publications/calcofireports/v51/Vol51_FisheriesReport_pg14-38.pdf

[56] John Sheehan, Terri Dunahay, and John Benemann (1998)."A Look Back at the U.S. Department of Energy's Aquatic Species Program—Biodiesel from Algae." U.S. Department of Energy's Office of Fuels Development. http://www1.eere.energy.gov/biomass/pdfs/biodiesel_from_algae.pdf

[57] J. Robert Waaland (2004). "Integrating Intensive Aquaculture of the Red Seaweed Chondracanthus exasperatus." *Bulletin of Fisheries Research Agency*, Supplement No. 1, 91-100.

[58] Doug Ernst. “Marine Macroalgae Aquaculture,” Söliv International (now Sol-Sea) PowerPoint presentation, posted by the Aquaculture Caucus at http://www.pacaqua.org/Documents/Marine_Macroalgae_Culture.pdf. Viewed 6/23/12.

[59] Doris Soto, ed. (2009). *Integrated Mariculture: A global review.* FAO Technical Paper 529. ftp://ftp.fao.org/docrep/fao/012/i1092e/i1092e.pdf

[60] Klaus Lüning and Shaojun Pangn. “Mass cultivation of seaweeds: current aspects and approaches,” Journal of Applied Phycology 15: 115–119, 2003.

[61] Waaland (2004).

[62] Ernst, “Marine Macroalgae Aquaculture.” Sol-Sea founder Diane Boratyn reports that the firm needs research funds and “a stable supply of fish” (now lacking) to complete biomass studies (pers. comm.).

[63] Sue Cudd, pers. comm..

[64] C. Pizarro, W. Mulbry, D. Blersch, P. Kangas. “An economic assessment of algal turf scrubber technology for treatment of dairy manure effluent.” *Ecological Engineering* Volume 26, Issue 4, 31 July 2006, Pages 321–327. http://www.sciencedirect.com/science/article/pii/S0925857406000218; http://www.enst.umd.edu/files/posteralgalturfeconomics.pdf.

[65] Qualco Energy (n.d.) “Qualco Energy Bio-Gas Project.”

[66] Paul Dobbins, pers. comm.

[67] Christine Buckley, “Seaweed: the new trend in water purification.” http://today.uconn.edu/blog/2011/07/seaweed-the-new-trend-in-water-purification-2/ (accessed June 21, 2012.)

[68] Qisheng Tang*, Jihong Zhang, Jianguang Fang, “Shellfish and seaweed mariculture increase atmospheric CO2 absorption by coastal ecosystems.” Marine Ecology Progress Series Vol. 424: 97–104, 2011.

[69] Hongsheng Yang, Yi Zhou, Yuze Mao, Xiaoxu Li and Ying Liu, et al. (2005). “Growth characters and photosynthetic capacity of Gracilaria lemaneiformis as a biofilter in a shellfish farming area in Sanggou Bay, China.” *Journal of Applied Phycology*, 2005, Volume 17, Number 3, Pages 199-206.

[70] Xiugeng Fei (2004). “Solving the coastal eutrophication problem by large scale seaweed cultivation,” in “Asian Pacific Phycology in the 21st Century: Prospects and Challenges.” *Hydrobiologia*, Volume 512, Numbers 1-3, 145-151.

[71] “We estimate that these upwelled waters [in the easternmost North Pacific] contain $\mu 31 \pm 4$ μmol kg^{-1} anthropogenic CO_2.” (Feely et al., 2002.) I derived an extremely rough estimate, subject to further refinement, of an average upwelling rate of 50 cubic meters per second per 100 meters of shoreline, based on the NOAA Pacific Fisheries Environmental Laboratory’s monthly and six-hourly indices of upwelling volumes at 48˚ N http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/NA/data_download.html.

[72] Richard A. Feely, Chrisopher Sabine, J. Martin Hernandez-Ayon, Debby Ianson, Burke Hales (2008). “Evidence for Upwelling of Corrosive ‘Acidified’ Water onto the Continental Shelf.’ *Science* Vol. 320 no. 5882, pp. 1490-1492.

[73] Posted at http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/NA/data_download.html.

[74] G. Roesijadi, S.B. Jones, L.J. Snowden-Swan, and Y. Zhu (2010). “Macroalgae as a Biomass Feedstock: A Preliminary Analysis.” PNNL Report 19944.

[75] Christopher A. Langdon, pers. comm..

[76] Roesijadi et al. 2010.

[77] G. Rosesijadi, A.E. Copping, M.H. Huesemann, J. Forster, and J.R. Benemann (2008). “Techno-Economic Feasibilty Analysis of Offshore Seaweed Farming for Bioenergy and Biobased Products.” Battelle Pacific Northwest Division Independent Research and Development Report PNWD-3931.

[78] Ibid.

[79] For example, 42 percent, including the digestible polysaccharide laminarin, in *Saccharina latissima* kelp. (John Magnuson [2008]. “Canada Algal Collaboration-PNNL Algal R&D Review.” PNNL/National Research Council of Canada.)

[80] Rosesijadi et al. (2008).

[81] Ibid.

[82] Alison Rieser and Susan Bunsick (2008). “Offshore marine aquaculture in the U.S. Exclusive Economic Zone (EEZ): Legal and regulatory concerns,” in *Trends and Future Challenges for U.S. National Ocean and Coastal Policy*. Ed. by Biliana-Cicin-Sain et al., National Ocean Group, NOAA. http://oceanservice.noaa.gov/websites/retiredsites/natdia_pdf/16rieser.pdf

[83] Rosesijadi et al. 2010.

[84] Higher-value butanol is the product ultimately envisioned for this process. (U.S. ARPA-E and E. I. du Pont de Nemours and Company. “First Open Solicitation: MacroAlgae Butanol,” http://arpa-e.energy.gov/Portals/0/Documents/FundedProjects/Biomass%20Energy/FOA1_E.I.duPont_Final.pdf.)

[85] Adam J. Wargacki et al. (2012). “An Engineered Microbial Platform for Direct Biofuel Production from Brown Macroalgae.” *Science*, Vol. 335 no. 6066 pp. 308-313.

[86] Sinéad Collins and Graham Bell (2004). “Phenotypic consequences of 1,000 generations of selection at elevated CO2 in a green alga.” *Nature* 431, 566-569. http://www.nature.com/nature/journal/v431/n7008/abs/nature02945.html

[87] Sinéad Collins and Graham Bell (2006). “Evolution of natural algal populations at elevated CO2.” *Ecology Letters* Volume 9, Issue 2, pages 129–135. http://onlinelibrary.wiley.com/doi/10.1111/ele.2006.9.issue-2/issuetoc

[88] Christopher Krembs, Washington Department of Ecology. “Summary of Nitrogen Loads to the Salish Sea” (PowerPoint presentation).

[89] Agricultural fertilizers make up from 9 to 33 percent of the nitrogen load in eight major Puget Sound river basins. They are the principal nutrient source in one of the most severely affected basins, the Samish, contributing 10 tons of nitrogen per square mile. (Sandra S. Embrey and Emily L. Inkpen. “Water-Quality Assessment of the Puget Sound Basin, Washington, Nutrient Transport in Rivers, 1980-93,” U.S. Geologic Service, http://wa.water.usgs.gov/pubs/wrir/ps.pub.97-4270.ab.html.)

[90] Noel Gollehon, Margriet Caswell, Marc Ribaudo, Robert Kellogg, Charles Lander, and David Letson, "Confined Animal Production and Manure Nutrients." Agriculture Information Bulletin No. 771. Economic Research Service, U.S. Department of Agriculture. In 1997, phosphorus production in Snohomish County and phosphorus and nitrogen production in Thurston County surpassed those counties' total absorbtive capacity. In Pierce, King, Skagit, and Whatcom counties, phosphorus, nitrogen, or both exceeded 75 percent of absorbtive capacity. The USDA-ERS identified Western Washington as an "area of particular concern" for manure-nutrient overload, along with Central California and parts of four Southern states.

[91] Allen G. Good and Perrin H. Beatty (2008). "Fertilizing Nature: A Tragedy of Excess in the Commons," *PLoS Biology*, Volume 9, Issue 8,l e1001124.

Nationwide, 60 percent of manure nitrogen and 70 percent of manure nitrogen are "excess," produced by operations with insufficient land to apply it at agronomic rates. Twenty percent of that excess is produced in counties with insufficient cropland to absorb it all. (Noel Gollehon, Margriet Caswell, Marc Ribaudo, Robert Kellogg, Charles Lander, and David Letson [undated]. "Confined Animal Production and Manure Nutrients." Resource Economics Division, Economic Research Service, U.S. Department of Agriculture. Agriculture Information Bulletin No. 771.)

[92] Washington Administrative Code 173-200 and 173-201A.

[93] George Boggs, Whatcom Conservation District Manager (2011). "Achieving TMDL Bacterial Goals through Conservation Plan Implementation" (PowerPoint presentation).

[94] For example, property holders may keep up to six horse or cattle, or 30 smaller stock, on one-half acre. These standards may reflect the county's long tradition of thoroughbred racing, in which horses are often stabled in close concentration. (King County Livestock Ordinance, KC 21A.030; Rick Reinlansoder, pers. comm.)

[95] Jay Gordon, executive director, Washington Dairy Association, pers. comm.

[96] Bill Dewey, Ron Shultz, etc. ,pers. comm.

[97] U.S. Department of Agriculture, National Agricultural Statistics Service, "2007 Census of Agriculture." This most recent farm census counted nearly 37,000 cattle in Snohomish County alone, including nearly 8,000 identified as beef cattle and 10,600 dairy cows. Whatcom County had 95,500 cattle, a much larger share of them dairy cows, and King County 24,500. Estimates of the number of horses in King County run as high as 30,000; a 2002 study for the American Horse Council Federation http://ofp.scc.wa.gov/wp-content/uploads/2010/02/Open-Space_King-County-Horse-Industry-.pdf pegged it at 17,000. In 2012, the NASS reported (http://www.nass.usda.gov/Statistics_by_State/Washington/Publications/Agri-facts/agri1feb.pdf) that Washington has 1.2 million cattle, with equal numbers identified as dairy and beef. In volume of waste, "we probably have the equivalent of a 1 million-population city" in Whatcom County alone, says George Boggs, the Whatcom Conservation District's coordinator.

[98] The "horse people" tend to be particularly naïve, says Bobbi Lindemulder, the Snohomish County Conservation District's lead planner. "A lot of them consider their horses family, their children—not agriculture. Say someone's been living in a condo all their life—how do you get them to understand?" Lindemulder and her counterparts in other county conservation districts strive to educate these new farmers and enlist them in watershed protection. But it's an uphill struggle."

[99] King County, alone among Washington counties, has a livestock management ordinance that regulates those raising non-dairy stock. Enforcement is largely complaint-driven and affords violators extensive opportunity to get into compliance. (Josh Monahan, King County Conservation District, pers. comm.)

[100] Jessica Dexter et al. (2010). "Cultivating Clean Water: State-Based Regulation of Agricultural Runoff Pollution, A Report by the Environmental Law & Policy Center and the Mississippi River Collaborative." http://elpc.org/wp-content/uploads/2010/03/ELPC-Cultivating-Clean-Water-Report.pdf

[101] John Rhoderick, Maryland Department of Agriculture, pers. comm.

[102] Maryland's plans are "controversial" and "unpopular," but in 2009 all but 12 of 5,257 eligible farms had filed them and all but 57 updated them. (Dexter et al. 2010.)

[103] Mark Hedrich, pers. comm.

[104] The experiences of Maryland, Virginia, and Delaware illustrate the complexities of enrolling farmers in nutrient planning and enforcing compliance. Maryland, which pushed aggressively to achieve near-complete enrollment, reported that only 65 percent of poultry growers adhered to their plans. Virginia and Delaware took go-slower, more "farmer-friendly" approach. They reported 80 percent complied, perhaps because they enrolled only the more willing participants. (Michelle Perez, "Regulating Farmers: Lessons Learned From The Delmarva Peninsula." *Choices: The Magazine of Food, Farm, and Resource Issues*. 26:3, 3rd Quarter 2011.)

[105] State of Maryland BayStat, http://www.baystat.maryland.gov/sources2.html. No data on phosphorus releases from septic systems are available. Point source (wastewater treatment) discharges meanwhile declined by more than half.

[106] Laura Snively VanDyke (1997). "Nutrient Management Planning on Virginia Livestock Farms: Impacts and Opportunities for Improvement." Virginia Polytechnic Institute and State University (Master's thesis). http://scholar.lib.vt.edu/theses/public/etd-39581323973910/etd.pdf

[107] U.S. EPA. "Polluted Runoff (Nonpoint Source Pollution): Nutrient Management Measure." http://www.epa.gov/owow/NPS/MMGI/Chapter2/ch2-2c.html

[108] Perhaps they told farmers what they thought the farmers wanted to hear. Chad Lawley, 'Biases in Nutrient Management Planning." Department of Agricultural and Resource Economics, University of Maryland (white paper). http://faculty.arec.umd.edu/elichtenberg/Biases%20in%20Nutrient%20Management%20Planning%20Land%20Economics%20Final.pdf

[109] George Boggs, pers. comm..

[110] RCW 17.21, Washington Pesticide Application Act. SEPTIC INSTALLER

[111] http://www.isco.purdue.edu/pesticide/pest_pdf/fert_app_outreach_11_23_2010.pdf

[112] Maryland Lawn Fertilizer Law. http://www.mda.state.md.us/fertilizer/

[113] Leo Reed, Indiana State Chemist's Office, pers. comm.

[114] Leo Reed and Matt Pearson, Indiana state fertilizer program manager, pers. comm.

[115] Ron Shultz, pers. comm..

[116] Matt Pearson, pers. comm..

[117] Evergreen Funding Consultants, 2009. Washington Conservation Markets Study: Final Report. A report to the Washington State Conservation Commission. http://www.farmland.org/programs/states/wa/documents/WAConservationMarketsStudyReport_27Jan2009.pdf

[118] George Van Houtven, Ross Loomis, Justin Baker, Robert Beach, and Sara Casey (2012). *Nutrient Credit Trading for the Chesapeake Bay: An Economic Study.* A report to the Chesapeake Bay Commission.

[119] U.S. EPA (2008). "Water Quality Trading Evaluation Final Report." http://www.epa.gov/evaluate/pdf/water/epa-water-quality-trading-evaluation.pdf

[120] Ibid.

[121] John Rhoderick, pers. comm.

[122] http://www.arb.ca.gov/regact/2010/capandtrade10/copurbanforestfin.pdf

[123] http://www.arb.ca.gov/regact/2010/capandtrade10/coplivestockfin.pdf

[124] John Battaglia, pers. comm.

[125] Ben Rees, pers. comm.

[126] Natural gas's share has since increased somewhat, thanks to pollution and carbon restriction policies and cheap gas.

[127] Northwest Hydroelectric Association, "NW Hydro Generation: Hydropower Overview." http://www.nwhydro.org/resources/northwest_hydro_generation.htm (accessed 11/9/12)

[128] The equivalent of 1,732 teragrams of CO_2, out of a total 6,802 teragrams (before considering carbon sinks such as forestry). U.S. EPA (2012). "Inventory of Greenhouse Gas Emissions and Sinks, 1990-2010." http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html

[129] Northwest Hydroelectric Association, "NW Hydro Generation."

[130] Tire inflation and offshore drilling could each add about 1 percent to the United States' effective petroleum supply. Mike Allen "Obama's Call for Tire Inflation to Beat Gas Crunch: Reality Check." *Popular Mechanics* Oct. 1, 2009. http://www.popularmechanics.com/cars/how-to/4276844 (accessed Nov. 8, 2012)

[131] The stations surely don't mean to discourage tire inflation, inducing waste and greater gasoline sales, by charging ever-escalating sums for air to fill them. But they could encourage it by making air free (as it was for decades) and posting reminders to motorists to check their tires.

[132] It also spent $31 million to fill its own short-term shortfalls. (Seattle City Light. *2011 Annual Report*. http://www.seattle.gov/light/AboutUs/AnnualReport/flipbook/2011/files/inc/283854583.pdf)

[133] Tesla Motors. "Supercharger: The fastest charging station on the planet." http://www.teslamotors.com/supercharger

[134] http://www.betterplace.com/global/progress

[135] "Babbage: End of the Electric Car?" *The Economist* October 15, 2012. http://www.economist.com/blogs/babbage/2012/10/nitrogen-cycle?spc=scode&spv=xm&ah=9d7f7ab945510a56fa6d37c30b6f1709

[136] Note this prescient proposal for a nitrogen-powered car from a researcher at the University of Washington: Greg Orwig (1997). "UW smogmobile is cleaner, safer alternative to gas or electric cars." http://www.washington.edu/news/1997/08/01/uw-smogmobile-is-cleaner-safer-alternative-to-gas-or-electric-cars/

[137] The Dearman Engine Company. "The Dearman Engine: A truly clean, cool technology." http://www.dearmanengine.com/cms/

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