Many Little Hammers:

Fighting Weed Resistance with

Diversified Management

by Madeline Fisher

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When genetically engineered cotton cultivars that could survive spraying with the herbicide Roundup became available in 1997, many U.S. cotton growers began opting for the new "Roundup Ready" varieties, and Georgia farmers were no exception. The system, after all, had many plusses: It was simple, safe, and it gave growers the flexibility to spray weeds any time without harming their crops. Moreover, the technology's effectiveness made it easier to move away from tillage for weed control and follow soil- and fuel-saving no-tillage practices. By the early 2000s, nearly 60% of Georgia cotton farms were using reduced-till techniques, recalls University of Georgia extension agronomist, Stanley Culpepper.

Then in 2004, Culpepper helped identify the first specimens of a plant called Palmer amaranth, or pigweed, that had evolved resistance to Roundup (known generically as glyphosate); three years later, the weed was so out of control that Georgia farmers were mowing thousands upon thousands of cotton acres down. Today, approximately 98% of Culpepper's farmers have glyphosate-resistant pigweed in their fields, and the plant has spread to 76 counties. "So, that's the only weed we discuss," he says. "All of our management programs are directed at it."

Herbicide-resistant weeds aren't just on the minds of Georgia growers; today, the ag community around the world is finding itself increasingly preoccupied by the problem. In some ways, it's nothing new: Weeds have been developing tolerance to weed killers ever since the first triazine herbicides were introduced five decades ago. But what *is* new, many now argue, is our near-exclusive reliance on glyphosate to kill weeds these days, thanks to the unprecedented popularity of glyphosate-resistant crops. It's estimated that 95% of the U.S. soybean crop and 70% of U.S. corn and cotton are today Roundup Ready.

The result has been a "perfect storm sort of situation" for cultivating herbicide resistance in weeds, says Iowa State University extension agronomist Mike Owen—and a considerable upping of the weed control stakes. Glyphosate tolerance is now found in at least 20 weed species that reportedly infest millions of acres. And some weeds, such as water hemp in the U.S Midwest and *Lolium* in Australia (see sidebar on page 7), have evolved resistance to three or more herbicide mechanisms of action. That "doesn't leave a whole lot that we can use to deal with this problem," says Owen, an ASA Fellow and CSSA member. "So, we're going to have to look at a lot more clever solutions and tactics."

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The main solution seed companies are pursuing is the engineering of new cotton, soybean, and corn cultivars that can tolerate additional herbicides, such as glufosinate; 2,4-D; and dicamba—including "stacked trait" varieties than resist more than one. Yet, while these tools are likely to help, scientists like Owen also want to see much wider adoption of integrated weed management that relies less on technology and more on diverse weed-fighting strategies, including crop rotations, minimal tillage, and cover cropping.

In fact, diversified management—although admittedly more difficult—is the only sustainable way forward, says Penn State University weed scientist Dave Mortensen, especially with the push toward strict, no-till farming. "We're putting more and more pressure on herbicides to do all of the killing," he says. "And that's just not going to get the job done down the road. I'm certain of that."

High-residue interrow cultivator cultivating soybean in a rolled rye system. *Photo courtesy of William Curran.*

Lessening Selection Pressure with Diversification

This reason why comes down to the inescapable facts of evolution, Mortensen explains. When an herbicide, such as glyphosate, is applied year-in and year-out over very large areas, "you have an incredible ramping up of the selection pressure" on weeds to evolve resistance, he says—similar to how bacteria develop resistance when antibiotics are overprescribed. The probability that any one plant will become tolerant is miniscule; however, in glyphosate's case, repeated use on millions of acres did eventually select for a few individuals among billions that could survive it. And as glyphosate continued to be present in the environment, those glyphosate-adapted plants—such as pigweed—went on to reproduce in far greater numbers than their susceptible counterparts.

But the phenomenon isn't unique to glyphosate or even to herbicides. Any weed-killing tactic, whether mechanical, chemical, or otherwise, will inevitably select for plants that can withstand it. The trick is to prevent or delay the evolution of resistance by lessening the selection pressure that any one method exerts. This is where diversified management comes in, and for Penn State weed scientist Bill Curran, it has three critical components: herbicides, tillage, and crop rotations. "If you don't diversify those three, you have problems," says the ASA member. "But," he adds, "what is the right mix?"

It's a tough question to crack, which is why as he, Mortensen, and others at Penn State have been researching ways to reduce herbicide use—and, thus, the selection of resistant weeds—they've borrowed ideas from farmers who fight weeds without any chemicals at all: organic producers. Curran's background and training is in conventional agriculture, he explains. But about 10 years ago, he started working with organic growers who wanted to reduce their reliance on tillage for weed control. It didn't take him long to realize the research might have implications for conventional growers, too. Many of them have also been tilling less, but spraying more herbicide as a result.

One alternative to both deep tillage and heavy herbicide use that Curran's group focuses on is winter cover crops: especially cereal rye in soybean and hairy vetch in corn. In a paper in the September–October 2011 issue of *Agronomy Journal*, for example, Curran, Mortensen, and their collaborators describe a system in which they grew a rye cover crop under organic and conventional conditions and then rolled/crimped it down to create a weed-suppressive mulch. Once soybean was sown into the mulch, the researchers controlled emerging weeds in the organic plots with a high-residue cultivator designed for reduced tillage systems. In the conventional plots, meanwhile, they sprayed a post-emergence herbicide.

In other words, herbicides aren't eliminated completely under diversified management; in fact, chemicals are extremely useful when soil conditions are too wet or dry for mechanical weed control, Curran notes. At the same time, herbicide use can be significantly reduced in these systems because the mulch shoulders part of

Organic farmer rolling rye and drilling soybean. *Photo courtesy of William Curran.*

the weed-fighting work. In essence, "you're using the mulch like a pre-emergence herbicide," Curran says. "You're hoping to get four, five, or six weeks of control."

In another study published in the March–April 2012 issue of *Agronomy Journal,* Curran and his collaborators found that a combination of banded, residual herbicides and high-residue cultivation reduced the need for residual applications by two-thirds, without significantly affecting corn yield. It's important to note, however, that this doesn't hold when weed densities go sky high. Then, "you pretty much have to hit things with a hammer," he says—meaning heavy herbicide doses.

Still, the results demonstrate the value of sharing ideas between organic and traditional systems, and Curran thinks both sides could benefit if this happened more. "You start realizing the organic community doesn't really talk to the conventional ag people, and vice versa," he says. "But actually there are a ton of things they could learn from each other."

Many Little Hammers

ASA member and Cornell University assistant professor Matt Ryan can attest to this, too. As a graduate student working with Mortensen, Curran, and others, not only did he turn to cover crops and other organic practices to cut herbicide use, but his efforts also took him in the opposite direction: to studies of herbicide chemistry. There's a rich body of literature describing the interaction between herbicides, he says, including methods for determining whether two or more chemicals applied together interfere with one another's activity, fail to interact, or combine to produce a stronger weed-killing effect. That got the scientists thinking: Could they detect interactions between non-chemical control tactics, too?

The idea is based in the "many little hammers" concept of ecological weed management, Ryan explains. Certain weed-fighting strategies are admittedly weak when used in isolation; for example, just increasing the seeding rate to make a crop more competitive against weeds "doesn't

Corn no-till planted into a hairy vetch. The mulch helps suppress weeds for a period of time. *Photo courtesy of William Curran.*

get you very far," he admits. But when these tactics are used together, they can end up being more powerful than would be expected from each method's ability to suppress weeds alone. "That's really the idea of many little hammers," Ryan explains. "That combining these tactics, which are weak when applied individually, can amount to something that is effective."

To look for these interactions, Ryan set up an experiment with two gradients: five levels of rye cover crop biomass and five different soybean seeding rates. The result was a response surface in which he could examine both the weed-fighting ability of each approach alone, as well as the interaction of the two by using regression. And, in fact, he and his colleagues did find the interaction they were hoping for: In two of the experiment's site years, the weed control provided by the rye mulch was mediated by the soybean-seeding rate, with the two together having a bigger effect than either individually.

Moreover, the findings offer insight into the reasons behind the improved control, which to Ryan is the most important point of all. In the study, the action of the rye mulch was related to seed size: The mulch delayed emergence of small-seeded annual weeds long enough for the larger-seeded soybean to germinate and develop a competitive, weed-suppressing canopy. "That mechanistic understanding, I think, is going to be important for expanding the utility of these approaches and improving management in general," Ryan says. "Once you know why [a practice is effective], you can apply that information to other situations and tweak the practice so that you maximize its effectiveness."

Because pigweed is so competitive against cotton, farmers in Georgia now use two or three residual herbicides at planting, plus another three more during the season to keep the weed from sprouting. *Photo courtesy of Stanley Culpepper.*

What these mechanisms often come down to, adds Culpepper, is weed biology. Glyphosate kills regardless of biology, of course—or used to anyway. But now that glyphosate-resistant Palmer pigweed has emerged "you have to understand the biology of this plant if you're ever going to manage it," he says.

Because pigweed is so incredibly competitive against cotton, for example, Georgia farmers can't let it get any taller than an inch or two, or "they're mowing their crop down," Culpepper says. So, they now use two or three residual herbicides at planting, plus another three more during the season to keep the weed from sprouting. Pigweed seeds also can't germinate from a depth greater than two to three inches, which is why many farmers have returned to deep, moldboard plowing as another check on pigweed emergence. Even so, enough comes up that farmers hand-weed the plant to keep it from reproducing. "Last year, 92% of my growers hand-weeded 54% of the entire cotton crop," Culpepper says. "That tells you what a big problem this is."

He adds that while this combination of tactics is working for now, it's also expensive and economically unsustainable, especially as cotton prices have dropped. This is why he, too, has been experimenting for the past six years with an integrated program that includes cover crops and herbicides. In four, on-going farm trials in Georgia, he and his collaborators have found that a robust crop of rye can reduce pigweed emergence by 70 to 90%. Like the Penn State group, Culpepper then controls the remaining pigweed with herbicide, but the system still accomplishes important goals. It dramatically reduces the need for chemicals, thereby cutting costs. It moves cotton farmers back toward conservation tillage. Most importantly, cover cropping will help extend the life of valuable herbicide chemistries, such as Liberty (glufosinate), Culpepper asserts, because "we've reduced the selection pressure. We're spraying fewer plants."

With only 0.5% of Georgia cotton growers planting rye cover crops today, Culpepper now hopes that

continued on page 10

‘Smashing’ Weed Seeds in Australia

As farmers in the U.S. Southeast struggle to contain glyphosate-resistant Palmer amaranth, wheat growers in Australia are fighting an equally formidable foe. Once planted extensively as forage for sheep, *Lolium*, or Italian ryegrass, became a weed of Australia’s farm fields when sheep pastures were replaced by croplands about 40 years ago. At the same time, Australians became the world’s fastest adopters of no-till farming, and they devoted 70 to 80% of their agricultural lands to a single crop: wheat. As a result, the country’s farmers relied almost exclusively on herbicides for weed control, and *Lolium*, predictably, responded.

Today, 98% of the *Lolium* populations across the Australian wheat belt are resistant to at least one herbicide mechanism of action and, in most cases, several. “So, we’ve been forced into other forms of weed control,” says Michael Walsh, associate professor at the University of Western Australia and researcher with the institution’s Australian Herbicide Resistance Initiative. Those forms include many of the planks of diversified weed management, including crop rotations, tillage, and manipulations of seeding rates, row spacing, and fertilizer applications to make wheat more competitive. But the country is also now leading in a relatively new weed-fighting area: destroying the weed seed bank.

One critical biological weakness of *Lolium* and other annual weeds is that they don’t shed their seeds at maturity, Walsh explains. Instead, the weed seeds are “ready for harvest” at the end of the growing season, just like the wheat grain. When a combine takes the grain, it also collects *Lolium* seeds and then spits them back out in the chaff. The process, in other words, “quite effectively redistributes the weed seeds right across the soil surface, placing them perfectly, and readying the soil seed bank to be a problem in subsequent crop production seasons,” Walsh says.

Determined to prevent this, Australian farmers and scientists are now working together to invent and test technologies for collecting, removing, and destroying weed seeds. Among the most basic is a trailing cart that simply collects the chaff as it exits the harvester—along with 85% of *Lolium* seeds, Walsh’s research has found. Another system gathers and bales the chaff, straw, and 95% of weed seeds into what Walsh affectionately calls “weed seed packets.”

Instead of collecting weed seeds to be taken off site or burned, the Harrington seed destructor processes the weed seed-containing chaff fraction with a cage mill and spreads the material back on the soil.

Most popular right now is a method in which harvest residues are directed through a chute and into a narrow windrow that is subsequently burned to destroy the weed seeds. Ninety percent of Western Australia wheat growers currently use this technique to destroy the weed seed bank, Walsh reports.

And then there is a new innovation named the “Harrington seed destructor” for the western Australian grain grower, Ray Harrington, who invented it. Instead of merely collecting weed seeds to be taken off site or burned, the new approach employs a cage mill that processes the weed seed-containing chaff fraction and spreads the material back on the soil. Borrowed from the mining industry, the mill does such a good job of crushing that 95% of *Lolium* seeds are destroyed by the process, report Walsh, Harrington, and their collaborator, Stephen Powles, in the May–June 2012 issue of *Crop Science*. The technique also fits perfectly with Australia’s conservation crop production systems because all harvest residues are retained.

Plus, it’s nice to exact a little revenge. “There’s something very gratifying about smashing weed seeds,” Walsh says.

money he received from a $1.1 million grant will help convince more of them to try the program. "Because it is difficult, it is challenging," he says. "You grow the rye, you roll the rye, and then you strip-till cotton right into the rye."

Proper weed identification is essential for successful management. Here Matt Ryan explains how to identify velvetleaf to farmers in Easton, PA.

Will Farmers Embrace Diversification?

That seems to be the biggest question on everyone's minds: How to get farmers to embrace complex weed management strategies when they've grown used to the strength of herbicides like glyphosate and the simplicity of technologies like Roundup Ready. The task is much easier in places like Georgia, of course; farmers there essentially have no choice. But in Pennsylvania and Iowa, the goal of integrated management is mainly to avoid future problems rather than deal with existing ones, making it a much tougher sell. "Truthfully, until growers get [herbicide-resistance] in their fields, the likelihood of them actually doing something about it is unfortunately not very high," says Owen, adding that he has been urging farmers to take preventative measures for 35 years now.

One thing he thinks could help, though, is more research into the economics of diversified approaches. Farmers are rightly concerned that these practices will cost more time and money, while offering little benefit other than preventing a problem they may never actually see. But in a series of on-farm studies conducted in six states over five years, Owen and a group of collaborators found that an integrated system involving crop rotations and a diverse mix of herbicides actually saved money, or at least didn't cost farmers anything more than their standard practices.

Even so, change is hard, which is why Owen also thinks agronomists need to collaborate more with psychologists and sociologists. "In other words, here's a scientific solution," he says, "Now what do the social sciences say about getting growers to accept it?" He's also working with a team from the Weed Science Society of America to develop a set of best management practices—and simple messages about them—that will hopefully bring more farmers on board.

Or perhaps, suggests Mortensen, we need to approach the issue from a different angle altogether: Rather than promoting integrated management as a means to avoid a problem, we should be emphasizing the benefits of diversified agriculture instead. Cover crops, for instance, don't just suppress weeds; they also reduce insect pressure, increase soil tilth and organic matter, and curb nutrient and herbicide runoff. And yet, they're still mostly deployed to fix one environmental ill at a time; for example, concerns over the continued decline of Chesapeake Bay recently led Maryland to launch a program that pays farmers to plant winter cover crops expressly to curb nutrient runoff.

Now imagine taking that same program and measuring all the benefits that cover crops can offer as well as subtracting the disservices (more slugs under some conditions, for example). Would the analysis reveal a greater bang for the cover crop buck and possibly convince more growers to invest? It will be a "big research challenge," Mortensen admits, "to find ways that we can make modest adjustments in cropping system design and practice to increase the punch on the ecosystem services side" including weed suppression, carbon storage, soil health, or whatever else.

But it's also the future, he thinks. "Wouldn't it be exciting if we could get to the point—and I don't think we're that far away—where we could look at some of these practices as having multiple goods?"

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