Reducing the Risks of Herbicide Resistance: Best Management Practices and Recommendations

Theodore M. Webster

Crop Protection & Management Research Unit

USDA-Agricultural Research Service, Tifton, GA

Weeds

- **“Weeds are among the greatest contributors to production costs on American farms. The losses caused by weeds on farms in the US have now reached an estimated $4 billion annually. These losses are estimated to equal the combined losses from insects and diseases…”**

  Warren Shaw, USDA-ARS, November 1954

- **Herbicides are the primary means of weed control in the US**

*

A grower's field in Macon County, GA

Glyphosate 4X rate to 2.5 cm

Glyphosate 4X rate to 10 cm

Glyphosate 4X rate to 30 cm*

1st Herbicide Resistant Weeds

1957: 2,4-D resistance in Wild Carrot

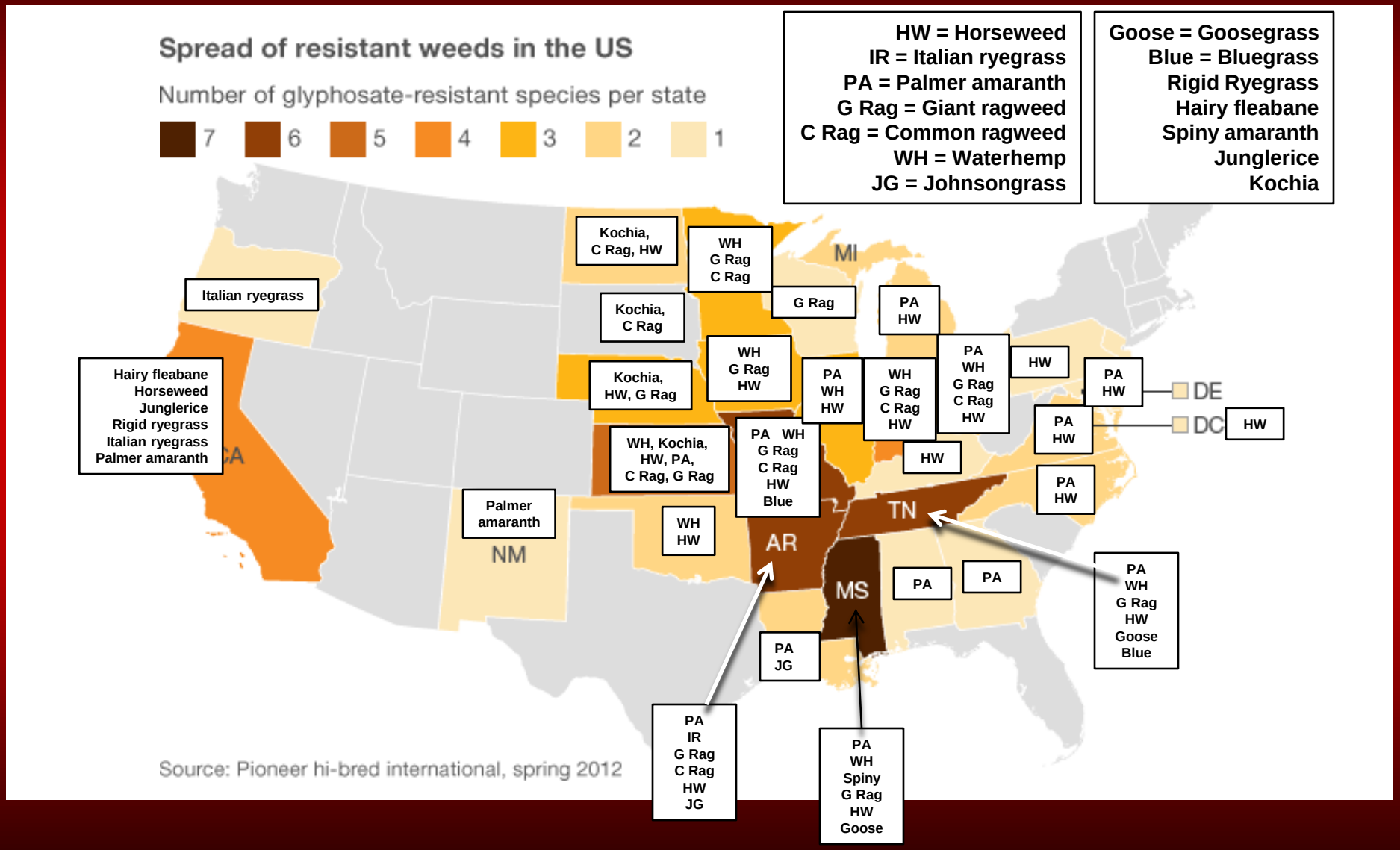
Photo by Chris Evans, invasive.org

1970: triazine resistance in Common Groundsel

Photo by Bruce Ackley, invasive.org

*

Occurrence of 14 GR weeds in the US



Source: International Survey of Herbicide Resistant Weeds (www.weedscience.org)

*

Herbicide Resistance

- **Palmer amaranth**
  - Glycine (e.g. Roundup)
  - ALS-inhibitors (e.g. Staple, Cadre, Pursuit)
  - Dinitroanilines: (e.g. Prowl, Treflan)
  - Triazines (e.g. Atrazine, Simazine)
- **Waterhemps: (all of the above and…)**
  - PPO-inhibitors (e.g. Reflex, Blazer, Cobra)
  - HPPD inhibitors
  - Multiple Resistance: PPO+ALS+Triazines

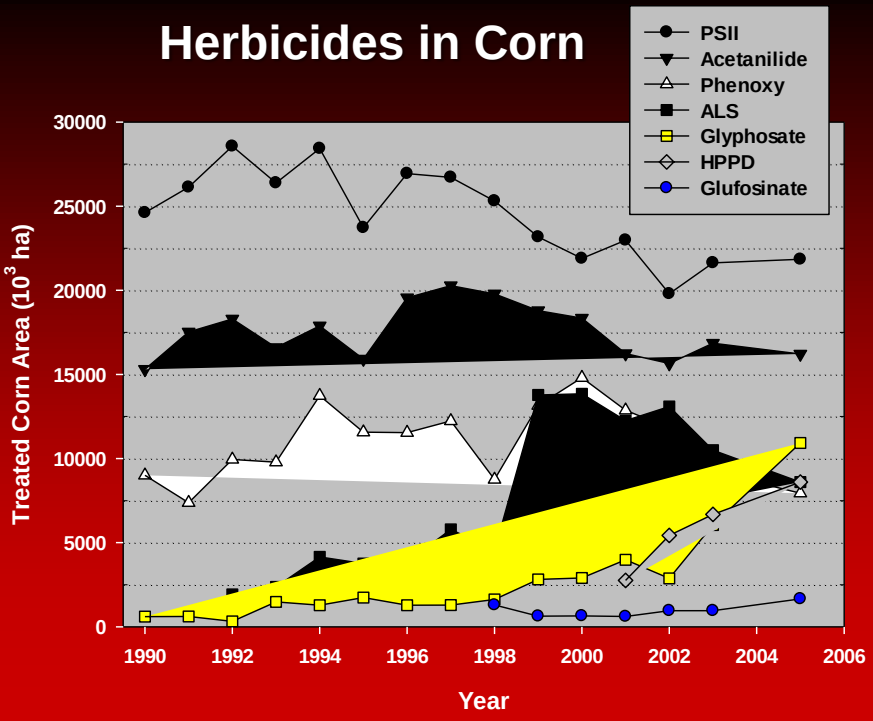
*

Why herbicide resistance?

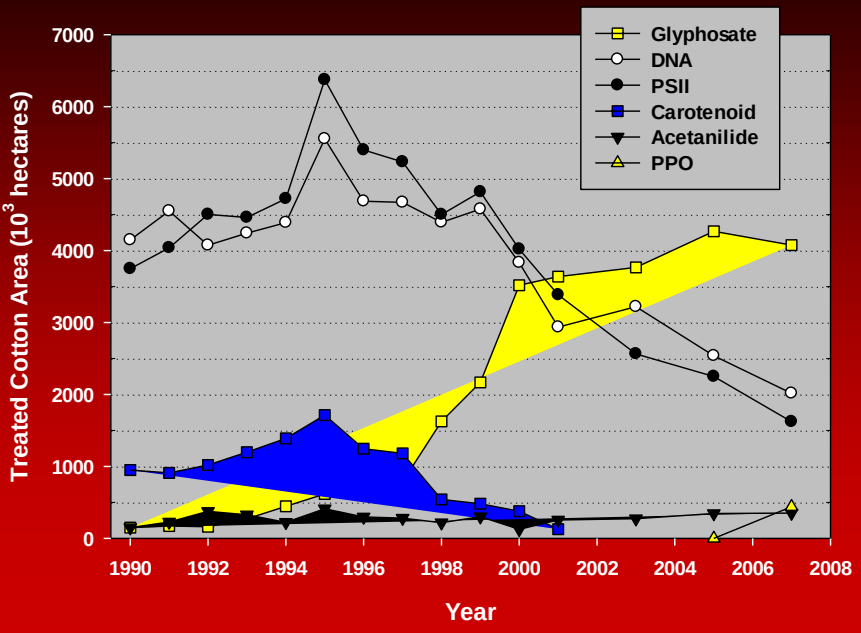
- Dramatic Change in Selection Pressure
- Selection pressure is anything used to alter the ability of the weed to survive
  - Not Weed specific
  - Not Herbicide specific
    - Lack of tillage and perennial weeds
    - Mowing will kill many weeds, but dandelions tolerate it
- 2 Key Principles (Harper 1956)
  - Reducing the intensity of selection
  - Preventing reproduction and survival

*

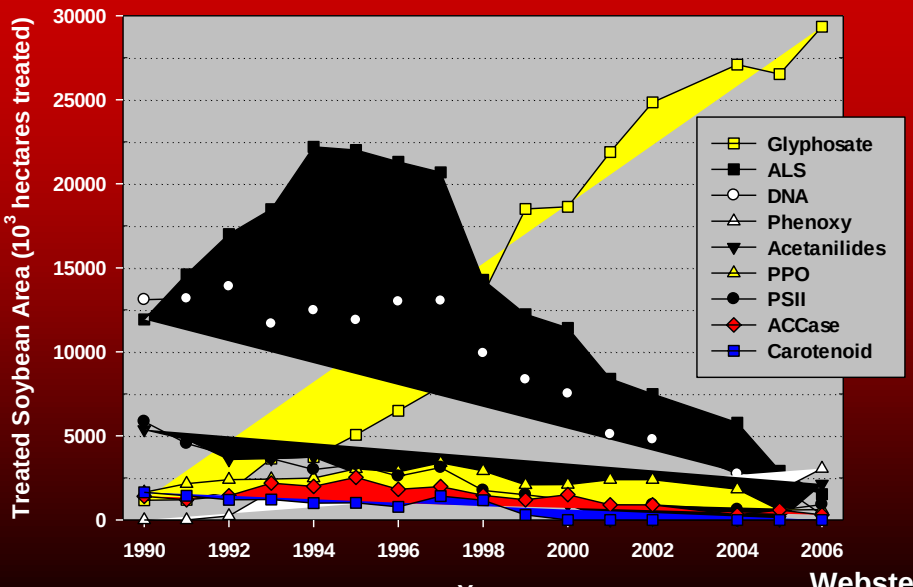
Herbicides in Corn



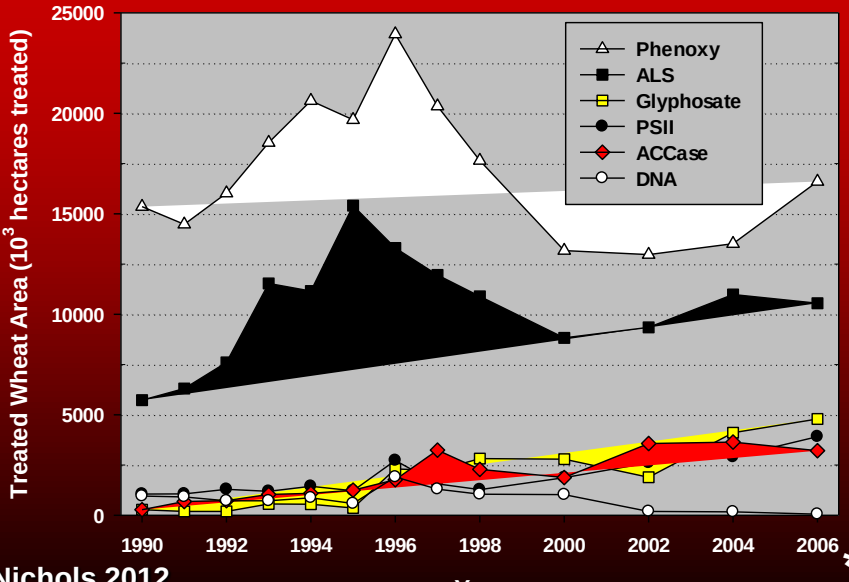
Herbicides in Cotton



Herbicides in Soybean



Herbicides in Wheat



Webster and Nichols 2012

*

Changes in Herbicide use patterns in GR Crops

- Adoption of GR crops often associated with:
  - Ceasing use of other herbicides
  - Reducing tillage (strip till cotton reduces preharvest labor costs 30%)
  - Relying almost exclusively on glyphosate
  - Growing more cotton (in GA)
- Glyphosate provides better, cheaper, and more flexible weed management than alternatives

Powles 2008 Duke and Powles 2008 Shurley 2006 *

Warren Shaw, USDA-ARS, November 1954

- "…Of much greater significance and practical importance are the changes in ecological relationships as a result of the use of herbicides."
- "In the North Central US, 2,4-D is used for the control of weeds in over 8 million acres of corn annually. The weedy grasses and many serious broadleaved weeds are not controlled by the treatments. As a result the broadleaved annual weeds are decreasing the and the grasses are increasing, presenting a different and in many cases a more difficult weed problem than the original."

*

Herbicide Resistant Weeds in the US

Mechanism of action	Group #	# of biotypes	# of weed spp.
ACCase	1	34	13
ALS	2	121	37
Auxins	4	12	8
Carotenoid biosynthesis	28	1	1
Chloroacetamides	15	1	1
Dinitroaniline	3	12	5
EPSPS	9	39	9
Not classified	27	3	1
Organic arsenicals	17	7	1
Protox	14	3	1
PS I	22	5	4
PS II (nitriles)	6	1	1
PS II (triazines)	5	91	25
PS II (ureas)	7	11	7
Thiocarbamates	8	6	5
Total		347	119

*

So what are we to do?

INDUSTRY COMMENTS

HOW FAR CAN TECHNOLOGY EVENTUALLY TAKE THE U.S. COTTON INDUSTRY?

Owen Gwathmey

Extension Agronomist, Jackson, Tenn.

Even though it's been more than 10 years since the introduction of *Bt* technology, I think we'll have new breakthroughs that will continue to carry this industry into the future. And I think that will occur despite these current acreage reductions in cotton. When I look around and see how many technological events that have occurred in cotton production, it's amazing and quite encouraging. We have a lot to look forward to in the future.

John McKee

Producer, Friars Point, Miss.

I share the excitement that the rest of the industry has about technology and what it's done for the cotton industry. But I also think that we have to take a long look at our own operations and see how certain kinds of technology will affect our bottom line profitability. As thin as margins are today, we just need to pick and choose what will work best on our farms. I think that's a smart approach to technology.

Lee Rivenbark

Bayer CropScience, Lubbock, Texas

I am absolutely confident that this first wave of technology in cotton is just the beginning. With the herbicide, insect and fiber traits that our company has in the pipeline – along with our competitors – there is reason for excitement. Producers obviously will look at many factors as they make the cropping decisions that are best for their own operations. That's what they should do. Having said that, I think there is a real opportunity to bring some of these acres back to cotton, and technology will help us get there. Cotton has a long history, and the producer will have plenty of tools available.

Stanley Culpepper

Extension Entomologist, Tifton, Ga.

We need to remember one thing in any discussion of technology as it pertains to the cotton industry. Technology will only carry us as far as the quality of the cotton production we have. We must protect, conserve and use that technology wisely, or we'll lose it, and it won't really matter in the grand scheme of things. I'm not being negative when I say that. I'm simply saying that we must be good stewards of that technology and use it the right way, or it won't do us any good. If I had to communicate any one thought on this topic to the industry, that's what it would be.

Larry McClendon

Producer-Ginner, Marianna, Ark.

Technology will obviously be an important component that will help stabilize agriculture – particularly cotton. I think the results of technology's influence will be better fiber, and we know that's the name of the game. We've got to find a way to have intensive production, and one of the methods that will help us get there is technology. As to how much a producer uses technology, that will be a discretionary issue for him. Quite frankly, what works on my farm might not work on yours. It's definitely an individual decision.

"We must protect, conserve, and use that technology wisely, or we'll lose it…we must be good stewards of that technology and use it the right way…" (Culpepper, *Cotton Farming* Aug 2008

Stewardship is the sum of the management decisions and practices that are used to preserve the utility of a weed management option (Owen 2007)

*

Stewardship Awareness?

- **Awareness does not always lead to proactive management:**
  - **Grower awareness of herbicide resistance issues in Canada was high (90%)**
  - **Growers that altered their weed control strategies based on this knowledge was low (40%)**
  - **Weed control performance and cost are often of greater importance than site of action when selecting a herbicide (Beckie 2006)**

Goodwin 1994 *

Constraints of Stewardship?

1. **Belief that new technology will be developed to solve the resistance problem**
   - Growers with this belief were less likely to adopt resistance avoidance strategies relative to those with greater uncertainty (Llewellyn et al. 2007).

- Precedence:
  - Triazine-R weeds "solved" by new ALS and ACCase
  - ALS-R and ACCase-R weeds "solved" by glyphosate.
  - No new mode of action since 1998.
    - 1946 to 1955: 23 new herbicides
    - 1956 to 1965: 62
    - 1966 to 1975: 74
    - 1976 to 1985: 80
    - 1986 to 1995: 96
    - 1996 to 2006: <20

*

Constraints of Stewardship?

2. Belief that resistance strategies are futile
   - Western Australia: 70% of growers surveyed believed they gained herbicide resistant weeds from neighboring farms through seed or pollen movement (Llewellyn and Allen 2006)
   - Ohio farmers attributed weed introductions from natural elements, with 23% specifically citing movement from neighbors' poorly managed fields (Wilson et al. 2008)

*

http://wssajournals.org/doi/pdf/10.1614/WS-D-11-00155.1

Weed Science 2012 Special Issue:31–62

Reducing the Risks of Herbicide Resistance: Best Management Practices and Recommendations

Jason K. Norsworthy, Sarah M. Ward, David R. Shaw, Rick S. Llewellyn, Robert L. Nichols, Theodore M. Webster, Kevin W. Bradley, George Frisvold, Stephen B. Powles, Nilda R. Burgos, William W. Witt, and Michael Barrett*

Table of Contents

Executive Summary

Herbicides are the foundation of weed control in commercial crop-production systems. However, herbicide-resistant (HR) weed populations are evolving rapidly as a natural response to selection pressure imposed by modern agricultural management activities. Mitigating the evolution of herbicide resistance depends on reducing selection through diversification of weed control techniques, minimizing the spread of resistance genes and genotypes via pollen or propagule dispersal, and eliminating additions of weed seed to the soil seedbank. Effective deployment of such a multifaceted approach will require shifting from the current concept of basing weed management on single-year economic thresholds.

Programs for herbicide-resistance management must con-

3. Plant into weed-free fields and then keep fields as weed free as possible.
4. Plant weed-free crop seed.
5. Scout fields routinely.
6. Use multiple herbicide mechanisms of action (MOAs) that are effective against the most troublesome weeds or those most prone to herbicide resistance.
7. Apply the labeled herbicide rate at recommended weed sizes.
8. Emphasize cultural practices that suppress weeds by using crop competitiveness.
9. Use mechanical and biological management practices where appropriate.
10. Prevent field-to-field and within-field movement of weed seed or vegetative propagules.
11. Manage weed seed at harvest and after harvest to prevent a buildup of the weed seedbank.
12. Prevent an influx of weeds into the field by managing field borders.

The long-term economic benefits of avoiding additional costs associated with managing HR weeds are clear. Nevertheless, widespread adoption of these BMPs must overcome several real barriers. In particular, growers' focus on immediate economic returns must be overcome as well as their beliefs that the evolution of herbicide resistance in weeds is unavoidable and that continued availability of novel herbicide technologies will solve the problem. There is, at present, no single database collating information on weed management practices employed by U.S. growers, so the

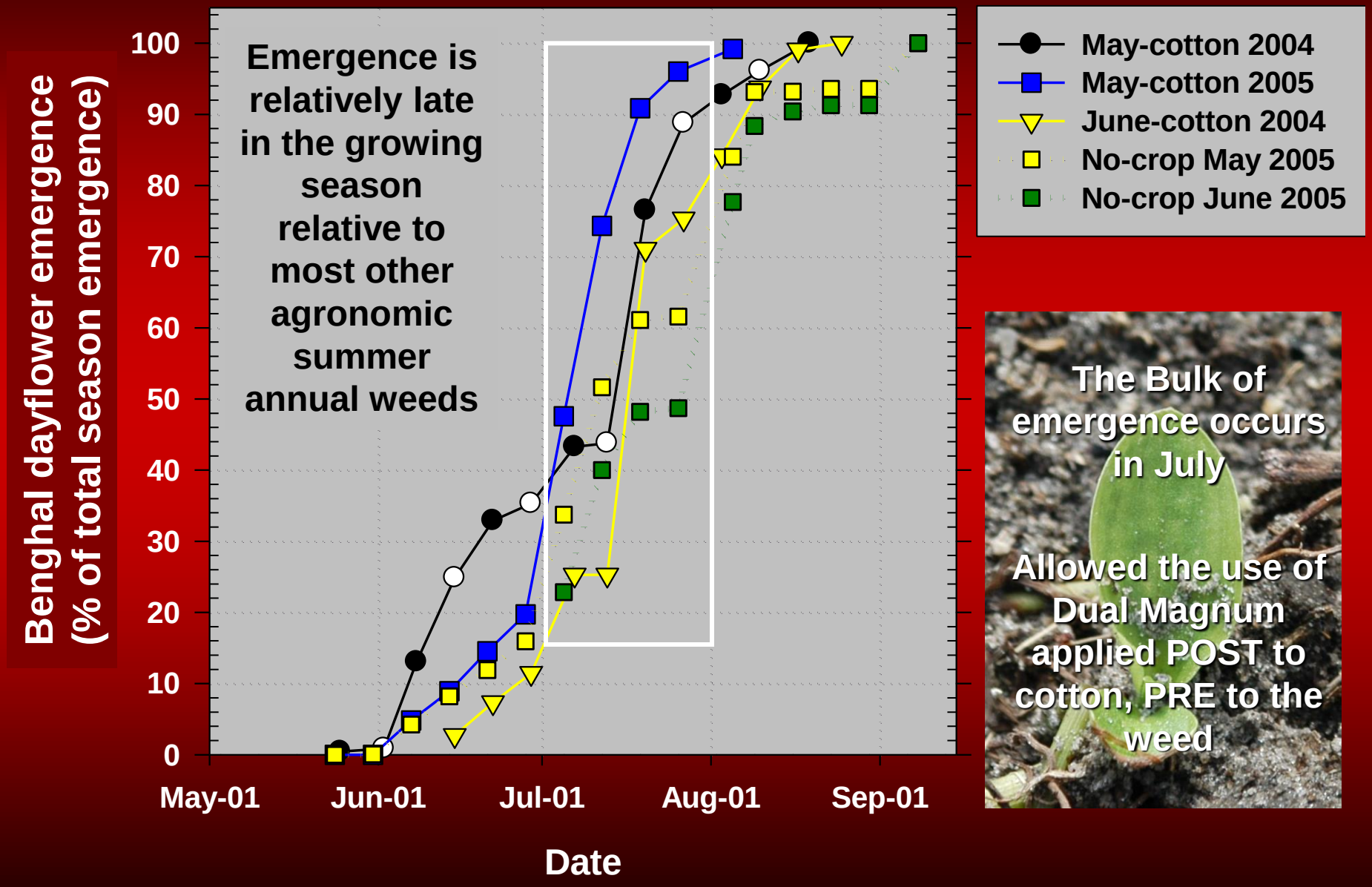
*

BMP 1: Understand the Biology of the Weeds Present

- **Prediction of Germination/Emergence:**
  - **Coordinate Tactics**
  - **Sequence usually consistent: phenology studies**
    - **25% SETFA emerged @ red chokeberry first bloom**
    - **80% SETFA emerged @ multiflora rose full bloom**

Cardina and et al. 2007, 2011

*


Benghal dayflower emergence
(% of total season emergence)
100
90
80
70
60
50
40
30
20
10
0
May-01
Jun-01
Jul-01
Aug-01
Sep-01
Date
Emergence is relatively late in the growing season relative to most other agronomic summer annual weeds
May-cotton 2004
May-cotton 2005
June-cotton 2004
No-crop May 2005
No-crop June 2005
The Bulk of emergence occurs in July
Allowed the use of Dual Magnum applied POST to cotton, PRE to the weed

*

BMP 1: Understand the Biology of the Weeds Present

- Germination/Emergence Requirements
- Reproductive Biology:
  - Breeding system may regulate speed of HR
  - How many seed?
- Timing of Reproduction:
  - When does it flower?
  - Viable seed?
    - Waterhemp pollination + 10d
    - Benghal dayflower: 42 d – seedling to seed

*

Challenges: BMP 1

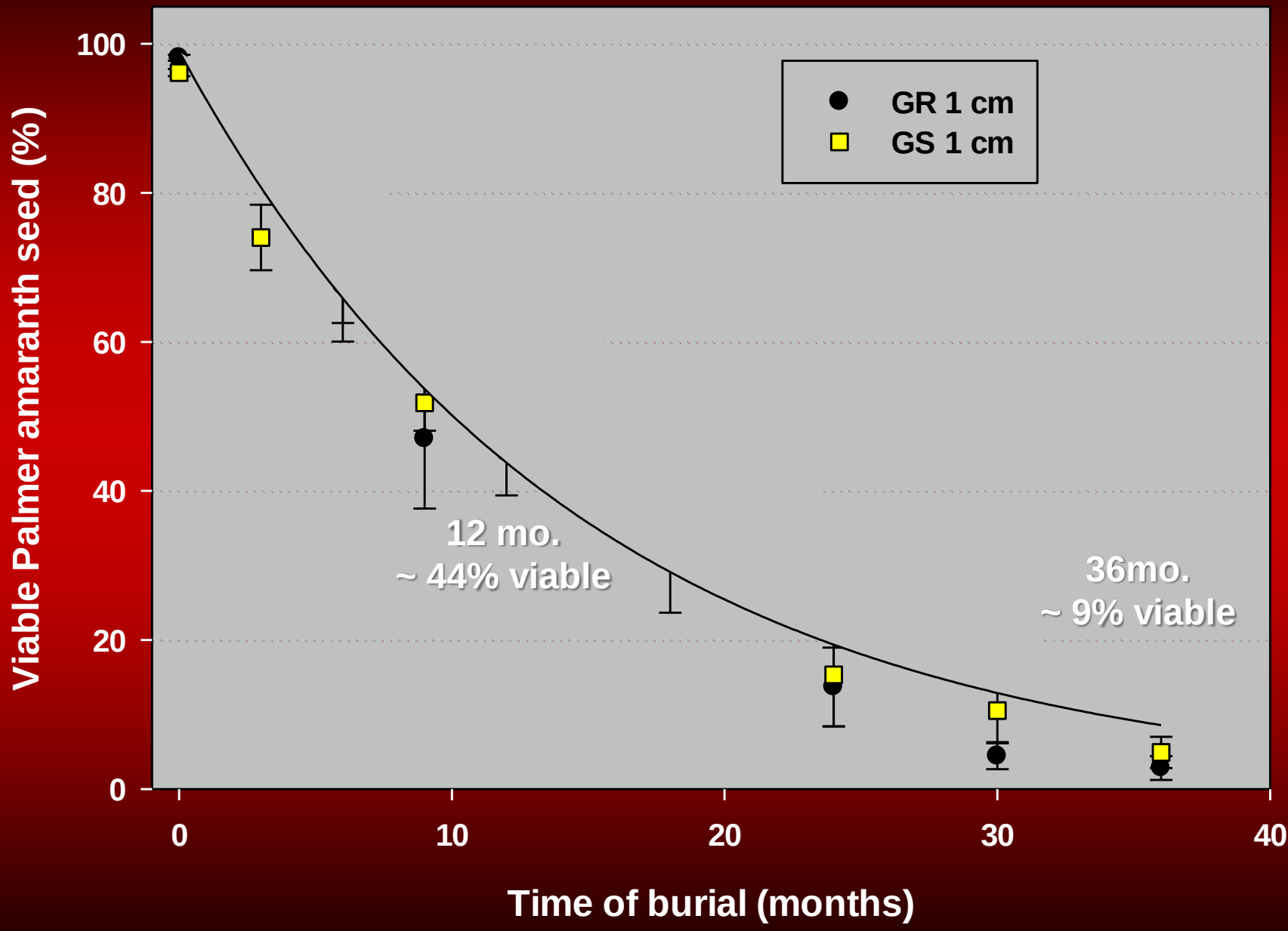
- Funding for this research is limited.
- Must economize through functional groups
- Requires us to identify the appropriate biological characteristics by which we can group weeds.

BMP 2: Diversified Approach to Weed Management Focused on Reducing Weed Seed Production and the Number of Weed Seeds in the Soil Seedbank

- ***One year's seeding, seven year's weeding…*Seedbanks are persistent**

*

Sosnoskie et al. 2013 (Weed Sci., *in press*)



*

BMP 2: Diversified Approach to Weed Management Focused on Reducing Weed Seed Production and the Number of Weed Seeds in the Soil Seedbank

- ***One year's seeding, seven year's weeding…*Seedbanks are persistent**
- **Seedbanks reduced 95% after 5-years of weed-free management, but…**

Hand weed

Slide from Stanley Culpepper, UGA

*

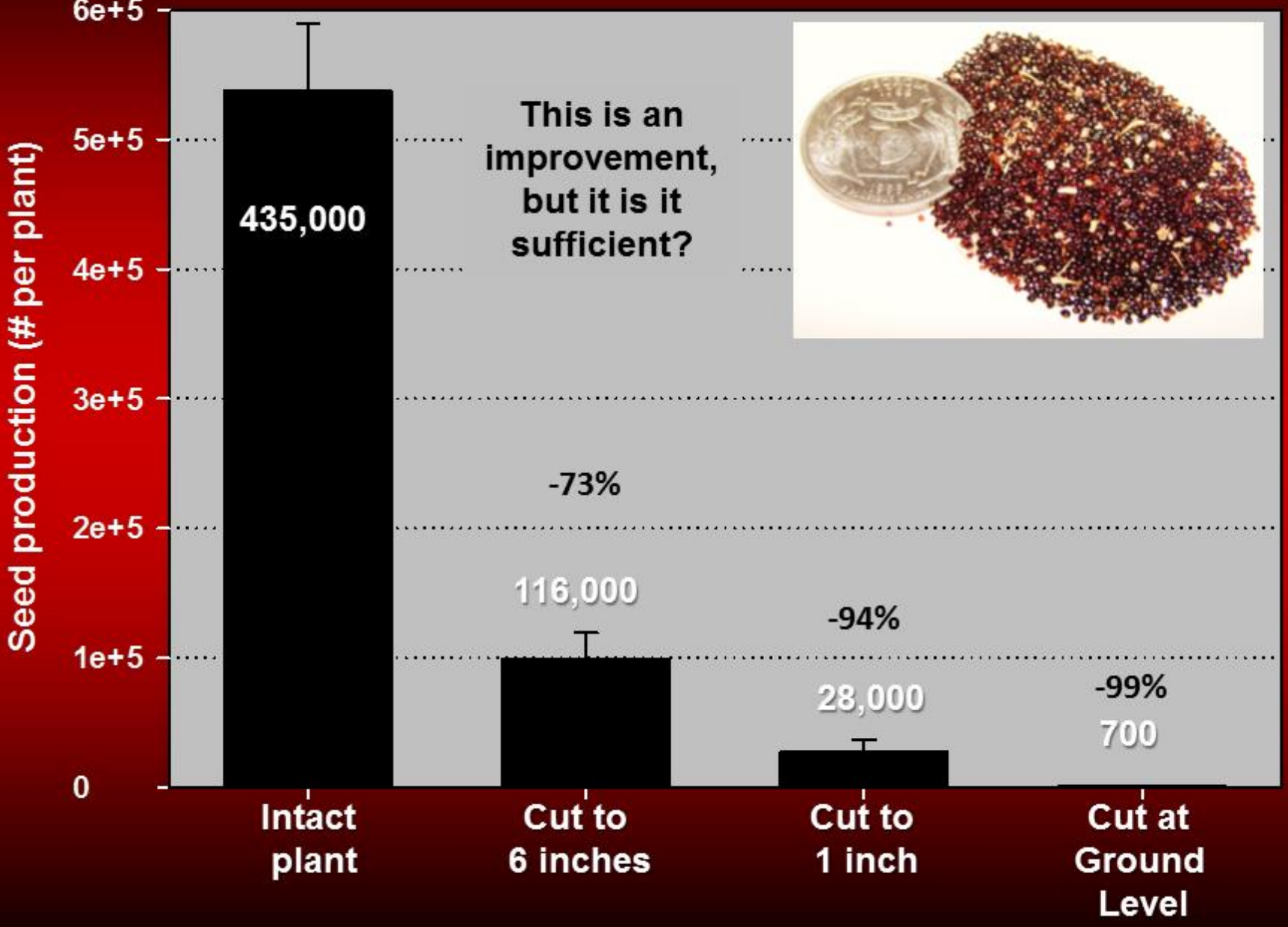

Cut at ground


Cut to 1”


Cut to 6”


Non-cut
*

Seed Production



*

Challenges: BMP 2

- Eradication of seedbanks is difficult…a goal that growers have tried to attain throughout history.
- I question our ability to prevent seed return over large areas of land that contain diverse, long-lived, dormant soil seedbanks.

BMP 3: Plant into Weed-Free Fields and Keep Fields as Weed-Free as Possible

- Once emerged (weed and crop) the management options are dramatically reduced.
- ↑Emphasis on residual herbicides (Georgia)
  - Valor burndown
  - Warrant + Reflex PRE
  - Roundup + Staple POST1
  - Roundup + Dual Magnum POST2
  - Direx + MSMA Layby
- Get crop established ASAP; dense crop canopy will suppress weed emergence

Webster, USDA-ARS, Tifton, GA

*

Challenges: BMP 3

- **Restrictions to ensuring a weed-free seedbed:**
  - **Conservation tillage programs**
  - **Local ordinances on burning fields**
- **Irrigation/Rainfall may be needed to move herbicides into germination zone**

BMP 4: Plant Weed-Free Crop Seed

- Initial step in preventing the introduction of new weeds
- Utah Wheat: 14% of seed samples had wild oat contamination of 21 seed/2.2 lb sample
- Australian Wheat shipped to Japan: 4500 HR ryegrass seed in 440 lb sample

Dewey & Whitesides 1990

*

Shimono et al. 2010

Challenges: BMP 4

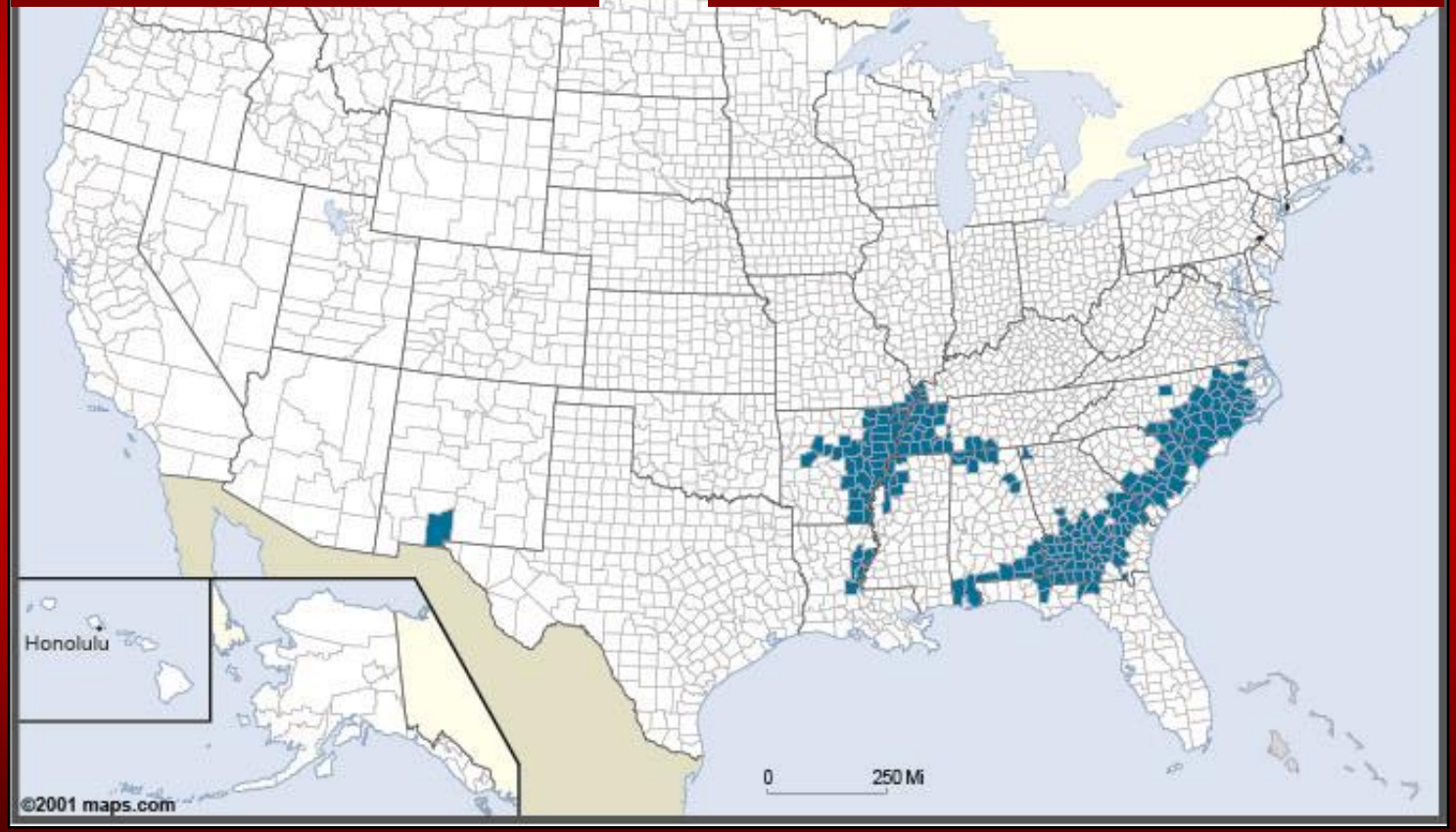
- Proper cleaning of grower-saved seed
- Convincing growers of cotton, soybean, rice, and wheat to forego saving seed (and money) and instead plant purchased seed

BMP 5: Scout Fields Routinely

- **Timely scouting: maintain an inventory of weed spp., location, density, & size.**
  - **Before: to determine what tools**
  - **After: to evaluate efficacy and ID problems**
- **Early detection and Rapid Response to problems.**

Distribution of Glyphosate-Resistant Palmer amaranth

One field in one county in Georgia in 2004 → **50% of upland cotton acres (13.4 million) in the US in 2010.**

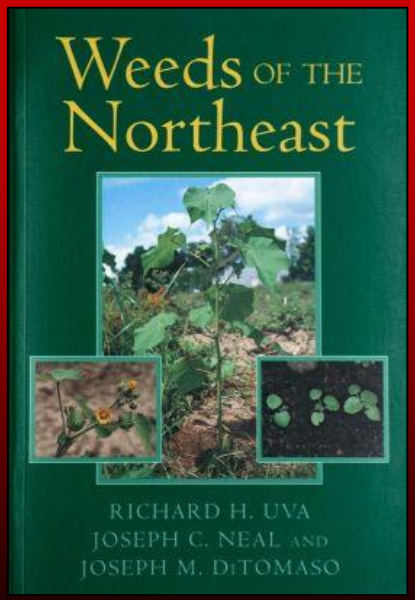


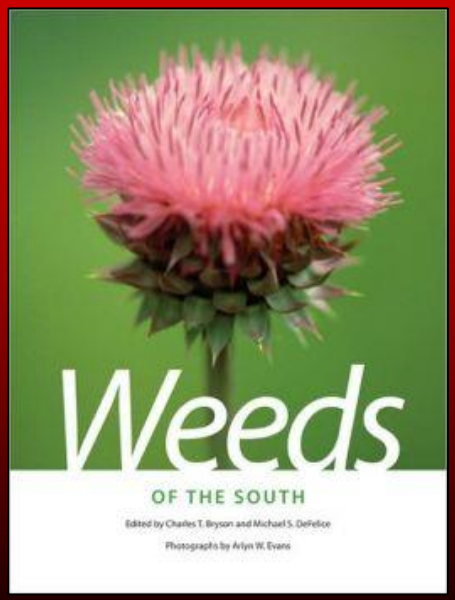
Map credit: Dr. Bob L. Nichols, Cotton Incorporated

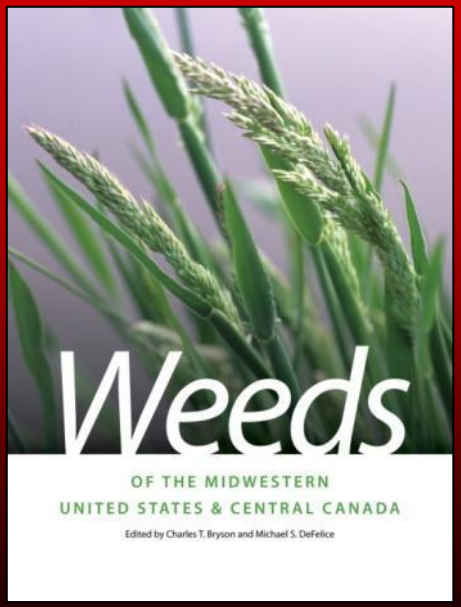
*

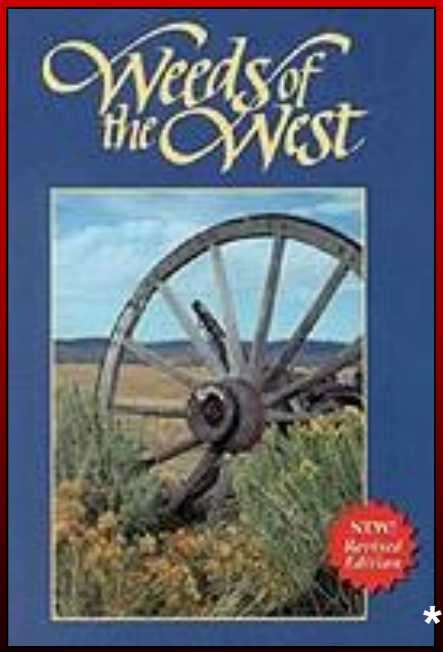
Challenges: BMP 5

- Scouting is time-consuming and costly
- Resistance management is an ever-changing process
- Proper training in weed ID is crucial









*

BMP 6: Use Multiple, Effective MOAs against the Most Troublesome Weeds and Those Prone to Herbicide Resistance

- Herbicides are often the strongest selection agents for weed species in a cropping system.
- Rapid increase in proportion of HR weeds with repeated use of MOA
- Models suggest diversity…
  - Tank mixes vs. sequential

Webster, USDA-ARS, Tifton, GA

*

Challenges: BMP 6

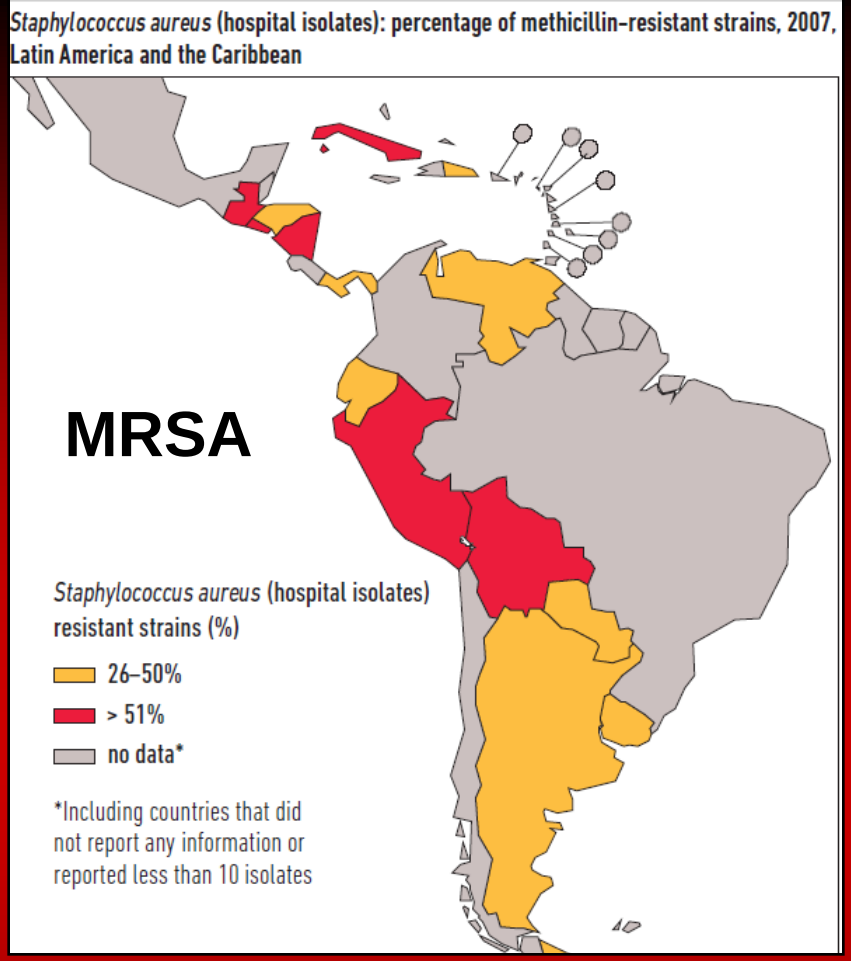
- **Increased short-term costs**
  - **2000-2005: Herbicide costs = *$32.30/A***
  - **2006-2010: Herbicide costs = *$62.50/A***
- **Matching MOA's of similar efficacy with weed spectrum.**
- **Herbicide antagonism**
- **Smaller herbicide toolbox**

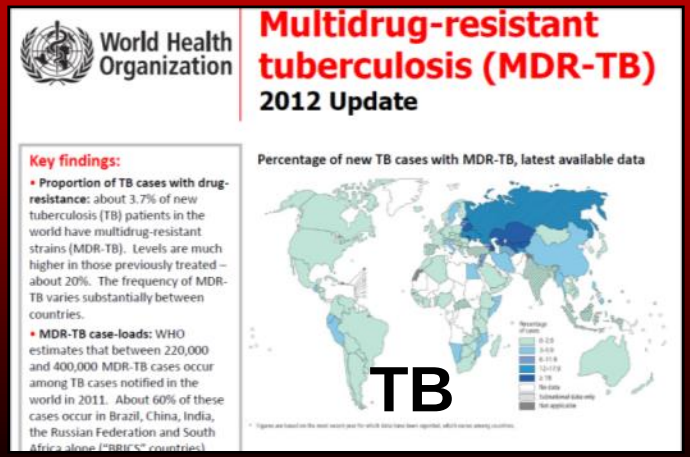
*

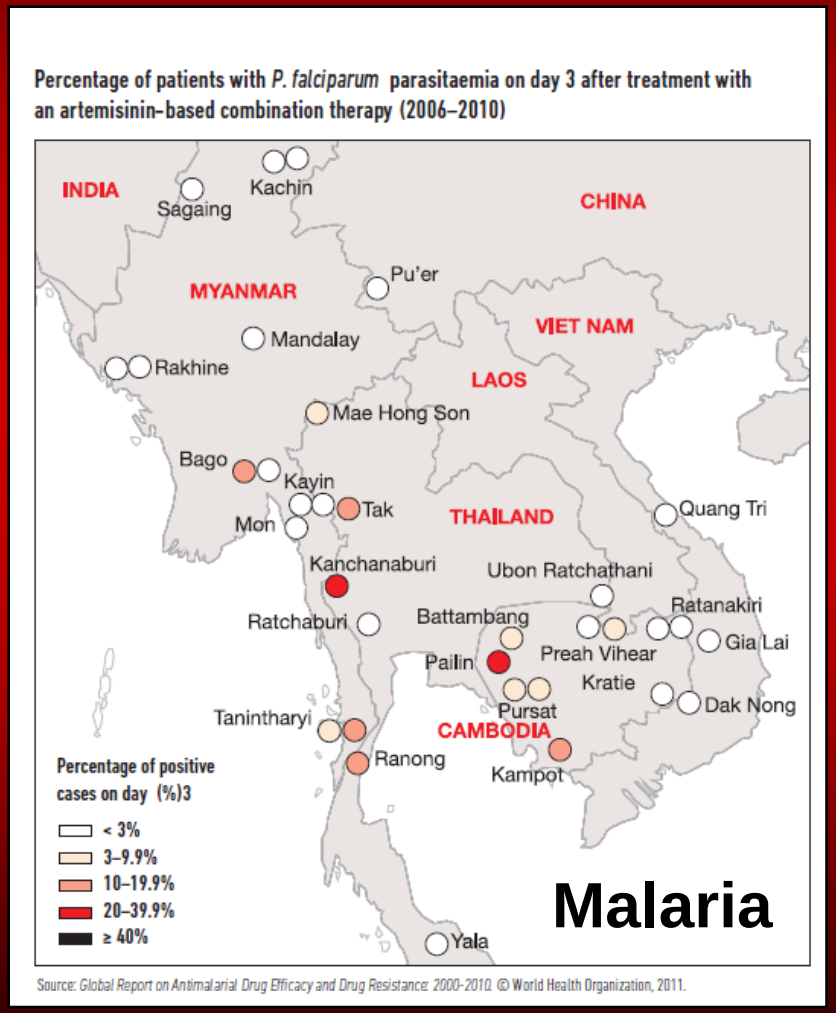
BMP 7: Apply the Labeled Herbicide Rate at Recommended Weed Sizes

- Contrary to the European model
- Do not reduce herbicide rates:
  - Long-established tenet of crop breeding
  - Polygenic resistance is greater risk

Multi-Drug Resistance







*

BMP 7: Apply the Labeled Herbicide Rate at Recommended Weed Sizes

- Contrary to the European model
- Do not reduce herbicide rates:
  - Long-established tenet of crop breeding
  - Polygenic resistance is greater risk
- Treat proper weed sizes

*

Palmer amaranth: Glyphosate-resistance comes to Georgia

Glyphosate 1X rate, 2 d after application to 41 cm Palmer amaranth

*

Weed Management in Glufosinate-Tolerant Cotton

- Timing is critical!
- 3 to 4 inches for consistent Palmer control

This is not a 4-inch pigweed!

Slide from Stanley Culpepper, UGA

*

Challenges: BMP 7

- Perceived and real risks to using herbicides.
- Crop phytotoxicity: labels will need to reflect Extension Recommendations
- Concern with minor-use crops
- Timely applications to target specific weed sizes
- Can be difficult to ensure adequate coverage

BMP 8: Emphasize Cultural Management Techniques that Suppress Weeds by Using Crop Competitiveness (BMP's)

- Planting time
- Competitive varieties
- Seeding rate
- Row spacing

Challenges: BMP 8

- Principles adaptable to most any cropping system…
- Not *Once Size Fits All*, but instead a part of an Integrated Pest Management system
  - Complex
  - Trial and Error
- Hurdles:
  - Equipment
  - Increased seed cost per area

*

BMP 9: Use Mechanical and Biological Management Practices Where Appropriate

- **Tillage changed regularly to avoid dominance by any particular species:**
  - **Reduced tillage:**
    - **↑ perennials, small seeded BL's, annual grasses**
    - **↑ in # and diversity of weed species**
  - **Conventional tillage:**
    - **↑ large seeded-BL's**

Webster, USDA-ARS, Tifton, GA

*

BMP 9: Use Mechanical and Biological Management Practices Where Appropriate

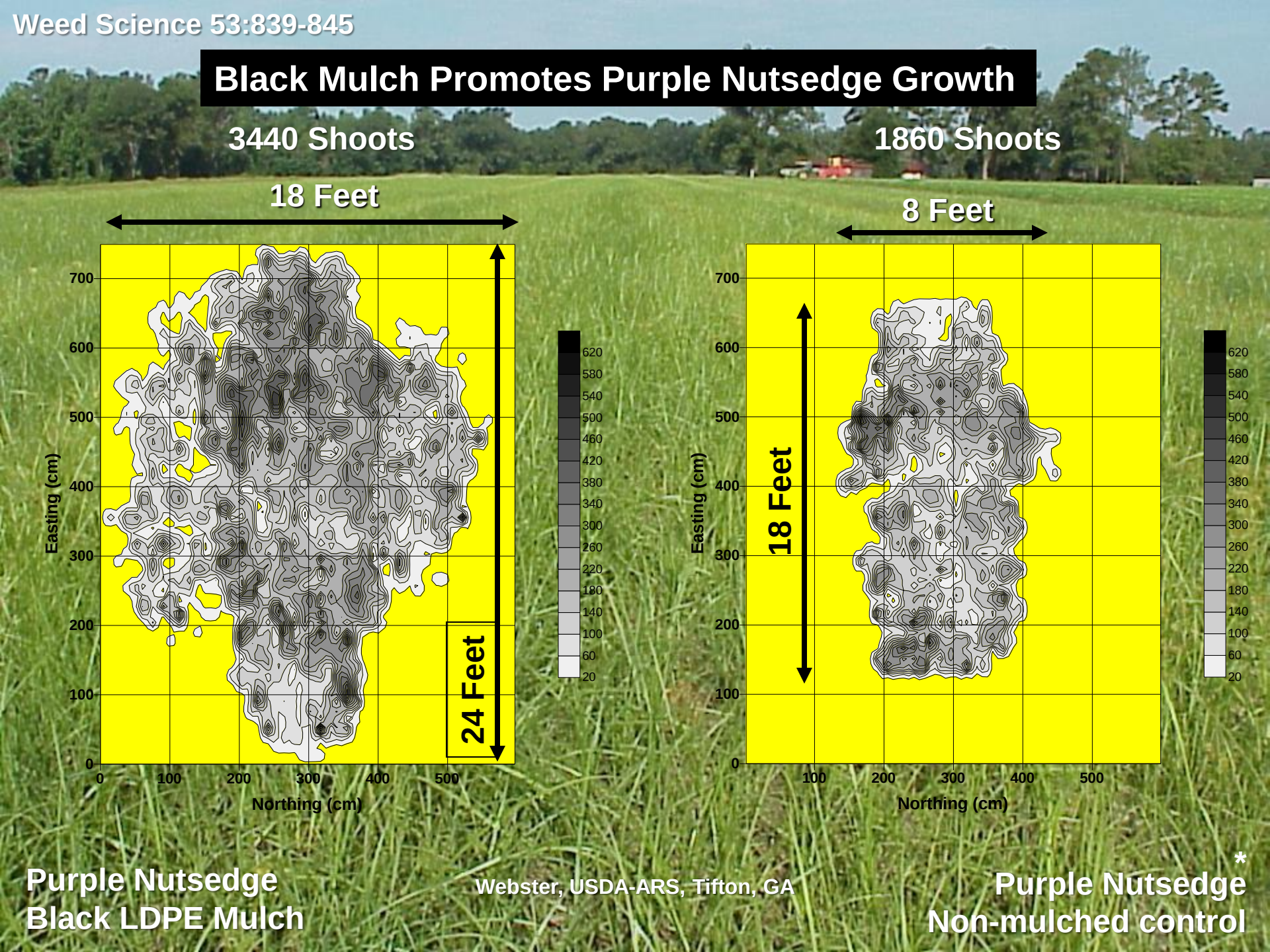
- Tillage changed regularly to avoid dominance by any particular species
- Mulches: can suppress weeds, but…

Webster, USDA-ARS, Tifton, GA

*

Weed Science 53:839-845

Black Mulch Promotes Purple Nutsedge Growth



Purple Nutsedge
Black LDPE Mulch

Webster, USDA-ARS, Tifton, GA

Purple Nutsedge
Non-mulched control *

BMP 9: Use Mechanical and Biological Management Practices Where Appropriate

- Tillage changed regularly to avoid dominance by any particular species
- Mulches
- Winter cover crops
  - Weed emergence inversely related to rates of mulch residue (Putnam & Defrank 1983; Teasdale & Mohler 2000)

Webster, USDA-ARS, Tifton, GA

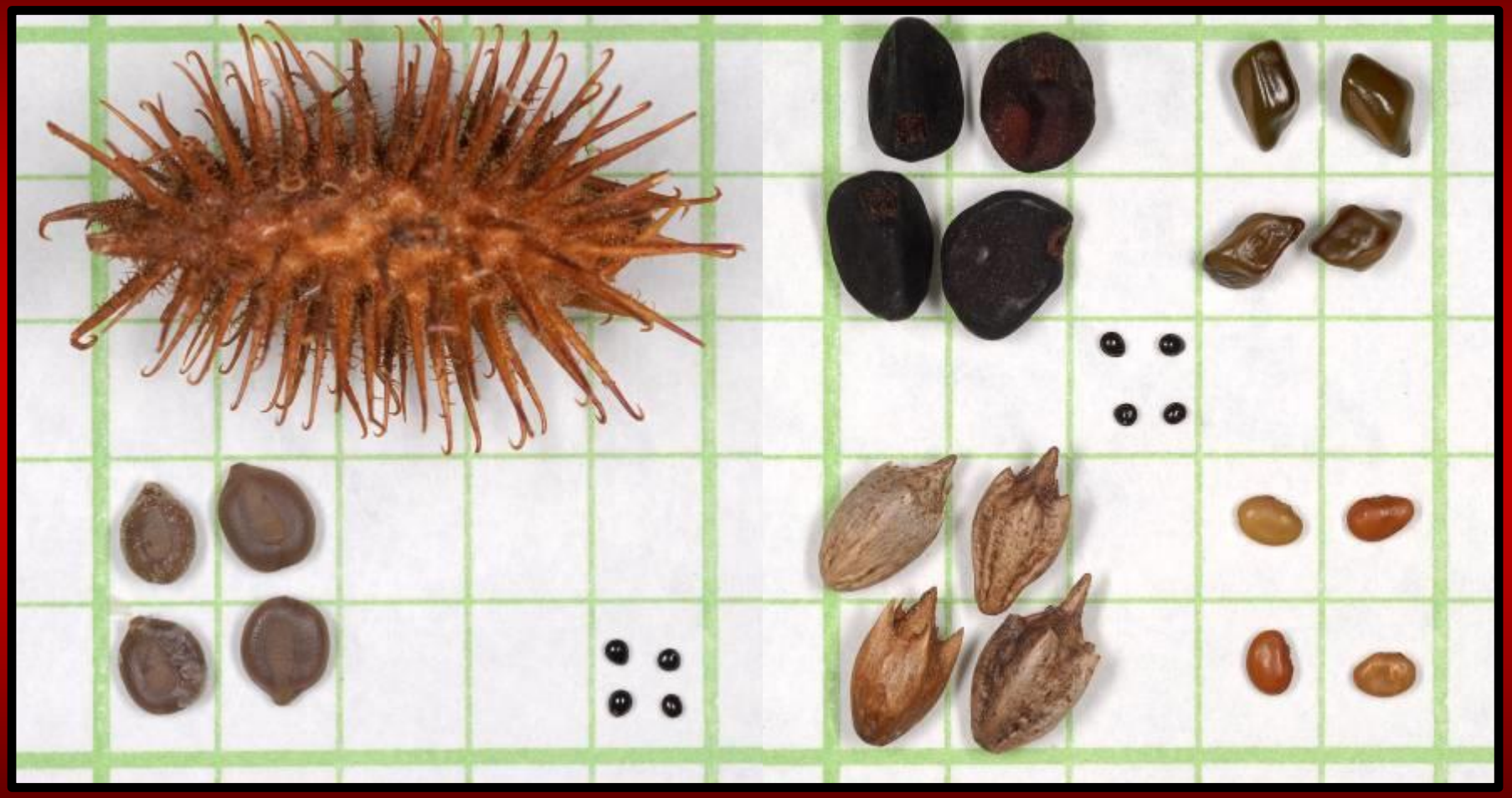
*

Relatively small-seeded species

Common cocklebur

Ipomoea morningglory

Sicklepod



Coffee senna

Palmer amaranth

Common ragweed

Florida beggarweed

*

- Reduces population / selection pressure
- Uniform cover crop mat
- Still require herbicides
- Need herbicides that are not bound to cover crop

*

Challenges: BMP 9

- Mechanical control requires specialized equipment and skilled labor
- Tillage operations vs. soil conservation programs
- Synthetic mulches are $$$ (+disposal)
- Cover crops = no marketable crop

BMP 10: Prevent Field-to-Field and Within-Field Movement of Weed Seed and Vegetative Propagules

- Natural seed dispersal limited to <15 ft from the mother plant, with exceptions…
- Handweeding


2000-2005:
17% of Georgia growers hand-weeded
5% cotton acres at $2.40/A
2006-2010:
92% of Georgia growers hand-weeded
52% cotton acres at $23.70/A
Photo by Eric Prostko, UGA Extension
*

BMP 10: Prevent Field-to-Field and Within-Field Movement of Weed Seed and Vegetative Propagules

- Natural seed dispersal limited to less than 5 m from the mother plant
- Handweeding
- Equipment and gin trash and manure

*

Cotton Gin Trash

*

BMP 10: Prevent Field-to-Field and Within-Field Movement of Weed Seed and Vegetative Propagules

- Seed dispersal limited to less than 5 m from the mother plant
- Handweeding
- Equipment and gin trash and manure
- Animals
  - Fire ants and Common ragweed
  - Benghal dayflower

*

Challenges: BMP 10

- Complex and costly
- Rented land
  - 38% nationwide
  - 50% in Midwest and Mississippi Delta
  - Returns: Immediate vs. Long-term
- Sanitation between fields and farms
- Preventative tactics…I told you so!
- Ohio Farmers: sources of new weeds
  - Wind (97%)
  - Wildlife (87%)
  - Birds (80%)

BMP 11: Manage Weed Seed at Harvest and Post-Harvest to Prevent Buildup of the Weed Seedbank

- **Weed seed "rain":**
  - 30 to 45% before harvest
  - 30 to 45% expelled from harvester
  - 10 to 25% retained with grain
- **Seed collection and destruction @ harvest**

Webster, USDA-ARS, Tifton, GA

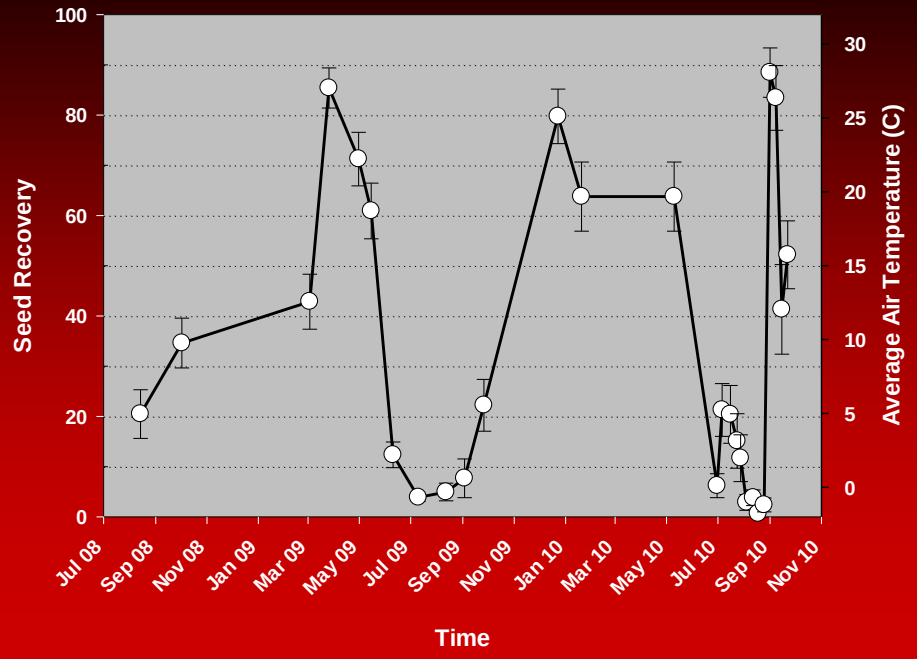
McCanny and Cavers 1988

*

Weeds present at harvest are good indicators of next year's weed issues

Benghal dayflower: September

No post-crop harvest management*



Photos by April Noble and Joseph Berger
(from *www.Bugwood.org*)

Challenges: BMP 11

- Development of technology to "*consume seed*"
- Predictions of "*seed rain*"
- What factors enhance seed herbivory?

Recommendations for Adoption of BMP's

1. Reduce the Weed Seedbank through Diversified Programs that Minimize Weed Seed Production.

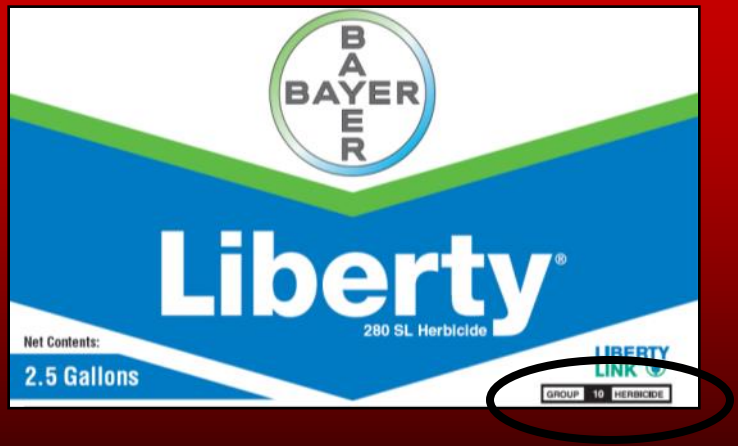
Adoption of Diverse Control Tactics is Crucial in Resistance Management

Slide from Stanley Culpepper, UGA

Recommendations for Adoption of BMP's

1. Reduce the Weed Seedbank through Diversified Programs that Minimize Weed Seed Production.
2. Implement a Herbicide-MOA Labeling System for All Herbicide Products, and Conduct an Awareness Campaign.

Group #’s beginning to appear…but it’s not yet standard



*

Recommendations for Adoption of BMP's

3. Communicate that Discovery of New, Highly Effective Herbicide MOA's is Rare and that Existing Herbicide Resource is Exhaustible.

4. Demonstrate the Benefits and Costs of Proactive, Diversified Weed Management Systems for the Mitigation of HR Weeds.

Recommendations for Adoption of BMP's

5. Foster the Development of Incentives by Government Agencies and Industry that Conserve Critical Herbicide MOA's as a Means to Encourage Adoption of Best Practices.

6. Promote the Application of Full, Labeled Rates at the Appropriate Weed and Crop Growth Stage.

Recommendations for Adoption of BMP's

7. Identify and Promote Individual BMP's that Fit Specific Farming Segments with the Greatest Potential Impact.

8. Engage the Public and Private Sectors in the Promotion of BMP's, Including Those Concerning Appropriate Herbicide Use.

Recommendations for Adoption of BMP's

9. Direct Federal, State, and Industry Funding to Research Addressing the Substantial Knowledge Gaps in BMPs for Herbicide Resistance and Support Cooperative Extension Services as Vital Agents in Education for Resistance Management.


ted.webster@ars.usda.gov
http://wssajournals.org/doi/pdf/10.1614/WS-D-11-00155.1