AgBioForum, 12(3&4): 244-248. ©2009 AgBioForum.

Overview: Herbicide Resistant Crops—Diffusion, Benefits, Pricing, and Resistance Management

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Weeds, along with insect pests and plant diseases, are sources of biotic stress in crop systems that reduce yields, raise production costs, and contribute to income risk to farmers (HarvestChoice, 2009). Transgenic, herbicide-resistant (HR) crop varieties, first introduced in 1996, offer the promise of more effective weed control. By 2008, more than 79 million hectares worldwide were planted to HR varieties of soybean, maize, canola, cotton, alfalfa, and sugar beets (James, 2009).

What accounts for the rapid diffusion of HR crops in countries where they have gained regulatory approval? Research suggests grower adoption decisions depend not only on farm profits, but also on the complex characteristics of herbicides and weed-management programs, such as simplicity, convenience, flexibility, and safety. HR crops, thus, may provide multiple pecuniary and non-pecuniary benefits, including environmental benefits. Herbicides used with most HR crops tend to be less toxic and persistent than the herbicides they replace, while HR varieties can complement the use of no-till systems that reduce soil erosion and fossil fuel emissions. Thus, benefits of HR crops are multi-faceted and difficult to quantify.

The benefits of HR crops, however, may be threatened by the evolution of weeds that are resistant to herbicides used with HR crops. The sustainable use of HR crops, therefore, requires strategies to delay the evolution of HR weeds.

This special issue includes 12 articles that examine different facets of HR crops. These include (a) adoption and diffusion of HR varieties, (b) characterization and estimation of the benefits of HR crops, (c) the implications of corporate seed-pricing strategies on grower welfare, and (d) strategies to manage weed resistance for sustainable use of HR crops.

Several institutions supported research leading to the articles in this issue. Among these were Monsanto, the HarvestChoice initiative (Pardey & Wood, 2009), the Agricultural Research Division of Cotton Incorporated (http://www.cottoninc.com/AgriculturalResearch), the USDA National Research Initiative, the European Union (EU), the Common Fund for Commodities (CFC), the Dutch Directorate-General for International Cooperation (DGIS), the Netherlands Foundation for the Advancement of Tropical Research (NWO-WOTRO), the Department for International Development (DFID), the Western Australia Herbicide Resistance Initiative at the University of the Western Australia, and the Cooperative Research Centre for Australian Weed Management. Collaboration among special issue editors and authors was further facilitated by the USDA Multistate Research Fund Project NC-1034: Impact Analyses and Decision Strategies for Agricultural Research.

Adoption and Diffusion of HR Seed Varieties

Frisvold, Boor, and Reeves (Article 1) use state-level data to explain the diffusion of HR cotton seed varieties and conservation tillage among US cotton producers. They estimated a simultaneous equation model by three-stage least squares to examine complementarities between the two technologies. They reject the null hypothesis that diffusion of one technology is independent of diffusion of the other. Elasticities calculated at sample means indicate a 1% increase in a state's adoption rate for HR cotton increases the state's adoption rate for conservation tillage by 0.48%. A 1% increase in the adoption rate of conservation tillage increases the adoption rate of HR cotton by 0.16%.

Using US farm-level cotton-producer data from the US Department of Agriculture's (USDA) Agricultural Resource Management Survey (ARMS), Banarjee et al. (Article 2), however, obtained less definitive results. Their study estimated logit models of adoption of conservation-tillage practices and herbicide-resistant/stacked-gene cottonseed. While their specification allowed for the possibility that adoption of one technology could influence adoption of the other, they could not reject the null hypothesis that the technologies are adopted independently. The coefficient for herbicide-cotton adoption was positive in the conservation tillage adoption equation but significant only at the 5.1% (10.2%) level in one- (two-) tailed tests. The coefficient for conservation-tillage adoption was positive in the herbicide-resistant-seed adoption equation but significant only at the 7% (14%) level in one- (two-) tailed tests. The authors' model specification, however, is less than ideal for testing hypotheses about simultaneity of technology adoption. Their system of equations is under-identified, and several of their regressors exhibit little variance. Future work on simultaneous estimation of HR-crop and conservation-tillage adoption would benefit from consideration of problems posed by weak instruments and greater use of structural model development to guide model specification. The careful structural modeling approaches taken by Fernandez-Cornejo et al. (2002); Fernandez-Cornejo, Klotz-Ingram, and Jans (2003); and Fernandez-Cornejo, Hendricks, and Mishra (2005) suggest fruitful paths to pursue.

Evaluating Attributes and Benefits of HR Crops

The next three articles in the issue examine the role and benefits of HR crops in weed management relying on primary data from a telephone survey of 1,205 randomly selected corn, cotton, and soybean growers from 22 states. The survey instrument, designed by Monsanto and Marketing Horizons in consultation with the authors, was administered by Marketing Horizons in 2007. The survey collected information about grower and operation attributes, grower weed-management practices, factors affecting herbicide choices, and grower evaluation of benefits from planting Roundup Ready® (RR) seed varieties.

Hurley, Mitchell, and Frisvold (Article 3) explore the importance of 13 characteristics that influence weed-management decisions. These characteristics included attributes of the weed-management system (such as cost, flexibility, or effects on yield) and grower concerns or objectives (such as water quality, erosion control, or safety considerations). The study first examined the relative importance that growers placed on different characteristics for weed-management decisions. In making herbicide choices, more than 95% of growers rated protection from yield loss and consistency of weed control as very important. Growers rated family health, public health, and water quality as very important more frequently than they rated cost as very important. Multivariate probit regression results found grower education and crop grown were the two factors most often significantly related to the importance growers placed on the herbicide and weed-management characteristics. Less educated gowers and cotton growers were more likely to rate characteristics very important. While corn and soybean growers rated most factors similarly, soybean growers placed greater importance on flexibility.

Finally, factor analysis results suggest that health and environmental, yield, and herbicide-application concerns capture important unobservable preferences that influence grower decisions. Therefore, attempts to decompose the benefits of herbicide-tolerant crops by assigning unique values to specific characteristics that influence grower decisions can be confounded because of the difficulty in developing unique indirect measures of directly unobservable grower preferences.

Weed best management practices (BMPs) help delay the development of weed resistance to herbicides but could increase weed-control costs, limiting their adoption. Hurley, Mitchell, and Frisvold (Article 4) next explore how adoption of BMPs affects weed-management costs in corn, cotton, and soybeans, controlling for farmer and regional characteristics. More experienced growers had lower weed-control costs. Cleaning equipment, using herbicides with different modes of action, and using supplemental tillage are BMPs associated with increased costs for some crops. This may explain why they are less widely adopted than other BMPs (see Article 12). However, growers commonly use other weed BMPs that also increase costs. Regression results suggest that adoption of RR crops reduces weed-control costs and that weed scouting reduces costs for cotton and soybean growers. Use of residual herbicides was associated with higher costs for cotton growers, but not for corn or soybean growers. Rotating RR and non-RR crops on the same acreage was associated with higher costs for soybean growers, but not for corn or cotton growers.

Hurley, Mitchell, and Frisvold (Article 5) estimate grower benefits of RR weed-management programs and how weed-resistance concerns and resistance-management practices affect those benefits. Direct survey methods were used to elicit grower valuation of pecuniary and non-pecuniary benefits. The study illustrates a hedonic strategy combined with principal component analysis to address part-whole bias present in previous assessments of non-pecuniary benefits of RR crops. The mean reported benefit of RR relative to conventional seed varieties was more than $20 per acre for corn and soybean growers and about $50 per acre for cotton growers. Growers concerned about weed resistance reported lower benefits, but this effect was statistically significant only for cotton growers, reducing their perceived benefits by 20% ($10 per acre). Use of a residual herbicide and annual rotation of herbicides are two practices to reduce the risk of weed resistance. Corn growers using residual herbicides perceived lower, though still positive, benefits. Soybean growers rotating herbicides perceived benefits to be higher. Growers more concerned about herbicide application costs and crop safety report lower benefits, while those more concerned about the flexibility of timing herbicide applications report higher RR benefits.

Gardner, Nehring, and Nelson (Article 6) is the first study (to our knowledge) to formally estimate household labor-saving impacts of trangenic crops in a multivariate setting. They estimate an average treatment effect model, where unpaid farm labor hours serve to approximate household farm labor. The study uses cross-section data from USDA's ARMS for corn (2001), soybeans (2002), and cotton (2003).

Adoption of HR soybeans had a strong, statistically-significant, household labor-saving effect, reducing household labor use by 14.5% on average. No such labor-saving effect was found for corn. For HR cotton, labor-saving effects were found in some model specifications, but not others. Nevertheless, the result for soybeans fills a gap in the literature, providing an explanation for why soybean growers have adopted HR varieties so rapidly despite limited evidence of a profit advantage. Fernandez-Cornejo et al. (2005) found evidence that adoption of HR soybeans increased off-farm and total household income, even though it did not increase on-farm income, and hypothesized that the simplicity and flexibility of the HR soybean system freed up farm management time for non-farm income. Gardner, Nehring, and Nelson's results provide direct evidence in support of this hypothesis.

In sub-Saharan Africa (SSA), estimated rice yield losses from weeds are equal to half the sub-continent's rice imports. Yet, African rice farmers have few options for effective and affordable weed management. HR seed varieties may offer labor-saving benefits from conventional chemical control of weeds but with lower phytotoxic risks. To date, however, the potential of HR rice in SSA has received little attention. Rodenburg and Demont (Article 7) review the literature on HR weed-management technologies and discuss their potential value for rice ecosystems in Africa. They conclude HR technologies would provide technically sound control of important yield-reducing weeds, such as wild rice in irrigated systems and rain-fed lowlands and of parasitic weeds in uplands. However, diffusion of HR technologies would require effective seed development and marketing systems, as well as micro-credit systems. Rodenburg and Demont suggest public-private partnerships and government intervention may be needed where these systems are weak.

HR Seed Pricing

Shi, Chavas, and Stiegert (Article 8) examine effects of structural changes in the US soybean seed market on the pricing of conventional and HR seeds. The last 20 years have seen dramatic privatization in the US soybean seed industry. Soybean acreage planted to publicly developed (as opposed to privately developed) varieties has fallen sharply. In addition, production of transgenic soybean seeds has involved the integration or coordination of upstream biotechnology firms and downstream seed companies. Such privatization and vertical integration have important implications for pricing of soybean seeds and soybean grower welfare.

Shi et al. use an econometric model to estimate the effects of market size, market concentration, and vertical organization (including vertical integration and transgenic trait licensing) on soybean seed prices. They use a "vertical" Herfindahl-Hirschman index (VHHI), which captures vertical as well as horizontal market concentration. The authors estimate effects of market changes on the pricing of four different seed types (public and private conventional varieties, HR seed varieties sold by vertically-integrated firms, and HR seeds sold via licensing agreements). They find greater market concentration tends to increase within-market (i.e., within seed type) prices. However, in a multi-market framework, complementarity in production and distribution mitigates this price-increasing effect. This highlights the importance of examining market power in a multi-market framework. Pricing of public-sourced seeds differs from pricing of privately produced seeds and the authors suggest further research is needed concerning the interactions of public institutions and private firms in US seed markets.

Literature on ex-ante assessment of biotechnologies has emphasized the need to account for differences among potential adopters to avoid "homogeneity bias" when estimating impacts of new technologies. Dillen, Demont, and Tollens (Article 9) argue that one must also account for heterogeneity in the pricing of innovations to avoid "pricing bias" in welfare estimates of new technologies. They develop a framework that explicitly considers how heterogeneity in adopter valuation of proprietary seed technology affects corporate pricing strategies and technology impact assessment. Their results provide an explanation of why innovators engage in third-degree price discrimination when the market structure discourages arbitrage. They apply their model to a case study of HR sugar beet in the EU-27. The authors quantify how the ability to price discriminate increases innovator returns, but reduces producer returns and possibly, total welfare. They illustrate that the combined effects of homogeneity and pricing bias can lead to significant overestimation of gains to producers from seed technology innovations.

Strategies for Sustainable Use of HR Crops

Duke and Powles (Article 10) document the quick and pervasive adoption of glyphosate-resistant (GR) crops throughout the globe. They provide a concise overview of economic benefits of GR crops, also noting non-pecuniary benefits (such a simplicity) and environmental benefits. The GR crop/glyphosate program is generally more environmentally benign than weed-management technologies it replaced.

Duke and Powles warn, however, that rapid adoption of HR crops has created continuous and intense selection pressure in some regions. This selection pressure has led to the evolution of HR weeds and weeds only partially controlled by glyphosate. The authors argue that diverse weed-management approaches are needed to sustain the benefits of HR crop varieties. The appropriate mix of strategies will vary by region, crop, and agro-ecosystem, but includes herbicide rotations, sequences, use of multiple herbicides with different modes of action, and non-chemical weed control. New transgenic crops with resistance to other herbicide classes, in some cases coupled with glyphosate resistance, will be introduced soon (Green, 2007; Green, Hazel, Forney, & Pugh, 2008). Used wisely, these tools can be integrated into resistance management and prevention strategies.

Llewellyn and Pannell (Article 11) evaluate a training workshop intended to modify weed-management-related perceptions and adoption intentions of farmers. They found the extension workshop significantly altered growers' perceptions about several aspects of herbicide-resistance management. These included the speed of resistance development, the potential for a population of herbicide-resistant weeds to return to herbicide-susceptibility, and the economic value of several treatments. The workshop appears to have altered the adoption intentions of a significant number of participating growers. Specifically it increased intentions to adopt a strategy to prevent development of resistance to glyphosate. Llewellyn and Pannell argue extension can be more effective if it targets grower perceptions identified as being influential in weed-management adoption decisions. Extension can be particularly effective if those grower perceptions are known to be inaccurate.

Frisvold, Hurley, and Mitchell (Article 12) examine adoption of 10 BMPs to control weed resistance to herbicides using the Monsanto / Marketing Horizons 2007 survey data. Count data models were estimated to explain the total number of BMPs frequently practiced. Ordered probit regressions were estimated to explain the frequency of adopting individual BMPs. Growers practicing a greater number of BMPs frequently had more education, but less farming experience; grew cotton; expected higher yields relative to the county average; and farmed in counties with a lower coefficient of variation (CV) for yield of their primary crop. Highly variable yields may be a barrier to adoption because they hinder the observability and trialability of BMPs (i.e., a grower's ability to assess outcomes or benefits of BMP adoption; Pannell & Zilberman, 2001). BMP adoption patterns were remarkably similar across crops. Most growers frequently adopted the same seven BMPs, while adoption of the same three BMPs was low for corn, cotton, and soybean growers. These BMPS were cleaning equipment, using multiple herbicides with different modes of action, and supplemental tillage.

Extension efforts may be more effective if they pursued two targeting strategies. First, extension programs could target the three practices with low adoption rates. Second, counties with a high yield coefficient of variation would be areas to look for low BMP adoption.

Some Lessons

We close by drawing some general lessons regarding the economics of HR crops. First, weed-management systems do not involve single inputs or technologies, but suites of interrelated practices and technologies. Second, grower weed-management decisions depend on multiple objectives and concerns that reach well beyond simple profit maximization. Benefits depend on pecuniary and non-pecuniary factors. These two features make estimation of the costs and benefits of HR crops difficult to measure. Nevertheless, the articles in this issue introduce novel methods to estimate producer benefits of HR crops and find they can be significant. Many farmers in the developing world (notably in Sub-Saharan Africa and Southeast Asia) have yet to benefit from HR crops. In these regions, farmers are typically poor and resource-constrained. This means that technology transfer will require additional strategies to strengthen seed development, marketing, credit, and public-private partnerships. The articles on corporate seed pricing highlight that, given the modern structure of the biotechnology/seed industries, estimation of welfare impacts on biotechnology requires an industrial-organization approach.

While measuring the size and distribution of benefits of HR crops is important, the last three articles seek to identify strategies to maintain those benefits. Sustainable use of HR crops will require diversified approaches to weed control by growers, technical support from extension programs, and development of complementary seed varieties by plant breeders.

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