**Public Policies, Research & the Economics of Herbicide Resistance Management**
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# Herbicide Resistant Weeds:
## How Did We Get Here & What Do We Do Now?

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# 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)

| | 1964 | 1995 | 2005 |
|---|---|---|---|
| Total Pesticides | 97.5 | 235.7 | 222.8 |
| Total Herbicides | 21.9 | 146.1 | 144.6 |
| Corn | 11.6 | 84.5 | 76.4 |
| Cotton | 2.1 | 14.7 | 13.1 |
| Soybeans | 1.9 | 30.9 | 38.9 |
| | | | |
| Herbicide a.i. / Total a.i | 22% | 62% | 65% |

# Specific Crop Herbicide a.i as share of Total Herbicides a.i.

| | **1964** | **1995** | **2005** |
|---|---:|---:|---:|
| Corn | 53% | 58% | 53% |
| Cotton | 10% | 10% | 9% |
| Soybeans | 9% | 21% | 27% |
| Three Crops | 71% | 89% | 89% |

# Trends in glyphosate use in US corn production

| Year | % Acres treated with glyphosate | Glyphosate a.i as % of total herbicide a.i |
|---|---|---|
| 1997 | 4 | 1 |
| 1999 | 9 | 3 |
| 2005 | 33 | 15 |
| 2010 | 66 | 35 |

# Trends in glyphosate use in US soybean production

| Year | % Acres treated with glyphosate | Glyphosate a.i as % of total herbicide a.i |
|---|---|---|
| 1995 | 20 | 11 |
| 1999 | 62 | 54 |
| 2006 | 95 | 89 |

# Trends in glyphosate use in US cotton production

| **Year** | **% Acres treated with glyphosate** | **Glyphosate a.i as % of total herbicide a.i** |
|---|---|---|
| 1995 | 9 | 3 |
| 1999 | 36 | 20 |
| 2005 | 74 | 57 |
| 2010 | 68 | 62 |

# US Trends in Corn Weed Management (% of acres)

| Practice | 1996 | 2000 | 2005 |
|---|---|---|---|
| Herbicide resistant seed | – | 11 | 31 |
| Field scouted for weeds | 81 | 83 | 89 |
| Burndown herbicide used | 9 | 12 | 18 |
| Pre-emergence control | 78 | 71 | 61 |
| Post-emergence control | 59 | 63 | 66 |
| Cultivated for weed control | 33 | 38 | 15 |

# US Trends in Soybean Weed Management (% of acres)

| **Practice** | **1996** | **2000** | **2006** |
|---|---|---|---|
| Herbicide resistant seed | 7 | 59 | 97 |
| Field scouted for weeds | 79 | 85 | 91 |
| Burndown herbicide used | 33 | 27 | 31 |
| Pre-emergence control | 67 | 46 | 28 |
| Post-emergence control | 78 | 87 | 95 |
| Cultivated for weed control | 29 | 17 | – |

# US Trends in Cotton Weed Management (% of acres)

| **Practice** | **1996** | **2000** | **2007** |
|---|---|---|---|
| Herbicide resistant seed | NA | 58 | 90 |
| Field scouted for weeds | 71 | 82 | 92 |
| Burndown herbicide used | 6 | 23 | 41 |
| Pre-emergence control | 90 | 79 | 73 |
| Post-emergence control | 62 | 76 | 89 |
| Cultivated for weed control | 89 | 63 | 38 |

# Corn Herbicide Treatments

| **Herbicide Family** | **1996** | **2005** |
|---|---|---|
| Phosphinic acid | 2 | 19 |
| Triazine | 19 | 48 |
| Amides | 38 | 4 |
| Benzoic / Phenoxy | 48 | 5 |
| Sulfonylurea | 27 | 5 |
| Pyridine | 4 | 6 |
| Other herbicides | 15 | 9 |

# Soybean Herbicide Treatments

| Herbicide Family | 1996 | 2006 |
|---|---|---|
| Phosphinic acid | 10 | 77 |
| Dinitroaniline | 20 | 3 |
| Imidazolinone | 21 | 2 |
| Sulfonylurea | 9 | NA |
| Diphenyl ether | 8 | 1 |
| Oxime | 7 | 1 |
| Other herbicides | 26 | 14 |

# Cotton Herbicide Treatments

| **Herbicide Family** | **1996** | **2007** |
|---|---|---|
| Phosphinic acid | 3 | 60 |
| Dinitroaniline | 26 | 14 |
| Urea | 20 | 6 |
| Triazine | 13 | 2 |
| Organic arsenical | 12 | 1 |
| Benzothiadiazole | 3 | 1 |
| Other herbicides | 23 | 17 |

# Changes in weed management from adoption of HR crops:

## Internet survey of 54 agricultural professionals

| Weed management practice | Respondents believing growers following practice “less” or “much less” as a result of HR crop adoption |
|---|---|
| Combination of weed control methods | >60% |
| Crop rotation for weed control | >40% |
| Annual rotation of herbicides | >50% |
| Use of multiple herbicides | >60% |
| Tillage for weed control | >80% |

# Bradshaw, et al. Perspectives on glyphosate resistance. *Weed Technology* 11, 189-198.

- 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

| Year | Species | Region |
|---|---|---|
| 1996 | Lolium rigidum (Rigid Ryegrass) | Australia |
| 1997 | Eleusine indica (Goosegrass) | Malaysia |
| 1998 | Lolium rigidum (Rigid Ryegrass) | California |
| 2000 | Conyza canadensis (Horseweed) | Delaware |

# 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

- Miranowski & Carlson. 1986. Economic issues in public & private approaches to preserving pest susceptibility. In Board on Agriculture (Ed.), *Pesticide resistance: Strategies and tactics for management.* Washington, DC: National Academy Press.

- 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

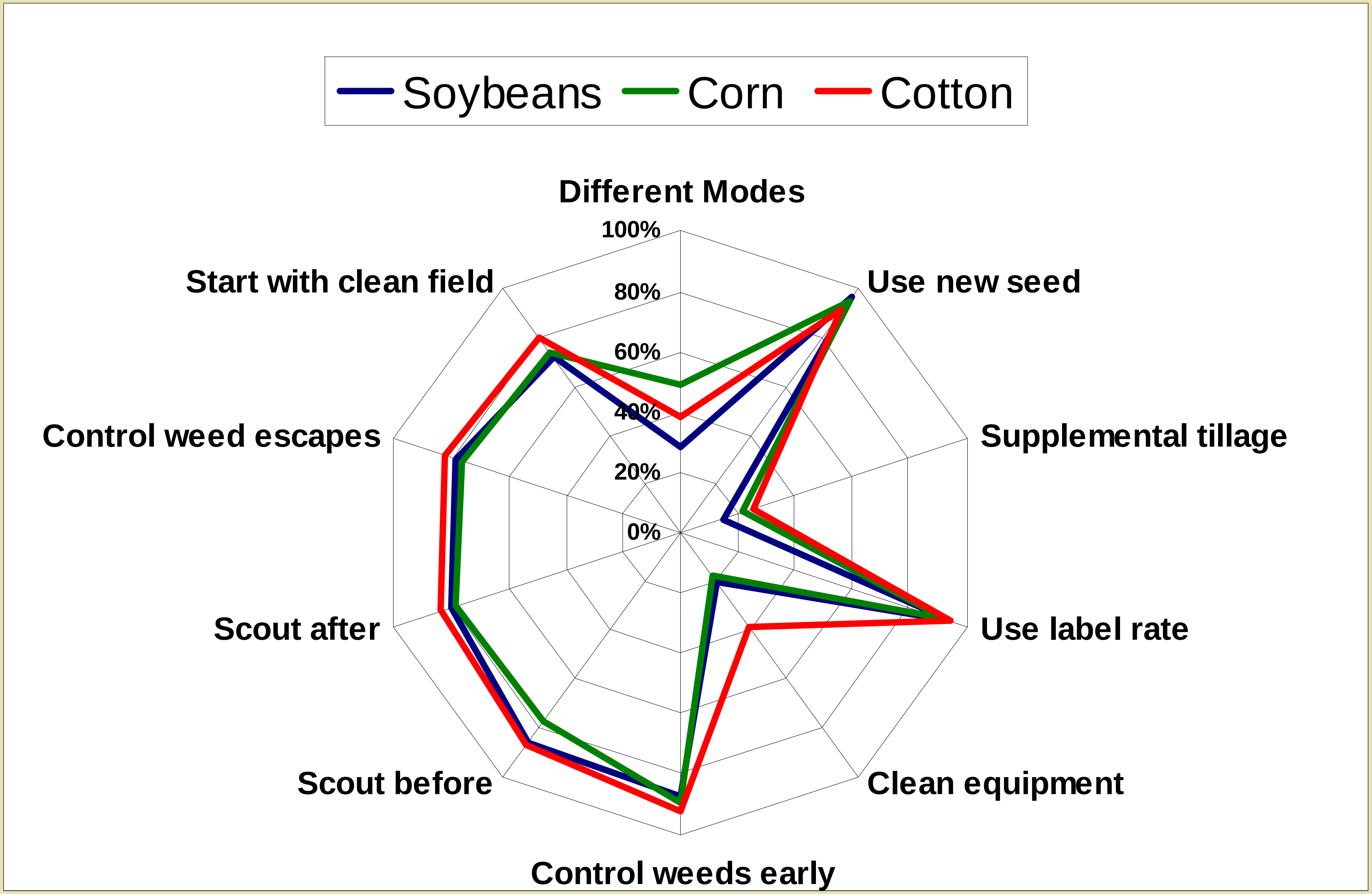
# Regulatory approach to resistance management for Bt crops

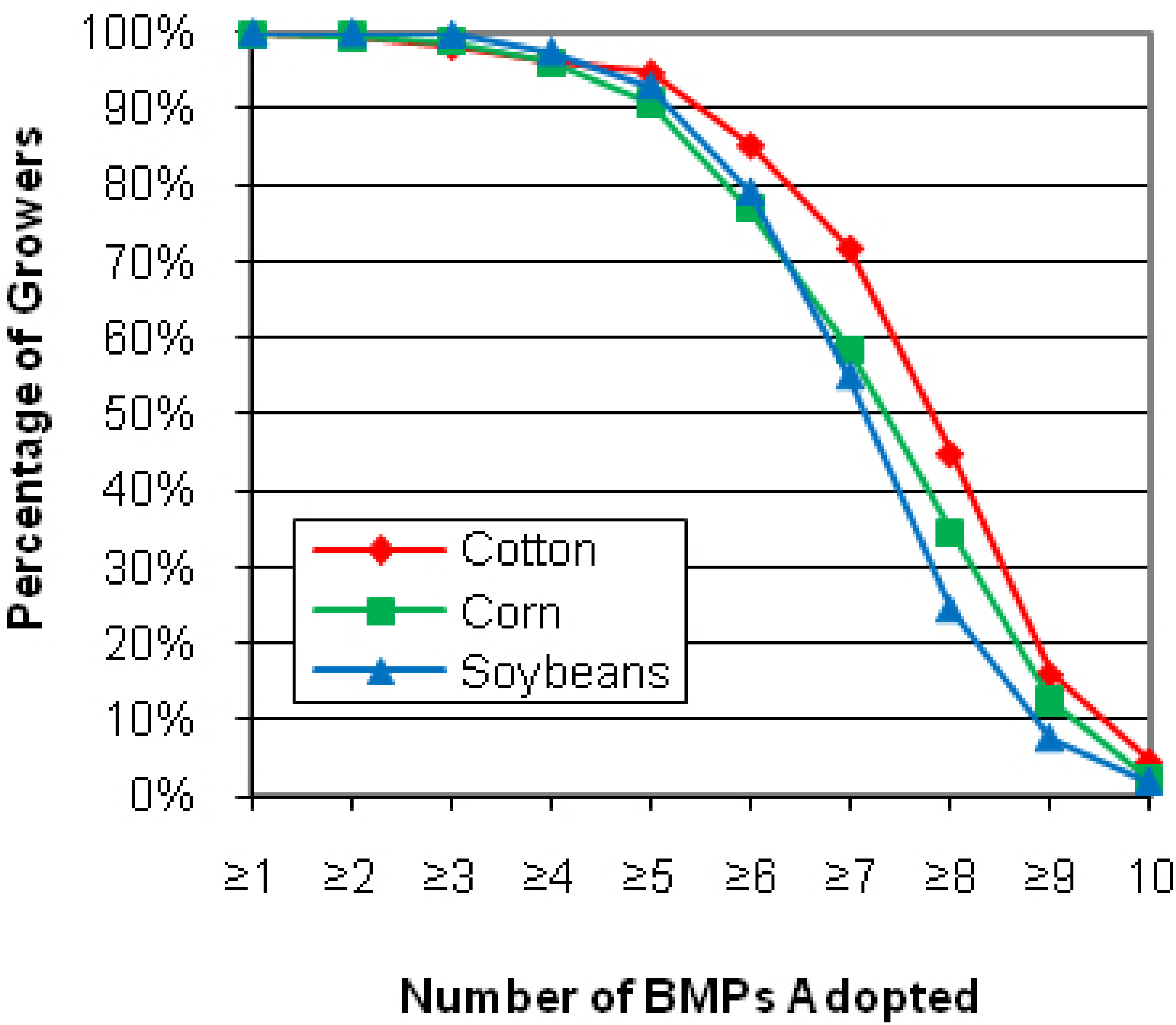
- How much did it improve *ex ante* resistance monitoring?
- How much did it improve scientific understanding?
- Now the big question . . . did EPA regulations save growers millions of dollars?

# 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




Percentage of Growers
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Cotton
Corn
Soybeans
≥1
≥2
≥3
≥4
≥5
≥6
≥7
≥8
≥9
10
Number of BMPs Adopted

# 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 “**W**eakest **L**ink **P**ublic **G**ood”

- 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. $A > \underline{A}$

where

- $T'_f(A) > 0$
- $\underline{A}$ is minimum acceptable operation size

# Farm Household Expected Utility

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

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

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

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

# Implications

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

$$\text{s.t. } T = T_f\,(A) + T_n + L;\; A > \underline{A}$$

- 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
- Frisvold, G & J Reeves (2014 in press) Herbicide resistant crops and weeds: Implications for herbicide use and weed management. *In Integrated Pest Management: Pesticide Problems*, *Vol. 3*. D Pimentel & R Peshin (eds.) Dordrecht, The Netherlands: Springer.