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

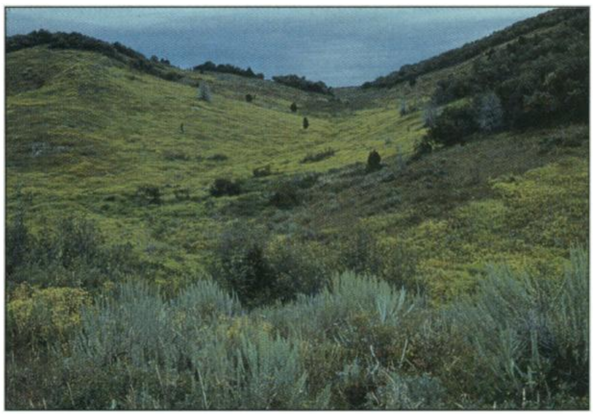
Fighting Fire With Fire

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 backbreaking 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.



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

CREDIT: S. DEWEY/UTAH STATE UNIVERSITY

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 Brazilian scale insect in southern India, where it successfully controlled prickly-pear cactus, a South American import. Since then, published surveys suggest that weed managers worldwide have introduced nearly 300 kinds of insects and pathogens in bids to control more than 50 plants, while pest scientists have loosed nearly 1000 predators, parasites, and pathogens against nearly 500 unwanted insect species.

Biocontrol has remained a hit-or-miss effort, however. Although statistics are scarce, researchers estimate that less than a third of the insects introduced to control other insects have taken hold, and just half of those imported to attack weeds have become established. Even fewer make a dent in target populations. The success rate may be lower still for many microbial, viral, and fungal biocontrols, which often can't stand the stress—differences in climate and sunlight, for example—of new settings. "There are a lot of things you let loose and never see again," says weed biocontrol specialist Ed Coombs of the Oregon Department of Agriculture in Salem.

As a result, some observers dismiss biocontrol as a long shot, especially compared to the seemingly sure bet of killer chemicals. But others argue that the statistics aren't really so gloomy. At a recent conference,* Australian weed scientist Rosalyn McFayden of the Queensland Department of Natural Resources in Sherwood argued that researchers have successfully tackled about 40 of the 50 weeds they have tried to hold in check worldwide, an 80% success rate—even though in many cases they had to try a number of insects or pathogens to find one that worked. "The number of unsuccessful releases is irrelevant," she argues, because it's unrealistic to expect that it will take just one try or one agent to control weeds. Researchers typically try four or more insects per weed, for instance, and U.S. Department of Agriculture (USDA) officials—who help research and must approve U.S. biocontrol agents—have already authorized the release of 13 insects against leafy spurge, with uneven results.

Although even some biocontrol advocates don't buy McFayden's rosy numbers, they agree there are spectacular success stories. Long-snouted weevils and other insects, for instance, have swept exotics such as water hyacinth and Eurasian milfoil from lakes and rivers around the world. The crawlers deliver a one-two punch: Some weaken the plant by gnawing on leaves, stems, or roots, while others devour seeds, eating into the next generation. From New Guinea to Florida, such teamwork has cleared massive mats of vegetation from

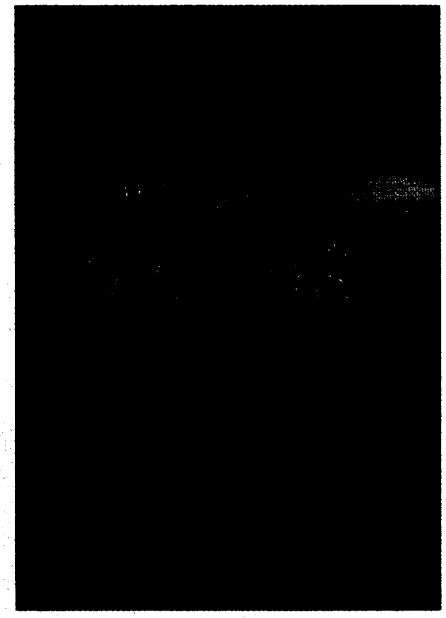
*10th International Symposium on Biological Control of Weeds, Bozeman, Montana, 4 to 14 July.

Australian Biocontrol Beats Rabbits, But Not Rules

MELBOURNE—In 1859, Thomas Austin, one of Victoria's landed gentry, introduced a few European rabbits onto his estate for sport—and Australians have been cursing him ever since. To stop millions of foliage-eating rabbits from turning huge tracts into desert, Australia has become the only nation to successfully use a biocontrol agent on a vertebrate. Officials released the myxomatosis virus in the 1950s, and then, as that virus's potency waned, followed it with the European rabbit calicivirus disease (RCD) in 1995. The new virus appears to be a stunning success: Rabbit numbers are way down and once barren deserts are blooming (*Science*, 10 January 1997, p. 154). Yet for biocontrol officials, the calicivirus experience has been a major embarrassment, a sobering lesson in the unpredictability of biocontrol agents.

The problem is that RCD escaped into the wild while it was still being tested on an island off the Australian coast. The Commonwealth Scientific and Industrial Research Organisation (CSIRO) had already determined that the virus would not harm humans or Australia's unique native mammals. But before the CSIRO could complete field tests on how well the virus spread, flying insects are thought to have picked it up from two infected rabbits and carried it to the mainland. The escape left the CSIRO legally vulnerable and has eroded public trust in biocontrol. "We have a track record of an escape," says Bob Seamark, director of another biocontrol institute, the Pest Animal Control Cooperative Research Center in Canberra. "This is a problem for us," one that may come back to haunt Seamark's agency in a few years when it attempts to release a next-generation biocontrol agent, a myxoma virus that carries an antifertility gene.

Officials had planned to seek public approval for the release—after they finished field trials—as part of an act protecting CSIRO legally should anything go wrong. But because the escape happened before the public consultation was finished, CSIRO now faces a lawsuit from those in the wild rabbit trade, including the makers of Australia's famous icon, the rabbit-pelt Akubra hat.



Next generation. The old cypress pine trees in Murray-Sunset National Park, Australia, predate rabbits; new seedlings now have a chance, as rabbit numbers are down.

CREDIT: P. SANDELL/PARKS VICTORIA

The lesson, biocontrol researchers say, is that biocontrol agents are so likely to escape that agencies should seek public approval before starting field trials. "The question is at what point should the public be responsible for [permitting] the release," says Niall Byrne, a former PR officer for the Australian Animal Health Laboratories in Geelong, which did the testing. If CSIRO had gotten approval before the field trial, then RCD might be considered a complete success.

Indeed, Australia's farmers already count it as such. In the arid zones that make up two-thirds of the country, where rabbits have been most voracious, farmers are reporting near-total eradication and saving an estimated $3 million to $4 million per year in rabbit control. CSIRO ecologist Brian Cooke's studies show that the virus is retaining its punch, unlike the myxomatosis virus, whose effectiveness dropped from 99% to 70% after 4 years. "This is no flash in the pan," he says. And for the first time since the 1800s, there are signs of regeneration in Australia's fragile ecosystems. The vast Nullarbor plain that stretches across the southern coast is coming alive with knee-high acacia seedlings next to big old trees that predate the rabbits; similar scenes of young and old cypress pines can be seen in northern Victoria.

Next time, biocontrol officials say, they'll be as smart about politics as they were about the science. "We got a lot of understanding from the process going wrong," says CSIRO scientist Lyn Hinds. "It wasn't the steps we took but the order we took them in."

—ELIZABETH FINKEL

Elizabeth Finkel writes from Melbourne, Australia.

major rivers once virtually closed to boats and fishing. "Water weeds are the big success of this decade," says McFayden.

Insect biocontrol experts have also claimed numerous victories, usually against agricultural pests. In the United States, for instance, introduced parasites have controlled the alfalfa weevil, once the nation's major alfalfa pest, saving an estimated $90 million annually. "The rate of return on biocontrol is something like $30 [in saved crops] for every $1 invested in research," estimates Keith Hopper, a population ecologist at the USDA's Beneficial Insects Introduction Research Station in Newark, Delaware. For some low-value crops such as dryland wheat, where the cost of pesticides would eat up any profits, biocontrol is the "best option," he says.

Minnows run amok

Along with the success stories, however, are an increasing number of cautionary tales of biocontrol agents gone awry. For instance, for decades Los Angeles County mosquito-control officials have handed out free bucketloads of a small insect-eating fish from the southeastern United States that researchers say also has a devastating appetite for tadpoles. Despite warnings that it should be stocked only into ponds, not free-running streams, in the last decade the *Gambusia* minnow—"Damnboosia" to its detractors—somehow made its way into once fishless streams in the Santa Monica mountains, ecologists Lee Kats and Jeff Goodsell of Pepperdine University in Los Angeles reported last month in *Conservation Biology*. Now, the fish appears to be eating its way through populations of increasingly rare Pacific tree frogs and two other amphibians, just as it has displaced native fish and amphibians in New Zealand and elsewhere. The government "should not be handing out the fish to anyone who asks," says Kats.

An even higher profile controversy involves the thistle-slaying Eurasian weevil *Rhinocyllus conicus*. Two years ago, ecologist Svata Louda of the University of Nebraska, Lincoln, and three other researchers, including Simberloff, published a paper in *Science* (22 August 1997, p. 1088) showing that the weevil's seed-eating larvae are attacking not only Russian thistle but several native North American thistles as well, including at least one rare species. The paper was accompanied by an essay (p. 1058) by ecologist and biocontrol researcher Donald Strong of the Bodega Marine Laboratory in Davis, California, who suggested that the weevil's release in the late 1960s was just one example of a continuing practice—"willy-nilly biological control without regard for environmental costs." The resulting ecological damage could reduce public support for biocontrol, Strong wrote.

Evil weevil? Larvae of *Rhinocyllus conicus* (*right*) attack invading thistles by eating the seedhead, but they may also attack native thistles.

Many in the U.S. weed biocontrol community were outraged by Strong's criticisms. Agents are hardly released "willy-nilly," says Ernest Delfosse, the USDA's point man on biocontrol in Washington, D.C. He says that in most industrialized nations, weed and insect biocontrol agents undergo lengthy "host-specificity" testing, designed to ensure that, even if it's starving, the insect will not attack valuable crops and insects. More and more, such tests—run in the United States by USDA's Animal and Plant Health Inspection Service and reviewed by a panel of government scientists—also include endangered species related to the target.

On the prowl. Mosquito fish (*left*) are given out to munch on mosquitoes but also attack tadpoles of the dwindling Pacific tree frog.

Even at the time of the weevil's release, Delfosse adds, the tests were good enough to show that the insect would feed on the native thistles. The decision to approve the release anyway says more about risk-benefit calculations 30 years ago than about the testing regimen, Delfosse insists. "You can't judge what was done 30 years ago by today's standards," he says, speculating that officials might make a different choice today. Louda and Simberloff aren't so sure: Both note that just 2 years ago, USDA approved the release of another thistle-eating weevil with worryingly broad tastes.

Others note that prerelease testing hasn't prevented some "near-misses," such as allowing imposter insects—which look like the control agent but may have very different behavior—to slip out. USDA researchers in California, for instance, discovered in 1996 that the "wrong" fly had become widely established on a weedy thistle. Luckily, the insect so far hasn't taken a liking to valuable sunflowers, which some tests suggested it might.

To try to eliminate such sloppy practices, researcher Joe Balciunas of USDA's invasive weeds research lab in Albany, California, is promoting a voluntary "code of conduct" for researchers, hoping to "cut out the cowboys" in biocontrol. At the moment, he says, "I'm ending up defending some practices that I'm not comfortable with anymore." His code encourages researchers to target only weeds that pose "serious" problems, and to release as few insects as possible. "Releasing more species is not necessarily better," he says. He's also pushing for expanded follow-up studies so researchers can better evaluate the results—good and bad—of their efforts.

Currently, such follow-up studies are difficult and therefore rare, say researchers. For example, insect "populations [naturally] fluctuate by orders of magnitude," so it can be hard to measure an agent's impact on either target or nontarget insects, says Hopper. And Louda notes that it took nearly 30 years for her weevil to spread into the range of rare thistles, implying long-lasting uncertainty over ill effects.

As a result, scientists don't really know how an insect interacts with other species a year or two—or 20—after its introduction. In particular, agents that get established but don't damage their target are often completely ignored, notes Delfosse. USDA's $40 million biocontrol program, he adds, will now fund only projects that have "detailed postrelease monitoring."

Delfosse and other biocontrol advocates hope such steps will boost public trust in biocontrol by promoting realistic assessments of both its risks and benefits. "Biocontrol is not risk free—and neither is any control strategy," says Delfosse. When it comes to fighting invasive species, he says, "there is no silver bullet."

–DAVID MALAKOFF

CREDITS: (TOP PAIR) N. PORITZ; (BOTTOM LEFT) D. ADDISON/VISUALS UNLIMITED; (BOTTOM RIGHT) P. ZIMINSKI/VISUALS UNLIMITED