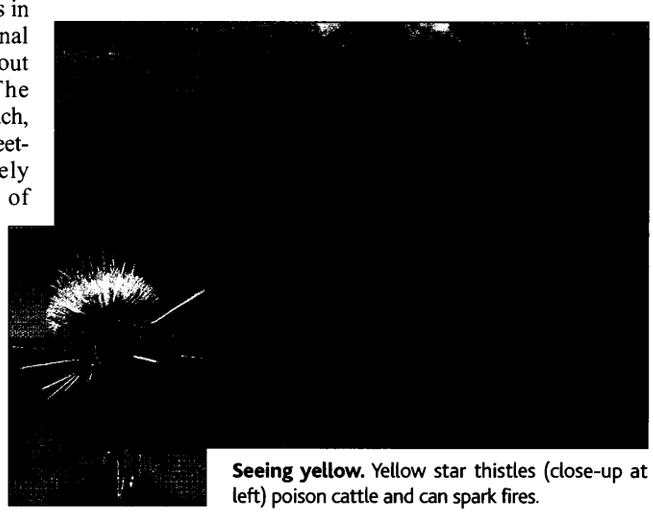
But a growing number of researchers think it's exactly the other way around. "To those small-scale experimenters and modelers I say: Go take a hike," says ecologist Tom Stohlgren of Colorado State University in Fort Collins—and he means it literally. His team recently sampled 100 plots in nine natural grasslands, national parks, and wildlands throughout the central United States. The number of exotic species in each, he reported at an ecological meeting last month, was positively correlated with the number of native species. The very circumstances that favor a wealth of native species, says Stohlgren, such as light, water, and nitrogen, also make a place attractive to newcomers. And experiments with just a few species don't remotely resemble real life, he adds.

There's yet another shadow on the prospects of prediction. Scientists have repeatedly witnessed exotic species living inconspicuously in their new habitat for decades—until the population suddenly explodes like Teletubbies in a toy store. In some cases, the reasons were obvious: Three species of exotic fig trees grown in Florida gardens for a century started spreading only 20 years or so ago—after the arrival of the fig wasp species that pollinate them. But often, such lag times are "quite mysterious," says ecologist Daniel Simberloff of the University of Tennessee, Knoxville. Take Brazilian pepper, "an incredibly awful" invader in south Florida, Simberloff says. "It sat around in people's yards as a harmless ornamental for many years, doing nothing. And suddenly in the late '40s, early '50s, it exploded"—and nobody knows why.

The zebra mussel is another case in point. Scientists have predicted its arrival into the Great Lakes from Europe via ballast water since the 1920s, says aquatic invasion expert James Carlton of Williams College–Mystic Seaport in Mystic, Connecticut. Yet the invasion just didn't happen. "By 1988, it would have been a worthwhile academic exercise to figure out why zebra mussels could not successfully establish themselves in America," says Carlton. It's still not clear why the animal finally invaded when it did. One possibility is that some change in the environment makes it more suitable to a particular exotic species, says Simberloff, although it's often unclear what that is. (In the case of the zebra mussel, ironically, improving water quality in the Great Lakes has been blamed.)

Another likely boost to an invader's chances is simply repeated and widespread introduction. Robert Pemberton, a weed scientist with the USDA Agricultural Research Service in Fort Lauderdale, Florida, recently leafed through old catalogs from the Royal Palm Nurseries, a famous, trendsetting company that bred and sold plants in Manatee County, Florida, from 1881 to 1937. He found that plants sold for just 1 year had only a 1.9% chance of establishing in the wild, while favorites that were in the catalog for over 3 decades had a 68.8% chance of taking hold.



Seeing yellow. Yellow star thistles (close-up at left) poison cattle and can spark fires.

And some species may simply need a stroke of good luck to get started. One reason that cheatgrass exploded in Canyonlands in 1995 and not before, says the USGS's Belnap, is unusually frequent rainfall in late 1994, which spurred germination of hundreds of thousands of dormant seeds. In other parts of the West, fires sometimes wipe out the existing perennials and give annuals like cheatgrass, yellow star thistle, and medusahead rye their lucky break.

Given all this uncertainty, many ecologists are quite modest about their power to predict. For now, just forecasting the advance of a limited group of species in a number of habitats is difficult enough. Belnap, for instance, discovered that at least in Utah soils, cheatgrass often strikes where the potassium-magnesium ratio in the soil is high, suggesting that potassium uptake may be limiting for this species. She's now looking to see if the same holds true for other annual weeds and for other soils. Such studies are arduous, but they may be the only way to go. Says Case of UCSD: "The best approach is case by case." It's scant comfort that there will be many more cases to study.

–MARTIN ENSERINK

BIOLOGICAL INVADERS
FIGHTING BACK

Stemming the Tide of Invading Species

Researchers agree that prevention is the best medicine, but they are also battling established exotic species with everything from chemicals to traps

Last Easter weekend, four divers from Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) research agency splashed into a marina in Darwin on the north coast in a routine inspection. They got an unpleasant surprise: Hundreds of millions of fingernail-sized mussels were clumped in balls stuck to boats, lines, and piers—where no mussels had been 6 months before. Taxonomists identified the critter as a Central American cousin of the zebra mussel, notorious for clogging up North America's Great Lakes. Within 5 days, Australia's Northern Territory government had braved objections from boat owners and quarantined all boats in the marina, closing off the entire 1.5-kilometer-area, and two other marinas where the black-striped mussel had been spotted. Then they poisoned the marinas with chlorine and copper, killing every living thing in the water.

It sounds like drastic medicine, but no black-striped mussels have been seen since, the natural biota is bouncing back, and CSIRO is counting the $1.5 million strike as perhaps one of the most dramatic defeats ever of a marine invader. "Nobody's questioning it at all," says Ron Thresher, head of the CSIRO Centre for Research on Introduced Marine Pests in Hobart, Tasmania. "If it shows up again, we'll do it again."

Australia's quick victory over the mussel, which probably arrived stuck to a yacht's hull, shows that it is possible to battle exotic species and win. The world's ecosystems will never revert to the pristine state they enjoyed before humans began to routinely crisscross the globe, and the pet and nursery industries still import many alien species. But people are fighting back against invasive species as never before, with weapons ranging from ballast-water exchanges that

CREDIT: U.S. DEPARTMENT OF THE INTERIOR (BLM)

Vanquishing Nutria: Where There's a Will, There's a Way

CAMBRIDGE, UNITED KINGDOM—In the 1920s, enterprising English farmers imported a large South American rodent whose glossy brown pelt was a hit with fur-loving flappers. But the farmers soon realized that the fur was the only appealing trait of the animal they called the coypu, which escaped their farms and ran rampant through the low-lying fields and wetlands of eastern England. The 7-kilogram rodents devoured crops and native reeds, and burrowed into river dikes. Early eradication efforts failed. But persistent British biologists zeroed in on the animal's weaknesses, and a campaign that killed nearly 35,000 animals in 6 years finally ended the invasion in 1989. Coypu, also called nutria, have never troubled the British Isles again.

Today, however, the rodents are wreaking havoc across the Atlantic. Worried biologists are watching them eat their way through sensitive coastal wetlands, where their digging allows salt water to invade and poison vegetation. Drawn by the unusual success of the British effort—the only eradication of widely dispersed vertebrates in recent decades—American researchers have adopted its strategies for their own efforts. "It could be a model of how to deal with invasive mammals," says Robert Colona, a biologist for the Maryland Department of Natural Resources (DNR).

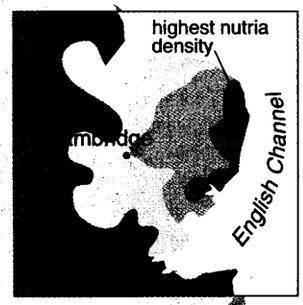
Conventional wisdom has it that once an alien species is well established in new territory, the prospect of eradicating it is rather dim (see main text). Most attempts—from whacking away Japanese seaweed clogging English harbors to poisoning fire ants in the southern United States—have failed, except on small islands. "When something builds up a strong population, getting rid of it is almost impossible," says Roger Mitchell, head of biodiversity for English Nature, a government advisory group.

But Britain's battle of the nutria belies that wisdom and suggests that, as in any territorial conflict, unanimous political support and overwhelming force can win the day. It was not a skirmish: By the 1950s, long after the market in pelts had faded, some 200,000 nutria had made their home in more than 12,500 square kilometers of English soil. In 1962 the Ministry of Agriculture, Fisheries and Food (MAFF) established the Coypu Research Laboratory (CRL) in Norwich, with a half-dozen scientists and 14 trappers. After 3 years—combined with a winter of record-breaking cold—researchers estimated that 90% of the nutria were dead.

But a spell of mild winters followed, and the population began to explode, says Morris Gosling, a zoologist at the University of Newcastle in the U.K., who headed the CRL. To create a more realistic battle plan, CRL scientists decided they needed to know more about the enemy. By catching and dissecting more than 30,000 nutria they learned, for example, that females abort litters in severe cold—implying that trappers would have their hands full after warm winters. To better estimate population size and therefore the number of trappers needed, the scientists tallied trapped animals' sexes and ages.

These data allowed researchers to predict the workforce needed, a firm price tag, and a completion date—all of which proved vital to winning the government's commitment to a second, $4 million assault, says Gosling. That second attack worked. From 1981 to 1986 trapping records and modeling indicated that the population had dropped to 40. No nutria were caught after 1987, although trappers searched for two more years. "The popular view was that it couldn't be done," says Gosling.

Can this success be repeated elsewhere? Officials in Maryland hope so. "It's like a cancer that's eating the marsh from the inside," says Colona. In the Blackwater National Wildlife Refuge alone, nutria ranks have swelled from 150 in 1968 to up to 50,000 today. With 21 partners, the DNR last year put the finishing touches on plans for a $3.8 million pilot project modeled heavily on the MAFF campaign. The plan—which is not yet fully funded—calls for research into how nutria behave and reproduce in Maryland, plus a trial eradication on a test site.



Entrenched. By 1981, nutria occupied much of eastern England.

Officials warn that eradication may be harder in the United States, where nutria seem to be much more prolific breeders. With the rodents gnawing on nearly half a million hectares of land in National Wildlife Refuges alone, the stakes are high. "Nothing like this has ever been tried in North America before," says Colona. "The other 15 states with nutria problems are waiting for us to give them the answer."

—ERIK STOKSTAD

CREDITS: (TOP TO BOTTOM) WADE HENRY/MARYLAND DEPT. OF NATURAL RESOURCES, WILDLIFE & HERITAGE DIVISION, CARIN CAIN

keep species out of harbors, to parasites that attack exotic plants and insects (see p. 1841). On heavily invaded territory, such as parts of Hawaii, fenced "exclosures" claim at least some patches of territory for the natives (see sidebar on p. 1837). "There's more interest in invasives now than there has been in the last 25 years," says Jim Carlton, a marine biologist at Williams College–Mystic Seaport in Mystic, Connecticut.

Researchers agree that preventing an invasive species from getting in is far and away the best and cheapest approach. But they are having increased success at managing exotics that have already landed. Although conventional wisdom once held that removing an already established exotic is all but impossible, some scientists are becoming more optimistic that local invasions can sometimes be stopped—if they're caught in time. Invaders such as parasitic worms in California abalone and a South American rodent ravaging British estates (see sidebar above) have succumbed to aggressive counterattacks. "The practical approach is to have a diverse portfolio: Prevent as many things as you can and control the things you can control," says Liz Chornesky, a senior scientist with The Nature Conservancy.

Still, stopping ongoing invasions is a daunting task, and even preventing them is not easy. Because of the scope of the problem, and because exotic plants and animals are transported as part of international trade, control measures "potentially step on a lot of toes," says Daniel Simberloff, an ecologist at the University of Tennessee, Knoxville. Tackling invasives requires not only beefing up the budget—more than $500 million in the United States, with the bulk of the money going for customs inspections—but also politically sensitive steps such as cracking down on what timber companies can import and plant nurseries can sell. "It's very easy to get people aware of the problem. ... But there are some parts of this that are really intractable," says Alan Holt, a senior scientist with The Nature Conservancy.

Closing the borders

One strategy is simply to ban traffic in exotic species known to pose a threat. Today, in addition to a hodgepodge of federal and state laws restricting transport of various plants, animals, and insects, the United States bans imports of more than 100 troublemaker taxa on "blacklists" established by various agencies. But blacklists will always be incomplete, leaving the door open for many other noxious organisms.

One solution comes from Australia. In mid-1997, in a policy also followed by New Zealand, it adopted a "white list" model for plants: All plant species are barred unless they have been determined to be safe. For new plants, officials developed a 49-question form handed out at airports and seaports that asks, for example, whether a species has been invasive elsewhere or reproduces by windblown seeds. The weed questionnaire has slowed influx of new species "by about 30%," says CSIRO ecologist Mark Lonsdale.

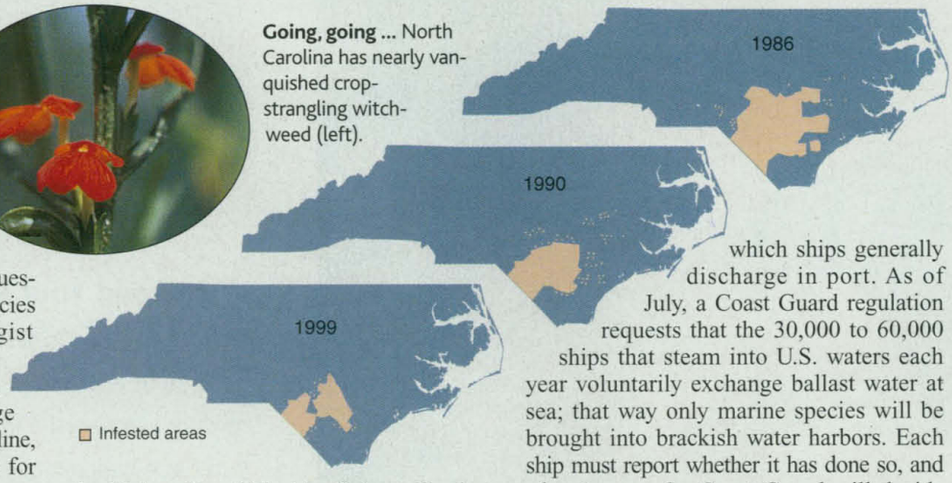
As U.S. exotics from the zebra mussel to a Western weed called leafy spurge make a huge dent in the nation's bottom line, researchers argue that the time is right for such strict measures. "I don't see why we couldn't do something as stringent as [what] Australia [has done], personally," says Bill Brown, science adviser to Interior Secretary Bruce Babbitt. Many scientists also favor this approach. "The burden of proof would be on the person bringing it in. That changes things quite a bit," says San Francisco Estuary Institute marine biologist Andrew Cohen.

Back in the 1970s, however, the U.S. Fish and Wildlife Service proposed such a white list policy—and got nowhere. "They had their heads handed back to them" after the pet and nursery industries—and even some scientific groups—skewered the idea, says Don Schmitz, a biologist with the Florida Department of Environmental Protection.

The prospect of tighter regulations on exotic species still riles powerful industries, including nurseries and pet stores. Marshall Meyers, general counsel for the Pet Industry Joint Advisory Council, fears that officials may regulate "easy targets" like animals sold in pet stores, even if accidental introductions or biocontrol agents gone awry are a greater threat.

And the booming gardening industry is probably an even bigger importer of pests, researchers say. Richard Mack, an ecologist at Washington State University in Pullman, says that he "keeps a collection of seed packets that I bought in U.S. garden stores and nurseries that shouldn't be sold anywhere in the country," like the Brazilian pepper and even seemingly innocent European baby's breath. Both species are already problem weeds in some states, yet are sold legally.

Nurseries are still opposed to legal restrictions, but they are beginning to take voluntary measures. For example, the Florida Nurserymen & Growers Association recently identified 24 marketed species on a blacklist drawn up by Florida's Exotic Pest Plant Council—and decided to discourage trade in 11 of them. True, those were the least promising sellers, says exotic plant expert Ken Langeland, a researcher at the University of Florida, Gainesville, but stopping such sales can help slow invasions: "It's a major step. Before, they were just pushing the issue aside and ignoring it."



Going, going ... North Carolina has nearly vanquished crop-strangling witchweed (left).

Of course, even if intentional traffic in exotic species is slowed, there remains the tougher problem of those organisms that sneak in with the inadvertent help of humans, such as the Asian clams that hitchhiked into San Francisco Bay in ballast water, or voracious brown tree snakes that arrived in Texas hidden in a cargo shipment. "Accidental introductions will be much more difficult to address," says ecologist Jennifer Ruesink of the University of Washington, Seattle. Global traffic is so heavy that "there's excellent evidence now that whatever can get in, will get in."

Still, there are ways to help prevent such stealth invasions, too. The United States is focusing on one vulnerable spot—ballast water, often a veritable aquarium of exotic species, which ships generally discharge in port. As of July, a Coast Guard regulation requests that the 30,000 to 60,000 ships that steam into U.S. waters each year voluntarily exchange ballast water at sea; that way only marine species will be brought into brackish water harbors. Each ship must report whether it has done so, and after 2 years the Coast Guard will decide whether to make exchanges mandatory. But exchanging ballast risks unbalancing the ship in rough seas, and spot checks in the United States and Australia suggest that many captains lie about the exchange. A better long-term fix may be to sterilize the water with ultraviolet light or biocides, says Smithsonian Institution marine biologist Greg Ruiz.

Lethal dose. At this marina in Darwin, officials poisoned everything, including invading mussels.

Other pathways require even more creative solutions. The Asian longhorn beetle, for example, a pest whose larvae are now devouring hardwoods in New York City and Chicago, likely hitchhiked in on wooden packing crates and pallets from China around 1996. Experts are still struggling with their options, Brown says: Short of banning wood packing materials altogether, the government might require that the wood be fumigated or heat-treated at its port of origin, or even allow only plastic pallets. Other pest conduits, such as personal mail, can't be addressed without trampling on people's civil rights. "If you want to send me a brown tree snake, just put it in first-class mail," says Holt.

Contain and control measures

For those invaders that inevitably get across borders, the other half of the challenge is to craft better management strategies, including a monitoring network for spotting invaders early, researchers say. Australia's victory over the mussels, for example, was triggered by a new monitoring effort that sent

CREDITS: (TOP) NORTH CAROLINA DEPT. OF AGRICULTURE AND CONSUMER SERVICES; (BOTTOM) NORTHERN TERRITORY DEPARTMENT OF PRIMARY INDUSTRY AND FISHERIES

divers down to inspect boats and piers. But most existing monitoring programs don't track species in sufficient taxonomic detail.

Once the alarm is raised, wiping out recently established invaders can be done if there's enough political will to do it, insists Simberloff. He notes that the medfly has twice been eradicated from Florida, and over the past decade North Carolina has almost conquered witchweed—a parasitic plant from Africa that strangles corn and sorghum crops—with a combination of hand pulling, chemicals, and quarantines (see maps on p. 1839). California scientists last month declared victory over a South African parasitic worm that infects a wild abalone species, after having plucked from shorelines 1.5 million black turban snails, one of the worm's main hosts. "By far and away, the most effective and cheapest way is to destroy it soon after you've discovered it," says Mack.

For those invaders already too entrenched to remove, coordinated effort can keep them in check—but such coordination is often lacking. Indeed, sometimes federal or state agencies actually help spread exotic species. For example, the Natural Resources Conservation Service, a U.S. Department of Agriculture agency that has focused on tasks such as helping farmers reduce soil erosion, has a history of planting non-native, weedy species to reduce the threat of forest fires or stabilize road embankments. Or one agency will spray weeds with pesticides, thwarting another agency's biocontrol insects released on the weeds in an adjacent field.

To eliminate such problems, President Bill Clinton in February signed an executive order calling on federal agencies to stop activities that spread invasive species; the order also created a high-level federal council charged with devising a "management plan" for invasive species by August 2000. With this new high-level directive, "I'm hopeful that cross-purposes will disappear," says Mack. For even more coordination, Simberloff, Schmitz, and some others are lobbying for a government-sponsored North American Center for Biological Invasions to keep a directory of experts and maintain a sort of 911 emergency number that anyone could call to report an invasion.

Ultimately, it will take action on the part of millions of individuals to stop the tide of invaders. Perhaps one model is Australia, where "the average taxi driver" is well aware of the devastation wrought by invading species, says CSIRO's Thresher, an American expatriate. Such a culture supports strong measures, such as insecticide spraying on arriving overseas flights, and airport "amnesty boxes" where passengers can hand over fruits or wood.

Right now such tactics are hard to envision elsewhere, but even so, some scientists are increasingly optimistic. "I'm amazed at the attention that's coalescing around this, the disparate factions," says Nature Conservancy senior scientist Bruce Stein. Adds Simberloff: "This has taken so long to get under way. I'm hoping for the moon."

—JOCELYN KAISER

BIOLOGICAL INVADERS
▶ BIOLOGICAL CONTROL

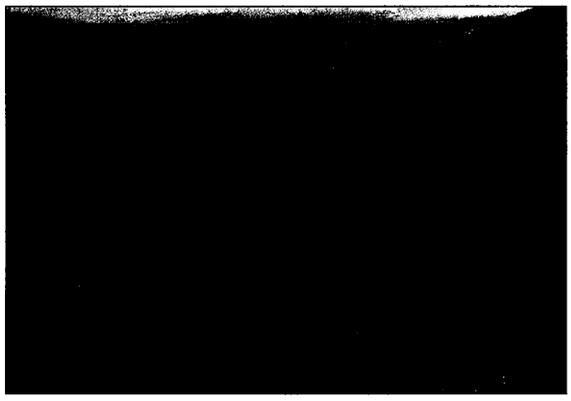
Fighting Fire With Fire

Demand is up for natural enemies, from insects to viruses, to keep invaders in check. But ecologists warn that this tactic may backfire

WEST BOULDER RIVER, MONTANA—On a hot afternoon, rancher Matt Pierson drags a heavy hose down a steep hillside, straining to spray weed killer on a patch of showy, yellow-leaved plants. "If we don't get 'em now, they'll spread and it will take even more spraying next year," says the fifth-generation rancher. His target: leafy spurge, a Eurasian perennial that invaded Montana at the turn of the century and now threatens to crowd out native grasses favored by cattle and wildlife. Someday, however, Pierson would like to hand off the back-breaking weed work to some unusual hired hands: swarms of flies and beetles, imported from the spurge's Asian homeland due to their taste for the plant.

The hungry swarms, he hopes, can repeat the success of another insect, a seed-eating weevil that Pierson and other ranchers used to subdue Russian thistles, a.k.a. tumbleweed. The weevil "knocked back the thistles in a year. It was great," Pierson says.

That's the promise of what researchers call classical biological control—fighting fire with fire by importing natural enemies of exotic weeds and pests. As the menace posed by biological invaders grows, many scientists are turning to biocontrol as the most sophisticated solution, safer and cheaper than chemicals or mechanical killing methods, and perhaps the only practical way to suppress exotics in remote areas. Governments bent on reducing chemical use are pushing the search for natural henchmen, and biocontrol—once chiefly restricted to agricultural pests—is becoming a high-profile tool for fighting invaders of all kinds, with dozens of agents released worldwide each year.



CREDIT: S. DEWEY/UTAH STATE UNIVERSITY

Green binge. Ranchers hope an array of imported insects can beat back leafy spurge (greenish yellow).

But biocontrol has its own dangers, some environmentalists and ecologists warn: The "good" exotics may become problems themselves, attacking nontarget native species or reshuffling ecosystems in unwanted ways. The weevil that Pierson admires, for instance, has also attacked some rare native thistles, sparking debate over prerelease testing and postrelease monitoring. Controversy also swirls around a host of other biocontrol agents, including a mosquito-eating fish that munches on threatened amphibians, and a virus that attacks Australia's rabbits (see sidebar). And even biocontrol researchers admit that the long-term fate of introduced agents is often unknown. Because of these risks, biocontrol "should be a method of last resort," argues ecologist Daniel Simberloff of the University of Tennessee, Knoxville, a longtime critic.

Thus, just as demand for biocontrol is rising, environmentalists and ecologists are scrutinizing it as never before. "The goalposts have moved—we're being challenged to meet tougher standards" for both safety and effectiveness, says weed biocontrol researcher Anthony Willis of Australia's Commonwealth Scientific and Industrial Research Organisation in Canberra.

Centuries of success

It's a new challenge for a strategy that goes back at least 2 centuries. In one of the earliest documented biocontrol efforts, British officials in 1836 released a Brazil-