Symposium: Management of Resistance in Genetically-Modified Plants
San Diego, California June 13, 2016

Weed Resistance in Herbicide-Resistant Cultivars: Challenges to Profitability of Agronomic Crops

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Cotton Incorporated, Cary, North Carolina
Weed Resistance to Herbicides of Herbicide-Resistant Cultivars

1. Herbicide Mechanisms of Action
2. U. S. Crops, Weeds, and Weed Management Systems
3. Herbicide-Resistant Cultivars and their Adoption.
4. Evolution of Resistant Weeds in Herbicide-Resistant Cultivars
5. What Will the Humans Do?
# Sources of Weed and Herbicide Data

<table>
<thead>
<tr>
<th>Data</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Weeds</td>
<td>Southern Weed Science Society Surveys</td>
</tr>
<tr>
<td>Resistant Weeds</td>
<td>Herbicide Resistance Action Committee</td>
</tr>
<tr>
<td></td>
<td><a href="http://weedscience.org">weedscience.org</a></td>
</tr>
<tr>
<td>Herbicides Used</td>
<td>National Agricultural Statistics Service</td>
</tr>
<tr>
<td>Weed Management Programs</td>
<td>State Cooperative Extension Services</td>
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</tbody>
</table>
Herbicide Mechanisms of Action (MOA)

Definition: ‘How the herbicide kills the weed’

MOA (Inhibitors)        Typical Chemical Classes

Pre-emergence Herbicides
- Mitosis                     Dinitroaniline (DNAs)
- Long Fatty Acids            Acetanilides
- Photosystem II              Triazines

Pre- and Post emergence Herbicides
- ALS                         Four Classes – ex. Imidazolinones
- PPOs                        Diphenyl Ethers

Post Emergence Herbicides
- ACCase                      Fops &Dims
- EPSPS                       Glyphosate
- Glutamine Synthetase Glufosinate
- Auxins                      2,4-D; Dicamba (Others)
<table>
<thead>
<tr>
<th>Crop</th>
<th>$10^6$ acres</th>
<th>Weeds – Problem Weeds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton</td>
<td>10</td>
<td>summer weeds - broadleaves</td>
</tr>
<tr>
<td>Soybean</td>
<td>76</td>
<td>summer weeds - broadleaves</td>
</tr>
<tr>
<td>Corn</td>
<td>87</td>
<td>summer weeds - grasses</td>
</tr>
<tr>
<td>Rice</td>
<td>2.5</td>
<td>water tolerant grasses</td>
</tr>
<tr>
<td>Wheat</td>
<td>49</td>
<td>winter grasses</td>
</tr>
</tbody>
</table>

Citation: U. S. Census of Ag. 2012
## U. S. Crops, Weeds, and Weed Management Systems

### Weed Management Systems Before Transgenic Herbicide-Resistant Crop Cultivars

<table>
<thead>
<tr>
<th>Crop</th>
<th>Management System</th>
<th>Mechanism of Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton</td>
<td>pre’s/ early posts/laybys</td>
<td>3-4</td>
</tr>
<tr>
<td>Soybean</td>
<td>pre’s /ALS (post)</td>
<td>2</td>
</tr>
<tr>
<td>Corn</td>
<td>pre’s/ (possible post)</td>
<td>2</td>
</tr>
<tr>
<td>Rice</td>
<td>pre/posts</td>
<td>2+</td>
</tr>
<tr>
<td>Wheat</td>
<td>post (broadleaf)</td>
<td>1/1</td>
</tr>
</tbody>
</table>
Weed Management System in Transgenic Herbicide-Resistant Crop Cultivars

<table>
<thead>
<tr>
<th>Crop</th>
<th>Management System</th>
<th>Mechanisms of Action</th>
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</thead>
<tbody>
<tr>
<td>Cotton</td>
<td>post (3-5)</td>
<td>1</td>
</tr>
<tr>
<td>Soybean</td>
<td>posts (2)</td>
<td>1</td>
</tr>
<tr>
<td>Corn</td>
<td>pre/post</td>
<td>2</td>
</tr>
<tr>
<td>Rice</td>
<td>pre/posts</td>
<td>2+</td>
</tr>
<tr>
<td>Wheat</td>
<td>post(broadleaf) post (grass)</td>
<td>1/1</td>
</tr>
</tbody>
</table>

............. No Transgenic Cultivars .............
U. S. Counties Growing Wheat

49 million acres
Herbicide Resistance - Winter Wheat

- Broadleaf weeds are managed with inexpensive phenoxy herbicides.
- Problem weeds are grasses, broadleaf biennials, and certain monocots such as wild garlic.
- ALS resistance is widespread in the western states; ACCase resistance also occurs in several southern states.
- ACCase resistance frequently changes a one-application program to a two-application program.
- Where both ALS and ACCase resistances occur, pre-emergence herbicides are applied between wheat emergence and the emergence of weedy grasses, a difficult timing.
Herbicide Resistance in Small Grains

Critical issue because of international importance of cereal grains in human diet.

Margin of selectivity between grass crops and grass weeds is narrow.

In the U. S. from north to south there are significant resistance issues with wild oat, cheat grass, and ryegrass in wheat, and barnyardgrass in rice.

The resistance problems in wheat and rice may be our worst, because of the availability of few mechanisms of action.
U. S. Counties Growing Rice

2.5 million acres
Herbicide Resistance in Rice

• The principal problems are with weedy grasses, especially barnyardgrass (*Echinochloa crus-galli*).
• Barnyardgrass is widely resistant to propanil (PSII) and often resistant to quinclorac (phenoxy).
• The standard treatment for grasses is clomazone (phthoene desaturase inhibitor).
• Red rice is a continuing problem because it is con-specific with the crop.
• ‘Clearfield’ rice cultivars are ALS-resistant by means of conventional breeding. A resistance management program is recommended by the vendor.
Herbicide-Resistant Crop Cultivars

Trait Introductions

- 2,4-D – Auxin Mimic - 2015
- Dicamba – Auxin Mimic – (pending)
Characteristics of Herbicides used to make Transgenic Herbicide-Resistant Cultivars

Have Broad-Spectrum Activity, because They Need to Replace Other Herbicides to Justify Development Costs & Tech. Fees.

Therefore:
They Reduce Use of other Mechanisms of Action & Tend to Accelerate Evolution of Resistance

U. S. Counties Growing Cotton

10 million acres
U. S. Counties Growing Soybeans

76 million acres
U. S. Counties Growing - Corn

87 million acres
Adoption of Herbicide-Resistant Crop Cultivars

Million Acres

- Cotton
- Corn
- Soybean
Cotton Acres Exposed to Herbicide Modes of Action
Soybean Acres Exposed to Herbicide Modes of Action

![Bar chart showing acres exposed to herbicide modes of action from 1990 to 2006. The x-axis represents years, and the y-axis represents acres (in thousands). The chart includes data for DNA, ALS Inhibitors, and Glyphosate.]
Corn Acres Exposed to Herbicide Modes of Action
Total Acres Exposed to Herbicide Modes of Action for Corn, Soybean, Cotton
Evolution of Herbicide-Resistant Weeds

- Resistance is a random genetic event
- Probability increases with
  - Weed populations
  - Genetic Recombination Events
  - Selection
- Diversification Extends Time of Use
- Reinforcing MOAs Increases Number of Effective Applications
Two Dioecious Amaranths in North America

– *Amaranthus tuberculatus* – Tall Waterhemp
  • Midwest; heavy soils - South Central

– *Amaranthus palmeri* – Palmer amaranth, Palmer pigweed
  • light soils - South & many soils Southwest

• The two dicots resistant to the most herbicide modes of action ( 6 each)
  – *A. palmeri* is invading the Midwest
Palmer Amaranth
Amaranthus palmeri Resistance Evolution

Heap (2016)
The International Survey of Herbicide Resistant Weeds.
Available www.weedscience.org

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EPSPS Gene Duplication: Glyphosate Resistance Mechanism

Powles, PNAS 2010;107:955-956
Counties Affected by Glyphosate-Resistant Palmer Amaranth - 2005
Counties Affected by Glyphosate-Resistant Palmer Amaranth - 2006
Counties Affected by Glyphosate-Resistant Palmer Amaranth - 2007
Expansion of Glyphosate-Resistant Palmer Amaranth – counties infested
Counties with Glyphosate-Resistant Palmer Amaranth
Amaranthus palmeri resistance evolution - 2010

Impacts of Glyphosate-Resistant Palmer Amaranth

• Increase complexity and costs of weed management in cotton and soybean
• Compromise conservation tillage in the short-term
• May precipitate a cascade of resistance in post emergence broadleaf herbicides
Economic Threat to Soybeans

If ALS and glyphosate are compromised, PPO herbicides are the only post emergence option except glufosinate

Economic Threat to Cotton

PPO herbicides are not an over-the-top option. If ALS herbicides and glyphosate are compromised, there are no selective post emergence options except glufosinate

Nichols, R. L. 2010 – “Pigposium”, Forest City, Arkansas
Glyphosate and PPO –Resistant Palmer Amaranth

PPO Resistant Amaranthus palmeri 2016

States with PPO-resistant Palmer Amaranth:
- Kentucky
- Tennessee
- Missouri
- Arkansas
- Illinois
- Louisiana
- Mississippi
- Georgia
- South Carolina
- North Carolina

Map showing the distribution of PPO-resistant Palmer Amaranth in the specified states.
Soil-Active Herbicides are a Must
Greater Selection Pressure
On Glufosinate

- Glyphosate is still a very useful herbicide, but
- Palmer amaranth is the ‘driver’ weed in the system.
- When glyphosate, ALS, and PPO herbicides fail, the only current post option is glufosinate.
- Traits that will be used:
  ‘Gytol Liberty Link’, ‘Wide Strike’, and eventually ‘Enlist’, and ‘Xtend Flex’.
2015 – Demonstration
No-till Drip Field
(Confirmed glyphosate resistant pigweed in 2014)

Total costs to control resistant pigweed in cotton this year

Liberty Link Systems
ST 4946 GLB2
$129/acre

Roundup Ready Flex System (no dicamba)
DP 1522 B2XF
$126/acre
### Current Cotton Situation

<table>
<thead>
<tr>
<th>Cost to Manage Palmer in GA Cotton</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Herbicide input:</td>
<td>$68.00/acre</td>
<td>$88 million</td>
</tr>
<tr>
<td>2. Hand weeding:</td>
<td>$11.40/acre</td>
<td>$15 million</td>
</tr>
<tr>
<td>3. Additional tillage:</td>
<td>$5.84/acre</td>
<td>$7.6 million</td>
</tr>
<tr>
<td>4. Yield loss</td>
<td>???</td>
<td>???</td>
</tr>
<tr>
<td></td>
<td>$110 million</td>
<td></td>
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</table>
Control with Trait-Based Auxin Herbicide Weed Management Program
Zero Tolerance

Destroy Escapes

Post Emergence Herbicides/Scout

Pre-Emergence Herbicides/Scout

Crop Rotation/Select Traits, Cultivar & Seeding Rate

Select Tillage System/Start Clean

Scout Fall Escapes/Manage Winter Cover

Seed Bank Management
What Will the Humans Do?

- Resistance Management depends on the interaction of three groups – Growers, Manufacturers (Registrants) and Regulatory Agencies
- Growers and Manufacturers have responded to Economics.
- Economics now says that Resistance Costs.
- Regulation is Focusing on Resistance
Current Situation

• Need New Weed Management Programs.
• Need to Save Conservation Tillage.
• Need to Implement Resistance Management - Manufacturers and Growers.
• Does Resistance Management Include Trait Management?
Weed Management Theme

Herbicide Stewardship
Protecting Crops Environment Technology