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Editors

Saving Biological Diversity

Balancing Protection of Endangered Species and Ecosystems

[redacted] (2008)

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Chapter 14
Anthropogenic Carbon Dioxide Emissions and Ocean Acidification: The Potential Impacts on Ocean Biodiversity

William C. G. Burns

> *Ocean acidification has the potential to cause large-scale changes in the structure of ecosystems and may pose a greater threat to ocean ecosystems than the effects of global warming or local effects of fishing.*[1]

Abstract Most of the focus in recent years on the potential impacts of rising levels of carbon dioxide in the atmosphere linked to anthropogenic activities has been on the ramifications of atmospheric warming for ecosystems and human institutions. However, there is growing evidence that the gravest peril for ocean species may be acidification of the world's oceans as a consequence of the influx of carbon dioxide absorbed in oceans as carbon dioxide emissions. This chapter assesses the likely impacts of ocean acidification on marine species, including calcifying species and fish. Ocean acidification may dictate changes in institutional strategies in the context of the United Nations Framework Convention on Climate Change and the Kyoto Protocol and may spur litigation in other international flora. However, a critical foundational agenda is a robust research program to comprehensively assess potential ocean acidification impacts and adaptation strategies.

14.1 Introduction

As the Executive Secretary of the Convention on Biological Diversity, Ahmed Djoghlaf, recently observed, "[c]limate change has become one of the greatest drivers of biodiversity loss."[2] Indeed, the latest assessment by the UN's Intergovernmental Panel on Climate Change (IPCC) concluded that 20–30% of species would likely face an increased risk of extinction if globally averaged temperatures rise 1.5–2.5°C above 1980–1999 levels, and that 40–70% of species could be rendered extinct should temperature increases exceed 3.5°C,[3] a temperature scenario that is becoming increasingly possible by the end of this century.[4] A large portion of the species that are imperiled inhabit the world's oceans, including many species of fish,[5] marine mammals,[6] coral reef organisms,[7] and plankton.[8]

The vast majority of oceanic climate research in recent years has focused on the potential impacts of increasing temperatures on ocean ecosystems as a consequence of rising levels of anthropogenically-generated carbon dioxide and other greenhouse gases, including methane, nitrous oxide and chlorofluorocarbons. However, there is

R.A. Askins et al. (eds.), *Saving Biological Diversity*,

growing evidence that the gravest peril for ocean species may be posed by what Fabry has termed "the other CO_2 problem,"[9] acidification of the world's oceans as a consequence of the influx of carbon dioxide generated by human activities.

This chapter assesses the threat posed by ocean acidification during this century and beyond. In this pursuit it: 1) outlines the science associated with ocean acidification; 2) assesses the likely impacts of ocean acidification on species and ecosystems over a horizon of the next three hundred years; and 3) lays out an agenda for future research.

14.2 Ocean Acidification: Overview

Prior to the Industrial Revolution, atmospheric concentrations of naturally occurring greenhouse gases, including water vapor or moisture, carbon dioxide, methane, nitrous oxide and ozone,[10] had been relatively stable for ten thousand years.[11] As a consequence, the net incoming solar radiation at the top of the atmosphere was roughly balanced by net outgoing infrared radiation.[12] However, with the advent of fossil fuel burning plants to support industry, automobiles, and the energy demands of modern consumers, as well as the substantial expansion of other human activities, including agricultural production, "humans began to interfere seriously in the composition of the atmosphere"[13] by emitting large amounts of additional greenhouse gases. The human-driven buildup of greenhouse gases in the atmosphere has resulted in "radiative forcing." That is, increased levels of greenhouse gases result in greater absorption of outgoing infrared radiation and ultimately an increase in temperatures when a portion of this radiation is re-radiated to the Earth's surface.[14]

The most important anthropogenic greenhouse gas over the past two centuries has been carbon dioxide, which is primarily attributable to fossil fuel combustion,[15] cement production, and land-use change.[16] Since 1751, over 297 billion metric tons of carbon has been released into the atmosphere from anthropogenic sources, with half of the emissions occurring since 1978.[17] Atmospheric concentrations of carbon dioxide were approximately 280 parts per million (ppm) at the start of the Industrial Revolution in the 1780s. It took a century and a half to reach atmospheric concentrations of 315 ppm. The trend accelerated in the 20th Century, reaching 360 ppm by the 1990s, and 384 ppm currently,[18] which exceeds atmospheric levels for at least the last 650,000 years,[19] and most likely the past 20 million years.[20]

Approximately 7.1 gigatons of carbon are currently emitted annually by human activities.[21] However, about 2.0 gigatons of carbon, or approximately 25–30% of annual anthropogenic emissions, are absorbed by oceans,[22] with 3.3 gigatons accumulating continuously in the atmosphere.[23] The oceans have absorbed approximately 525 gigatons of carbon dioxide from the atmosphere over the past 200 years,[24] a rate ten times the natural historical rate.[25] Over the next millennium, it is estimated that the world's oceans will absorb 90% of anthropogenic carbon dioxide currently being released into the atmosphere.[26]

While chemically neutral in the atmosphere, carbon dioxide in the ocean is chemically active.[27] As carbon dioxide dissolves in seawater, it reacts with water molecules (H_2O) to form a weak acid, carbonic acid (H_2CO_3), the same weak acid found in carbonated beverages. Like all acids, carbonic acid then releases hydrogen ions (H^+) into solution;[28] leaving both bicarbonate ions (HCO_3^-) and, to a lesser extent, carbonate ions (CO_3^{2-}) in the solution (Fig. 14.1).[29] The acidity of ocean waters is determined by the concentration of hydrogen ions, which is measured on the pH scale. The higher the level of hydrogen ions in a solution, the lower the pH.[30]

Fig. 14.1 Impacts of carbon dioxide on ocean chemistry

$$CO_2 + H_2O \leftrightarrow H_2CO_3$$

$$H_2CO_3 \leftrightarrow H^+ + HCO_3^- + CO_3^{2-}$$

The increase of atmospheric concentrations of carbon dioxide since the advent of the Industrial Revolution has decreased surface pH values by 0.12 units.[31] While this may not sound like a substantial change, the pH scale is logarithmic.[32] Thus, a 0.1 unit change in pH translates into a 30% increase in hydrogen ions.[33] The pH of the world's oceans now stands at approximately 8.2, with a variation of about ±0.3 units because of local, regional and seasonal variations.[34] The pH unit change over the past 150 years is probably the greatest seen over the past several million years.[35]

While increases in ocean acidification have been substantial to date,[36] far more dramatic changes are likely to occur during this century and beyond as a substantial portion of burgeoning levels of anthropogenic carbon dioxide emissions enter the world's oceans. Under a "business as usual" scenario, carbon dioxide emissions are projected to grow at 2% annually during the remainder of this century,[37] although emissions have grown far more substantially in the past six years,[38] exceeding even the upper range of the projections of the IPCC.[39] The IPCC in its *Special Report on Emissions Scenarios* projected that carbon dioxide emissions could be as high as 37 gigatons of carbon annually by 2100, with the median and mean of all scenarios being 15.5 and 17 GtC, respectively.[40] Atmospheric concentrations of carbon dioxide may reach twice pre-industrial levels by as early as 2050,[41] and could triple or quadruple by 2100.[42]

The "business as usual" scenario for carbon dioxide emissions during this century, in turn, is projected to result in a tripling of dissolved carbon dioxide in seawater by 2100, producing an additional decline in ocean pH by approximately 0.3–0.4 units.[43] Moreover, continued oceanic absorption of carbon dioxide may result in a further decline of pH levels of 0.77 units by 2300, reaching levels not seen for the past 300 million years, with the possible exception of rare, extreme events.[44] These levels will persist for thousands of years even after oceanic concentrations of carbon dioxide begin to decline.[45]

As the United Kingdom's Royal Society recently observed, "seawater pH is a critical variable in marine systems; even small changes will have a large impact on ocean chemistry."[46] As discussed in the next section, the changes in ocean chemistry precipitated by acidification are likely to exert profound and highly adverse impacts on ocean species and ecosystems.

14.3 Potential Impacts of Ocean Acidification

14.3.1 Impacts on Calcifying Species

14.3.1.1 Overview

As indicated above, rising levels of carbon dioxide result in a substantial increase in the release of hydrogen ions, which lowers oceanic pH levels. One important consequence of the release of hydrogen ions is that they combine with any carbonate ions in the water to form bicarbonate, thus removing substantial amounts of carbonate ions from solution (Fig. 14.2).[47] The uptake of anthropogenic carbon dioxide by the oceans has already resulted in a 10% decline ($\sim 30\,\mu\text{mol kg}^{-1}$) in carbonate concentrations compared to pre-industrial levels,[48] and is likely to precipitate a 50% decline by 2100.[49]

The saturation of seawater with carbonate ions is extremely important for marine species that construct their shells or skeletons with limestone (calcium carbonate, $CaCO_3$) in a process known as calcification. These species include most corals, mollusks, echinoderms, foraminifera and calcareous algae.[50] The shells and skeletons of such species do not dissolve because the upper layers of the ocean are supersaturated with calcium (Ca^{2+}) and carbonate ions.[51] However, as the pH of the oceans drops as a consequence of rising levels of carbon dioxide, carbonate levels begin to drop, ultimately resulting in an undersaturation of carbonate ions, which in turn impairs the calcification process.[52]

Calcium carbonate occurs primarily in two forms in marine organisms, aragonite and calcite. Aragonite more easily dissolves when oceanic carbonate concentrations fall; thus, organisms with aragonite structures will be most severely impacted by ocean acidification.[53]

14.3.1.2 Coral Reefs

Among the most imperiled species may be coral reef building organisms, which must deposit aragonitic calcium carbonate in excess of physical, biological and chemical erosion to facilitate the building of a scaffolding or framework for coral reefs.[54] Studies have documented that coral organisms produce calcium carbonate more slowly as the extent of carbonate ion supersaturation decreases.[55] Continued declines in pH levels, as a consequence of the rising uptake of carbon dioxide in the oceans, may ultimately imperil the very existence of coral reefs in many parts of the world.

A recent study by Hoegh-Guldberg, et al., concluded that oceanic carbonate concentrations will drop below 200 μmol kg^{-1} when atmospheric carbon dioxide concentrations reach 450–550 ppm, a scenario that may occur by the middle of this century.[56] At that point, the rates of calcification by coral polyps will be exceeded by reef erosion, which in conjunction with the impacts of increasing temperatures,[57] may "reduce coral reef ecosystems to crumbling frameworks with few calcareous corals."[58] By the end of the century, Caldeira concludes that "there is no place left with the kind of chemistry where corals grow today."[59] The diminution of reefs could also result in half or more of coral-associated fauna becoming rare or extinct.[60]

Fig. 14.2 Bicarbonate

$$H^+ + CO_3^{2-} \leftrightarrow HCO_3^-$$

Massive declines in coral reefs could have grave environmental and socio-economic implications. Coral reefs are among the most diverse ecosystems in the world. While covering only 0.17% of the ocean floor, coral provide habitat for one quarter of all marine species.[61] In the Pacific region, reefs serve as habitat for fish and other marine species that provide 90% of the protein needs of inhabitants of Pacific Island Developing Countries[62] "and represent almost the sole opportunity for substantial economic development for many small island nations."[63] A World Bank study estimated that 50% of the subsistence and artisanal fisheries will be lost in regions of high coral reef loss.[64]

Moreover, coastal peoples rely on the marine life found on corals for many medicinal needs, including venom from tropical cone snails that serve as a substitute for morphine, and coral skeletons that can replace bone grafts.[65] Overall, it has been estimated that the food, tourism revenue, coastal protection and new medications that reefs provide are worth about $375 billion annually,[66] with nearly 500 million people dependent on healthy coral reefs for their services.[67]

14.3.1.3 Potential Impacts on Other Calcifying Species

While corals are the most prominent calcifying organisms in the world's oceans, they account for only 10% of global calcium carbonate production.[68] Seventy percent of global calcium carbonate precipitation is contributed by several groups of planktonic organisms, including coccolithophores, foraminifera, and pteropods,[69] many of which are extremely important components of ocean ecosystems.[70]

Coccolithophores are one-celled marine phytoplankton that inhabit the upper layers of coastal waters and the open ocean.[71] Coccolithophores are the primary calcite producers in the ocean,[72] constructing elaborate calcite plates or liths.[73] Recent studies indicate that rising pH levels associated with increased oceanic carbon dioxide uptake may imperil coccolithophore species in the future. One study concluded that a doubling of present-day concentrations of carbon dioxide could result in a 20–40% reduction in biogenic calcification of coccolithophores, resulting in malformed calcareous plates and layers of plates,[74] while another concluded that coccolithophores exposed to carbon dioxide levels triple those of the present day could lose half their protective coatings.[75]

The particulate organic material of coccolithophores sinks and contributes substantially to carbon mineralization deep in the water column.[76] A reduction in the transport of organic carbon to the deep ocean would diminish the flux of food to benthic organisms.[77] Additionally, the decline of coccolithophores in an ecosystem can result in a shift to a diatom-dominated phytoplankton community, which can restructure an ecosystem at all trophic levels.[78]

Diminution of coccolithophores could also amplify global warming trends for several reasons. Chalky coccolithophore blooms can extend over hundreds of thousands of square kilometers,[79] and when blooming, lighten the surface of the ocean and reflect substantial amounts of sunlight back towards space.[80] Substantial reductions in their numbers might thus accelerate warming because more incoming solar radiation would be absorbed by the oceans.[81] Moreover, coccolithophores produce substantial amounts of dimethylsulphide, which account for substantial portions of atmospheric sulphate particles around which cloud droplets grow. Reductions in cloud development might ultimately result in additional warming, as some clouds reflect incoming solar radiation back to space.[82] Finally, calcium carbonate is very dense, and acts as ballast, which serves to accelerate the deposition of particulate carbon in the deep ocean. A reduction in calcium carbonate production thus could ultimately imperil a mechanism that helps remove carbon dioxide from the atmosphere, potentially intensifying the greenhouse effect.[83]

Aragonite-producing pteropods, sometimes called sea butterflies, are a group of 32 species of planktonic snails.[84] While the species have a global distribution, population densities are highest in polar and subpolar regions, and they are the primary calcifiers in the Southern Ocean.[85] Pteropods are particularly threatened by ocean acidification both because of the high solubility of aragonite and the fact that the calcite saturation state is lowest in near-polar regions.[86] Under a business as usual scenario for growth of carbon dioxide emissions, the aragonite saturation horizon may rise to the surface of the oceans before 2100, rendering the skeletons of pteropods unstable throughout the water column of the Southern Ocean.[87] Pteropods incapable of growing stable shells are not likely to survive in waters that become undersaturated with aragonite.[88] Moreover, the weakening of the pteropods' health would most likely allow competing species to assert dominance.[89]

Pteropods play an extremely important role in many ocean ecosystems. In the Ross Sea, the subpolar-polar pteropod *Limacina helicina* sometimes replaces krill as the dominant zooplankton species in the ecosystem.[90] In many polar and subpolar regions, pteropods are an important food source for a wide range of species, including North Pacific salmon, mackerel, herring, cod, and large whales.[91]

Planktonic foraminifera are single-celled organisms related to amoeba, some of which form shells from the calcite form of calcium carbonate.[92] Recent research in the Southern Ocean revealed that foraminifera have thinner shells with considerably more porosity than fossilized foraminifera that lived in the ocean thousands of years ago.[93] A doubling in atmospheric concentrations of carbon dioxide from current levels is projected to reduce the calcification rates of foraminifera by an additional 20–40%.[94] Changes in the distribution and abundance of this group could have significant impacts on the global carbon cycle.[95]

Echinoderms, a phylum that includes starfish, sea urchins and brittle stars, are especially threatened by ocean acidification because their calcite structures contain larger amounts of magnesium and thus dissolve far more readily than even aragonite under increased carbon dioxide conditions.[96] Recent research, albeit limited, indicates that echinoderms can be seriously impacted by declines in pH of as little as 0.3 units.[97] Diminution of echinoderms could have serious implications for many ocean ecosystems as some are keystone predators which are very important grazers.[98] Other calcifying species that may be adversely affected by ocean acidification include mussels,[99] oysters,[100] copepods,[101] and crabs.[102]

Finally, it should be emphasized that the historical record associated with previous incidents of ocean acidification and calcifying species may be a foreboding portent. The mass extinction of huge numbers of calcifying marine species 55 million years ago (the Paleocene-Eocene Thermal Maximum) [illegible]

to ocean acidification and associated carbonate undersaturation.[103] Moreover, it took over 110,000 years for calcium carbonate levels to return to previous levels.[104] Because the release of carbon was more gradual during this era, facilitating some buffering by deep-sea carbonate dissolution, it is likely that contemporary acidification will be more "rapid and intense."[105]

14.3.2 *Toxic Effects on Ocean Organisms*

While we know far less about the potential direct toxic effects of carbon dioxide or acidification on marine species than potential impacts on calcification processes in marine species,[106] there is some evidence that such impacts will occur. For example, some fish species may be threatened by declining pH through a process called acidosis, which is a build up of carbonic acid in body fluids that can lead to death.[107] Hypercapnia, or excessive carbon dioxide in the blood, may also threaten fish species in the future. For example, a recent study concluded that elevated levels of carbon dioxide can result in high levels of mortality for Japanese amberjack and bastard halibut.[108]

A recent study concluded that decreases in ocean pH by 0.5 units or more may severely disrupt the internal acid-base balance of sea urchins, which can ultimately result in their death.[109] Cephalopods such as squid might be particularly affected by increases in oceanic carbon dioxide because they require very high amounts of oxygen in the blood to sustain their energy-demanding method of swimming. Lower pH can impair oxygen supplies in these species,[110] reducing oxygen capacity by about 50% with a pH decrease of 0.25 units.[111]

14.4 Future Research Needs and Translating Research into Policy

Many in the climate community now believe that ocean acidification may prove to be one of the most serious manifestations of burgeoning anthropogenic carbon dioxide emissions.[112] Yet the current research agenda in this context is egregiously inadequate, marked by insufficient funding for conducting pertinent experiments, monitoring and modeling and the absence of a coherent framework for assessment.[113] As Kurihara, et al., recently observed, "the investigation of the biological impacts of future ocean acidification is still in its infancy."[114] In the final section of this chapter, I will outline some of the critical components of a viable research program during the next decade and beyond.

A core priority must be to expand substantially the scope of marine species that are assessed for potential acidification impacts. For example, while many calcifying plankton species are at the base of marine ecosystems,[115] to date only 2% of these species have been studied in terms of potential ocean acidification impacts.[116] The highest priority should be accorded to assessing potential impacts on shelled pteropods and deep-sea scleractinian corals, two aragonite-secreting species that may be the first to experience carbonate undersaturation within their current geographic rates.[117] A broader assessment will help to facilitate the timely development of precautionary measures and potential adaptation responses, as well as to establish priorities necessi-

One severe limitation of acidification research to date is that the vast majority of studies have been conducted in the laboratory. This is problematic for several reasons: 1) the experiments are usually not run long enough to assess whether the species threatened by acidification can adapt to their changing environment, either through physiological adjustments or migration;[118] 2) laboratory studies usually focus on one species rather than an assemblage, and thus cannot assess the possibility of replacement of acid-sensitive by more acid-tolerant or acid-insensitive species that could help maintain ecosystem integrity; and 3) the absence of an ecosystem makes it impossible to assess trophic effects of acidification, a critical proposition given the key role of many calcifying species in the marine ecosystem.[119]

While an expensive proposition, assessments should focus on large-scale marine field experiments that mirror land-based Free Air Carbon Dioxide Enhancement (FACE) experiments. FACE experiments consist of towers on a small plot of land that send measured amounts of carbon dioxide into the air to determine the potential impacts of rising levels of carbon dioxide on terrestrial species.[120] Engineers have begun to develop robotic submersibles to facilitate the study of deep-sea organisms;[121] but it is far from clear that adequate funding will be forthcoming to develop a robust field program.

Field experiments must also seek to assess the synergistic impacts that rising open water temperatures associated with climate change and carbon dioxide accumulation might exert on marine species.[122] Other potential synergistic factors, such as pollution and harvesting of species should also be incorporated into such studies.[123]

Finally, acidification experiments must include assessments of potential impact of acidification on the early development of marine calcifying organisms since: 1) early life stages are usually more sensitive to environmental impacts; and 2) most benthic organisms possess planktonic larval stages and fluctuations in these stages exert a profound impact on population size.[124] For example, a recent study concluded that reproduction rates and larval development of copepods were sensitive to increased carbon dioxide concentration in seawater, while adult female survival was not affected at this concentration.[125]

Should additional research confirm the extremely serious ramifications that ocean acidification may pose for marine ecosystems, there may be far-ranging implications for policymaking under the two primary mechanisms at the international level to control carbon dioxide emissions: the United Nations Framework Convention on Climate Change (UNFCCC)[126] and the Kyoto Protocol[127] established under the UNFCCC.[128] The Parties to both instruments may fulfill their obligations by reducing emissions among a "basket" of "greenhouse gases," i.e., atmospheric gases that absorb and re-emit infrared radiation.[129] Carbon dioxide is one of these gases, but the basket also includes methane, nitrous oxide, hydrofluorocarbons, perflourocarbons and sulphur hexafluoride,[130] all of which have much higher "global warming potential" than carbon dioxide, i.e., absorption of radiation per molecule.[131]

The basket approach reflects the overarching objective of both treaty instruments to reduce emissions of anthropogenically-generated gases that can trap infrared radiation in the stratosphere, and thus contribute to climate change. Additionally, it affords the Parties the flexibility to focus their efforts on reducing emissions of those greenhouse gases that pose the least cost for their respective economies.[132]

However, if carbon dioxide poses a unique risk to marine ecosystems by leading to acidification, then the Parties to the UNFCCC and the Kyoto Protocol might consider amending their respective instruments to focus more attention on reducing emissions of this gas. On the other hand, should the Parties conclude that their mandate is, and should be, limited to combating climate change, then other international fora might be more germane for addressing this issue. For example, under the United Nations Convention on the Law of the Sea[133] Parties are required "to prevent, reduce and control pollution of the marine environment from any source,"[134] including "the release of toxic, harmful or noxious substances, especially those that are persistent[135] . . . from land-based sources, [or] from or through the atmosphere . . ."[136] Anthropogenic carbon dioxide emissions appear to clearly fall under the rubric of this mandate since they are a "harmful" substance when introduced into the marine environment, and are released "from or through the atmosphere."[137]

14.5 Conclusion

As the Royal Society of the United Kingdom concluded in its study of ocean acidification, "without significant action to reduce CO_2 emissions into the atmosphere, this may mean that there will be no place in the future oceans for many of the species and ecosystems that we know today."[138] While warming associated with rising levels of carbon dioxide certainly warrants the steadfast commitment of the world's major emitters to reverse this trend, the "other CO_2 problem" may provide an equal or even more compelling rationale. One can only hope that the world's policymakers will mobilize more quickly to address this issue than was the case with climate change.

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Chapter 15
Advancing Conservation in a Globalized World

Jonathan M. Hoekstra

Abstract In an increasingly globalized world, the impacts of industrial agriculture, forestry, fisheries, and natural resource extraction have become faraway notions that are out of sight, out of mind for too many consumers. To stimulate awareness and fresh thinking about nature conservation, this chapter begins by examining people's expansive ecological footprint – cumulatively through population density, land use and infrastructure, and individually through the products people purchase. A global analysis juxtaposing maps of habitat loss and habitat protection reveals a "biome crisis" in the world's temperate grasslands and Mediterranean habitats, and in 305 "crisis ecoregions" where the extent of habitat loss has outpaced habitat protection by at least a factor of two. This disparity threatens species and puts the sustainability of entire ecosystems in peril. Rising to this and other challenges to conservation in a globalized world depends on harnessing information technologies like Google Earth to raise awareness of problems and solutions around the world. It also depends on valuing nature for the essential benefits it provides to people – benefits such as clean water for cities and climate-moderating carbon sequestration. Establishing these values promises to make conservation a more integrated part of both local and global economies.

15.1 Introduction

We live in an increasingly globalized world. Corner markets sell fresh fruit from thousands of miles away. Retail stores sell clothing and electronics manufactured halfway around the world. Cell phones and the internet enable people to talk to almost anyone, anytime, anywhere around the world. This is all possible because of globalization. And it seems to be accelerating as government policies promoting free trade, multilateral institutions like the World Trade Organization, and technology allow more goods and services to be exchanged more rapidly over longer distances. People are connected to one another, and economies are integrated as never before.

At the same time, people seem to be more disconnected from their natural environment. For the first time in human history, more people live in cities than in rural areas (United Nations 2006). With so many goods and services transported from other places, the impacts of industrial agriculture, forestry, fisheries, and natural resource extraction have become faraway notions that are out of sight, out of mind. The impacts are tangible only where urban development encroaches on natural habitats. Even then,