Stop loss. Plowed fields (*left*) suffer much more soil erosion than their no-till counterparts.

GLYPHOSATE—THE CONSERVATIONIST'S FRIEND?

Weeds resistant to the powerhouse herbicide glyphosate not only threaten the livelihoods of farmers worldwide, but they could have environmental downsides as well. Among the worst, glyphosate's disappearance could increase the loss of topsoil, require farmers to switch to more harmful herbicides, and force them to use more fuel to rid their fields of weeds.

The current combination of herbicide-resistant crops and herbicide use is hardly an environmental panacea. A 2003 farm-scale evaluation in the United Kingdom, for example, found that the combination contributed to a loss of biodiversity both by reducing the numbers of weeds and by indirectly affecting insects that rely on those weeds for food. Many governments have also been cautious about allowing the use of herbicide-resistant crops for fear that genes that confer herbicide resistance could spread far beyond agricultural fields.

Despite such concerns, many agricultural researchers now say glyphosate-resistant (GR) crops have had widespread environmental benefits, at least compared with the previously used alternatives. "Glyphosate-resistant crop weed management systems are generally safer to the environment than what they replace, and in many cases much safer," says Stephen Duke, a plant physiologist at the U.S. Department of Agriculture's Agricultural Research Service in Oxford, Mississippi.

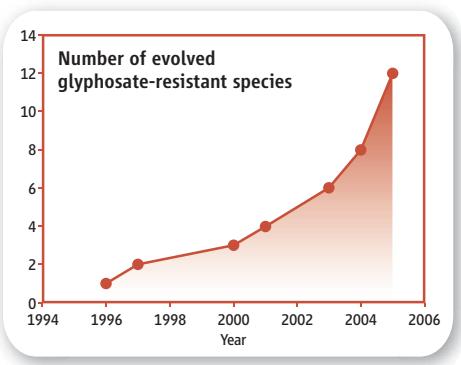
One of the biggest benefits of GR crops is their indirect impact on topsoil. Modern farming encourages heavy topsoil losses because farmers traditionally plow fields before planting seeds. Turning over the topsoil buries many weed seeds that were present under 4 to 6 inches of dirt. Although that reduces the likelihood that weeds will compete with emerging crop plants, it also dramatically increases the amount of topsoil that washes away with rain and irrigation.

By contrast, many farmers don't plow their fields before planting GR crops. Instead, they simply plant seeds and spray glyphosate on their fields shortly after their crops have emerged, wiping out their weedy competitors. The upshot is that herbicide-resistant crops often require minimal

GR weeds don't make a frontal attack on glyphosate. According to Christopher Preston, a weed-management scientist at the University of Adelaide in Australia, one common resistance mechanism centers on the way glyphosate moves within plants. In a presentation at a symposium on glyphosate resistance held as part of the American Chemical Society (ACS) meeting in March in Chicago, Illinois, Preston noted that when glyphosate is sprayed on the leaves of a susceptible plant, it is normally absorbed quickly and moves readily throughout its tissues. Once inside, it accumulates at the growth point in roots and stems and kills the plants. However, when Preston and his colleagues looked at a resistant form of rigid ryegrass, they found that the glyphosate accumulated in the leaf tips. The plant was essentially steering the compound away from areas where it could inflict lethal damage. Preston's team found a similar mechanism of resistance in two populations of horseweed as well, suggesting that glyphosate sequestering could be a mode of resistance common to many weeds.

For now, however, resistant weeds are still the minority. According to the Syngenta survey, 24% of farmers in the northern portion of the Midwestern United States and 29% in the south say they have GR weeds. But only 8% say it's a problem across all of their acreage. Still, Syngenta's Chuck Foresman, who presented the data at the ACS meeting, says, "the resistance issue is across the Midwest, South, and Southeast. Nobody is exempt." Crop scientists from Argentina, Brazil, and Australia echoed growing concerns about the problem in their countries as well.

Backlash. Weeds that tolerate glyphosate are starting to appear throughout the world.



What to do?

Fighting resistance is something of an uphill battle, says Duke. At the moment, not all farmers see resistance as a major issue, but by the time they do, resistance may be so widespread that it will be hard to combat. In recent decades, when resistance to one herbicide has spread, farmers have simply switched to another. But glyphosate's recent dominance of the herbicide market has reduced work on alternatives just when they are needed most. "Weed control is shifting to herbicide-resistant crops, and so are the research budgets," Green says. That's bad news, NCSU's Wilcut says: "We need to have more of a diversity of herbicides out there." But there are no new silver-bullet herbicides that are safe and broadly effective waiting in the wings. "We are not likely to get additional herbicide modes of action," Wilcut says.

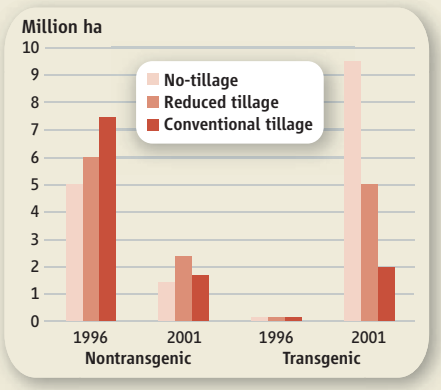
With a multibillion-dollar market for herbicides and transgenic seeds at risk, agricultural researchers underscore the need to educate farmers to use long-standard methods of combating weeds, to preserve glyphosate's effectiveness as long as possible. Among these, says Weeks, are traditional resistance-management strategies of rotating crops and using a variety of different herbicides to combat weeds, practices that hinder resistant organisms from gaining a foothold in their fields. In many cases, that's likely to mean rotating in crops that don't rely on using glyphosate.

Aside from proper stewardship practices, most researchers feel that the best hope for combating herbicide-resistant weeds is the continued development of transgenic crops. Nicholas Duck and colleagues at Athenix, a crop sciences start-up in Durham, North Carolina, for example, are developing crop varieties that are resistant to even higher levels of glyphosate. Planting them may allow farmers to buy some time by applying heavier doses of the herbicide to their crops, but it could add to the selective pressure on weeds to develop resistance.

Other companies, meanwhile, are pushing crops resistant to herbicides other than glyphosate. Bayer Crop Sciences, for example, has already commercialized soybean and corn seeds resistant to glufosinate, a herbicide that kills plants by a different mechanism from glyphosate's. These crops, sold under the trade

Published by AAAS

tilling or no tilling at all. In March, at a symposium on glyphosate at the American Chemical Society meeting in Chicago, Illinois, Pedro Christoffoleti of the University of São Paolo in Brazil reported a recent study in South America that found that growing soybeans with conventional tillage produced topsoil losses of 1.2 tons per hectare. With GR crops planted with no-till practices, those losses shrank to 0.2 tons per hectare, a reduction of more than 80%.



No-till agriculture saves farmers time and money, and for that reason the practice has grown dramatically with the rise of GR crops. In one recent study, the American Soybean Association in Washington, D.C., found that in just 5 years from 1996 to 2001 when herbicide-resistant soybeans first came on the market, the area of soybean land farmed by no-till agriculture in the United States increased from about 5 million hectares to more than 11 million hectares, whereas conventional tillage dropped from close to 8 million hectares to under 4 million hectares. By 2001, almost all no-tillage soybeans were GR varieties. What is more, because no-till agriculture requires less tractor use, the practice reduces soil compaction and cuts fuel use on farms. All those benefits could take big hits should the emergence of GR weeds prompt farmers to abandon glyphosate, Duke says.

Additional impacts could come as farmers switch to herbicides that are more toxic to mammals. Gerald Nelson, an agricultural economist at the University of Illinois, Urbana-Champaign, and his colleagues have recently begun looking at the likely impact of that shift. To do so, they used a common yardstick, known as the LD_{50} dose, to compare the toxicity of various herbicides. The LD_{50} dose is a widely available measurement of the amount of a particular compound required to kill half of a population of rats in lab studies. When the researchers looked at the effect of switching from GR crops to conventional seeds with other herbicides, they found that the switch would require farmers to increase the LD_{50} doses applied to the average U.S. farm by about 10% per hectare in soybeans and 25% per hectare in cotton. Nelson says it's not yet clear how such changes will translate into impacts on organisms other than mammals, such as insects and birds. However, Nelson adds, "there will be some more effects on anything else susceptible to these [alternative] herbicides." **–R.F.S.**

name Liberty Link, have not done as well in the market as glyphosate has because the herbicide is more expensive yet less effective at killing a broad range of weeds. But if GR crops continue to falter, Bayer could find itself a beneficiary.

Dicamba, another cheap herbicide that has been on the market for 4 decades, could also emerge as a successor. Researchers in Texas created dicamba-resistant plants in 2003 by adding the gene for an enzyme that deactivates the herbicide. Seed companies have never managed to develop varieties that expressed enough of the enzyme to fully protect the crops. But in their report in this issue, Weeks and his colleagues managed to do just that, developing soybeans that in 3 years of field trials proved highly resistant to dicamba.

As with previous herbicide-resistant crops, Weeks's team engineered their soybeans to express a bacterial gene that confers resistance, in this case by breaking down the herbicide. But in an ingenious twist, the Nebraska researchers targeted the engineered gene to be expressed in the plants' photosynthetic chloroplasts. The move offers two benefits, Weeks explains. First, the resistance-conferring enzyme works better because it can swipe the electrons it needs from the steady stream generated during photosynthesis. Also, like mitochondrial DNA, chloroplast DNA is inherited through the maternal side. That means a GM crop can't spread resistance through wind- or insect-carried pollen, which comes from the male side.

Weeks says Monsanto has licensed the technology and that it could be commercially available within 3 to 4 years. If so, he says, it could allow growers to rotate their crops between varieties resistant to two different herbicides. "It gives farmers an alternative to the continual use of glyphosate-resistant crops," Weeks says. And the development of herbicide-resistant crops won't stop with dicamba. "We have the technology today to develop herbicide resistance to about anything we want to," Green says.

New front. Soybeans resistant to the herbicide dicamba may help farmers diversify their antiweed arsenal.

SOURCE: S. DUKE, NPURU/USDA/ARS; CREDIT (BOTTOM): D. WEEKS/UNIVERSITY OF NEBRASKA

Another approach being pursued at Monsanto and elsewhere is to combine, or "stack," genes for resistance to multiple herbicides in the same plants. Researchers at Pioneer HiBred, a division of DuPont, for example, are working to create crops that are resistant to both glyphosate and herbicides that target a plant enzyme called acetolactate synthase. ALS inhibitors have also been on the market for years and face resistant weeds of their own. And scientists elsewhere announced last year that they plan to create crops resistant to herbicides that inhibit ACCase, an initial enzymatic step in lipid synthesis that is critical to grasses.

In addition to stacking traits for resistance to multiple herbicides, researchers at Pioneer and elsewhere are looking to add other traits to crops, such as heat and drought resistance, increased yield, and insect resistance. In some cases, they hope to add genes for novel nutrsients and even pharmaceutical compounds. "There is a tremendous opportunity to do this for the next generation of traits," Duck says. Although such efforts are still in the early stages, he adds, "in the future, everything is going toward product stacks." The question is whether crops resistant to multiple herbicides will prolong the life of one of the farming community's favorite herbicides.

–ROBERT F. SERVICE

Published by AAAS