As a tidal wave of exotic species transforms environments worldwide, ecologists are scrambling to predict where and when new invaders may strike

Biological Invaders Sweep In

One spring morning in 1995, ecologist Jayne Belnap walked into a dry grassland in Canyonlands National Park, Utah, an area that she had been studying for more than 15 years. "I literally stopped and went, 'Oh my God!'" she recalls. The natural grassland—with needle grass, Indian rice grass, saltbush, and the occasional pinyon-juniper tree—that Belnap had seen the year before no longer existed; it had become overgrown with 2-foot-high Eurasian cheatgrass. "I was stunned. It was like the aliens had landed," says Belnap, a researcher with the U.S. Geological Survey (USGS) in Moab. "Now, we've lost this ecosystem forever."

BIOLOGICAL INVADERS

Invasive species now threaten ecosystems of all kinds. As this special Focus explores, predicting invasions is difficult, but scientists are fighting back with weapons ranging from simple traps to biological control.

A few years earlier and a continent away, as Yugoslavia fell apart in a series of wars, Serbian scientists discovered a new enemy in a field near Belgrade airport: the western corn rootworm, apparently flown in from the United States. Vigorous international action might have curbed this pest's first known venture outside North America, says entomologist József Kiss of the University of Agricultural Sciences in Gödöllő, Hungary, but the turmoil of war prevented such a collaboration. Now it's too late. By 1995, the rootworm—which is actually a beetle, *Diabrotica vigifera*, whose wormlike larvae feed on corn roots—had spread into Croatia and Hungary. It has now been spotted in Romania, Bosnia-Herzegovina, Bulgaria, and Italy. There's little doubt that *Diabrotica* will eventually gnaw its way into every corn-producing country in Europe and perhaps beyond, reducing crops and forcing farmers to use chemicals, says Kiss: "There are no limits. It's a big disaster."

Meanwhile, in South Africa, ecologists are bracing for the rise of *Varroa*, a mite that parasitizes honeybees. After sweeping through Europe and North America for decades, *Varroa* was found near the Cape Town harbor in 1997; now it's all over South Africa, and the first colonies have died, says Mike Allsopp, who heads the honeybee section of the Plant Protection Research Institute in Stellenbosch. What worries Allsopp most is the fact that between 50% and 80% of South Africa's native flower species are pollinated by bees—a much higher percentage than in Europe or the United States. "Commercial keepers can keep their colonies alive with chemical treatments," says Allsopp. "But if *Varroa* wipes out 99% of the natural colonies, as it has done elsewhere, what effect is that going to have on the indigenous flora? No one really knows."

These are just three examples on a list that could be extended almost endlessly. As the world shrinks and travel and trade boom, plant and animal species have become globetrotters too, sometimes because humans decide to take them along, sometimes by accident. And whereas globalization may be the mantra of the new economy, for the environment it may spell disaster. The innocent-looking zebra mussel, a Eurasian invader that entered U.S. waters in the late 1980s and clings by the thousands to every hard surface it finds, does tens of millions of dollars worth of damage each year by clogging U.S. water pipes. Even worse, exotic species can devour or outcompete species that have called an ecosystem home for tens of thousands of years. Biological invasions are the second biggest cause of biodiversity loss in the United States, after habitat destruction, according to a 1998 study; they could soon become the first.

Marching in. From zebra mussels infesting the Great Lakes (above, a once-submerged shopping cart) to Argentine ants beating back natives in California, no ecosystem is safe from invaders.

Ecologists are paying more and more attention, if only because they increasingly find themselves studying not primordial ecosystems but collections of microbes, plants, and animals from around the world, flung together in an ecological melting pot. "It's the fate of all ecology," says marine ecologist Jeb Byers of the University of California, Santa Barbara. Some ecologists have suggested, only half-jokingly, that the field should start calling itself "mixoecology" or "recombination ecology." Many fear that another century or so of frenetic international traffic will lead to an "ecological homogenization" of the world, with a small number of immensely successful species, like the zebra mussel, cheatgrass, the European house sparrow, and the Argentine ant dominating nature everywhere—a global McEcosystem.

Hopes of arresting this process are spurring new studies. Policy-makers trying to restrict traffic in exotic species and prevent invaders from running rampant (see p. 1836) are hampered by not knowing exactly where the danger will spring up next. If ecologists could identify likely invaders, governments could simply restrict imports of those treacherous species, and managers could mercilessly weed them out or trap them. But making such predictions has been devilishly difficult; the few predictive models are still hotly debated, and they apply to only a narrow range of organisms at best. Some past invasions seem to fit no pattern at all. A true theory of prediction—what several

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researchers call the "Holy Grail of invasion biology"—still proves elusive. "It will always be very difficult to predict," says ecologist Ted Case of the University of California, San Diego (UCSD).

Portrait of an invader

For most of human history, shipping animals and plants around has been considered a good thing. New World colonists brought in seeds, plants, and livestock and took other species back to Europe; 19th century "acclimatization societies" strived to populate America and Australia with European plants, birds, and mammals, including every bird mentioned in Shakespeare's work. Most such imports quickly die, but others—perhaps one in 10—settle into their new home. Of those, perhaps another 10% spread unchecked. As early as the late 19th century, when imported rabbits started ravaging Australian vegetation (see p. 1842), it became clear that newcomers could be dangerous. Now, the U.S. Department of Agriculture (USDA) intercepts about 3000 potential pests at the border every year, but many others make it through, and thousands of exotics are firmly established. In a lush state like Florida, one in every three or four plant species is non-native; in parts of San Francisco Bay, a staggering 99% of all biomass is thought to belong to non-native species.

At home on the range. Eurasian cheatgrass and medusahead rye have invaded and taken over this part of the Snake River Valley in Oregon.

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After a slow start, the field of invasion biology is at last taking off. The journal *Biological Invasions* was launched just last month, and invasion biologists suddenly find themselves attracting more and more grants, students, and postdocs. Hundreds of scientists are staging plant takeovers in the lab or fencing off patches of sea floor to watch competition between marine critters in action. "People who worked on invasions used to feel like bastard children," says ecologist Sarah Reichard of the University of Washington, Seattle. "Like we had said something dirty. Now, all of a sudden everybody is interested. It's great!"

For scientists seeking the ecological principles behind invasions, one place to start is with common traits of invaders. Many researchers have noted, for example, that invaders often grow fast and have short reproductive cycles; plants typically have small seeds that spread easily, and most invaders are generalists that aren't too picky about their environment. Some researchers are now trying to use these commonalities to understand why certain alien species overrun natives while others don't.

Take one of South Africa's biggest pests, pine trees from Europe and the Americas. Introduced for forestry as early as 1680, pines have spread out of plantations and into the Cape's fynbos biome, a richly diverse belt of shrublands north and east of Cape Town, says David Richardson of the University of Cape Town. To understand why only a handful of the 100 or so introduced pine species have encroached on native territory, Richardson, together with Marcel Rejmánek of the University of California, Davis, compared the life histories of invasive and noninvasive pine species. They found that "invasiveness" depends largely on three characteristics that help a species reproduce fast and spread widely: a short interval between successive large seed crops, small seed size, and a short juvenile period. Richardson used these factors to create a "discriminant function" that is "pretty accurate in distinguishing invasive from noninvasive species," he says. And although built on pine studies, it works for other plants as well—the model gave the right answer for 38 of 40 known invasive woody plants.

But such tidy results are rare in other systems. In a recent review in *Ecography*, Mark Williamson of the University of York pointed out serious disagreements among three studies since 1995 that sought common traits among Britain's invasive plants. One found that large seeds favored invasions, another found that it was small seeds, while a third said size didn't matter. Back in the 1980s, the Scientific Committee on Problems of the Environment had raised similar doubts after trying to tease out the factors that make for successful invaders or vulnerable habitats, says Williamson. "We just didn't find anything," he says. "I don't think there is an answer to come up with."

Vulnerable territory

Even if the stereotypical invader's signature is still uncertain, is there a typical ecosystem that easily gets invaded? Many researchers have found that exotic species move in more easily amid other types of ecological disruption. That was the common denominator Case identified in a set of invasions by ants, birds, and geckoes. Argentine ants are abundant in Californian towns and suburbs, says Case, and although they sometimes spread into the surrounding coastal sage scrub, they are never farther than 50 or 100 meters from the humanmade landscape.

Case also studied why native, asexually reproducing geckoes were driven out of Pacific islands by a sexual species from Southeast Asia. Turning Hawaiian aircraft hangars into makeshift laboratories, he watched how well the two species do under different circumstances and found that the newcomers are good at snapping insects on smooth surfaces with abundant light—in other words, on the walls of buildings. The invaders don't do nearly as well in forests, and without urbanization, Case says, they wouldn't have made it.

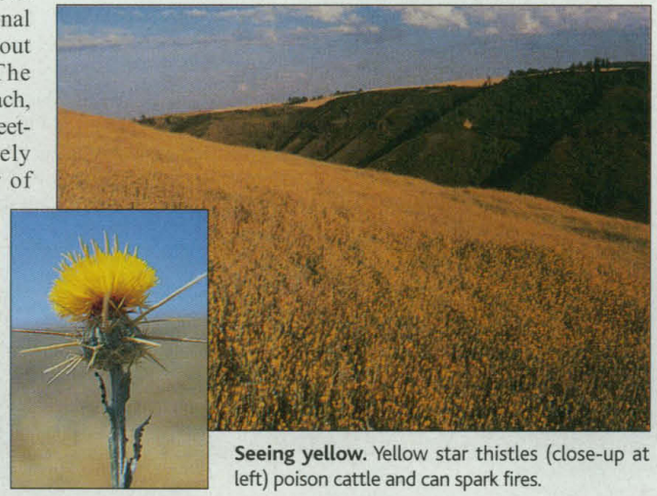
Another long-standing theory is that ecosystems rich in species, with their dense, interconnected webs of ecological relationships, can resist invasions, while those with fewer species succumb. For example, islands—which usually have fewer species than comparable areas of mainland—are often also the most heavily invaded. Models and lab experiments seem to support the idea; in an as-yet-unpublished study, for instance, a team led by John Stachowicz of the University of Connecticut, Groton, created artificial marine ecosystems with anywhere from zero to three North Atlantic species and then seeded each with a known invader, a Pacific tunicate called *Botrylloides diegensis*. The more species there were, the smaller the tunicate's chance of survival.

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

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