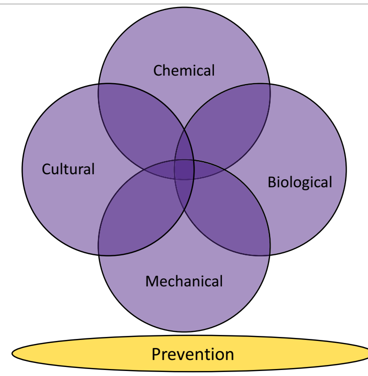
Integrated Weed Management:
Rationale and Strategies

Sarah Lancaster
Assistant Professor and Weed Science Extension Specialist
Kansas State University

Integrated weed management

Using multiple, complementary weed control practices



Integrated weed management

Chemical

Sequential

Residual

Multiple sites of action

Well-timed

Cultural

Good agronomic practices

Crop rotation

Seeding date

Row spacing

Plant populations

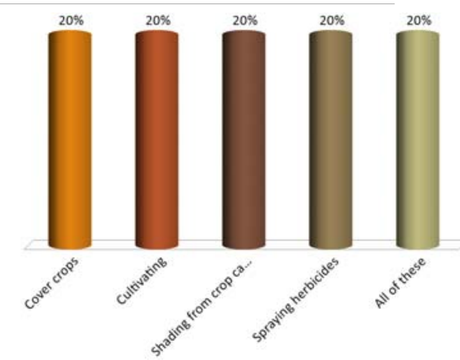
Physical

Tillage

Cover crops

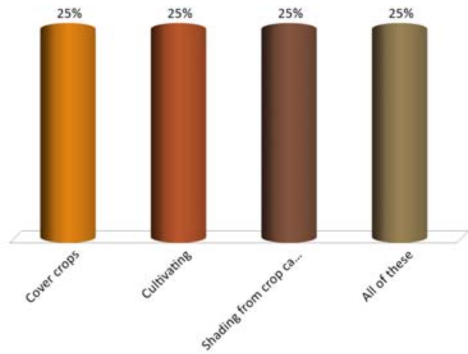
Which of the following IWM practices do you use most?

A. Cover crops
B. Cultivating
C. Shading from crop canopy
D. Spraying herbicides
E. All of these



Which of the following IWM practices do you use most?

A. Cover crops
B. Cultivating
C. Shading from crop canopy
D. All of these



Why integrated weed management?

Herbicide resistance

Sustainability

Herbicide resistance

Herbicide tolerance

The inherited ability of a species to survive and reproduce following herbicide application

- Naturally occurring trait
- Expected result due to herbicide selectivity

Herbicide selectivity

Application rate

Placement

Absorption and translocation

Metabolism or altered metabolism

Altered site of action

Herbicide resistance

The ability of a formerly susceptible plant population to survive herbicide doses greater than those that were once used to control the original plant population

- Herbicide resistance is a heritable trait

Herbicide resistant weeds in Kansas

	Palmer amaranth	Waterhemp	Kochia	Marestail
ALS inhibitors Group 2 (Classic, Harmony, Pursuit)	X	X	X	X
Plant growth regulators Group 4 (2,4-D, dicamba, Starane Ultra)	X		X	
PSII inhibitors Group 5 (atrazine)	X	X	X	
EPSPS inhibitor Group 9 (glyphosate)	X	X	X	X
PPO inhibitors Group 14 (Cobra, Blazer)	?	X		
HPPD inhibitors Group 27 (Armezon, Callisto, Laudis)	X			
Multiple resistance	3- & 5-way (7-way?)	2-way	2- & 4-way	

Herbicide options for pigweed control

Preplant

Corn
- Atrazine
- Flumioxizan
  - Valor, Fierce
- Isoxaflutole
  - Balance Flexx
- Pyroxasulfone
  - Zidua
- Rimsulfuron+thifensulfuron
  - Crusher

Soybean
- Chloransulam
  - Firstrate
- Flumioxizin
  - Valor
- Imazaquin
  - Scepter
- Imazethapyr
  - Pursuit
- Pyroxasulfone
  - Zidua
- Saflufenacil
  - Sharpen
- Sulfentrazone
  - Spartan

Postemergence

Corn
- Atrazine
- Dicamba
  - Distinct
- Mesotrione
  - Callisto
- Tembotrione
  - Laudis
- Tolpyralate
  - Shieldx
- Topramazone
  - Impact

Soybean
- Aciflurofen
  - Blazer
- Fomesafen
  - Reflex
- Lactofen
  - Cobra
- Thifensulfuron
  - Harmony
- Imazethapyr
  - Pursuit
- Imazamox
  - Raptor
- *Dicamba (Xtendimax)*
- *Glyphosate*
- *2,4-D (Enlist)*

Herbicide options for pigweed control

Preplant

Corn
- ~~Atrazine~~
- Flumioxizan
  - Valor, Fierce
- Isoxaflutole
  - Balance Flexx
- Pyroxasulfone
  - Zidua
- ~~Rimsulfuron+thifensulfuron~~
  - ~~Crusher~~

Soybean
- ~~Chloransulam~~
  - ~~Firstrate~~
- Flumioxizin
  - Valor
- ~~Imazaquin~~
  - ~~Scepter~~
- ~~Imazethapyr~~
  - ~~Pursuit~~
- Pyroxasulfone
  - Zidua
- Saflufenacil
  - Sharpen
- Sulfentrazone
  - Spartan

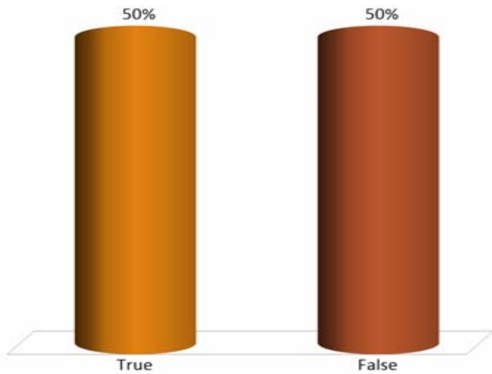
Postemergence

Corn
- ~~Atrazine~~
- Dicamba
  - Distinct
- ~~Mesotrione~~
  - ~~Callisto~~
- ~~Tembotrione~~
  - ~~Laudis~~
- Tolpyralate
  - Shieldx
- ~~Topramazone~~
  - ~~Impact~~

Soybean
- ~~Acifluorfen~~
  - ~~Blazer~~
- Fomesafen
  - Reflex
- ~~Lactofen~~
  - ~~Cobra~~
- ~~Thifensulfuron~~
  - ~~Harmony~~
- ~~Imazethapyr~~
  - ~~Pursuit~~
- ~~Imazamox~~
  - ~~Raptor~~
- *Dicamba (Xtend)*
- ~~*Glyphosate*~~
- ~~*2,4-D (Enlist)*~~

Do you think you have weeds resistant to ALS-inhibitors?

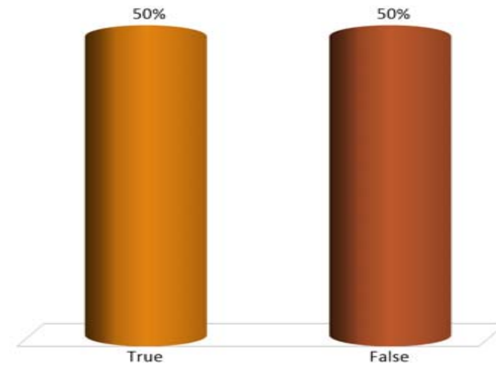
A. True
B. False



K·STATE Research and Extension

Do you think you have weeds resistant to plant growth regulators?

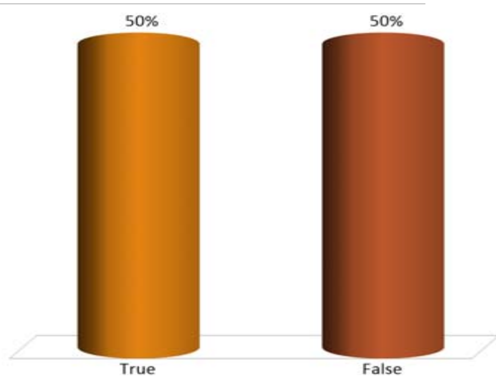
A. True
B. False



K·STATE Research and Extension

Do you think you have weeds resistant to triazines?

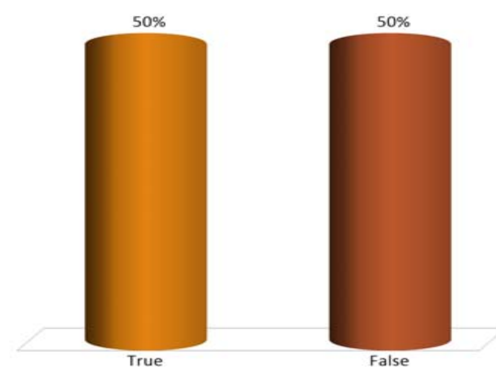
A. True
B. False



K·STATE Research and Extension

Do you think you have weeds resistant to PPO inhibitors?

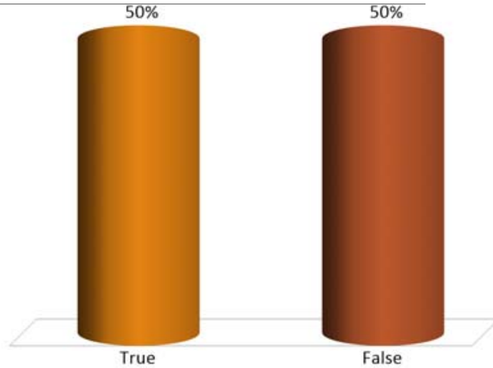
A. True
B. False



K·STATE Research and Extension

Do you think you have weeds resistant to HPPD inhibitors?

A. True
B. False



CROSS RESISTANCE

Single mechanism confers resistance to multiple herbicides

Negative cross resistance – genetic change that causes resistance to one herbicide causes 'hypersusceptibility' to another

MULTIPLE RESISTANCE

Multiple mechanisms confer resistance to multiple herbicides

Cross resistant common cocklebur

Multiple resistant Palmer amaranth


Nontreated


Chlorsulfuron (Glean)


Glyphosate


Atrazine


Lactofen (Cobra)


Mesotrione (Callisto)


2,4-D


Pyrasulfotole + bromoxynil (Huskie)

Shyam et al., 2019

Causes of resistance

TARGET-SITE MUTATION

One gene

Develops faster

Most cases observed in
- ACCase inhibitors (G1)
- ALS inhibitors (G2)
- PSII inhibitors (G5)

NON-TARGET-SITE MUTATION

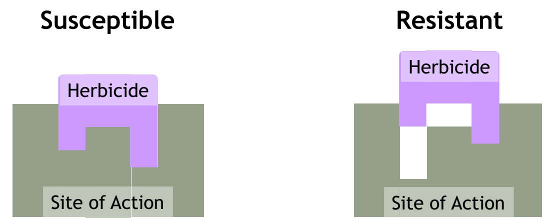
> 1 gene

Develops slower
- Begins with low degree of resistance
- Cross resistance more likely

Most frequent form observed in
- ACCase inhibitors
- ALS inhibitors
- EPSPS inhibitor

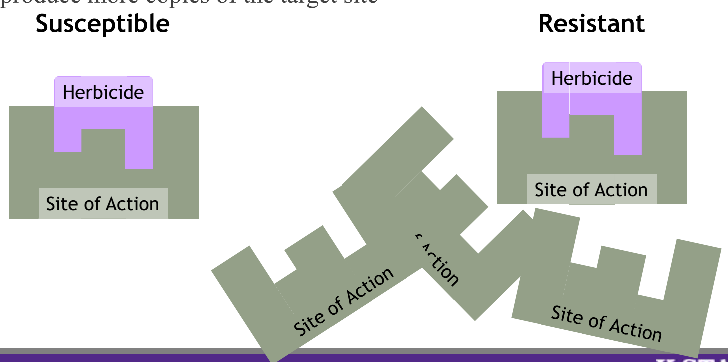
Altered Site of Action

Plant changes target site



Increased Protein Expression

Plant produce more copies of the target site



Causes of resistance

TARGET-SITE MUTATION

One gene

Develops faster

Most cases observed in
- ACCase inhibitors (G1)
- ALS inhibitors (G2)
- PSII inhibitors (G5)

NON-TARGET-SITE MUTATION

> 1 gene

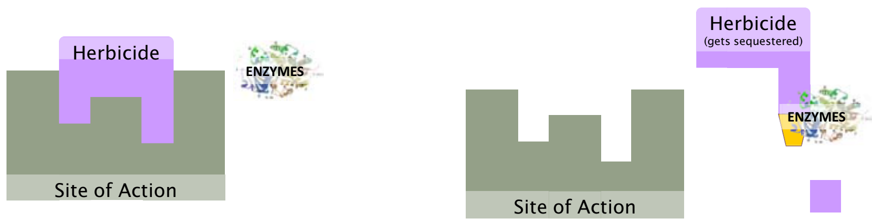
Develops slower
- Begins with low degree of resistance

Cross resistance more likely

Most frequent form observed in
- ACCase inhibitors
- ALS inhibitors
- EPSPS inhibitor

Enhanced Herbicide Metabolism

Plant alters &/or sequesters herbicide, making it ineffective



K·STATE Research and Extension

Reduced Absorption or Translocation

Herbicide transport altered

K·STATE Research and Extension

Best Management Practices

for Herbicide Resistance

Take ACTION Herbicide-Resistance Management

Scouting

Get a representation of the whole field

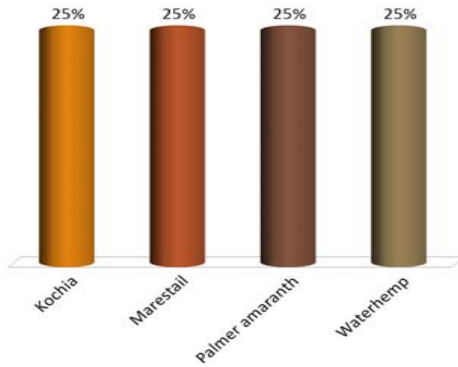
- 5-10 stops, spread throughout
- At each stop, walk 10 paces and record the following:
  - Weed species present – ID is critical
  - Life stage or height of weeds
  - Lifecycle (summer annual, winter annual, perennial)
  - Severity of the infestation based on number of plants (Low, medium, high)

Before planting, before herbicide, **after herbicide**

K·STATE Research and Extension

What weed is shown below?

A. Kochia
B. Marestail
C. Palmer amaranth
D. Waterhemp

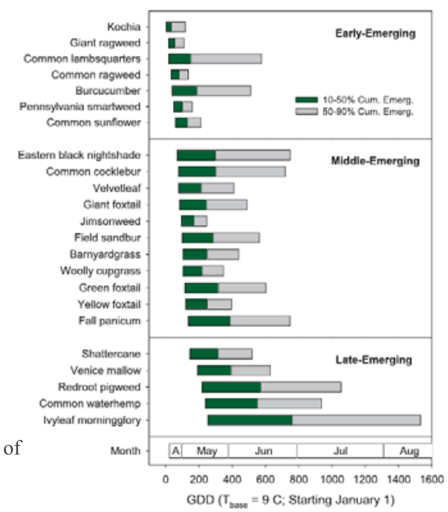


Best Management Practices

for Herbicide Resistance

Take ACTION
Herbicide-Resistance Management

Germination characteristics of weeds interacts with management practices



Emergence sequence and duration of summer annual weeds
2 years, Ames IA

Kochia emergence in Kansas

Site	Year	Field	Date 10%	10%	50%	90%
				Growing Degree Days		
Garden City	2010	NT	3/30	245	425	2369
Garden City	2011	NT	3/21	266	436	2400
Garden City	2011	T	3/21	279	443	1473
Hays	2010	T	3/10	173	300	590
Hays	2010	NC	3/24	23	148	430
Hays	2011	T	1/28	43	168	444
Hays	2011	NC	2/6	96	223	511
Manhattan	2011	NC	3/3	115	237	500

Effect of temperature on Palmer amaranth germination

Temperature (F)	Total germination (%)	Days to maximum germination rate
41	8	--
50	20	5.3
59	49	2.3
68	57	1.9
77	66	1.1
86	83	1.5
95	73	2.2
$LSD_{0.05}$	12	1.5

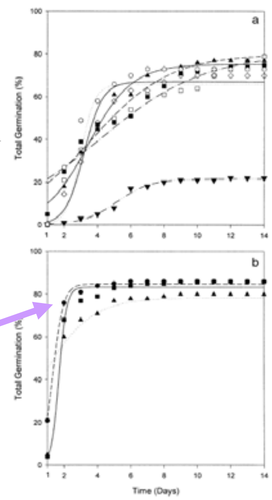
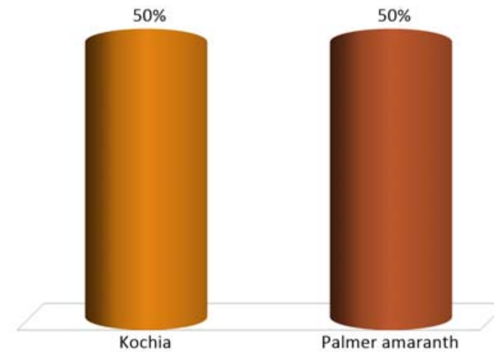


FIGURE 1. Cumulative germination during the 14-d experimental period for the nine *Amaranthus* spp. at the 30 C alternating temperature regimen: (a) AMABL (– –▼), AMARE (– –■), AMAAL (—▲), AMATU (---◇), AMATA (—○), AMASP (– –□); (b) AMAPO (---▲), AMACH (—■), AMAPA (– –●).

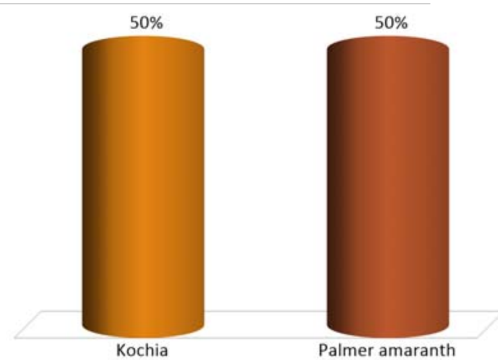
Which weed would be more likely to be suppressed by crop canopy?

A. Kochia
B. Palmer amaranth



Which weed would be more likely to be suppressed by a fall cover crop?

A. Kochia
B. Palmer amaranth



Best Management Practices

for Herbicide Resistance

Take ACTION Herbicide-Resistance Management

Integrated pigweed management in Kansas

2 crops, 2 years, 3 locations

Cover crop, row-width, cultivation, herbicides

Integrated pigweed management in Kansas

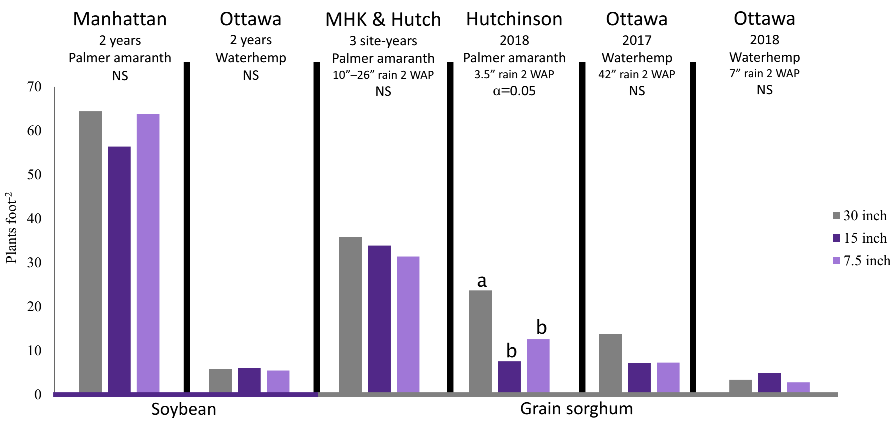
Herbicide program provided ≥ 97% weed control

Row width reduced pigweed growth in some environments

Cover crop generally suppressed pigweeds

Row width effects on pigweed density 8 WAP

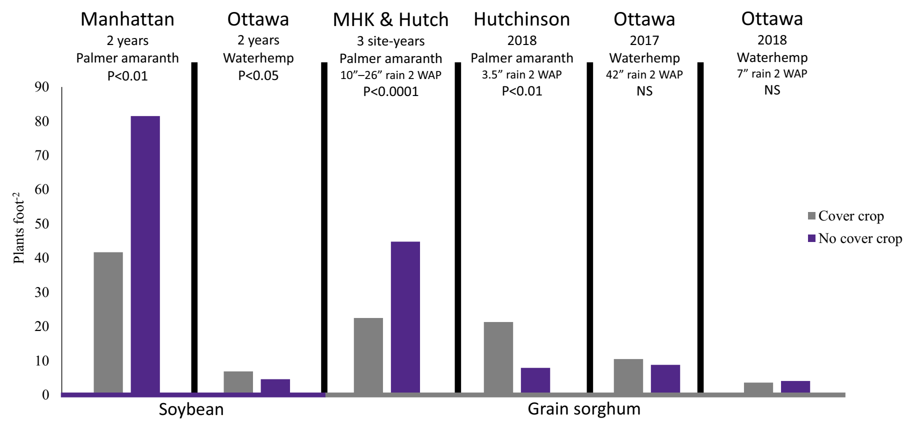
No herbicide, no tillage



Means within a site-year followed by the same letter are similar.

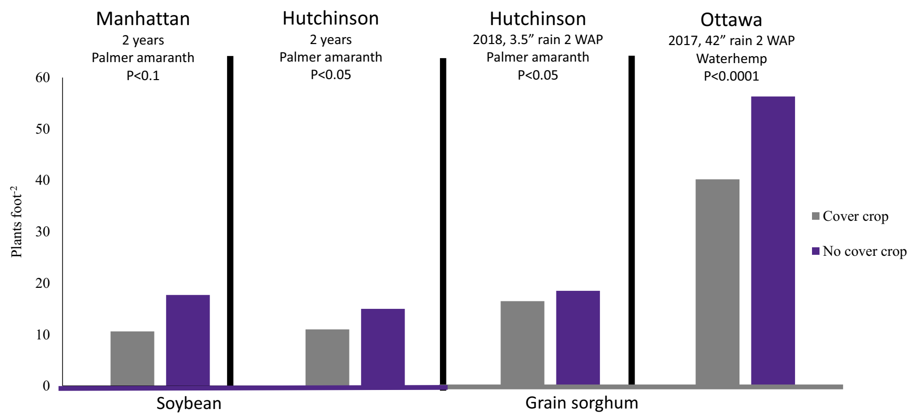
Cover crop effects on pigweed density 8 WAP

No herbicide, no tillage



Cover crop effects on pigweed height 8 WAP

No herbicide, no tillage



Means within a site-year followed by the same letter are similar (α=0.1).

Hay et al., 2019

Best Management Practices

for Herbicide Resistance

Take ACTION Herbicide-Resistance Management

Understanding sites of action

Mode of action
- How the herbicide affects the plant
  - Amino acid synthesis inhibitor

Site of action
- Specific binding site the herbicide interferes with
  - EPSPS inhibition
  - Group 9

Chemical family
- Elements in the molecule
  - Glycine

Herbicide sites of action

Group	Site of Action (Mode of Action)
1	ACCase inhibitors (Lipid synthesis inhibitors)
2, 9	ALS inhibitors, EPSP Synthase inhibitor (Amino acid synthesis inhibitors)
3	Microtubule inhibitors (Seedling root growth inhibitors)
4, 19	Synthetic auxins, Auxin transport inhibitors (Growth regulators)
5, 6, 7	PS II inhibitors-3 unique sites of action (Photosynthesis inhibitors)
8, 15, 16	Lipid synthesis inhibitors, Long-chain fatty acid inhibitors, Site unknown (Seedling shoot growth inhibitors)
10	Glutamine synthetase inhibitor (Nitrogen metabolism inhibitor)
12, 13, 27	PDS inhibitor, DOXP inhibitor, HPPD inhibitors (Pigment inhibitors)
14, 22	PPO inhibitors, PSI electron diverter (Cell membrane disruptors)
17	Nucleic acid inhibitor (Undefined)

49 species with resistance

ALS Inhibitors (2)

Inhibit acetolactate synthase (aka acetohydroxy acid synthase)
- Necessary to produce branched chain amino acids (valine, leucine, isoleucine)

ALS-inhibitor injury to soybean

Symptoms in 3-14 d
- Shoots stop growing and turn yellow,
- Purple veins – dicots
- "Bottlebrush" roots

IMAGE: D. PETERSON

8 species with resistance

Synthetic auxins (4)

Activate auxin response genes (bind to auxin receptor protein)
- Regulate plant growth

Auxin transport inhibitor (diflufenzopyr, group 19) used as a synergist with dicamba

Synthetic auxin injury to corn and soybean

Symptoms appear in 7-14 days
- Bent/twisted stems and petioles
- Misshapen leaves
- Short/thickened roots

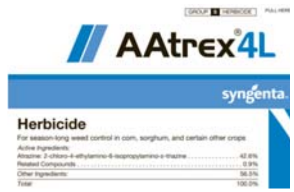
IMAGE: D. PETERSON

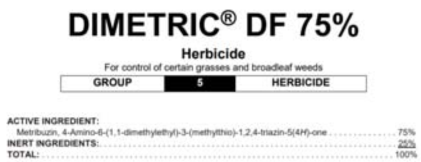
26 species with resistance

Photosynthesis Inhibitors (5)

Bind to D1 protein in PSII

- Blocks electron transport
- Stops CO2 fixation, ATP & NADPH production
- Reactive oxygen and chlorophyll form, chlorophyll lost, reactive species cause lipid peroxidization, which causes leaky membranes (with 5-10 h)





Triazine injury to soybean

Symptoms appear first on older leaves, death in 5-10 days

- Leaf tip & margin necrosis
- Interveinal chlorosis

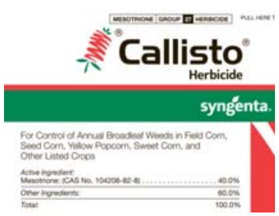
IMAGE: D. PETERSON

2 species with resistance

Pigment Inhibitors (Group 27)

Carotenoids are necessary to dissipate reactive oxygen

- Without carotenoids, reactive oxygen peroxidizes lipids, destroying membranes



Callisto injury to grain sorghum

Symptoms include white/creamy colored leaves

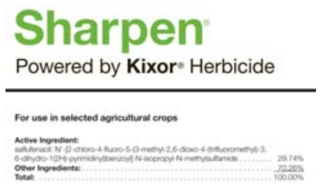
- AKA "bleachers"

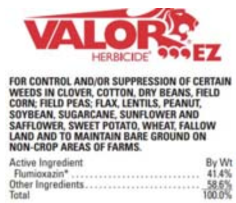
IMAGE: D. PETERSON

4 species with resistance

PPO inhibitors (14)

Inhibit protoporphyrinogen oxidase
- Necessary to produce chlorophyll
- Accumulated protoporphyrin IX results in formation of reactive oxygen and lipid peroxidation





Cobra and Reflex injury on soybeans

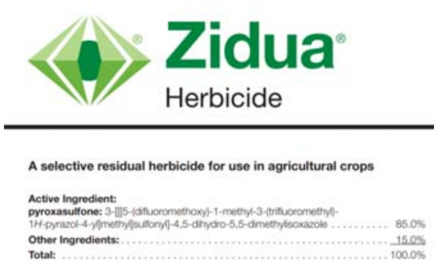
Symptoms appear in 3 days
- Bronzing, necrosis
- Drawstring leaves

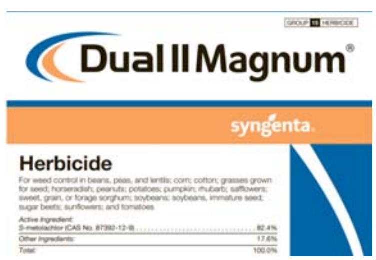
IMAGE: D. PETERSON

3 species with resistance

Long –chain Fatty acid Inhibitors (15)

Interfere with very long chain fatty acid synthesis





Chloroacetamide injury to grain sorghum and soybean

Grasses that emerge may have buggy-whipping; broadleaf plants stunted, 'drawstring' leaves, dark green
- Plants will germinate

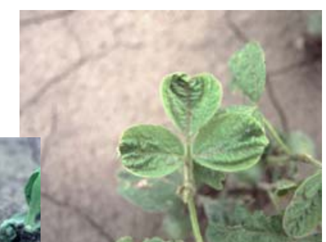


IMAGE: D. PETERSON

Multiple effective sites of action

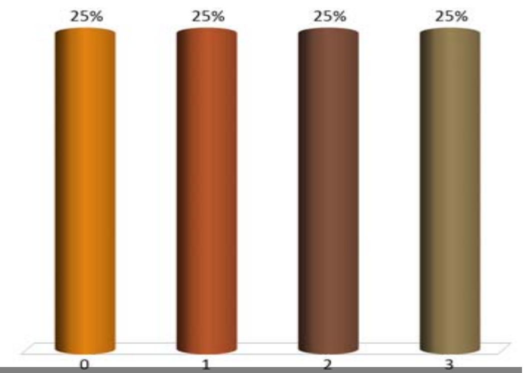
glyphosate + ALS-resistant Palmer amaranth

Herbicide	Timing	Effective sites
Authority XL (2 + 14)	PRE	2
Glyphosate (9)		
2,4-D (4)		
Tavium (4 + 15)	EPOST	2
Glyphosate (9)		

If you have glyphosate and atrazine-resistant kochia, how many effective modes of action are you using?

A. 0
B. 1
C. 2
D. 3

Herbicide
Atrazine (5)
Glyphosate (9)
Dicamba (4)



Which of the following do you practice in your herbicide program?

A. Rotating herbicide groups from year to year
B. Rotating herbicide groups within a year
C. Mixing groups within an application
D. More than one of these

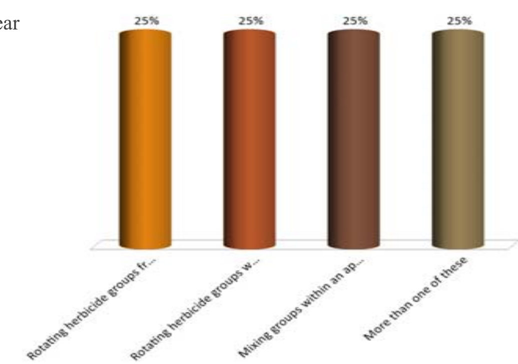


Table 3. Years until resistance occurs (first year that crop yields fall below 75% of maximum, which is equivalent to weed densities exceeding 200 m^{-2}) for 15 different rotation and mixture (M) strategies (rows) and four initial allele frequencies (1,0.1 and 100 times the baseline frequencies shown in Table 1) and three different genetic scenarios: GS1(fitness penalties and no negative cross-resistance), GS2 (fitness penalties and negative cross-resistance) and GS3 (no fitness penalties and no negative cross-resistance). Results for other initial allele frequencies are not shown for clarity, but follow the same trends

	GS1			GS2			GS3			
	frequency			frequency			frequency			
Herbicide use patterns	1	0.1	100	1	0.1	100	1	0.1	100	Rank
1111	16	20	8	16	20	9	14	18	7	6
2222	8	9	4	8	9	4	7	9	4	7
3333	8	9	4	8	9	4	7	9	4	7
4444	8	9	4	8	9	4	7	9	4	7
1114	22	29	11	22	29	11	18	23	9	4
1234	18	23	10	19	23	10	15	19	7	5
12141314	32	N	14	**35**	N	**16**	24	31-33	10	2
124134	26	32	12	26	33	12	20	26	9	3
11241134	32	50	14	**34**	50	**16**	24	30	10	2
111422243334	21	N	10	21	N	10	18	22	9	4
M12,M13,4	N	N	32-38	N	N	N	51-N 28%	N	17-18	1
M12,M13,1,4	N	N	25-27	N	N	**44**	N	N	16	1
Trifluralin first 'tr1st'	32	N	11	**34**	N	11	22	50	9	2
2323[a]	8	10	5	8	10	5	7	9	4	6[a]
234234[a]	13	16	7	13	16	7	10	13	5	5[a]
2434[a]	15	19	7	15	19	7	12	15	6	3[a]
M23,M23,4[a]	16	19-23	8	16	19-25	8	13	14-17	6-7	2[a]
M12,M13,4[a]	28-44	N	15	**N**	N	**33**	17-20	22-N 35%	9	1[a]
CR-234234234114234[a]	14	20	7	19	23	7	11	14	5	4[a]

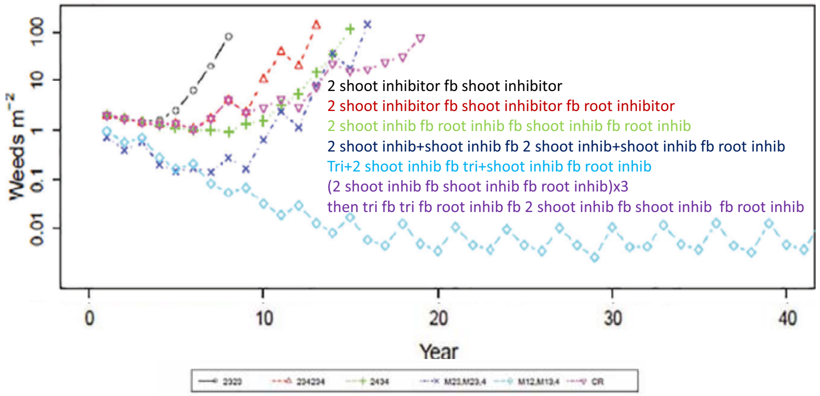
'N' indicates that resistance did not occur within 60 years of simulation. In most cases the same result was found in all 100 replicate runs, in which case the single result is reported, otherwise the range if reported (e.g. 25–27 means resistance occurred as late as 27 years and as early as 25 years) and, if relevant, the percentage of replicate runs in which resistance did not occur within 60 years of simulation. The rank column indicates the relative efficacy of the strategy in delaying resistance under GS1, which is not affected by allele frequency GS3 versus GS1 (1 = most effective; 7 = least effective). **Bold values** indicate where GS2 makes a difference versus GS1.

[a] These simulations assumed existing trifluralin resistance and are ranked separately.

1, trifluralin (dinitroaniline, G3);
2, prosulfocarb + *S*-metolachlor (thiocarbamate + chloroacetamide, G8 + 15);
3, pyroxasulfone (pyrazole, G15);
4, propyzamide (benzamide, G3).

Schwartz et al., 2020

Modeling the effects of herbicide rotation on trifluralin-resistant annual ryegrass



Best Management Practices

for Herbicide Resistance

Take ACTION
Herbicide-Resistance Management

Pigweed seed retention at soybean maturity

	State	Seed Retention (%)	
		2013	2014
Palmer amaranth	AR	99.98 + 0.00	99.85 + 0.05
	IL	99.95 + 0.03	--
	NE	98.89 + 0.23	99.93 + 0.02
	MO	99.98 + 0.00	99.67 + 0.20
	TN	99.96 + 0.01	--
Waterhemp	IL	99.98 + 0.01	94.98 + 0.94
	NE	99.99 + 0.00	99.63 + 0.10
	MO	100.00 + 0.00	99.84 + 0.04
	WI	99.96 + 0.01	98.80 + 0.30

Schwartz et al., 2016

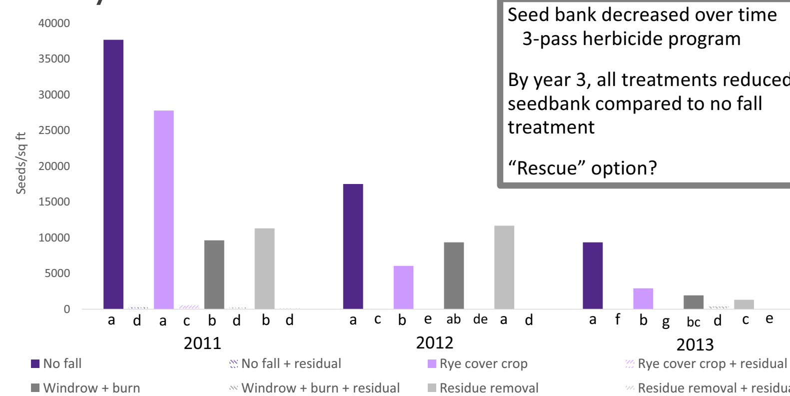
K·STATE
Research and Extension

HWSC effects on Palmer amaranth seedbank at soybean harvest

Seed bank decreased over time
- 3-pass herbicide program

By year 3, all treatments reduced seedbank compared to no fall treatment

"Rescue" option?



Means within a year with similar letters are similar

Norsworthy et al., 2019

K·STATE
Research and Extension

Grower adoption of HWSC in Australia

Cropping region and zone	Narrow-windrow burning		Chaff tramlining		Chaff cart		Bale-direct system		
	Adoption[a]	Crop area[b]	Adoption	Crop area	Adoption	Crop area	Adoption	Crop area	Total adoption
	%								
Northern	**4**	**23**	**13**	**77**	**1**	**78**	**1**	**15**	19
Qld Central	-	-	18	88	4	78	-	-	22
NSW NE/Qld SE	-	-	18	71	-	-	-	-	18
NSW NW/Qld SW	11	23	4	75	-	-	2	15	17
Southern	**28**	**23**	**6**	**70**	**1**	**63**	**4**	**27**	39
NSW Central	12	30	2	100	-	-	2	10	16
NSW Vic. Slopes	33	29	12	63	-	-	12	14	57
SA Midnorth-Lower Yorke Eyre	31	15	-	-	4	50	-	-	35
SA Vic Bordertown-Wimmera	38	13	2	100	-	-	4	45	44
SA Vic Mallee	21	18	6	39	-	-	6	37	33
Vic. High Rainfall & Tas.	33	34	12	82	2	90	2	60	49
Western	**51**	**30**	**4**	**86**	**7**	**59**	**1**	**13**	63
WA Central	56	25	7	70	13	57	2	5	78
WA Eastern	45	33	4	90	-	-	-	-	49
WA Sandplain-Mallee	33	23	4	100	9	73	2	20	48
WA Northern	75	36	3	100	8	47	-	-	86
National average	**30**	**26**	**7**	**76**	**3**	**61**	**3**	**25**	**43**

Walsh et al., 2017

K·STATE Research and Extension

Wrap up

Various forms of herbicide resistance are common in Kansas in multiple species

Using cultural or mechanical weed management can improve activity of herbicides and reduce selection pressure leading to herbicide resistant weed populations

Mixing multiple herbicide groups is more effective than rotating herbicide groups

Consider practices to reduce deposits to weed seedbank

K·STATE Research and Extension

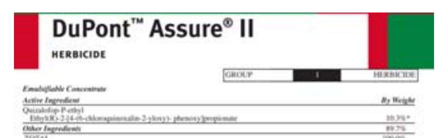
K·STATE Research and Extension

15 species with resistance

ACCase Inhibitors (1)

Inhibit acetyl Coenzyme A carboxylase in grasses

- Required for lipid synthesis within the plant
- Prevents cell membrane development



K·STATE Research and Extension

ACCase inhibitor injury to corn

Symptoms start in 2-4 days, plant death takes up to 7 days

- Susceptible plants stop growing, leaves turn purplish then necrotic, leaf sheaths fall away
- Whorl easily removed from plant

Modeling the effects of herbicide rotation on trifluralin-resistant annual ryegrass