Herbicide Resistant Weeds: How Did We Get Here & What Do We Do Now?

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University of Arizona
HR weeds, How did we get here?

- Beliefs

- Dramatic reduction in diversity of weed management tactics
  - Increased reliance on chemical control
  - Reduced diversity of chemical control
  - Reliance on a single mode of action

- Less *ex ante* resistance monitoring & development of scientific understanding (compared to Bt crops)
HR Weeds: Beliefs

- Evolution of resistance to glyphosate unlikely
- Monopolist technology supplier had incentive to manage any resistance problems
- Among economists, no common pool externalities (so growers have private incentives to manage resistance)
- Among growers, resistance beyond their control (in part, because of common pool externalities)
- Among growers, new technology would become available
HR Weeds: Beliefs

- HR crops complemented conservation tillage with attendant environmental benefits
- Glyphosate resistant (GR) crops would reduce overall environmental impact of herbicides
Enormous Selection Pressure Led to Resistance

- Easier to see with hindsight than at the time

- Dramatic reduction in diversity of weed management tactics
  - Increased reliance on chemical control
  - Reduced diversity of chemical control
  - Reliance on a single mode of action
US Herbicide applications
(kilotons of active ingredient applied)

<table>
<thead>
<tr>
<th></th>
<th>1964</th>
<th>1995</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Pesticides</td>
<td>97.5</td>
<td>235.7</td>
<td>222.8</td>
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<tr>
<td>Total Herbicides</td>
<td>21.9</td>
<td>146.1</td>
<td>144.6</td>
</tr>
<tr>
<td>Corn</td>
<td>11.6</td>
<td>84.5</td>
<td>76.4</td>
</tr>
<tr>
<td>Cotton</td>
<td>2.1</td>
<td>14.7</td>
<td>13.1</td>
</tr>
<tr>
<td>Soybeans</td>
<td>1.9</td>
<td>30.9</td>
<td>38.9</td>
</tr>
<tr>
<td>Herbicide a.i. / Total a.i</td>
<td>22%</td>
<td>62%</td>
<td>65%</td>
</tr>
</tbody>
</table>
## Specific Crop Herbicide a.i as share of Total Herbicides a.i.

<table>
<thead>
<tr>
<th>Crop</th>
<th>1964</th>
<th>1995</th>
<th>2005</th>
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<tbody>
<tr>
<td>Corn</td>
<td>53%</td>
<td>58%</td>
<td>53%</td>
</tr>
<tr>
<td>Cotton</td>
<td>10%</td>
<td>10%</td>
<td>9%</td>
</tr>
<tr>
<td>Soybeans</td>
<td>9%</td>
<td>21%</td>
<td>27%</td>
</tr>
<tr>
<td>Three Crops</td>
<td>71%</td>
<td>89%</td>
<td>89%</td>
</tr>
</tbody>
</table>
Trends in glyphosate use in US corn production

<table>
<thead>
<tr>
<th>Year</th>
<th>% Acres treated with glyphosate</th>
<th>Glyphosate a.i as % of total herbicide a.i</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>1999</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>2005</td>
<td>33</td>
<td>15</td>
</tr>
<tr>
<td>2010</td>
<td>66</td>
<td>35</td>
</tr>
</tbody>
</table>
Trends in glyphosate use in US soybean production

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<tbody>
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<td>20</td>
<td>11</td>
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<tr>
<td>1999</td>
<td>62</td>
<td>54</td>
</tr>
<tr>
<td>2006</td>
<td>95</td>
<td>89</td>
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</table>
Trends in glyphosate use in US cotton production

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<tbody>
<tr>
<td>1995</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>1999</td>
<td>36</td>
<td>20</td>
</tr>
<tr>
<td>2005</td>
<td>74</td>
<td>57</td>
</tr>
<tr>
<td>2010</td>
<td>68</td>
<td>62</td>
</tr>
</tbody>
</table>
# US Trends in Corn Weed Management (% of acres)

<table>
<thead>
<tr>
<th>Practice</th>
<th>1996</th>
<th>2000</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Herbicide resistant seed</td>
<td>–</td>
<td>11</td>
<td>31</td>
</tr>
<tr>
<td>Field scouted for weeds</td>
<td>81</td>
<td>83</td>
<td>89</td>
</tr>
<tr>
<td>Burndown herbicide used</td>
<td>9</td>
<td>12</td>
<td>18</td>
</tr>
<tr>
<td>Pre-emergence control</td>
<td>78</td>
<td>71</td>
<td>61</td>
</tr>
<tr>
<td>Post-emergence control</td>
<td>59</td>
<td>63</td>
<td>66</td>
</tr>
<tr>
<td>Cultivated for weed control</td>
<td>33</td>
<td>38</td>
<td>15</td>
</tr>
</tbody>
</table>
US Trends in Soybean Weed Management (% of acres)

<table>
<thead>
<tr>
<th>Practice</th>
<th>1996</th>
<th>2000</th>
<th>2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>Herbicide resistant seed</td>
<td>7</td>
<td>59</td>
<td>97</td>
</tr>
<tr>
<td>Field scouted for weeds</td>
<td>79</td>
<td>85</td>
<td>91</td>
</tr>
<tr>
<td>Burndown herbicide used</td>
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<tr>
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<td>29</td>
<td>17</td>
<td>–</td>
</tr>
</tbody>
</table>
## US Trends in Cotton Weed Management (% of acres)

<table>
<thead>
<tr>
<th>Practice</th>
<th>1996</th>
<th>2000</th>
<th>2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>Herbicide resistant seed</td>
<td>NA</td>
<td>58</td>
<td>90</td>
</tr>
<tr>
<td>Field scouted for weeds</td>
<td>71</td>
<td>82</td>
<td>92</td>
</tr>
<tr>
<td>Burndown herbicide used</td>
<td>6</td>
<td>23</td>
<td>41</td>
</tr>
<tr>
<td>Pre-emergence control</td>
<td>90</td>
<td>79</td>
<td>73</td>
</tr>
<tr>
<td>Post-emergence control</td>
<td>62</td>
<td>76</td>
<td>89</td>
</tr>
<tr>
<td>Cultivated for weed control</td>
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<td>63</td>
<td>38</td>
</tr>
</tbody>
</table>
## Corn Herbicide Treatments

<table>
<thead>
<tr>
<th>Herbicide Family</th>
<th>1996</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphinic acid</td>
<td>2</td>
<td>19</td>
</tr>
<tr>
<td>Triazine</td>
<td>19</td>
<td>48</td>
</tr>
<tr>
<td>Amides</td>
<td>38</td>
<td>4</td>
</tr>
<tr>
<td>Benzoic / Phenoxy</td>
<td>48</td>
<td>5</td>
</tr>
<tr>
<td>Sulfonylurea</td>
<td>27</td>
<td>5</td>
</tr>
<tr>
<td>Pyridine</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Other herbicides</td>
<td>15</td>
<td>9</td>
</tr>
</tbody>
</table>
# Soybean Herbicide Treatments

<table>
<thead>
<tr>
<th>Herbicide Family</th>
<th>1996</th>
<th>2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphinic acid</td>
<td>10</td>
<td>77</td>
</tr>
<tr>
<td>Dinitroaniline</td>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td>Imidazolinone</td>
<td>21</td>
<td>2</td>
</tr>
<tr>
<td>Sulfonylurea</td>
<td>9</td>
<td>NA</td>
</tr>
<tr>
<td>Diphenyl ether</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>Oxime</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>Other herbicides</td>
<td>26</td>
<td>14</td>
</tr>
</tbody>
</table>
Cotton Herbicide Treatments

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<thead>
<tr>
<th>Herbicide Family</th>
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<td>26</td>
<td>14</td>
</tr>
<tr>
<td>Urea</td>
<td>20</td>
<td>6</td>
</tr>
<tr>
<td>Triazine</td>
<td>13</td>
<td>2</td>
</tr>
<tr>
<td>Organic arsenical</td>
<td>12</td>
<td>1</td>
</tr>
<tr>
<td>Benzothiadiazole</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Other herbicides</td>
<td>23</td>
<td>17</td>
</tr>
</tbody>
</table>
## Changes in weed management from adoption of HR crops:

Internet survey of 54 agricultural professionals

<table>
<thead>
<tr>
<th>Weed management practice</th>
<th>Respondents believing growers following practice “less” or “much less” as a result of HR crop adoption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combination of weed control methods</td>
<td>&gt;60%</td>
</tr>
<tr>
<td>Crop rotation for weed control</td>
<td>&gt;40%</td>
</tr>
<tr>
<td>Annual rotation of herbicides</td>
<td>&gt;50%</td>
</tr>
<tr>
<td>Use of multiple herbicides</td>
<td>&gt;60%</td>
</tr>
<tr>
<td>Tillage for weed control</td>
<td>&gt;80%</td>
</tr>
</tbody>
</table>

- Few plant species are inherently resistant to glyphosate . . .

- . . . the long history of extensive use of the herbicide has resulted in no verified instances of weeds evolving resistance under field situations . . .

- . . . Unique properties of glyphosate . . . may explain this observation . . .

- . . . Selection for glyphosate resistance of crops is unlikely to be duplicated under normal field conditions. . .

- . . . development of [GR] crops are unlikely to be duplicated in nature to evolve [GR] weeds.
“History shows again and again how nature points out the folly of men”

— Donald Brian “Buck Dharma” Roeser, from Blue Oyster Cult song, *Godzilla* [1977]
## First Documented Resistance Cases

<table>
<thead>
<tr>
<th>Year</th>
<th>Species</th>
<th>Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>Lolium rigidum (Rigid Ryegrass)</td>
<td>Australia</td>
</tr>
<tr>
<td>1997</td>
<td>Eleusine indica (Goosegrass)</td>
<td>Malaysia</td>
</tr>
<tr>
<td>1998</td>
<td>Lolium rigidum (Rigid Ryegrass)</td>
<td>California</td>
</tr>
<tr>
<td>2000</td>
<td>Conyza canadensis (Horseweed)</td>
<td>Delaware</td>
</tr>
</tbody>
</table>
Perceptions that discourage BMP adoption

- Attribution of spread of resistant weeds to natural forces or neighbors’ behavior

- Belief that individual action has little effect on resistance

- As of mid-2000s, low awareness of
  - How practices affect weed resistance
  - Importance of rotating herbicides with different modes of action & use of tank mixes for managing resistance
Perceptions that discourage BMP adoption

- As of early 2000s, low concern over resistance
- Confidence that new products will become available
Institutional Structure of Resistance Management: a Conceptual Framework


- What types of resistance regime will develop?

- Includes major actors (e.g. technology providers, government agencies) and not just growers
Applying Miranowski/Carlson framework

- Predicts regulatory approach for Bt crops
  - Pest mobility
  - Significant potential externalities (effects on Bt foliar sprays used in organic agriculture)

- Predicts a laissez-faire approach to HR crops
Regulatory approach to resistance management for Bt crops

- How much did it improve *ex ante* resistance monitoring?

- How much did it improve scientific understanding?

- Now the big question . . . did EPA regulations save growers millions of dollars?
What do we do now?

- Status of resistance management (RM): Adoption of BMPs
- Identifying barriers to adoption
- Bottom up vs. top down approaches to RM
Percentage of growers adopting BMPs always or often

Different Modes

- Start with clean field
- Control weed escapes
- Scout after
- Scout before
- Use new seed
- Supplemental tillage
- Use label rate
- Clean equipment
- Control weeds early

Soybeans
Corn
Cotton
BMP adoption survey summary

- **Good news**
  - many growers (surveyed) are following most practices most of the time

- **Bad news**
  - This has proven insufficient to prevent resistance
  - We don’t know about the behavior of many (if not most) growers
Industry surveys of grower attitudes and perceptions

- Sample frame based on a marketing approach

- Includes growers that account for most purchases, but . . .

- Usually sampling cut-off below 250-500 acres
  - 250 acres for corn & soybeans
  - 250-500 for cotton
Industry grower attitude surveys missing most growers

- <250 corn acres
  - 22% of acres
  - 71% of growers
- <250 soybean cares
  - 26% of acres
  - 72% of growers
- <500 cotton acres
  - 21% of acres
  - 62% of growers
- <250 cotton acres
  - 8% of acres
  - 42% of growers
Upshot

- We know very little about attitudes and perceptions of most growers
- They still account for 20-25% of acreage planted to HR crop varieties
Resistance Management as a “Weakest Link Public Good”

- Potential for free-riding, plus

- Effective provision of good requires supply of effort from those with
  - Least incentive
  - Least capacity
Oilseed / grain farms (NAIC)

- 49% with net cash income <$25,000
- 20% with net losses (<$0)
- 34% of principal operators reported principal non-farm occupation
- 32% of principal operators worked >200 days off-farm
Cotton farms (NAIC)

- 36% with net cash income <$25,000
- 18% with net losses (<$0)
- 19% of principal operators reported principal non-farm occupation
- 24% of principal operators worked >200 days off-farm
Upshot

- A significant share of growers regularly lose money or earn below poverty level income from farming

- Significant share of growers
  - Spend large share of time in off-farm work
  - List non-farm activities as principal occupation

- Results are robust across Ag Census years
Research Question: How important is pure profit motive in decision making?

- Are calculations on net returns per acre capturing enough?

- Would looking at household utility make more sense?
  - Per acre net returns do not appear to explain rapid adoption of HR soybeans
  - How important are time-saving aspects?
  - How important are ease, flexibility, lower capital equipment requirements, etc. as issues?
Farm Household Utility

- Farm Income: $Y_f$
- Non-farm Income: $Y_n$
- Variance of income: (risk) $\Sigma_f, \Sigma_n$
- Time constraints
  - $T = T_f + T_n + L$
  - Time farming, other work, & leisure
- Act of farming itself or acres farmed, A
Farm Household Expected Utility

\[
\max EU = EU(Y_f, Y_n, \Sigma_f, \Sigma_n, A)
\]
\[
s.t. T = T_f(A) + T_n + L
\]
\[
s.t. A > A
\]

where

- \( T'_f(A) > 0 \)
- \( A \) is minimum acceptable operation size
Farm Household Expected Utility

max $EU = EU(Y_f, Y_n, \Sigma_f, \Sigma_n, A)$

s.t. $T = T_f(A) + T_n + L; A > \Lambda$

HR crops make $T'_f(A)$ less pronounced

- Allows larger farms to get larger
- Allows small, part-time farms to maintain minimal operation
Implications

\[ \text{max } \text{EU} = \text{EU}(Y_f, Y_n, \Sigma_f, \Sigma_n, A) \]
\[ \text{s.t. } T = T_f(A) + T_n + L; A > \Delta \]

- Small farms may continue to operate even if they frequently lose money
- Time-saving technologies/practices have a value not captured in per-acre returns
- Threat of economic losses from resistance may not be sufficient to overcome barriers to more time-consuming resistance management
Implications

- If participation by many small-scale producers is needed, then transactions costs of collection active could be large

- Monsanto’s Residual Rewards Program
  - Subsidizes adoption of residual herbicides
  - Overcomes collective action problem
  - Direct incentive through pricing system
  - Economists know power of pricing mechanisms to spur decentralized changes in behavior
Top-down vs. Bottom-up Approaches

- Top-down (federal government)
  - Command-and-control
  - Monitoring compliance difficult for HR weed management

- Top-down (private sector)
  - “Buy and apply” approach
  - Growers as “passive purchasers of products”
  - Emphasis on next “silver bullet” technology
Stacking multiple herbicide resistance traits

- Advantages
  - Herbicide products are known so approval may be faster
  - Possible to develop “optimal rotations” of herbicides
  - Could develop tank mix products
Stacking multiple herbicide resistance traits

- Disadvantages
  - Some weeds already resistant to multiple herbicides
  - Stacking less effective if resistance already a problem
  - May provide false sense of security and increase selection pressure inadvertently
Bottom-up Approaches

- Examples of grower-driven collective action
  - Groundwater management
  - Pest Eradication programs
  - Area-wide pest management
  - AZ Bt Cotton Working Group
  - Marketing orders

- Indirect role of government
  - Growers vote on rules
  - Government helps constrain free-riding
  - Government helps enforce rules agreed upon *ex ante*
Research Agenda

- ARMS data analysis
  - Potential to track changes over time
  - Do data capture smaller-scale producers missed by industry surveys?
  - What are growers doing and what aren’t they doing to manage resistance
  - How do adopters and non-adopters differ?

- How is Residual Rewards Program working?
  - Is it changing grower behavior significantly?
  - Is this making a difference?
Research Agenda

- Costs and returns to RM practice adoption
  - Do we need to frame issue in terms of utility in a household model?
  - What are non-chemical options?
  - What is nature of trade-offs in terms of time and money?
Research Agenda

- Potential for grower-initiated, bottom-up programs
  - How applicable are examples from other areas?
    - Area-wide pest management
    - Pest eradication programs
    - Groundwater management
  - Role of small-scale producers
    - How much of a problem would their free-riding be?
    - How do other programs overcome free-riding and include smaller scale producers?
Thank You

- Questions?

- Contact: frisvold@ag.arizona.edu