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Environmental Costs of Aquaculture

Introduction:

Fish farms produce about 25 percent of the seafood people eat worldwide. That percentage is likely to increase because most wild fish stocks are overexploited. Traditional fish farming as practiced in parts of China and India has been sustainable and has provided people with an important source of protein. These fish — tilapia, carp, catfish — eat microscopic plants and animals. Salmon on the other hand are high level predators that eat fish in the wild. Three pounds of wild-caught fish need to be processed into feed to produce one pound of farmed salmon. About one third of the world's total fish harvest is now coverted to fish meal and fish oils to make livestock feed, primarily for chickens, but also pigs, cattle, and farmed fish. This places an additional burden on the world's already overtaxed fisheries.

In addition, some forms of aquaculture are highly destructive, especially in Latin America and Asia where wholesale conversion of shorelines to shrimp farms has wiped out mangrove forests and displaced local fishermen. We spoke with Rebecca Goldburg one of the authors of a recent *Science* article about the environmental costs and benefits of aquaculture[1].

ER: Dr. Goldburg, what is your training?

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RG: I have a Bachelor's degree in statistics from Princeton University, a Master's degree in statistics, and a Doctorate in ecology from the University of Minnesota in the College of Biological Sciences. My Ph.D. dissertation involved a study of plant-insect interactions, nothing to do with fish, but since coming to the Environmental Defense Fund I have worked more on issues related to marine life. I have been at EDF for twelve years and I'm a senior scientist here. During my time here I have primarily worked on issues concerning agriculture, I've done a lot of work on risks associated with genetic engineering in agriculture, and more recently have spent a lot of time looking at the rapid growth of the fish farming industry.

ER: What is EDF's mission?

RG: EDF is a national non-profit environmental research and advocacy organization. We were founded in 1967 on Long Island by a group of scientists who were also bird watchers and who had observed the decline of osprey populations. They attributed that to the spraying of DDT to control mosquitoes, and when they tried to convince the Suffolk County mosquito control district that they shouldn't spray DDT, they didn't meet much success so they got together with a lawyer and brought the first lawsuit against the use of DDT. And that was how EDF was formed.

EDF has grown tremendously since then. We now have six offices around the country; we're headquartered in New York State on eastern Long Island. We have many staff members who are trained as scientists, and in addition have a number of economists on staff. We try to bring together staff members with complementary technical and advocacy skills to advocate solutions to environmental problems. So we work on a variety of environmental issues: from large scale problems like global warming to various state issues in areas where we have offices[2].

ER: How did you get involved in shrimp and salmon farming?

RG: Several years ago EDF founded an Oceans Program and soon afterwards went through a strategic planning process and made the Oceans Program one of it's four core areas. I became interested in aquaculture when I realized that in the context of my work on genetic engineering that the first genetically engineered animal likely to be commercialized would be a fish. That's because the aquaculture industry is relatively immature compared to agriculture. Fish that are grown in aquaculture have not been genetically modified much if at all. The industry has been growing worldwide about 10 percent per year, so there is a big interest in improving fish stocks for fish farms.

That realization piqued my interest in aquaculture as an area that wasn't getting much attention from the environmental community, yet it has the potential to have considerable environmental impact, since fish are necessarily grown in the water. And with my background working in agriculture, a mantra there is you don't want fertilizers or pesticides to end up in the water supply. But in aquaculture everything's already happening in the water, and so it struck me that there was probably a need to take a hard look at aquaculture practices. So several years ago I began to do that and immediately discovered that shrimp and salmon farming are the two forms of aquaculture that are both fairly large and highly unsustainable, and that despite the problems, these activities were being promoted with aquaculture in general, in part as a way of providing more fish for the world. Yet I already knew that assumption, that reason for promoting aquaculture, wouldn't stand close scrutiny.

ER: How did you know that?

RG: About two years ago I started working on a report on the environmental effects of aquaculture in the United States, and about a year ago published a report called *Murky Waters: Environmental Effects of Aquaculture in the United States*[3] and at that time examined the environmental effects of aquaculture practices.

For the past several years I have also been involved with non-government organizations around the world that are concerned about aquaculture. A burning issue was shrimp farming because it has grown extraordinarily rapidly in the past couple decades in many areas of the world, particularly in Asia and Latin America, and the result has been considerable destruction of coastline, destruction of mangrove forests and displacement of subsistence fishermen. It's one of the hot-button environmental issues in Ecuador, India, Thailand. So I came to the *Science* paper having spent a fair amount of time on the issues surrounding aquaculture. And while I remain a supporter of aquaculture in general, my feeling is that some forms of aquaculture are highly environmentally destructive, shouldn't be promoted, make no sense as alternative forms of fish production, and are destroying ocean resources not augmenting them.

...the shrimp farming industry in some parts of the world has been so rapacious that countries have taken extreme measures to block it.

In working with my colleagues to think through pressing marine issues, it struck us that the most pressing set of marine issues weren't pollution, weren't oil spills, but were overfishing and fisheries practices which are collapsing fish stocks and ruining marine habitat around the world. And if EDF was going to address fisheries we shouldn't ignore fish farming since it supplies more than one quarter of the seafood consumed by people worldwide. That percentage will grow because we simply can't take more fish out of the ocean, we're taking too many already, so the only way to supply more fish is through fish farming.

Moreover, while some forms of fish farming are highly environmentally destructive, at least in principle fish farming makes sense ecologically because fish are cold-blooded creatures and have lower feed conversion ratios than, say, cows or pigs or even chickens. So in theory, fish farming offers many benefits. In fact some forms of fish farming, like production of carp in China or various carps and tilapia in India, have proven a sustainable form of aquaculture over the past hundreds of years or even millennia, and remain important in providing local people with protein. So aquaculture can be a useful way of producing animal protein for the world. However, that's not true for all fish, particularly shrimp and salmon, which are produced

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around the world primarily for consumption in industrialized countries as luxury products.

ER: What are the problems with shrimp farming?

RG: My experience working on shrimp farming issues has been a real education to me in that there are still some fairly black and white issues in this world. Environmental issues in the U.S. are often complicated, but the shrimp farming industry in some parts of the world has been so rapacious that countries have taken extreme measures to block it. For example, in India in the early to mid-1990s several non-government organizations sued to block the continuing growth of the Indian shrimp farming industry, which was eating up coastline along the east coast of India, displacing people and causing environmental destruction.

The effects of shrimp farming in India were so devastating both socio-economically and environmentally that in December 1996 the Supreme Court of India ruled that shrimp farming as practiced there was a violation of the Indian Constitution and banned most types of shrimp farming in eastern India within a certain distance of the shoreline. Since then most of the larger shrimp farms in eastern Indian have been dismantled. There is still some shrimp farming, but much less than there was. For the government of India to take such an action says something about the industry, at least as it was in India.

In the early 1990s huge sections of the coastline were converted to ponds because there was so much money to be made from growing shrimp, and shrimp farming was so profitable that people didn't care about stewardship. They wanted to make a fast buck, and so shrimp farming had a Wild West quality.

1995 U.S. Fish Farm Production

	Quantity (Tons)	Percentage of total	Value in millions $U.S.
Total Production	413,431	100	729
Catfish	202,706	49	350
Oysters	109,080	26.4	70.6
Crawfish	26,375	6.4	34.8
Trout	25,240	6.1	52.7
Salmon	14,106	3.4	75.5
Clams	13,481	3.3	19.2
Baitfish	9,883	2.4	71.3
Tilapia	6,838	1.7	22.6
Hybrid striped bass	3,772	0.9	21.2
Marine shrimp	1,000	0.2	8.8
Mussels	930	0.2	1.2
Sturgeon	20	---	.290

Source: FAO 1997

ER: What would they leave behind, when the farms played out?

RG: Craters and destruction of wetlands, particularly mangroves. In some cases rice paddies along coast-

lines were converted into shrimp ponds. In India the conversion was so quick, the land grabs were sometimes so brutal, that Human Rights Watch documented a series of human rights violations in India where people would beat up villagers to get them to relinquish their land rights.

In other parts of the world shrimp farming has had a somewhat different history. The shrimp farming industry isn't one industry, it has national characteristics or at least regional characteristics, because they are not for the most part huge multinational corporations. Most shrimp farms have grown up with capital that comes from relatively wealthy people in India or Thailand or Ecuador. So it's to some degree a home-grown industry and is not as vertically integrated or consolidated as some other forms of agriculture.

In Thailand the shrimp farming industry is different than in India in that there are many small shrimp farmers along the coastline. There has been enormous loss of mangrove forests in Thailand as shrimp farms were built.

ER: Disease has been a big problem for salmon hatcheries. Is it with shrimp farming?

RG: Disease is the Achilles heel of the shrimp industry: it's so self polluting that shrimp are stressed and have big problems with disease. In part because of disease problems, Thai shrimp farmers have moved farms inland and are learning how to farm shrimp at much lower salinity levels, as salt water is imported inland to ponds which are built in rice paddies. And there has been enough growth of the inland shrimp farming industry in Thailand that the Thai government recently banned inland shrimp farming because of concerns about soil salinization and loss of farmland. So although it remains to be seen how successful the Thai government will be at enforcing this new ban, it's another example of a government finding that the effects of the shrimp farming industry are not acceptable. This in a developing country which by U.S. standards doesn't have very rigorous environmental laws.

Ecuador has banned the cutting of mangroves to create shrimp ponds for a number of years, but the ban is frequently flouted by the industry. They go in and build ponds anyway in mangroves. So there are problems with enforcement in many developing countries when it comes to rules and regulations concerning shrimp farming.

I think there can be many beneficial effects of world trade and globalization, but the rapacious sort of development that has occurred with shrimp farming is an example of how if globalization proceeds quickly without attention to the environmental effects of new industries that quickly form to provide products to global markets, there can be some ugly effects.

But I think shrimp farming is not inherently unsustainable. It is possible in theory to run a shrimp farm in a way that makes ecological sense. But unlike salmon, shrimp in the wild are not obligate carnivores, they're more scavengers. And although shrimp feed as it's currently formulated has about 35 percent fish meal content, shrimp feed need not be like that. Shrimp could be and in fact in many traditional systems, are raised largely to eat algae and zooplankton and whatever else is floating in the water. And if one develops a shrimp farm where water is properly treated and shrimp are not stocked too densely, and feeds are formulated in an ecologically sound way, and farms are sited so they're not in the middle of important wildlife habitat or agricultural land, the industry in theory could be relatively environmentally sound. Unfortunately, there are not many examples of shrimp farms like that at the moment.

> ... many people in this country who view themselves as ecologically conscious consumers often prefer to eat fish because they view fish as an environmentally sound and healthier alternative to beef or even chicken. But the ecological effects of fish production are often much worse than other kinds of animal protein production.

ER: What about shrimp farms in the U.S?

RG: There are a number of shrimp farms in the U.S. where the industry historically has not behaved very well, primarily in Texas, because Texas exempted shrimp farms in the late 1980s from wastewater discharge regulations to promote the industry's growth. The industry didn't treat its wastewater and was pouring vast amounts into the Laguna Madre, a

shallow body of water on the Gulf Coast.

But shrimp farmers have to have some reason to develop and, when applicable, pay the extra cost to run environmentally sound systems. And without regulations, or regulations that are enforced, and without any consumer or public perception of what's going on in the industry, there's been no incentive to do that.

One of my realizations has been that many people in this country who view themselves as ecologically conscious consumers often prefer to eat fish because they view fish as an environmentally sound and healthier alternative to beef or even chicken. But the ecological effects of fish production, and I'm using the term broadly to include fin fish and shell fish, are often much worse than other kinds of animal protein production.

So consumers don't have such simple choices to make. I think there is a strong need to create market differentiation in the seafood industry so that consumers can make choices and create some market incentives for seafood producers to produce and market their products as environmentally sound.

I've been working with a committee of the National Organic Standards Board to develop organic certification standards for farm fish. It won't be tomorrow, but perhaps in the next few years consumers will be able to choose organically produced fish as at least one form of market differentiation.

ER: Organic means what?

RG: It means no use of antibiotics; although you can use antibiotics to treat a sick animal, you just then can't sell the animal as organic. But no subtherapeutic use of antibiotics. And it means that the animals are fed organic feed and can't be raised in factory-like conditions. I hope that in the future there will be market incentives for producers who aren't organic to still produce fish in an environmentally sound manner too.

ER: What are the problems with salmon farms?

RG: Well, aquaculture is often promoted, as a means to produce more fish for the world. But what often goes unacknowledged or unrealized is that many fish, particularly those eaten in the developed world, are carnivores and are fed fish meal and fish oil, which are made from wild-caught fish. So we feed fish to fish, with the result that at least for some species there's a net loss of fish protein when fish are farmed.

In the *Science* paper we calculated that it takes almost three pounds of wild-caught fish to produce one pound of farmed salmon. So it's hard to argue that salmon farming takes pressure off of the world's oceans. Arguably it increases the fishing pressure on wild fish populations.

ER: What kinds of fish are converted to fish food?

RG: Most fish that are turned into fish meal and fish oil are small fish such as anchovies, herring, sardines, jack mackerel, and these fish are key components of marine food chains. They tend to be fish that are fairly far down on the food chain and provide food for larger fish, particularly more commercially valuable species.

About one third of the world's total fish harvest is small fish that are converted to fish meal and fish oil. We are taking 30 million metric tons of wild fish out of the ocean every year to make fish meal and fish oil. Given that the oceans produce about 90 million metric tons of fish per year, that has got to be undercutting marine food chains.

Another disturbing aspect of the use of these small fish to make fish meal is that many of these small fish are perfectly acceptable for human consumption. Fishes like sardines or herring are sometimes directed towards human consumption and sometimes directed towards fish meal, depending on market conditions. And in a protein-short world and a world where many people, particularly in developing countries, are quite happy to eat small fish, we are essentially taking fish away from people who could eat them.

I might also point out that small fish are regarded by some nutritionists as an important part of the diet of women and children in developing countries because people eat the bones, and in cultures where much milk isn't drunk they can be an important source of calcium.

So it's a social justice as well as an ecological issue. If we didn't make

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fish meal and fish oil from small fish, or at least made less, there would be a question as to how much of those fish get left in the ocean to support marine food webs and how much should be distributed to people who would eat them directly.

We're using the small fish not for domestic consumption in developing countries where many of these fish are actually caught, but rather for making fish meal to produce fish and other types of animals too for consumption in the developed world.

I should note that aquaculture is not the largest user of fish meal. The largest amount of fish meal is used for poultry production. However, poultry feed has small amounts of fish meal in it as a nutritional supplement, and when fish meal gets expensive, as it does in El Nino years, the poultry industry can substitute it out.

... for some species there's a net loss of fish protein when fish are farmed. It takes almost three pounds of wild-caught fish to produce one pound of farmed salmon.

But for carnivorous fish like salmon, fish meal is an essential ingredient in salmon feeds, which are about 45 percent fish meal. So fish meal is used differently in aquaculture. People are working on substitutes but it's not easy to do.

Salmon farming is quite different than shrimp farming. In principle shrimp farming could some day, if done right, be a relatively sustainable industry. I don't have that feeling about salmon farming.

As it's now practiced, salmon are now largely grown in net pens or net cages in coastal bays and estuaries around the world in places with cold water like the U.K., Norway, Canada, Chile, and the Northern U.S. Basically we're developing salmon feed lots and sticking them into bays and estuaries. Now, people make a big fuss, and EPA is doing a lot of work to consider all the muck that comes out of hog lots and poultry farms, I should say poultry factories. Salmon are not produced, especially in the U.S. on the scale that hogs and pigs are, but if we can't dump pig waste directly into the water, why should fish farmers be able to dump fish waste directly in the water?

Some Swedish colleagues of mine who are co-authors of the *Science* paper, did an analysis some years back of salmon farming in Nordic countries and found that if one applied the same treatment costs to the wastes produced by salmon farms, that salmon farming wouldn't be profitable. In other words, the industry is being subsidized by not having to treat its waste like other industries.

People may argue that salmon farming doesn't cause harm. And it's probably correct that a well sited salmon net pen — in deep water, well flushed water — doesn't have much environmental effect. But if the salmon farming industry grows, it can have serious environmental effects.

The difference is comparable to cattle ranching on the range versus finishing cattle in feed lots. Modern salmon farming methods are an extension of modern confined feed lot methods that have grown up in terrestrial agriculture. In terrestrial agriculture it's OK to have a few cows out in the pasture or on the dairy farm, but when you get concentrated animal feeding operations it's not okay to just dump the waste. And as salmon farms become larger and are more like terrestrial feed lots, they should be subject to the same sort of waste treatment conditions.

ER: Can escaped farm fish cause problems?

RG: Well, it's certainly of real concern. I find it hard to believe that Atlantic salmon aren't going to be eventually established in the Pacific Northwest. There's some evidence in B.C. now that Atlantic salmon may be breeding there, although it has not been confirmed.

But it seems reprehensible to me to grow an exotic species with lots of potential for escape and some potential for establishment in something as flimsy as net pens down the coast of the Pacific Northwest, not so much Washington state, but certainly British Columbia in huge quantities. But the way the industry grows fish in huge net pens where they're so vulnerable to escape is clearly a big problem.

ER: What can be done to improve salmon farm operations?

RG: There's no easy fix. Salmon feeds would have to be radically changed. Many people are working on

Reported Authorized Kill of Bird Predators at Aquaculture Facilities in the U.S. from 1989 to 1993

Species/Group	Total
Swimming Birds	
Double-crested commorant	25,930
Grebes	708
American Coot	475
Common merganser	285
Pelican	225
Mallard	76
Merganser	52
White-winged scoter	48
Western grebe	45
Anhinga	42
Pied-billed grebe	22
American pelican	19
Common eider	14
Goldeneye	10
Old squaw	7
Waders	
Great blue heron	9,443
Great egret	4,242
Black-crowned night heron	1,734
Light blue heron	1,379
Snowy egret	1,208
Heron	362
Green-backed heron	19
Egret	5
Aerial-Divers	
Ring-billed gull	1,050
Belted kingfisher	1,197
Herring gull	847
Gull	514
Common grackle	391
California gull	364
Forster’s tern	285

Caspian tern	178
Common raven	93
Common tern	38
Great horned owl	18
Franklin's gull	17
Bonaparte's gull	17
American crow	14
Total Reported Killed	51,373

Source: OTA

decreasing the fish meal content of salmon feeds, but that would have to be successful and those feeds commercially available. And then I think salmon would have to be grown in some sort of facility where escapes are rare and wastes are treated.

ER: The Swedish paper indicates that would make fish farms uneconomical.

RG: Right. Those calculations only pertained to the Nordic countries. I would argue that to the extent that aquaculture development is encouraged by governments and international agencies, that the kinds of aquaculture that should be encouraged are quite different than salmon farming. We should grow species that are low on the food chain and grow them in a way that doesn't create large pollution problems.

Marine water shellfish are one example. Obviously, there can be problems with growing shellfish too, but they are filter feeders and from the fundamental trophic level perspective they make more sense. Growing a shellfish is like growing a cow or a chicken; salmon, a top level predator, is like growing a tiger or lion. We don't raise tigers for food, we don't raise lions for food, we raise things like cows or chickens, animals that are towards the bottom of the food chain; we should apply the same principle to fish production. But most people think about fish as being cold blooded and therefore efficient. They don't realize that many of them are at the top of the food chain.

ER: Those are the most attractive fish, like tuna and salmon.

RG: Right. And that's okay as long as those fish are taken in limited quantities from sustainable ocean fisheries, but growing them on land and in aquaculture is different.

ER: Whereas traditional lower level seafood is a proven technology.

RG: Yes, and profitable. There are other sorts of fin fish that are farmed in this country and other countries, particularly in fresh water, that are grown in ways that are environmentally more sensible. I don't want to give any form of fish farming an environmental blessing because there are varied issues as fish farming is practiced around the world.

But, for example, catfish are bottom of the food chain fish. Catfish feed in this country is about 3 percent fish meal. Waste from catfish ponds in this country are not now treated, which is a problem, but that could be changed. And if you are starting out to promote aquaculture, they are a good choice of species to raise.

Carp in China are a good example of species that make sense to raise; tilapia can make sense, they are an African fish. Tilapia are very hardy fish that are relatively easy to raise. Their one problem is that they are hardy, and so when they escape they often establish themselves and cause problems that way. But again, grown in the right place or under highly confined conditions, they are ecologically sensible.

ER: What are the disease problems in fish farms?

RG: One issue with fish disease is the importation of fish diseases and the effects of those diseases on other fish. And the other issue is diseases associated with fish that may produce human infections.

On the former issue, I think there is a fair amount to worry about with

aquaculture. As fish are moved around the world to aquaculture facilities with little thought to what diseases are coming with them, obviously you can create some big problems.

For example, there is considerable controversy in Scotland right now that native Scottish salmon have been nearly wiped out by sea lice that have come in with stock for Scottish salmon farms. With shrimp farming there is a disease problem right now in the Gulf of Mexico. Four different shrimp viruses have been detected in the U.S. both in shrimp farms and in wild shrimp. And although the origins of those viruses are not known, it's probable that some have come in with stock imported for shrimp farms in Texas, and others may have come in with frozen shrimp that are processed along the Gulf Coast. Shrimp processors along the Gulf Coast usually don't treat their wastes, shrimp viruses survive freezing, and wastes from shrimp processing plants are heavily laden with viruses. There is considerable concern that we are threatening our Gulf of Mexico shrimp fishery by introducing shrimp viruses.

ER: If any population of animal is concentrated, diseases can become epidemics.

RG: That's one reason confined animal feeding operations, be they aquatic or terrestrial, have bigger problems with disease than more traditional forms of ranching. We now have a problem with transfer of diseases from terrestrial livestock to people, Salmonella is one of the clearest examples. And farm fish do not in any way at the moment pose the same degree of hazard. That said, there is at least some evidence that diseases can be transferred from farm fish to people. There is one well documented incident in Canada, two years ago in which researchers in Toronto showed that a number of people in the Toronto area who bought tilapia got invasive infections of *Streptococcus* from handling diseased tilapia[4]. *Streptococcus* is a fish pathogen. These infections were not life threatening but were serious enough to require treatment.

> If one develops a shrimp farm where water is properly treated and shrimp are not stocked too densely, and feeds are formulated an an ecologically sound way, and farms are sited so they're not in the middle of important wildlife habitat or agricultural ground, the industry in theory could be environmentally sound.

And it is conceivable that as more and more fish are farmed under feedlot conditions, we will see a rise in food-borne pathogens just as we have seen with meat production.

Antibiotics in fish farming is an additional issue, not so much in this country as abroad. Although there is some use of antibiotics in fish farming in the U.S., the process of getting approval to use an antibiotic in farming is expensive, and therefore not so many antibiotics have been licensed for use in aquaculture, although the FDA is working to change that.

But shrimp farms in Asia use large quantities of antibiotics in feeds which are put in the water. That creates low-level concentrations of antibiotic in the water, which is one of the best ways to select for antibiotic-resistant microorganisms. Using high doses of toxins or antibiotics is the way to prevent resistance if you kill virtually all the bugs. The biggest problems occur when you use low doses, so that any bug with a gene that confers drug resistance survives. So there is concern that antibiotics in aquaculture are one more factor leading to antibiotic resistant human pathogens. Scientists at the Centers for Disease Control in Atlanta this year have called on the FDA to quit pushing to register more antibiotics for use in aquaculture in this country because they view putting antibiotics in the water and creating selection pressure for resistance as something that's highly undesirable.

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Tree Reproduction in Fragmented Tropical Forests

The acorn doesn't fall far from the oak. It is common sense that a seedling near an adult tree is likely to be the offspring of that tree. However Preston Aldrich found that this pattern does not hold, at least for one tree species, in tropical rainforests that have been cleared or logged. He used a kind of paternity test to determine which trees in a fragmented forest mosaic had produced which seedlings. The point of the study was to see in what ways the disruption of the forest had changed the behavior of the trees' pollinators and seed dispersers, and to see if the population genetics of the trees were altered. The paternity tests revealed that most of the seedlings of the tree *Symphonia globulifera* were found in forest patches, not out in the clearings, and they were produced by the trees out in the clearings, not by the trees they were near. This spatial pattern could be explained by changes in the behavior of the tree's pollinators which are hummingbirds, and its seed dispersers which are bats.

The reproductive dominance by a few trees could have serious long term consequences for the genetic make up of the population. We spoke with Preston Aldrich, one of the authors of the *Science* paper in which this work was published, about tropical forest recovery patterns[1].

ER: Dr. Aldrich, what is your training?

PA: My Bachelor's degree in chemistry was completed in 1987 at Saint Olaf's College in Minnesota. I got my Master's in botany at the University of Minnesota studying genetic diversity in the grain crop sorghum using seed collections from around the world to study genetic variation and the domestication process. I got my Ph.D. at the University of Georgia in the botany department where I did conservation research with tropical trees. One of the leaders of using genetics in conservation is Jim Hamrick and our paper in *Science* was a portion of my Ph.D. dissertation research.

Then I got a National Science Foundation postdoctoral fellowship to go to the Smithsonian and that's where I am right now. I'm beginning my second year as a fellow at the Smithsonian in the botany department at the Natural History Museum.

There were quite a few seedlings in the forest and the vast majority of them were produced by trees out in the pasture, not by trees inside the patches.

ER: Where was your field work done?

PA: I conducted the field research for my dissertation in Costa Rica working in a mid-elevation thousand-meter rainforest that was fragmented.

ER: Is that site administered by the Organization for Tropical Studies?

PA: Yes, it's near one of their three sites in Costa Rica, the Los Cruces field station. I studied a population of trees in fragmented forest on private property that is close by the Los Cruces field station, and then Los Cruces is associated with a tract of more or less continuous forest, 235 hectares in size, which I used as a control. *[235 hectares is about 580 acres. Ed.]*

My study area is fairly widely fragmented. The entire canton of Coto Brus, the equivalent of a U.S. county, consists of a mosaic of forest patches and pasture; the patches range in size from a half hectare with single trees in a pasture all the way up large pieces of forest like the 235-hectare reserve.

ER: So the large patch was your control forest?

PA: That's right. That's what I treated as continuous forest, though the argument certainly can be made that that patch is a fragment too. And in comparison to what I'm studying now in the Amazon Basin, that control forest was actually a pretty small fragment.

ER: Why were you interested in the animals?

PA: Well, one of the basic things about tropical plants — tropical trees are my particular interest, but tropical plants in general — is that they typically have their pollen moved around by animals, and their seeds are typically moved around by animals as well. In temperate regions in the trees most of the pollination is by wind, as is the seed dispersal. There is a limited amount of animal participation in that process in temperate regions; it's much more prevalent in the tropics.

And so for quite some time it's been of interest to scientists how tropical trees would respond to deforestation and forest fragmentation in that they had these pollination and seed dispersal relationships with bees and bats and butterflies and moths and a variety of animals. How would the trees respond not only as individual

organisms, but as a community? In the trees I studied, *Symphonia globulifera*, the pollen was moved about by hummingbirds — the tree has nice little red flowers — and it has small green fruits that are dispersed largely by bats.

So there were at least three potential components that could change when the forest environment was changed: the plant could respond in some fashion, the hummingbird could respond; and the bat could respond; and all of these alone or together could influence the population biology of the trees.

I initially went in with the intention of studying the genetics of the process. Five to ten years ago when this study was started, the dogma was that once you'd fragmented forest, the pollinators and the seed dispersers would disappear, either they'd go someplace else or the populations would die out; the pollen would stop being moved around and the trees would not be able to mate with other individuals in the population. They would have to self fertilize, which could lead to inbreeding depression and possible genetic troubles.

So my initial idea was to measure rates of gene flow, the movement of pollen and seed genes into fragmented populations to see if these populations in fact were becoming genetically isolated, becoming autonomous units that might diverge on their own paths and eventually crash or have kind of a genetic meltdown.

But in fact I found that the interactions with the animals didn't dissipate, but they changed substantially. I did that by using genetic markers to reconstruct patterns of parentage in the landscape.

ER: How did you do that?

PA: I selected a large plot of forest that had several fragments in it but was predominantly pasture. I mapped all of the adult trees in the area and I collected leaves from them; and I mapped all of the seedlings and collected leaves from those individuals.

And then using the leaves I did genetic analysis on each of these individual trees using highly variable genetic markers called microsatellite markers. This allowed me to do a parentage analysis just like DNA fingerprinting.

Rather than any one tree having an equal chance at reproduction, there were a few individual trees that became dominant in the landscape.

ER: A paternity test.

PA: Exactly. It's just like you'd do for a paternity case with humans where paternity is contested where you'd genotype them and determine who was the likely parent. In that way I was able to reconstruct which trees had produced what seedlings and in what habitats.

There were quite a few seedlings in the forest and the vast majority of the seedlings were being produced by trees out in the pasture, not by trees inside the patches.

Once the population-level genealogy was reconstructed, it became apparent that rather than any tree in the landscape having a more or less equal chance of being involved in a pollination event, instead, there were a few individual trees that became dominant in the landscape.

ER: How could a disrupted forest account for that?

PA: It's possibly because these few pasture trees weren't being shaded by other trees and at least for several years were able to crank out the flowers in large amounts. I would see this when I'd walk around the pasture and see that these trees were producing a lot of flowers. It didn't occur to me until later that they were actually doing most of the reproduction in the landscape, but that's what was happening. The pasture trees were producing tremendous numbers of flowers, and of course the hummingbirds liked that. They would stay there and eat at that tree canopy, as opposed to flying between trees and effecting out crossing. They'd stay at one tree and increase the selfing rate. *[Selfing occurs when a plant pollinates its own flowers. Ed.]* And so many of these seedlings were being produced through self fertilization. That was the first change that appeared.

ER: From the genetic analysis you could see that out crossing was reduced.

PA: Right, yes, relative to continuous forest, and so therefore more or less considered the standard for the species.

ER: What would be the consequences of increased selfing?

PA: That is uncertain for any particular tree species. There is not much information regarding the direct

consequences of inbreeding on development, for instance. It is likely that there is increased possibility for inbreeding depression in the sense that the more selfing there is in a population, the more likely there is going to be homozygous recessive alleles in the population that become expressed.

ER: This is the same reason we don't marry our cousins and sisters.

PA: It's the exact same reason: there is the potential that there could be birth defects revealed in the population from high rates of self fertilization. But there's no guarantee of that. It may be that the population could survive such a thing. But one thing this work does for certain demonstrate is that increased selfing changes the genetic composition of the population.

ER: How do you think inbreeding would affect the forest over time?

PA: Well, the landscape is ordinarily the recruitment pool for the forest, but the new seedlings are no longer a random sample from the population, rather, recruitment is biased towards a few individual trees. Are those trees necessarily the best, most robust individuals in the population? Maybe not. Maybe they became the most fecund and produced the most seedlings just because they happened to be at the right place at the right time during this fragmentation event, and all the sudden now they've produced all of the seedlings. So fragmentation can produce a rapid change in the forest gene pool that may or may not relate to any adaptive change. That's separate from the inbreeding depression problem.

ER: The spatial pattern of new seedlings was odd wasn't it?

PA: Yes. When I was out walking I almost never saw a seedling out in the pasture, I only saw them in remnant forest patches. So even though these trees out in the pasture were producing a copious number of fruits and eventually seedlings, they weren't just dropping beneath the tree and dying in the pasture, they were being brought into the remnant forest. And since the species' seeds are predominantly bat dispersed, it seemed fairly apparent that the bats were taking the seeds and dropping them into the patches. So that is indeed a behavioral change.

In a continuous forest, the bats are in there foraging between the trees, but they typically don't eat the fruit at the tree they collect it from. If there were a large fruiting tree and all of the bats flocked and stayed there, then predators could key on that. So it's a good strategy for the bats to go somewhere else and eat in a roost area.

In a continuous forest the roost could exist pretty much anywhere in the landscape, and so there was no concentration of the seedlings in one particular spot, they were distributed more or less randomly. But when a forest landscape is fragmented, then the distribution of suitable habitats — in this case roosting areas — becomes concentrated into the remnant patches, and so the fragmentation process funnels seeds into the habitat that is still forested and concentrates those pasture seeds there.

ER: You were talking about testing the dogma that if you fragment a forest then the pollinators would have trouble finding their foraging trees, or the pollinators and the dispersers may change. But sometimes dogmas are true, and I was wondering if your pollinators and dispersers are a representative sample or maybe you found a pollinator disperser system that is unusual.

PA: That's a good point. Not all animals are going to behave in the same way, and many species have been documented to behave differently in a fragmented environment: they won't use habitat that has been opened up into a pasture environment. Some species of hummingbirds and some species of bats are known to be willing to use disturbed habitat, whereas other species of the same type are much less inclined to do so.

There are going to be some systems in which fragmentation will produce a loss of pollinators. And then what happens is either you get the dogma occurring where there's a complete lack of pollination service and predominantly selfing if any seed set is produced, or it's possible then that the community response may take

over in the sense that other pollinators may become more abundant and start serving that tree, but perhaps in a different way. And so they could experience a shift in the pollination and a shift in the seed dispersal process because they are now interacting with a different suite of animals.

ER: Are there any general principles by which we can predict changes in a fragmented forest?

PA: That is one of my main concerns. Are there any behavioral aspects that are general across pollinators and seed dispersers that might offer some prediction to what's going to happen? It has been documented for instance, that in fragmented environments Africanized honeybees can become dominant pollinators.

And I'm not saying that what I found is going to apply in each circumstance, but the principles from which these phenomenon occur are quite general. For instance I saw that the pollination process was a density-dependent response. That is, when there is a pocket of high resource, the animal that's foraging is more likely to stay put in one spot and continue eating, as opposed to have just a little lunch and then traipsing twenty miles across the forest to get their next meal. That's called positive density dependence, and that is a widely observed phenomenon across animals.

So if we do have a general response in plants where if they find themselves in a pasture or at a forest edge and they find themselves in a high light environment, granted they may die in five years because the environment is harsh and they may get blown over by wind, but as long as they are experiencing high light levels, they may produce massive flushes of flowers that could attract a pollinator that would be more likely to stay in that environment and produce higher rates of selfing than in a continuous forest environment where the flower set is typically at a smaller level.

And whether that pollination is effected by the native pollinator or some new pollinator that has taken over that habitat now that it's become disturbed, there perhaps is a generalist response that could be important here.

I'm not saying that what I observed is going to be observed in every case. I think that there are going to be many instances where forest fragmentation produces basically what was dogmatized and that is still a big concern. But I think my study shows that these responses can be cryptic. I don't think I would have detected this pattern had I not gone in there with high-powered genetic markers. I was walking around the forest and the seedlings were quite abundant in patches and everything looked fine and I could have left and told someone that that species was doing fine in that habitat.

ER: By cryptic you mean where reproduction was being dominated by a few trees?

PA: That and the fact that the complexity of recruitment in the habitat was not intuitive in the sense that the individuals inside the remnant forest patches were not doing as much of the reproduction as seemed to be the case. When you go into a patch and you see adults of the species and you see seedlings of the same species close by, the inclination is to think that they are linked.

ER: The trees were more like brothers and sisters rather than sons and daughters.

PA: That's right, and the parentage was disassociated or dislocated from the place of recruitment.

ER: How do you intend to test these ideas in your future research?

PA: The project I am going to work on in Brazil has been going on for about twenty years and is to date the largest experimental manipulation of tropical forest. They have different sized patches that are replicated and have been separated from the mainland forest, primary forest, twenty years ago. They've been followed now for some twenty years, people have been studying different aspects of the biology, the birds and the plants.

Not a whole lot has been done with plant genetics though,up to this point, so I and several other people are interested in looking at the plant genetic and population processes. One of the appealing aspects of the project is the ability to replicate different forest size patches. The study site that

> My work is an example of the importance of adapting a landscape perspective whether you're studying basic biology, basic ecology, or if you're doing something more applied, like forestry: to consider the dynamics of the entire landscape to the extent that is feasible.

I worked at in Costa Rica was predominantly pasture with one-hectare patches, whereas down in Brazil there are one-, ten-, and one hundred-hectare patches. I'm going to study the *Symphonia globulifera*, the same species that I studied in Costa Rica, and other species as well. There's *Heliconia acuminata*, an understory herb that is also pollinated by hummingbirds. So it'll be interesting to see how the forest understory behaves as opposed to the canopy layer as far as pollination is concerned.

One of the key questions is to try to understand the spatial dimension at which tropical tree populations are occurring and how that entity changes with fragmentation, because it is an open issue. We're still in the early stages as we're just starting to figure out what a population is. It seems a fairly simple concept. But unless you're talking about a simplistic issue of a population being a collection of organisms, it gets difficult to define. What is a collection of organisms that are interacting in such a way that we can call them a biological population? How much area does that occupy? Where do you draw the lines, and why?

So therefore, if you want to make a forest reserve, how much area do you need to set aside? And how small can you make the patch before the tree population ends up going through substantial changes because of some aspect of its biology, and what aspect is that that's changing?

ER: Conservationists use flagship species or umbrella species when they are trying to put together conservation areas. They will often take the top predator and say if we protect that, then that will protect enough habitats that most other species will also be protected. Is there any corollary to that idea in the plant world?

PA: Probably the closest that you could come to that, at least at this point with our rudimentary knowledge, are the fig species, the species of *Ficus*. There's a fellow who was in the same lab while I was doing my dissertation who was working with fig trees, and what he found was that the population sizes, as he could measure them, appeared to be quite large, covering thousands of kilometers. It's also known that fig species are important keystone species, producing fruit that feed many species in the forest.

Fragmentation can produce a rapid change in the forest gene pool that may or may not relate to any adaptive change.

And so that is a point of departure that one could look at a species such as the genus, or a group of plants such as the genus *Ficus*, and try to decide if there is any way that those species could be managed as an umbrella group.

He found that there was quite a bit of pollen dispersal even over fragmented habitat. And so whether you're actually going to see disruption of that system by fragmentation remains to be seen.

The principle remains, and that is a valid way to look at the problem. If you can manage a population or a species that occupies a large area and is considered important for some reason, then many other species and interactions will fall in place and be maintained below that spatial scale.

At this point, unfortunately, it's difficult to be able to pick and choose species. My study is among the first to start getting at the issue of what the actual size of a population is. It's hard to say, Well, we could use this species and that species. We don't know enough. It underscores the need for basic biology in how that can play into applied science.

ER: It also underscores the need for forest reserves.

PA: That's right.

ER: How does your research fit in with conservation as it is practiced?

PA: Well, I guess an important perspective that's not new but has become a more dominant perspective in ecology and conservation is the landscape perspective. My work is an example of the importance of adapting a landscape perspective whether you're studying basic biology, basic ecology, or if you're doing something more applied like forestry: to consider the dynamics of the entire landscape to the extent that is feasible. I went into this study not with much of a landscape perspective, but with a focus on the patches. I was interested in the dynamics of the patches and measuring the rate of reduction of gene flow into the patch because that's what I thought was going to happen.

But as it turned out, the big interest was in the broader scheme. Not just the patches, but how they were linked together with other aspects of the landscape, predominantly, in this instance at least, with

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trees in the pasture. I didn't foresee that; I had much more of a patch-based mentality going into it.

I left this study with a landscape mentality where if you want to manage that species in that landscape you can't just look at the patches. One could go in there and say, I'm going to maintain this tree species at a high density in these patches because I want to keep it in the landscape, but let's get all these pasture trees out of here. Let's cut them all down because the farmers must not have been complete with their job and, let's just clear it out and put crops in here. But that would reduce the seedling densities in the forest patches quite substantially because that's not landscape perspective.

So I think those are the major implications. I think using genetic markers for things other than just population genetics is also an important aspect that's coming out of the current trend in science too: to study patterns of relatedness and to study population demography as opposed to just genetics. What that allows you to do is to address some basic ecological questions that have gone unanswered or, even worse, assumed wrongly. For instance, because one sees a seedling sitting next to an adult tree, if you read the ecological literature almost without exception it's assumed that the seedling was made by that tree. But at least from my study, and it's not always going to turn out that way, but at least in my study that assumption would be erroneous. This is not rocket science, it's a basic ecological issue that has been answered incorrectly for some time in many different instances.

NEXT MONTH

MONARCH BUTTERFLIES: LOSING HABITAT IN NORTH AMERICA AND MEXICO: CHIP TAYLOR

TRACKING NEOTROPICAL MIGRATORY BIRDS: PETER MARRA

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