History: Our Best Guide to Understanding the Future of Western Corn Rootworm

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I ILLINOIS

Acknowledgments:

Monsanto/Bayer CropScience
Syngenta
Pioneer/Corteva

USDA Laboratory – Brookings, SD
Illinois Agricultural Experiment Station
University of Illinois:
Illinois Natural History Survey
Dept. of Crop Sciences
Dept. Ag. & Bio. Engineering

Many hourly assistants, including:
Jason Folkerts & Joshua Kim
Dr. Nick Seiter

Thanks!

***Indiana Certified Crop Advisor Program**

Outline:

Diabrotica v. virgifera
Western corn rootworm
F. Chrysomelidae, WCR

1. Historic Pests, Biology/Ecology
2. Management History and Today
3. Future & Conclusions

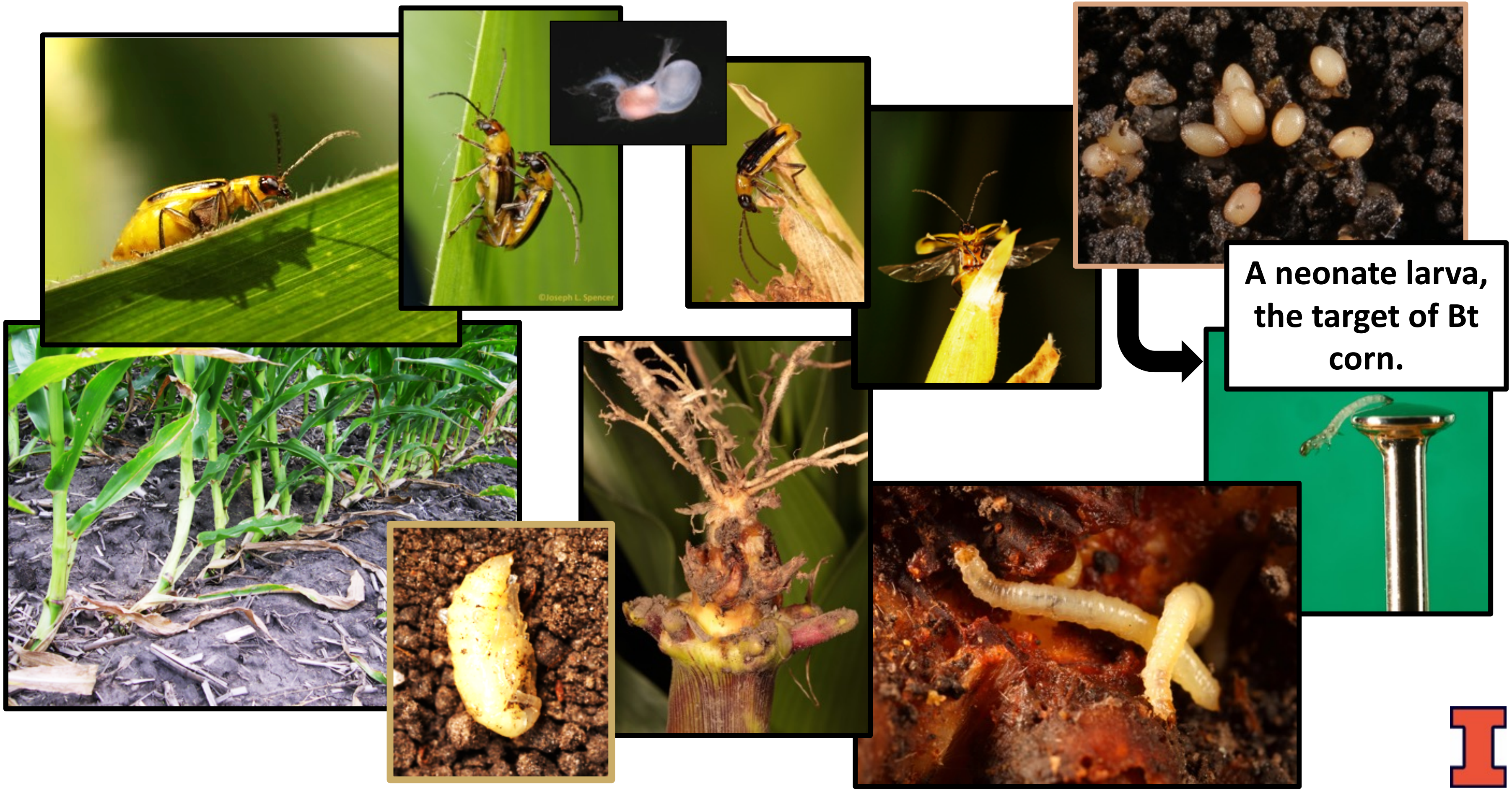
Corn Rootworms are Historic Pests

'Billion Dollar Insects'

'Northern', NCR

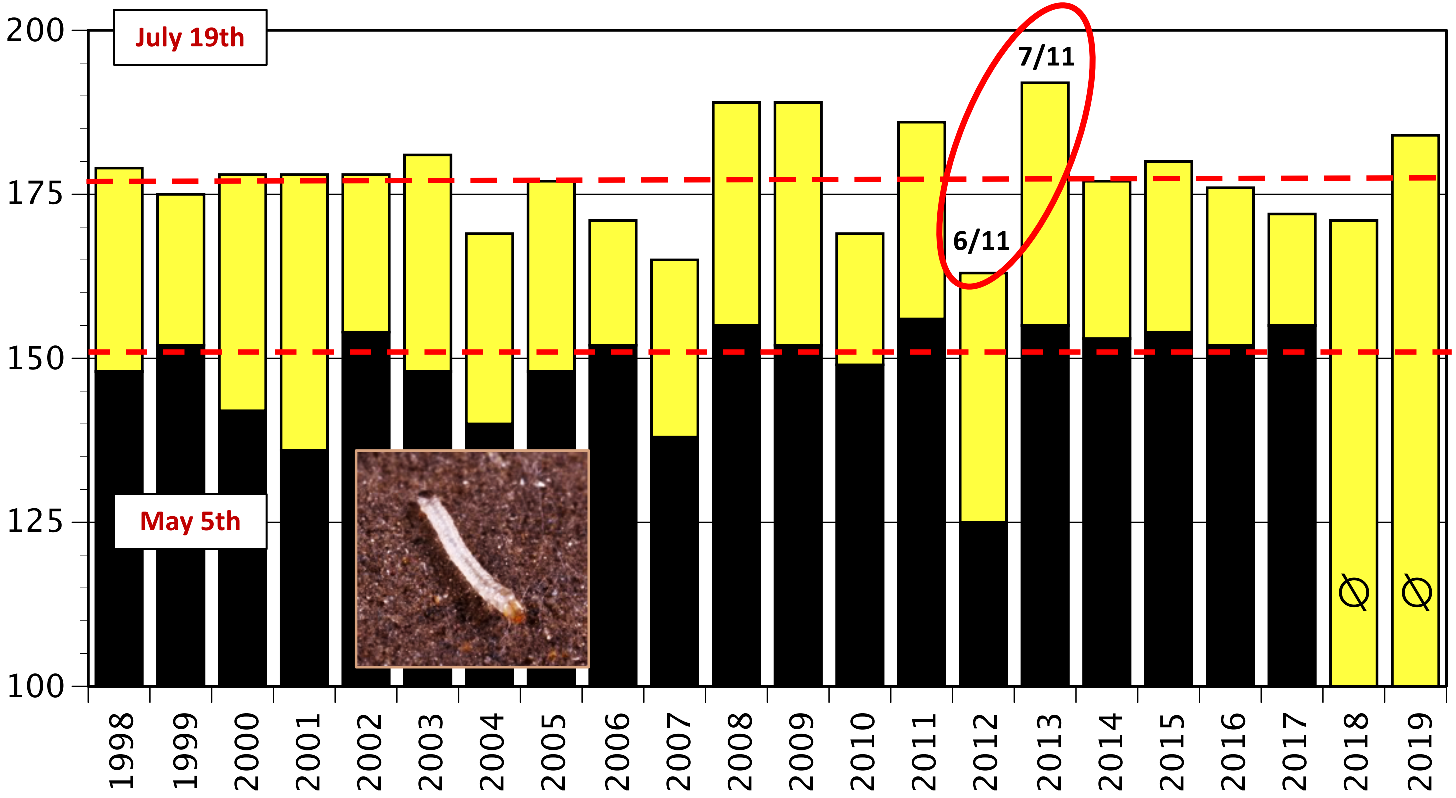
'Western', WCR

Western corn rootworm, *Diabrotica virgifera virgifera* LeConte



A neonate larva, the target of Bt corn.

1st Indiana WCR Egg Hatch & 1St Illinois WCR Adult Detection

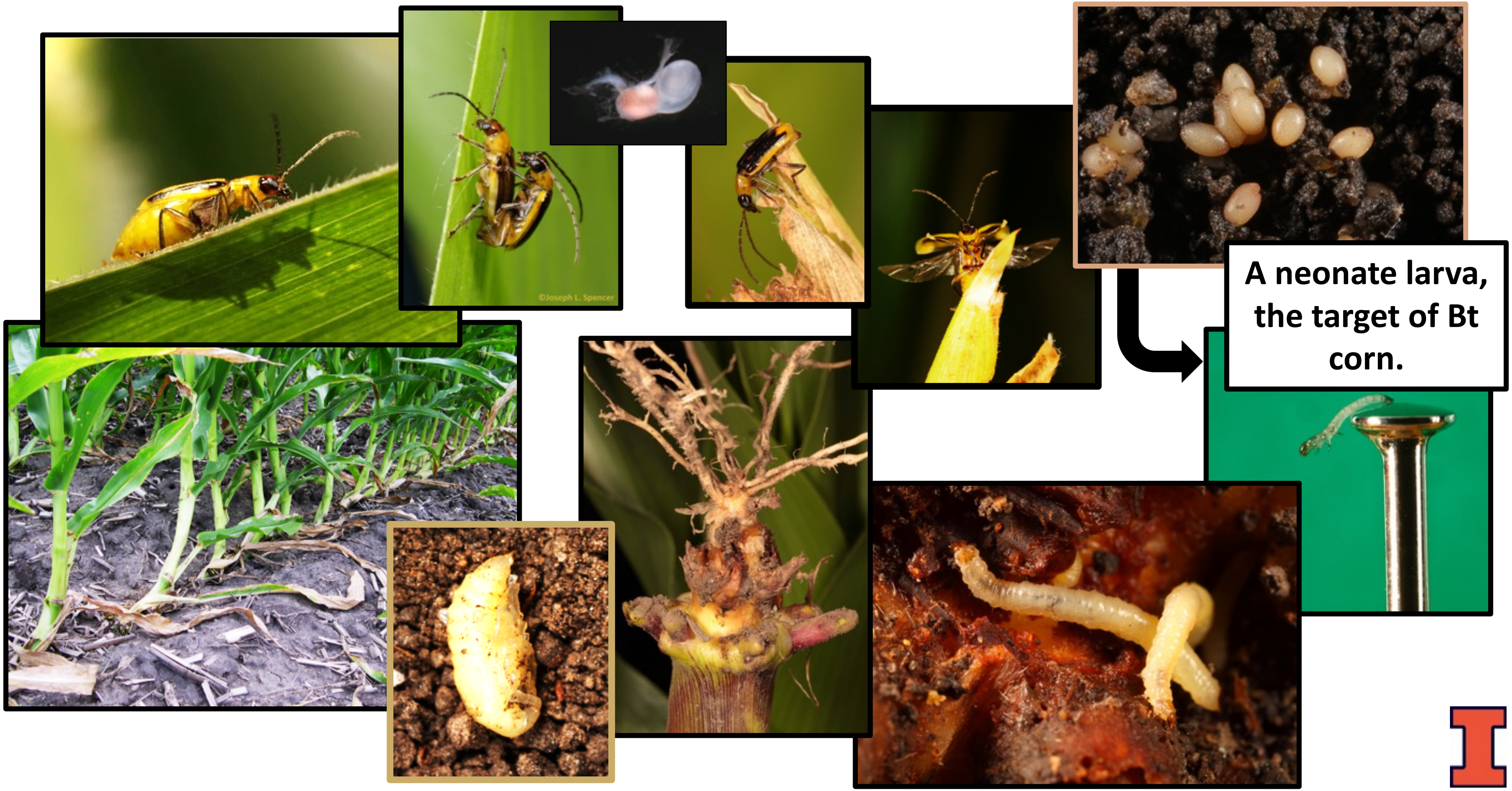


Ave 1st Adult JD 177; June 26th

29 Days

JD 151; May 31st Ave. Hatch Date: (1982-2017)

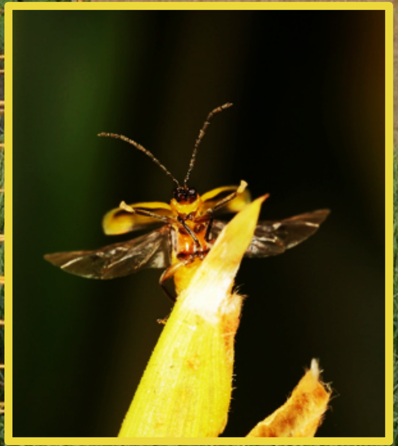
Western corn rootworm, *Diabrotica virgifera virgifera* LeConte



Post-mating dispersal:

High-flying WCR adults at 10m:

- **15-24% of young WCR females engage in sustained flight.**
- **≥85% of high-fliers are mated females, most (65-85%) are newly-mated.**
- **May travel ≥24 km/night.**



Coats et al. (1986) Environ. Ent. 15:620-625.
Naranjo (1990) Entomol. Exp. et. Appl. 55:79-90.

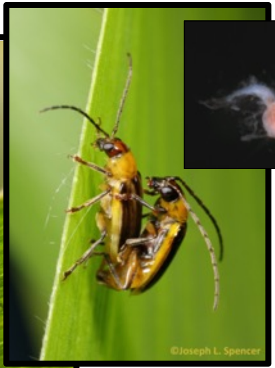
Greatest transport is by thunderstorms—updrafts suck flying WCR high into storms; they're later washed out with rain up a hundred miles away.

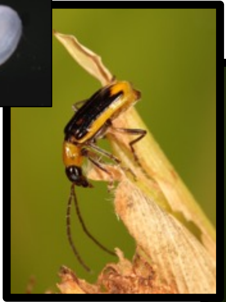
Storm transport

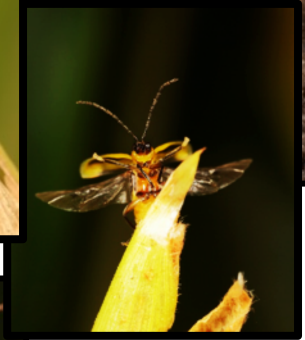
WCR wash-up along L. Michigan – 1980s

Grant and Seevers (1989) Environ. Ent. 18:266-272.

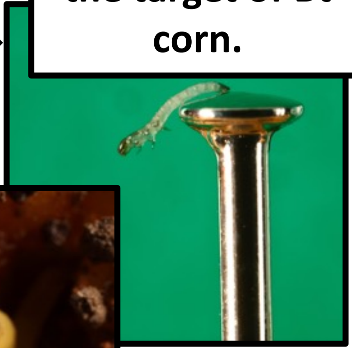
Western corn rootworm, *Diabrotica virgifera virgifera* LeConte

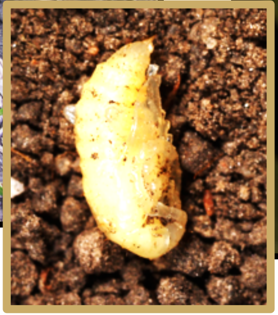






A neonate larva, the target of Bt corn.



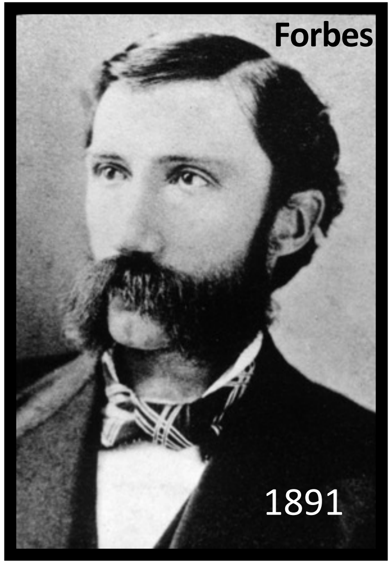


Key Points of WCR Biology:

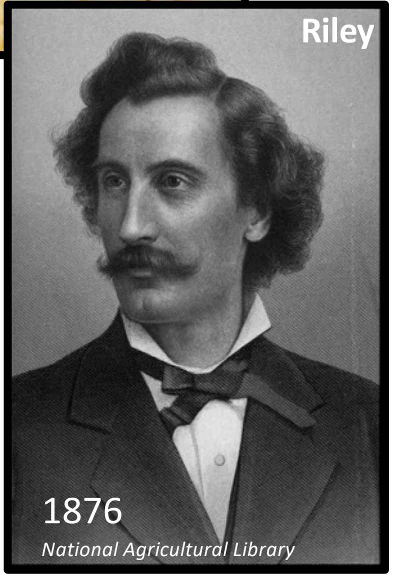
- Larvae largely restricted to corn roots
- Females historically laid eggs primarily in cornfields
- Females mate once, shortly after emergence, near their point of emergence
- Males mate multiple times
- A mobile species

Forbes and Colleagues Studied NCR Behavior & Ecology: Crop Rotation was an 'Obvious Solution':

- ✓ Larvae must feed on corn roots
- ✓ Females laid eggs primarily in corn

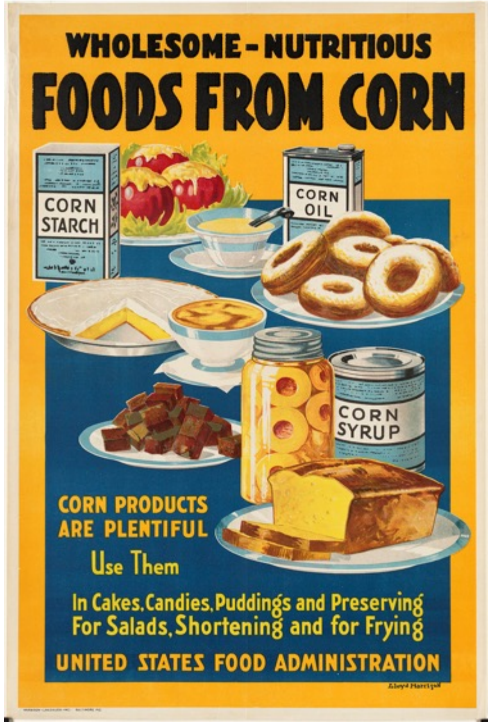


Dr. Stephen A. Forbes:
Illinois State Entomologist



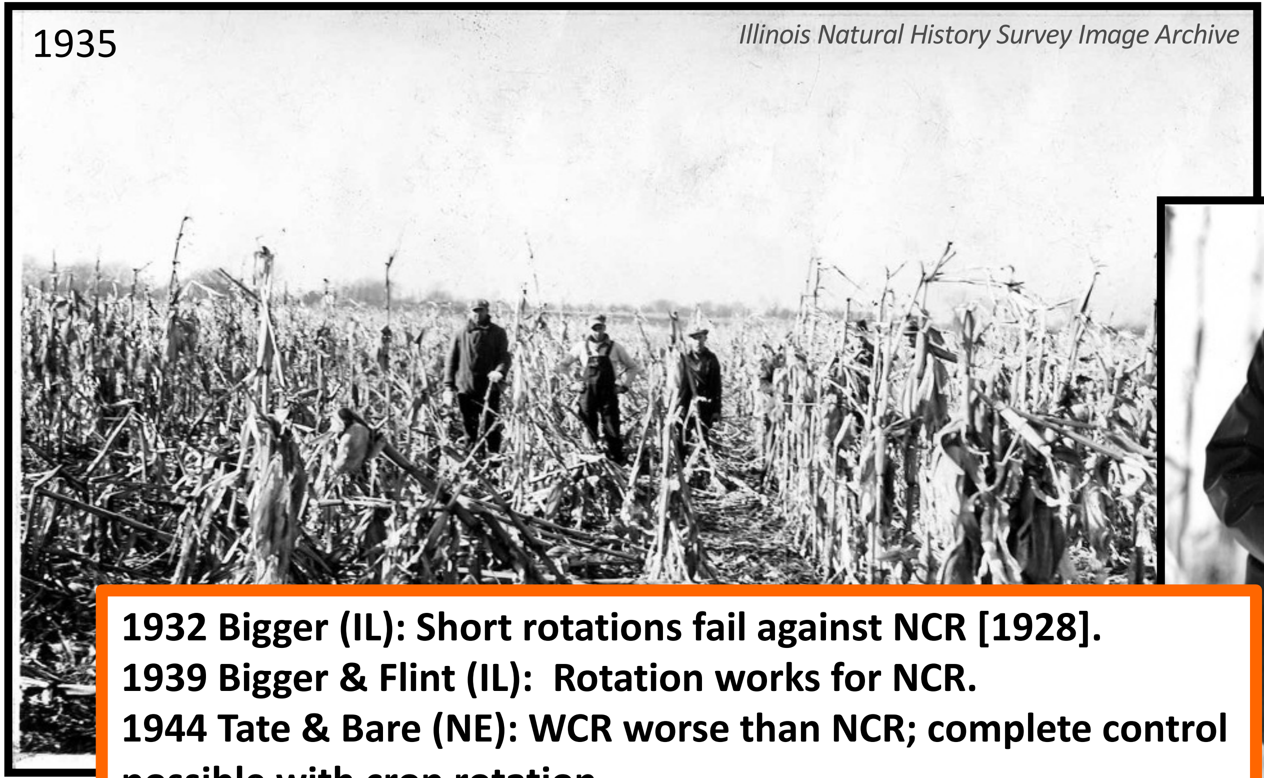
Charles Valentine Riley:
Missouri State Entomologist

Our Need for Corn Assured that Corn Rootworms Wouldn't Go Hungry.



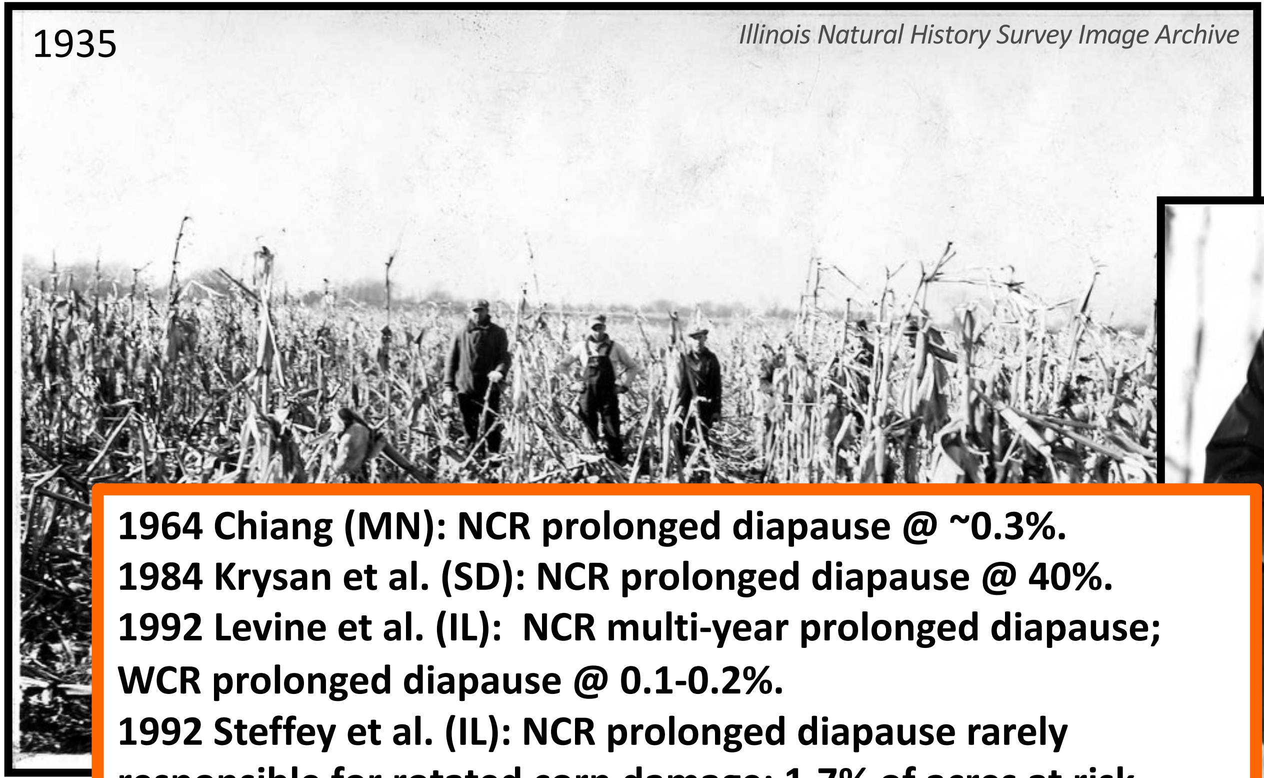
<u>WW1</u>: Corn was needed to replace wheat that was shipped to Europe to feed troops and refuges.

Annual Crop Rotation Failed to Control the Northern Corn Rootworm in 1932…



1932 Bigger (IL): Short rotations fail against NCR [1928].
1939 Bigger & Flint (IL): Rotation works for NCR.
1944 Tate & Bare (NE): WCR worse than NCR; complete control possible with crop rotation.

Annual Crop Rotation Failed to Control the Northern Corn Rootworm in 1932…



1964 Chiang (MN): NCR prolonged diapause @ ~0.3%.
1984 Krysan et al. (SD): NCR prolonged diapause @ 40%.
1992 Levine et al. (IL): NCR multi-year prolonged diapause; WCR prolonged diapause @ 0.1-0.2%.
1992 Steffey et al. (IL): NCR prolonged diapause rarely responsible for rotated corn damage: 1.7% of acres at risk.

NCR Evolved Resistance to Crop Rotation

Northern corn rootworm

- Eggs laid in cornfield soil, some remain dormant in diapause for ≥2 yrs, some will later hatch in cornfields. [1932, 1965]

“Prolonged Diapause”

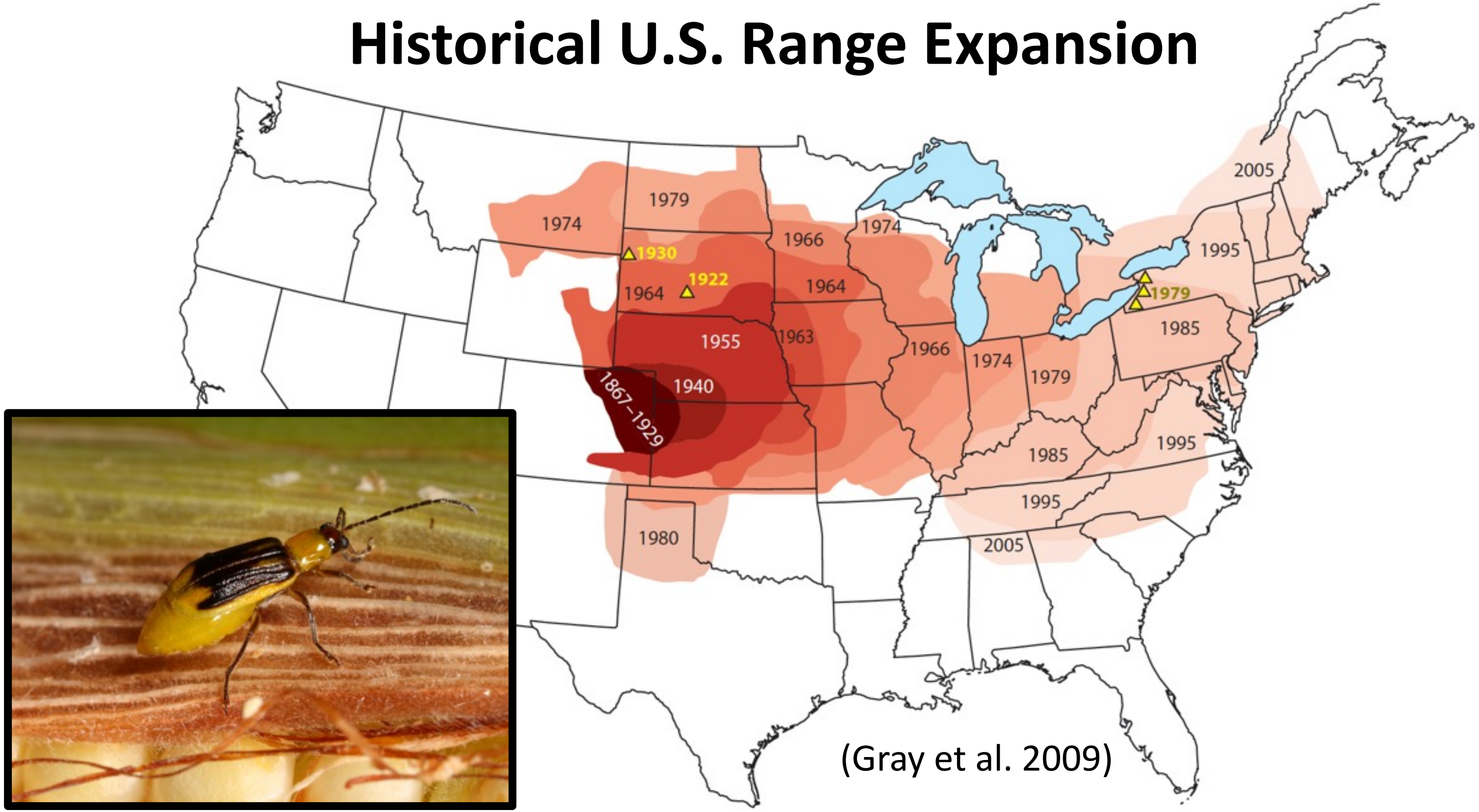
An unexpected variation in a “fundamental of rootworm biology”.

Insecticide to the Rescue in the 1940s

The rootworm reputation for resistance is well earned!

1948 Hill et al. (NE): First insecticide trials on NCR/WCR: chlorinated hydrocarbons.
1953 Decker (IL): Farm advisors report DDT, Toxaphene, Chlordane, BHC, Lindane, Parathion, Dieldrin, Aldrin in use against 10 insects.
1958 Bigger (IL): 98.7% control of NCR with Heptachlor or Aldrin
1962 Ball & Weekman (NE): Insecticide-resistant WCR; Aldrin & Heptachlor-1959.
1963 Bigger (IL): Aldrin-resistant NCR isolated in N. central IL.
1965 Hamilton (SD, IA, KS, MO, IL, WI): Broad Aldrin resistance WCR/NCR.
1978 Chio et al. (IL): CRW resistance to 4 insecticides.
1998 Meinke et al. (NE): WCR resistance to methyl-parathion and carbaryl.
2015 Pereria et al. (NE/KS) WCR resistance to pyrethroid (Bifenthrin).

Western Corn Rootworm (*Diabrotica v. virgifera* LeConte): Historical U.S. Range Expansion



(Gray et al. 2009)

Gray ME, Sappington TW, Miller NJ, Moeser J, Bohn MO, 2009. Adaptation and invasiveness of western corn rootworm: intensifying research on a worsening pest. Ann. Rev. Entomol. 54, 303–321.

By the 1980s, Crop Rotation & Soil Insecticides were the Rootworm Management Tools in Common Use.

Despite the logic of crop rotation, soil insecticides were needlessly applied to many rotated cornfields to protect it from rootworms. Steffey et al. (1992) showed even low use was excessive – just 1.7% of Illinois’ rotated corn was threatened.

The threat was attributed to NCR prolonged diapause.

Unexpected WCR injury in Illinois' rotated corn

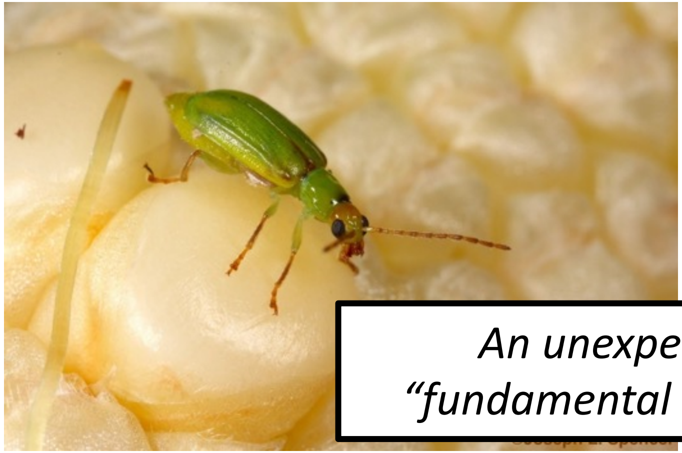
Initially:
seed corn
fields 1987

1995: 50%
yield loss in
IL & IN corn

NCR & WCR Both Evolved Resistance to Crop Rotation

Northern corn rootworm

- Eggs laid in cornfield soil, some remain dormant in diapause for ≥2 yrs, some will later hatch in cornfields. [1932, 1965]



"Prolonged Diapause"

Western corn rootworm

- Adult female moves between corn and soybean; lays eggs in soybean fields (and corn, alfalfa, etc); some hatch into cornfields. [1992, 1996]

"Rotation Resistance"

An unexpected variation in a "fundamental of rootworm biology".

- **Growers had to protect both continuous and rotated corn.**
- **Spread of rotation resistance lead to dramatically increased insecticide use; WCR monitoring could have reduced use.**

O'Neal et al. (2001) J. Econ. Ent.

Alarming Insurance-type Soil Insecticide Use Skyrocketed.

- It was argued that corn hybrids expressing rootworm-killing toxins from *Bacillus thuringiensis* (Bt) could be used to dramatically cut soil insecticide use.

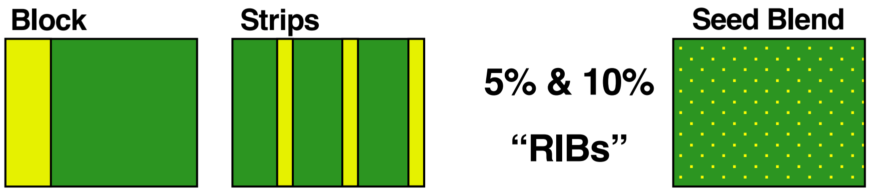
The <u>High Dose Refuge Strategy (Gould 1998)</u> would be used to delay rootworm resistance to Bt corn hybrids.

- **Areas of non-Bt corn in or near Bt cornfields.**
- **Bt susceptible beetles developing non-Bt refuge plant roots will disperse into nearby Bt corn where they will mate with any rare Bt-resistant beetles that developed on Bt corn.**
- **The 'flood' of susceptible beetles will make mating between Bt-resistant beetles unlikely -> few resistant offspring**

Refuge strategy assumes a lot about rootworm beetle behavior in Bt corn, as well as Bt toxin dose in plants (High), the initial frequency of resistance genes in populations (low), and how R-genes are inherited (recessive), and etc.

20% -5%

Structured Refuges



5% & 10%

"RIBs"

Gould. 1998. Ann. Rev. Entomol. 43:701-726.

Bt Traits for Corn Rootworm Management

- Four Bt toxins for corn rootworm management have been commercialized:
  - Cry3Bb1 (Yieldgard Rootworm)
  - mCry3A (Agrisure RW)
  - eCry3.1Ab (Agrisure Duracade)
  - Cry34/35Ab1 (Herculex CRW)

"Cry3" toxins

Rootworm Bt trait/toxin commercialization dates:

2003: Cry3Bb1
2006: Cry34/35Ab1
2007: mCry3A
2010: Cry3Bb1 + 34/35Ab1
2012: mCry3A + 34/35Ab1
2014: eCry3.1Ab + mCry3A

- Stacked corn rootworm and Lepidopteran Bt traits:
  - 2003: Cry1Ab + Cry3Bb1
  - 2006: Cry1F + Cry34/35Ab1
  - 2007: Cry1Ab + mCry3A
  - 2008: Cry1A.105 + 2Ab2 + Cry3Bb1

- Pyramided rootworm Bt hybrids express multiple rootworm Bt toxins in the sample plant.
  - Multiple MOAs are more durable; larvae need to be resistant to two different Bt toxins.
  - To fully exploit the benefits, two novel toxins should be pyramided.

Bt Traits for Corn Rootworm Management

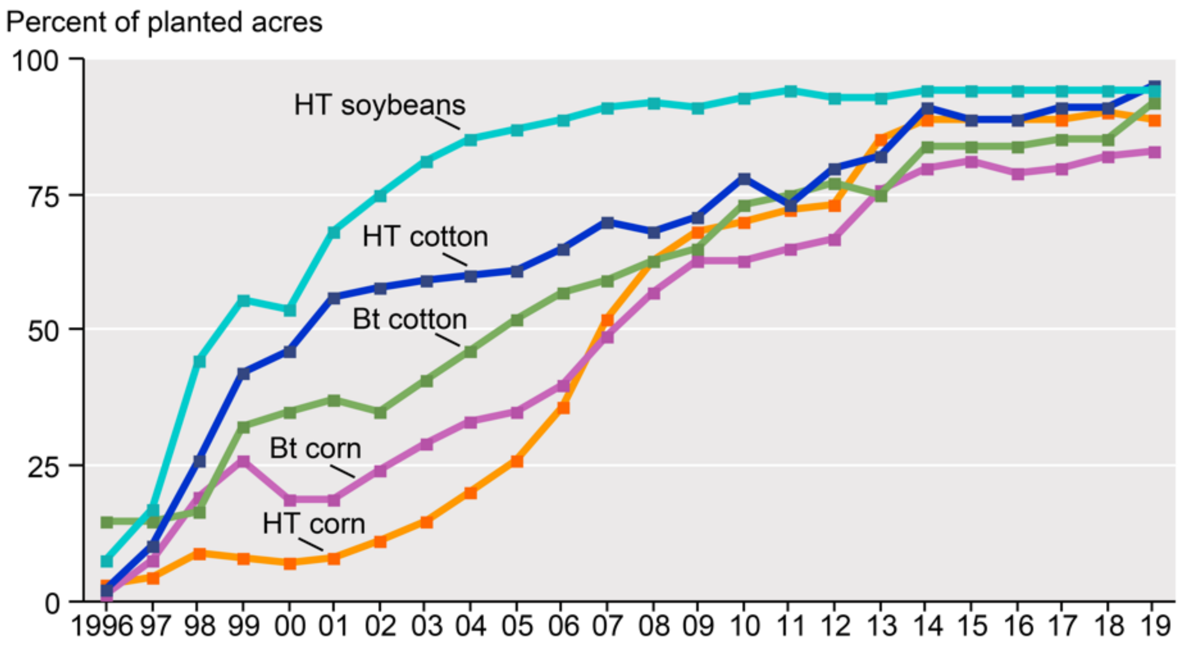
- 21 different trait packages with Bt CRW traits
  - Some combinations of the same toxins; see the Bt Trait Table.
  - Search “Handy Bt Trait Table” on a browser.
- Most pyramided rootworm hybrids combine Cry34/35Ab1 + one of the “Cry3” toxins.

The Handy Bt Trait Table for U.S. Corn Production, updated May 2019

Trait packages in alphabetical order (acronym)	Bt protein(s) in the trait package	Marketed for control of: BCW	CEW	ECB	FAW	SB	SCB	SWCB	TAW	WBC	CR	Resistance confirmed to the combination of Bts in package (check local situation)	Herbicide trait: GT RR2	LL	Non-Bt Refuge % (cornbelt)
AcreMax (AM)	Cry1Ab Cry1F	x		x	x	x	x	x				FAW WBC	x	x	5% in bag
AcreMax CRW (AMRW)	Cry34/35Ab1										x	NCR/WCR	x	x	10% in bag
AcreMax1 (AM1)	Cry1F Cry34/35Ab1	x		x	x	x	x	x			x	ECB FAW SWCB WBC NCR/WCR	x	x	10% in bag 20% ECB
AcreMax Leptra (AML)	Cry1Ab Cry1F Vip3A	x	x	x	x	x	x	x	x	x			x	x	5% in bag
AcreMax TRIsect (AMT)	Cry1Ab Cry1F mCry3A	x		x	x	x	x	x			x	FAW WBC WCR	x	x	10% in bag
AcreMax Xtra (AMX)	Cry1Ab Cry1F Cry34/35Ab1	x		x	x	x	x	x			x	FAW WBC NCR/WCR	x	x	10% in bag
AcreMax Xtreme (AMXT)	Cry1Ab Cry1F mCry3A Cry34/35Ab1	x		x	x	x	x	x			x	FAW WBC WCR	x	x	5% in bag
Agrisure 3010 and 3010A	Cry1Ab			x			x	x					x	x	20%
Agrisure 3000GT and 3011A	Cry1Ab mCry3A			x			x	x			x	WCR	x	x	20%
Agrisure Viptera 3110	Cry1Ab Vip3A	x	x	x	x	x	x	x	x	x			x	x	20%
Agrisure Viptera 3111	Cry1Ab Vip3A mCry3A	x	x	x	x	x	x	x	x	x	x	WCR	x	x	20%
Agrisure 3120 E-Z Refuge	Cry1Ab Cry1F	x		x	x	x	x	x				FAW WBC	x	See bag tag for code EZ0 NO EZ1 YES	5% in bag
Agrisure 3122 EZ Refuge	Cry1Ab Cry1F mCry3A Cry34/35Ab1	x		x	x	x	x	x			x	FAW WBC WCR	x		5% in bag
Agrisure Viptera 3220 E-Z Refuge	Cry1Ab Cry1F Vip3A	x	x	x	x	x	x	x	x	x			x		5% in bag
Agrisure Viptera 3330 E-Z Refuge	Cry1Ab Vip3A Cry1A.105 + Cry2Ab2	x	x	x	x	x	x	x	x	x			x		5% in bag
Agrisure Duracade 5122 E-Z Refuge	Cry1Ab Cry1F mCry3A eCry3.1Ab	x		x	x	x	x	x			x	FAW WBC WCR	x		5% in bag
Agrisure Duracade 5222 E-Z Refuge	Cry1Ab Cry1F Vip3A mCry3A eCry3.1Ab	x	x	x	x	x	x	x	x	x	x	WCR	x		5% in bag
Herculex I (HXI)	Cry1F	x		x	x	x	x	x				ECB FAW SWCB WBC	x	x	20%
Herculex RW (HXRW)	Cry34/35Ab1										x	NCR/WCR	x	x	20%
Herculex XTRA (HXX)	Cry1F Cry34/35Ab1	x		x	x	x	x	x			x	ECB FAW SWCB WBC NCR/WCR	x	x	20%
Intrasect (YHR)	Cry1Ab Cry1F	x		x	x	x	x	x				FAW WBC	x	x	5%
Intrasect TRIsect (CYHR)	Cry1Ab Cry1F mCry3A	x		x	x	x	x	x			x	FAW WBC WCR	x	x	20%
Intrasect Xtra (YXR)	Cry1Ab Cry1F Cry34/35Ab1	x		x	x	x	x	x			x	FAW WBC NCR/WCR	x	x	20%
Intrasect Xtreme (CYXR)	Cry1Ab Cry1F mCry3A Cry34/35Ab1	x		x	x	x	x	x			x	FAW WBC WCR	x	x	5%
Leptra (VYHR)	Cry1Ab Cry1F Vip3A	x	x	x	x	x	x	x	x	x			x	x	5%
Powercore [a] Powercore Refuge Advanced [b]	Cry1A.105 Cry2Ab2 Cry1F	x	x	x	x	x	x	x				CEW WBC	x	x	[a] 5% [b] 5% in bag
QROME (Q)	Cry1Ab Cry1F mCry3A Cry34/35Ab1	x		x	x	x	x	x			x	FAW WBC WCR	x	x	5% in bag
SmartStax [a] Smartstax Refuge Advanced [b] SmartStax RIB Complete [b]	Cry1A.105 Cry2Ab2 Cry1F Cry3Bb1 Cry34/35Ab1	x	x	x	x	x	x	x			x	CEW WBC WCR	x	x	[a] 5% [b] 5% in bag
Trecepta [a] Trecepta RIB Complete [b]	Cry1A.105 Cry2Ab2 Vip3A	x	x	x	x	x	x	x	x	x			x		[a] 5% [b] 5% in bag
TRIsect (CHR)	Cry1F mCry3A	x		x	x	x	x	x			x	ECB FAW SWCB WBC WCR	x	x	20%
VT Double PRO [a] VT Double PRO RIB Complete[b]	Cry1A.105 Cry2Ab2		x	x	x	x	x	x				CEW	x		[a] 5% [b] 5% in bag
VT Triple PRO [c] VT Triple PRO RIB Complete [d]	Cry1A.105 Cry2Ab2 Cry3Bb1		x	x	x	x	x	x			x	CEW NCR/WCR	x		[c] 20% [d] 10% in bag
Yieldgard Corn Borer (YGCB)	Cry1Ab			x			x	x					x		20%
Yieldgard Rootworm (YGRW)	Cry3Bb1										x	NCR/WCR	x		20%
Yieldgard VT Triple	Cry1Ab Cry3Bb1			x			x	x			x	NCR/WCR	x		20%

https://www.texasinsects.org/bt-corn-trait-table.html

Adoption of genetically engineered crops in the United States, 1996-2019



Note: HT indicates herbicide-tolerant varieties; Bt indicates insect-resistant varieties (containing genes from the soil bacterium Bacillus thuringiensis). Data for each crop category include varieties with both HT and Bt (stacked) traits.
Source: USDA, Economic Research Service using data from the 2002 ERS report, Adoption of Bioengineered Crops (AER-810) for the years 1996-99 and National Agricultural Statistics Service, (annual) June Agricultural Survey for the years 2000-19.

Rootworm Resistance to Bt Traits

- 2009: first evidence of field-evolved resistance to Cry3Bb1 in western corn rootworm
  - Gassmann et al. 2011 PLOS One 6 (7)
- Cross-resistance among Cry3Bb1, mCry3A, and eCry3.1Ab
  - Gassmann et al. 2014. PNAS https://doi.org/10.1073/pnas.1317179111
  - Zukoff et al. 2016. J. Econ. Ent. https://doi.org/10.1093/jee/tow073 PMID: 27106225
- 2016-2019: confirmed reports of field-evolved resistance to Cry34/35Ab1 in Iowa and Minnesota
  - Gassmann et al. 2019. Pest Man. Sci. DOI: 10.1002/ps5510
  - Gassmann et al. 2016. J. Econ. Ent. DOI: 10.1093/jee/tow110
  - Ludwick et al. 2017. J. Appl Ent. https://doi.org/10.1111/jen.12377
- 2019: confirmed reports of field-evolved resistance to Cry3Bb1 & Cry34/35Ab1 in North Dakota WCR & NCR!
  - Calles-Torrez et al. 2019. J. of Econ. Ent. DOI: 10.1093/jee/toz111

Western Corn Rootworm Bt Resistance: "Local" Situation

- Resistance to "Cry3" traits (Cry3Bb1, mCry3A, eCry3.1Ab) is common in Illinois.
  - Yieldgard RW/VT Triple Pro, Agrisure RW, Agrisure Duracade
  - Rotated and continuous corn are vulnerable.

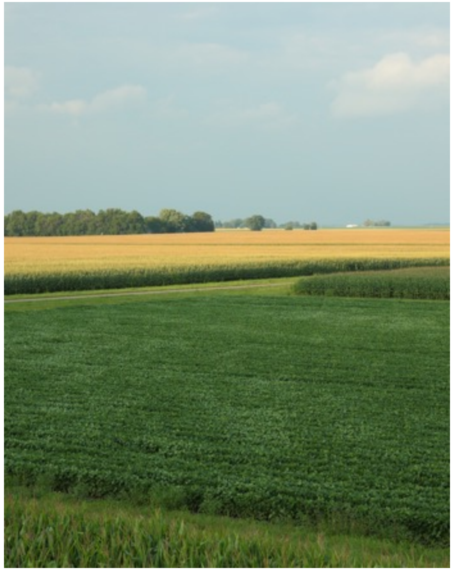
- Resistance to Cry34/35Ab1 (Herculex RW) confirmed in NE Iowa, Minnesota, North Dakota – limited areas.
  - Evidence of reduced susceptibility in IL, not widespread (?)

- Pyramided hybrids still performing well in Illinois. (SmartStax, Agrisure 3122, AcreMax Xtreme, etc.).
  - Expression of Cry34/35Ab1 is key to efficacy.

- No documented Cry3 or Cry34/35Ab1 resistance in Indiana.

What Does the Future Look Like?





Rootworm Management: Future Prospects

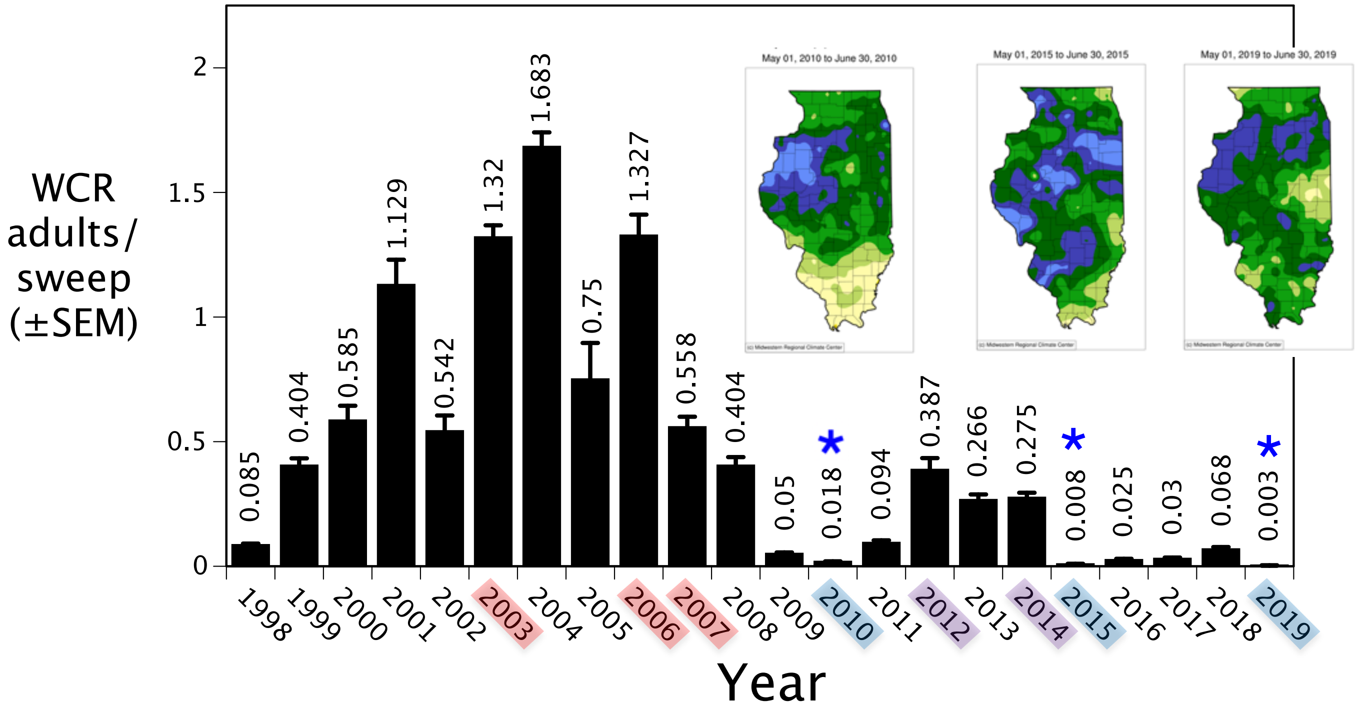
- New novel Mode of Action (MOA) for rootworm management is coming: RNA interference, "RNAi".
  - Method disrupts the expression of rootworm specific genes leading to death.
- RNAi will be pyramided with existing Bt toxins.
  - Cry3Bb1 + Cry34/45Ab1 Bt toxin efficacy will be important to the durability of RNAi.
  - Multiple different and effective MOAs in one hybrid make resistance less likely.
  - Growing resistance to Bt traits presents challenges.
- Expect renewed emphasis on IPM, Best Management Practices (and monitoring).
  - Delay resistance evolution by using only when warranted.

Will Bt resistance go away if we stop using Bt?

- Pests with resistance may be at a disadvantage when the material to which they they are resistant is absent - Fitness costs.
- So far there are not major fitness costs associate with Bt resistance.
- Bt resistance genes and resistance will likely remain in populations.

- Consider the cyclodiene Aldrin: Banned in 1974, yet WCR still have >>1000x resistance to it.

1998-2019 Western Corn Rootworm (WCR) Abundance in Rotated Soybean Fields in Urbana, IL.



Notable events:

2003: Cry3Bb1

2006: Cry34/35Ab1

2007: mCry3A

2010: Cry3Bb1 + 34/35Ab1

2012: mCry3A + 34/35Ab1

2014: eCry3.1Ab + mCry3A

2010, ‘15, ‘19: Spring Floods

- **WCR populations NE of Urbana, Illinois have fluctuated dramatically.**
- **Bt hybrids helped reduce WCR abundance, with help from weather!**

WCR adults/100 sweeps in soybean fields. Tinsley et al. 2018. *American Entomologist.*

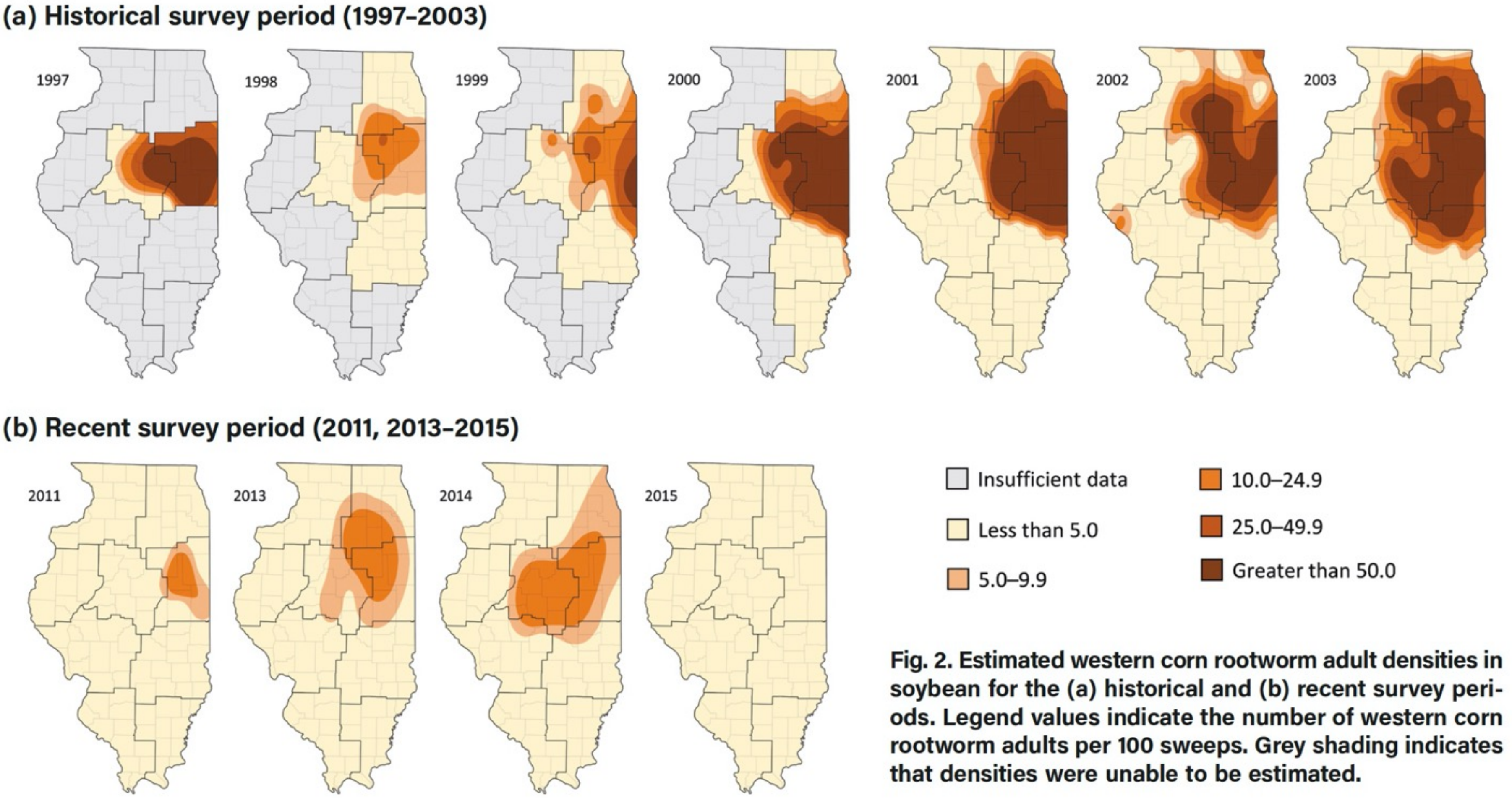
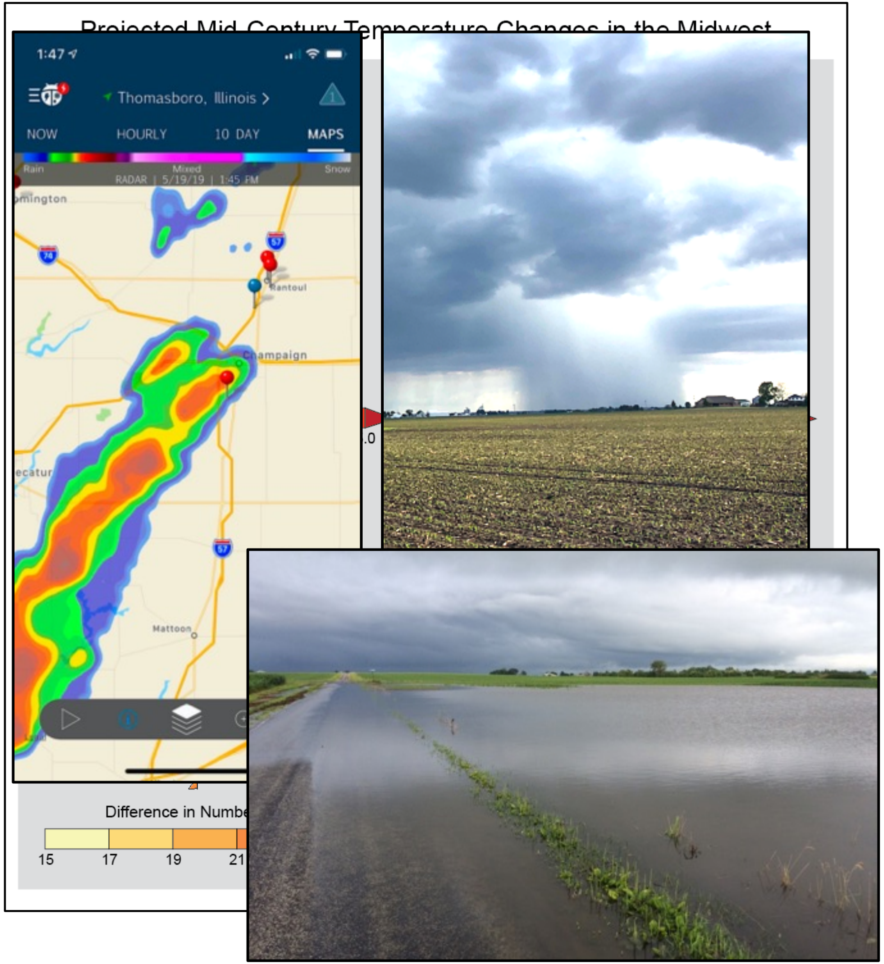
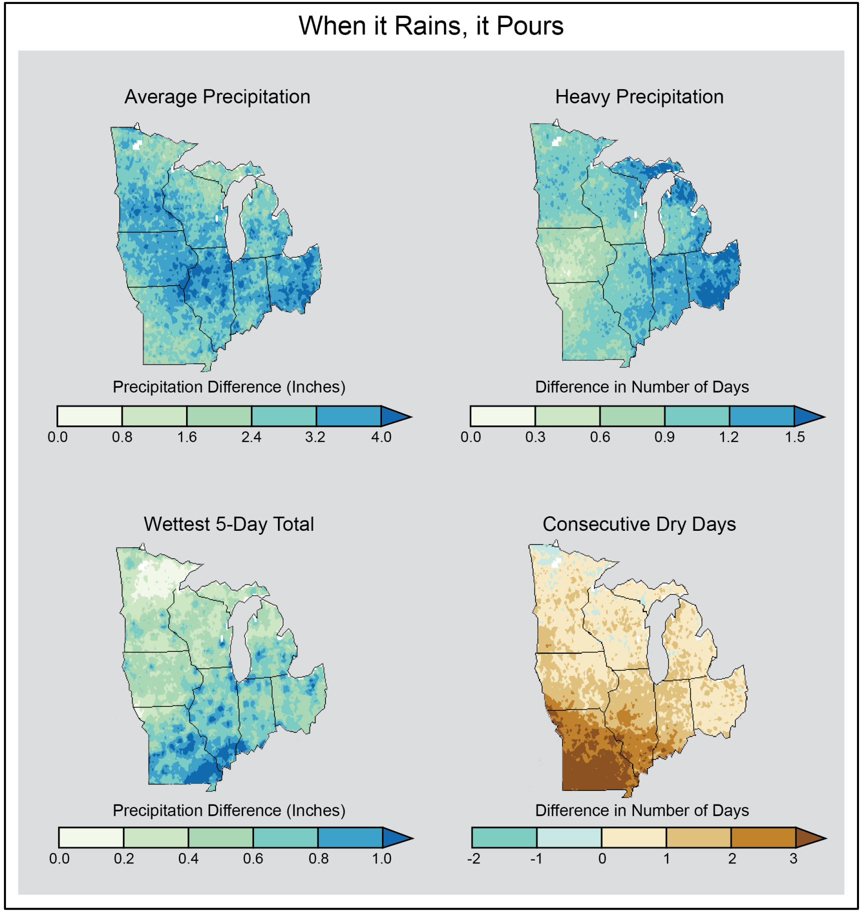


Fig. 2. Estimated western corn rootworm adult densities in soybean for the (a) historical and (b) recent survey periods. Legend values indicate the number of western corn rootworm adults per 100 sweeps. Grey shading indicates that densities were unable to be estimated.





https://nca2014.globalchange.gov/report/regions/midwest

The Question: "Do I need to use Bt corn, SAI, or rotate next year?" "What will the WCR pressure be like next year?"

- Eggs may be killed by cold weather or not!
  - Crushed by freeze-thaw cycles or frozen.
  - Insulated under an insulating blanket of snow.
- Larvae may be killed by floods & saturated soil conditions or not!
  - Eggs survive fine underwater & even hatch.
  - Neonates very sensitive: travel through soil pores toward CO_2.
  - Older larvae can go anaerobic, 50% of 3^{rds} live 24h underwater, 50% of 2^{nds} live 56h!
  - Survival is lower in warm water.
- Planting time can reduce injury potential or not!
  - Late planting may mean significant proportion of egg hatch with no roots to eat.
  - Relatively late planted fields attract hungry WCR adults that clip silks, laying lots of eggs for next year! is critical –context to interpret what happens!
- Evidence of Bt resistance, hybrid performance issues, unexpected damage?
  - UXD: ½ node of roots pruned on pyramid, 1 node pruned on single trait hybrid.
- Current season pest abundance is critical –context to interpret what happens!

Conclusions:

We consistently underestimate corn rootworms.

Forbes and Riley made recommendations based on sound corn rootworm biology. Crop rotation was the obvious rootworm solution. Neither man anticipated the impact of applying crop rotation over vast areas. Natural selection reared its ugly head and we got prolonged diapause and rotation resistance.

In the 1940s, who would have anticipated that the advances in fertilizers and pesticides that allowed vast areas of continuous corn cultivation would turn the NCR and WCR into enormously destructive, insecticide resistant pests?

In recent decades, the inevitability of resistance was acknowledged and literally "baked" into the commercialization of rootworm Bt corn hybrids. Unfortunately, many of the expectations and assumptions around which we built rootworm IRM were not accurate. The speed with which it appeared suggests we have more to learn about rootworm biology and what real insects do in the field.

History provides ample opportunities to learn, but will we?

Questions?

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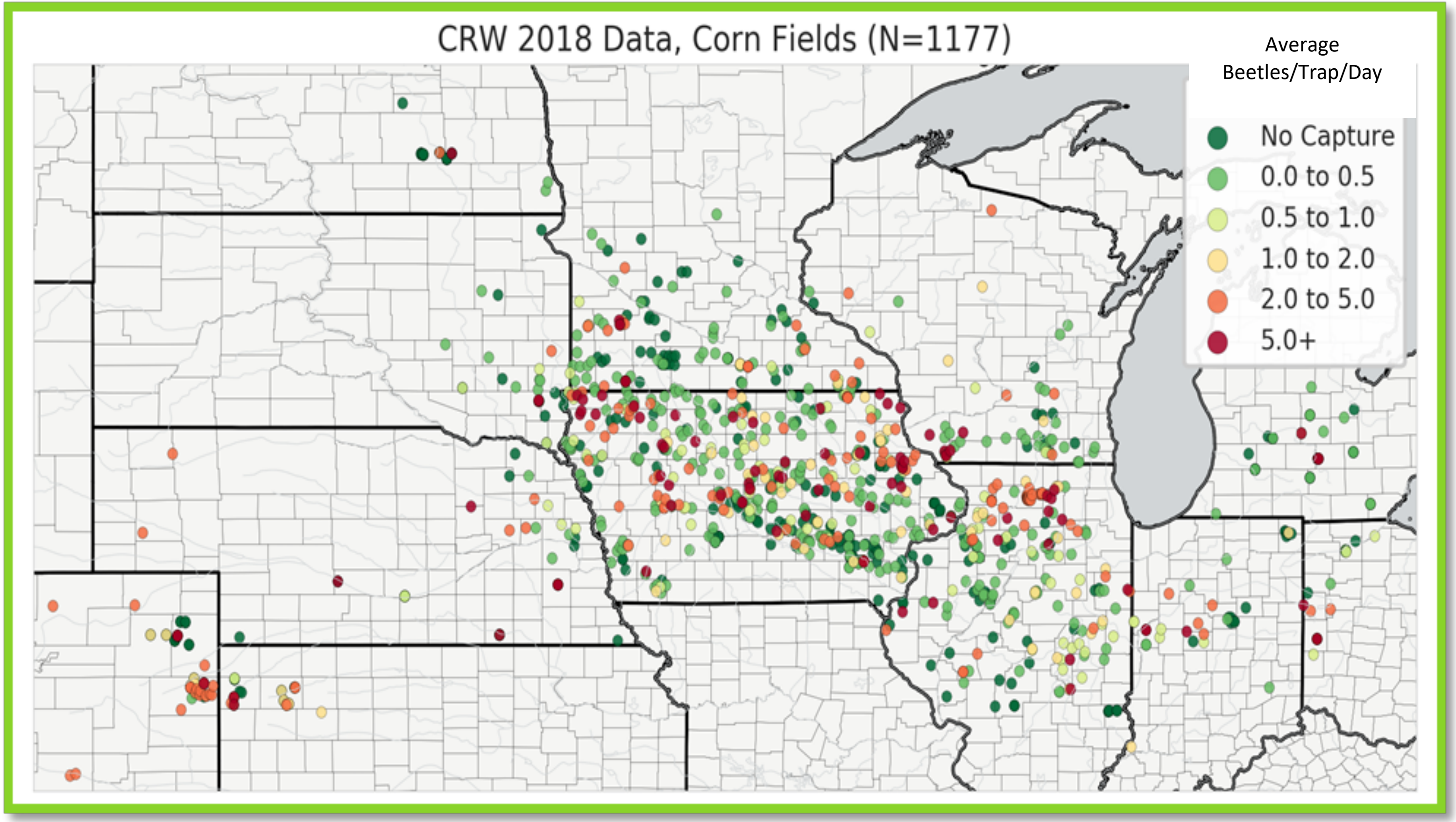
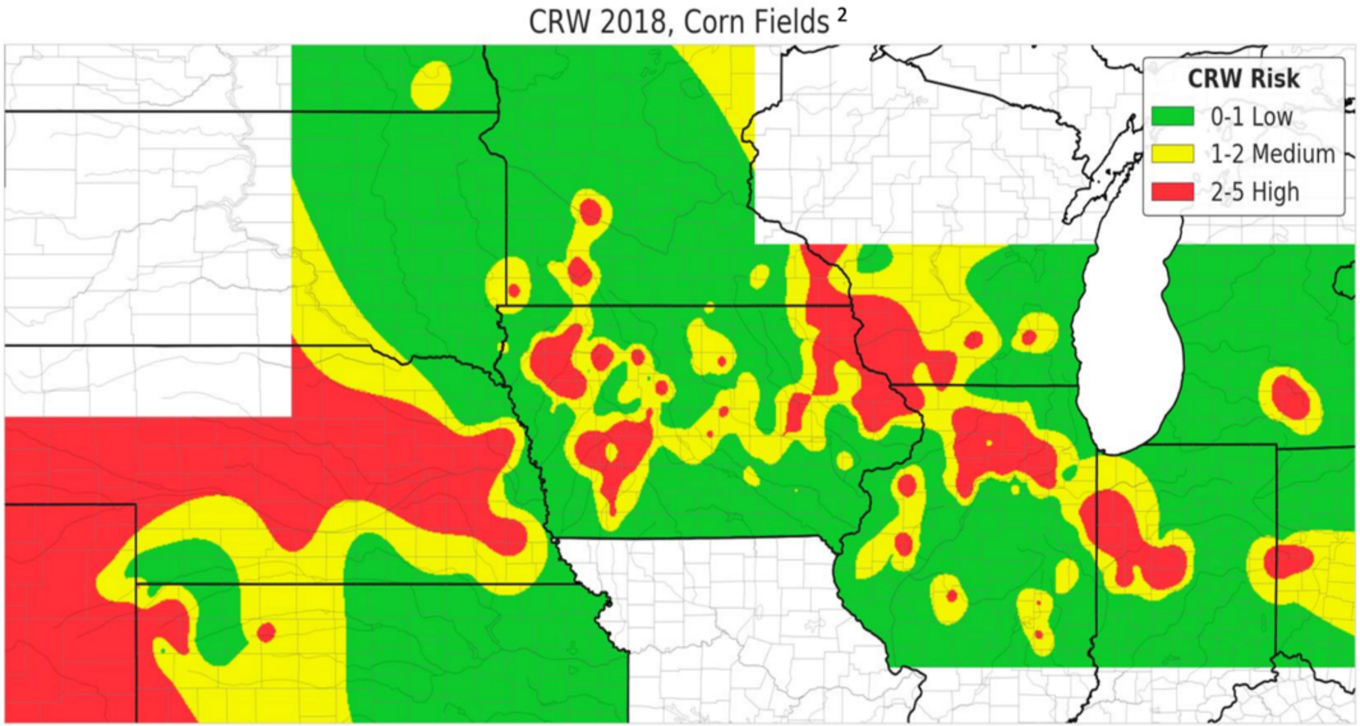

CRW 2018 Data, Corn Fields (N=1177)
Average Beetles/Trap/Day
No Capture
0.0 to 0.5
0.5 to 1.0
1.0 to 2.0
2.0 to 5.0
5.0+

Estimated Risk of Damaging Corn Rootworm Populations in 2019

Areas in Red are estimated to have potential risk of above action threshold populations[1].



Sources:

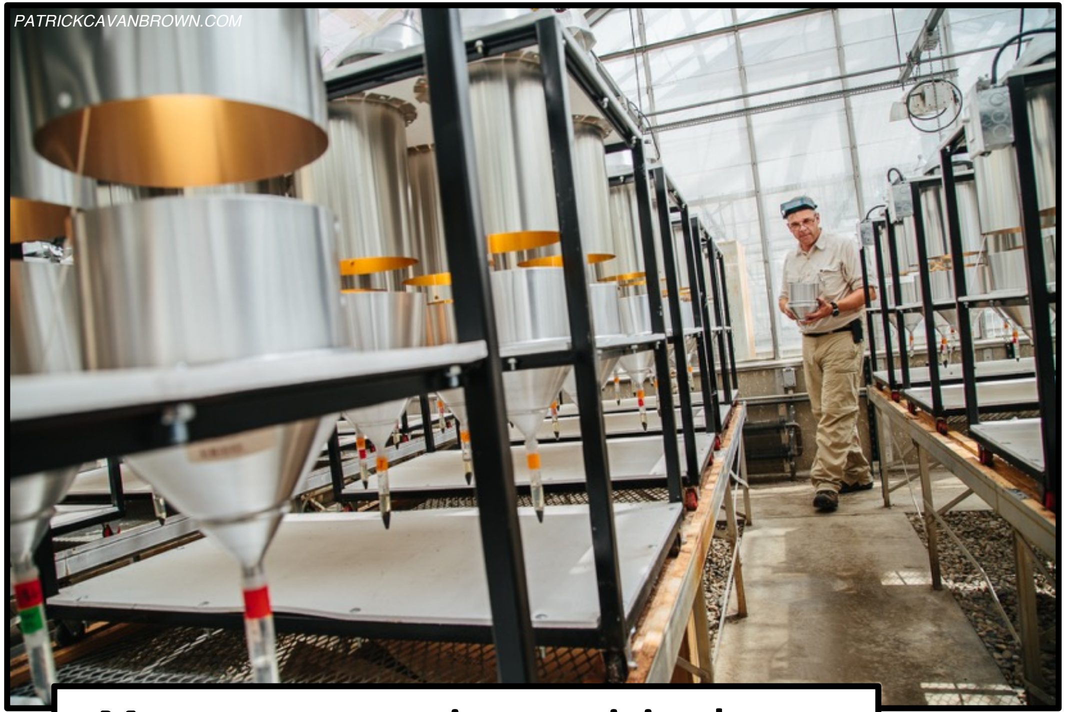
[1]Hodgson, E. 2016. Guidelines for using sticky traps to assess corn rootworm activity. Integrated Crop Management. Iowa State University. https://crops.extension.iastate.edu/cropnews/2016/06/guidelines-using-sticky-traps-assess-corn-rootworm-activity

[2]Field trials conducted on 1177 Corn field plots in 10 different states in 2018.

Current Corn Rootworm Management Recommendations

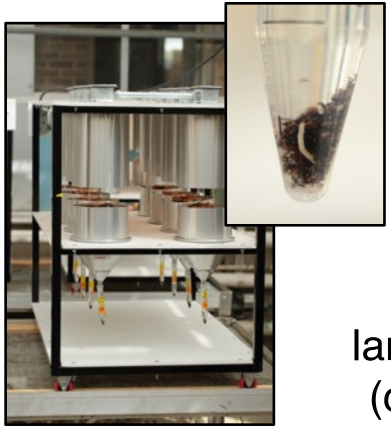
- Implement rootworm management where needed, based on monitoring of adult numbers during the previous year
  - While overall numbers are currently low, there are local and regional “hot spots”.
  - Make the decision based on local populations, not just overall trends and commodity prices.
  - Evaluate trait (and insecticide) performance on your farm
  - Look for changes over time
  - Leave check strips
- Where rootworm management is justified:
  - A pyramided Bt corn hybrid is the most effective option for ground going into corn.
  - Rotating to soybean is the most effective way to manage a high field population.
  - Soil insecticides are still viable.
- Where unexpected damage to Bt corn is observed and/or Bt resistance is expected:
  - Best option: rotate field to soybean (kills all WCR larvae in the soil at hatch)
  - Next best: rotate to a soil insecticide
  - Switch to a different Bt mode of action -?
  - Unexpected damage (EPA definition):
    - ½ node pruned, pyramided hybrid
    - 1 node pruned, single-trait hybrid

- Single-plant Bt-resistance bioassay (Gassmann et al. 2011)
  - **Cry3**-expressing hybrids (Cry3Bb1 + mCry3A) + isolines
  - **Cry34/35Ab1**-expressing hybrid + isolines
- Champaign Co. “R” populations vs. USDA Bt-susceptible WCR

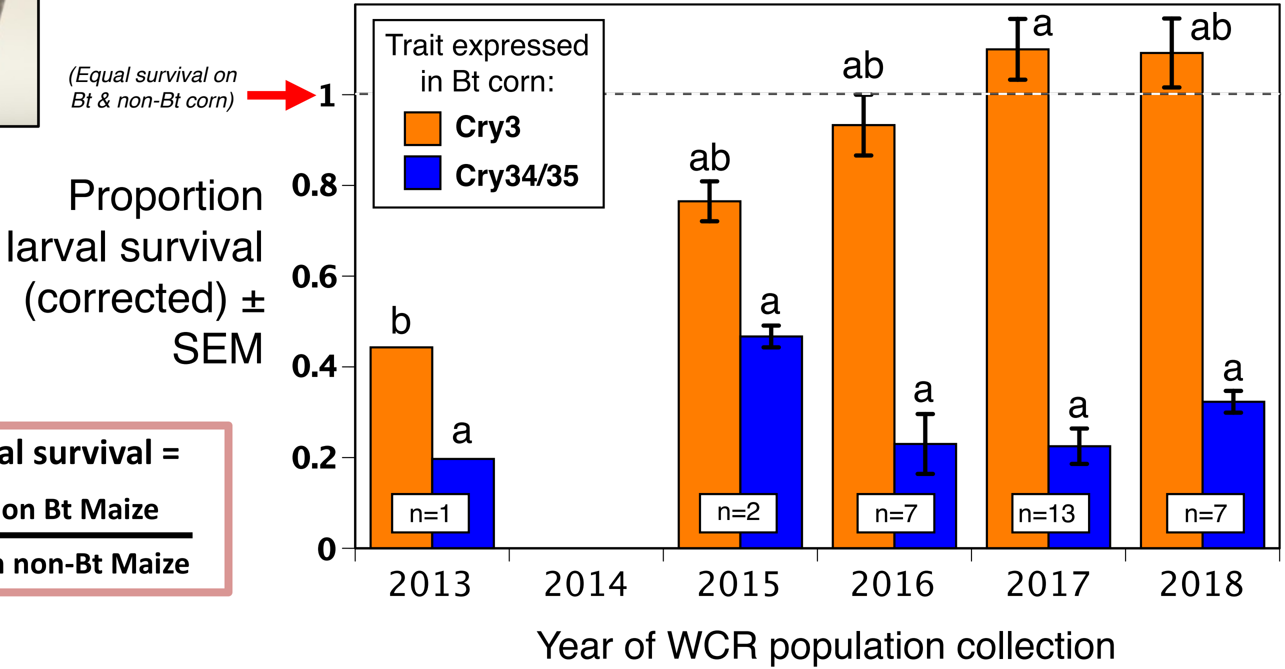


Measure: proportion surviving larvae

Gassmann et al. 2011. *PLoS ONE* 6(7): e22629.

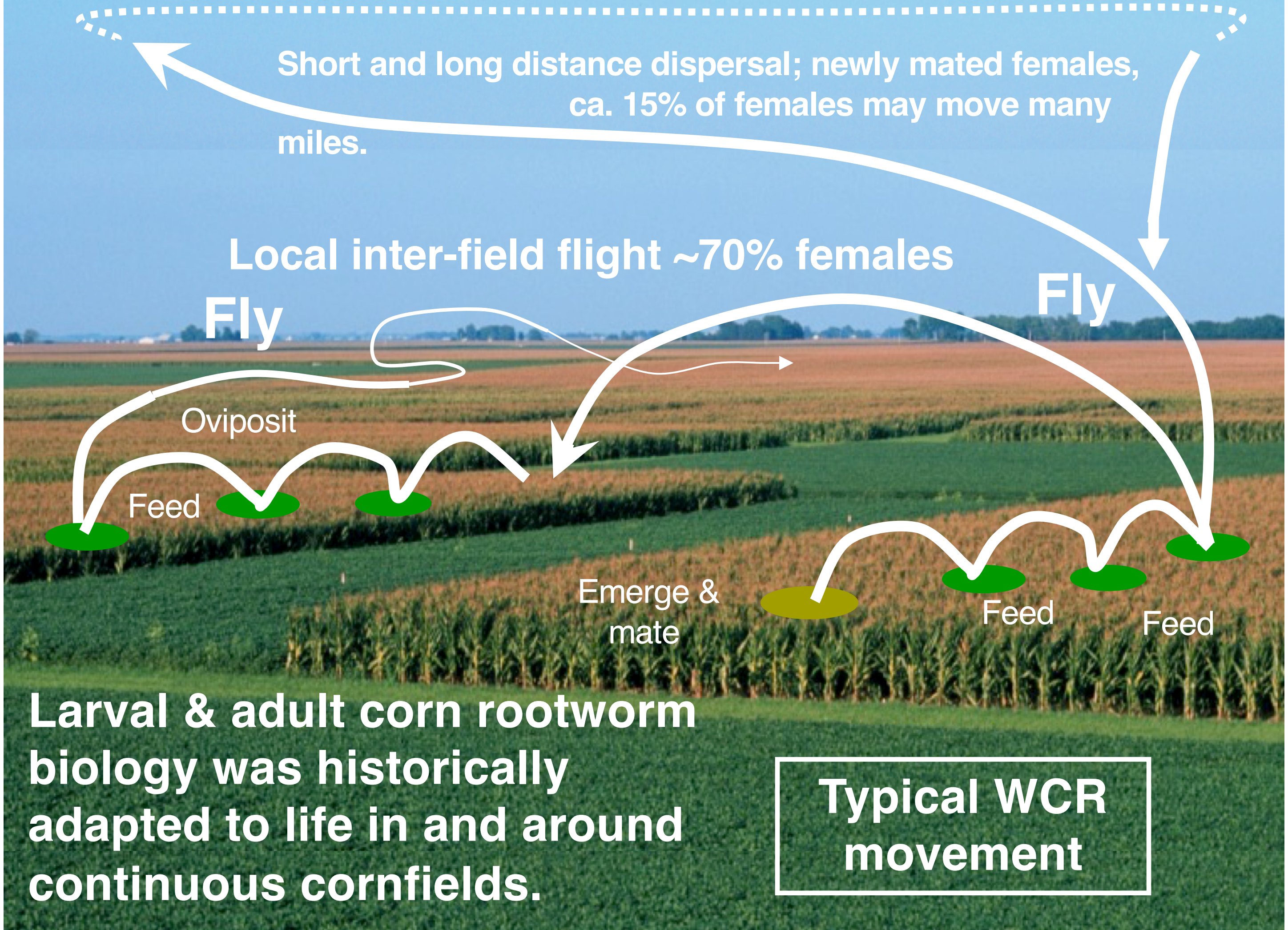


Corrected WCR larval survival on Cry3 & Cry34/35 Bt corn hybrids in bioassays

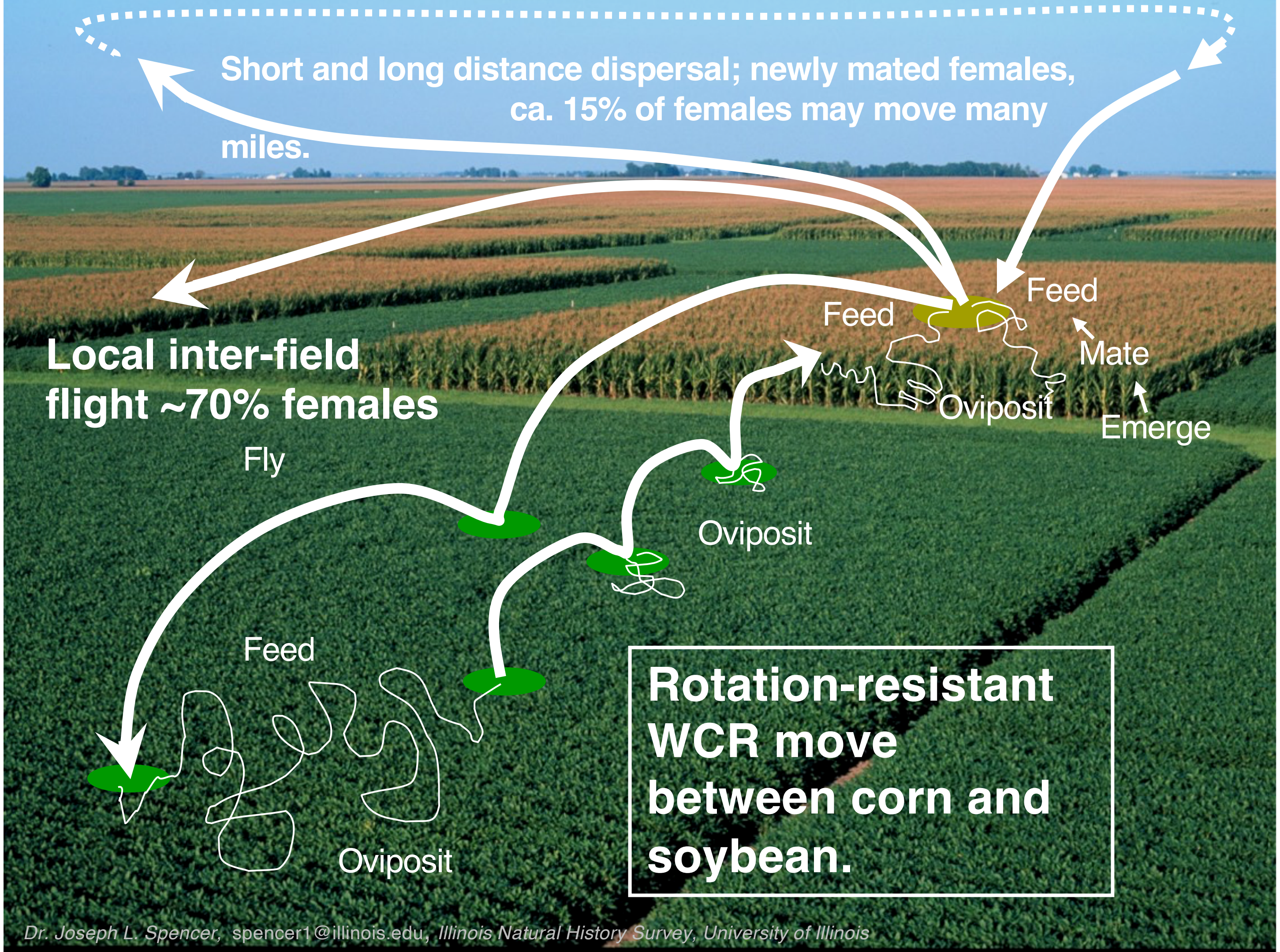


$$\text{Corrected larval survival} = \frac{\text{Prop. Survival on Bt Maize}}{\text{Prop. Survival on non-Bt Maize}}$$

- **During a time of high Bt adoption + low WCR density, corrected larval survival on Cry3 toxins reached 1.0.**
- **Corrected larval survival on Cry34/35Ab1 toxin has remained steady at a modest level (mean= 0.32).**



Dr. Joseph L. Spencer, spencer1@illinois.edu, *Illinois Natural History Survey, University of Illinois*


Short and long distance dispersal; newly mated females, ca. 15% of females may move many miles.
Local inter-field flight ~70% females
Fly
Feed
Feed
Mate
Emerge
Oviposit
Oviposit
Feed
Oviposit
Rotation-resistant WCR move between corn and soybean.
Dr. Joseph L. Spencer, spencer1@illinois.edu, Illinois Natural History Survey, University of Illinois

Trait and Hybrid Registration History:

Single corn rootworm Bt traits:

- **2003**: Cry3Bb1-YieldGard RW
- **2005**: Cry34/35Ab1-Herculex RW
- **2007**: mCry3A-Agrisure RW
- **2014**: eCry3.1Ab-Agrisure Duracade*

Stacked corn rootworm and Lepidopteran Bt traits:

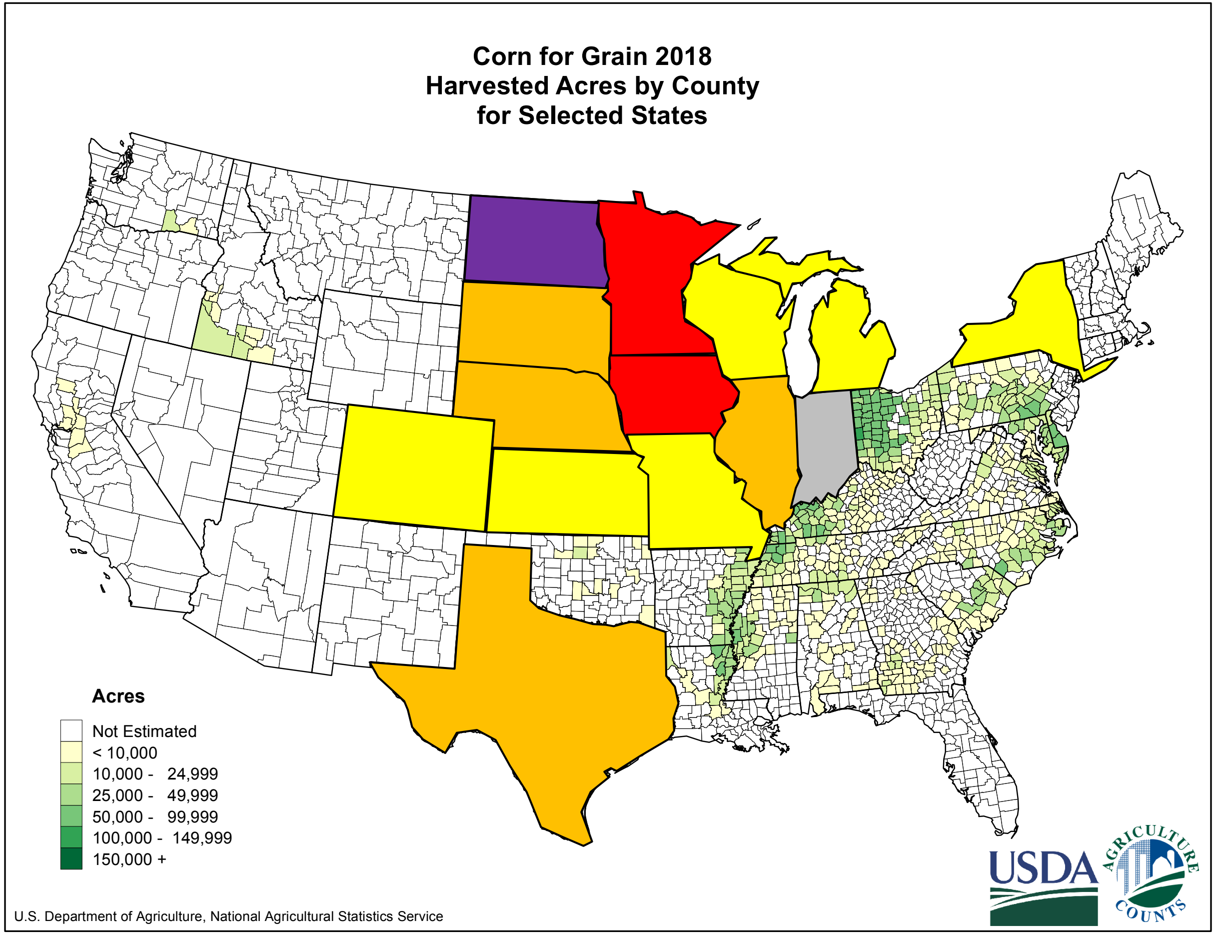
- **2003**: Cry1Ab + Cry3Bb1
- **2005**: Cry1F + Cry34/35Ab1
- **2007**: Cry1Ab + mCry3A
- **2008**: Cry1A.105 + 2Ab2 + Cry3Bb1

20% structured refuge: in-field or adjacent refuge.
➔ *One MOA = large refuge area is needed to generate susceptible WCR to mate with numerous survivors from Bt.*

Pyramided corn rootworm and Lepidopteran Bt traits:

- **2009**: Cry1A.105 +Cry2Ab2 + Cry3Bb1 + Cry34/35Ab1 (SmartStax, REFUGE ADVANCED-**2011**)
- **2012**: Cry1Ab + Cry1F + mCry3A + Cry34/35Ab1 (Agrisure E-Z Refuge, Optimum AcreMax XTreme)
- **2014**: Cry1Ab + Cry1F + mCry3A + eCry3.1Ab (Agrisure Duracade 5122)
- **2016**: Cry1Ab + Cry1F + VIP3A + mCry3A + eCry3.1Ab (Agrisure Duracade 5222)

5-10% refuge: structured refuge or integrated seed blend refuge (refuge in the bag: RIB).
➔ *Two effective MOAs = smaller refuge is needed because there are fewer survivors from Bt, fewer refuge WCR needed to mate with Bt WCR.*



WCR Cry3 Resistance

WCR Cry3 & Cry34/35 Resistance

WCR Isolated Cry3 Resistance

WCR Cry34/35 Resistance

High dose refuge strategy (Gould 1998)

Assumptions

- Bt traits at high dose in corn; 99.99% die.
- Resistance is initially rare; ~0.0001.
- Resistance is recessive and costly.
- Matings with susceptible refuge WCR will dilute resistance. Refuges will be adopted.

Reality

- Low-Moderate dose, only 95-98% die.
- Resistance is not initially rare ~0.1- 0.01
- Resistance is not recessive without fitness costs
- Too many Bt survivors for too few refuge WCR. Matings are not random & WCR move too little. Poor refuge compliance.

Consequences

- Resistance to single trait Bt hybrids evolved quickly.
- Benefits of combining 2 different Bt traits in one hybrid (Pyramiding) were lost because of existing resistance

IPM recommendations to delay the further evolution and spread of Bt resistance:

- ✓ Rotate to a nonhost crop to break the rootworm life cycle and to eliminate point sources of resistance.
- ✓ Switch to CRW Bt trait that is different from one that performed poorly.
- ✓ Switch to a hybrid expressing multiple CRW resistance traits (i.e., pyramided hybrid).
- ✓ Consider use of a planting-time soil insecticide (SI) with non-Bt corn hybrid.
- ✓ If you cannot rotate and don't have a pyramid option, adult suppression will reduce the number of resistant adults that survive. This is a remediation step that should be used within IPM!
  - SI use on a pyramided hybrid is not recommended.
  - SI does not significantly improve Bt root protection or yield.
  - Delayed adult emergence from SI-treated Bt-hybrid plants may diminish the efficacy of the non-Bt refuge.
- ✓ **Consider a long-term integrated approach to CRW management that includes multiple tactics.**

Cullen et al. (2013): **Resistance to Bt Corn by Western Corn Rootworm (Coleoptera: Chrysomelidae) in the U.S. Corn Belt.** Journal of Integrated Pest Management, Vol 4(3) pp. D1-D6(6). **DOI:** http://dx.doi.org/10.1603/IPM13012

Questions?

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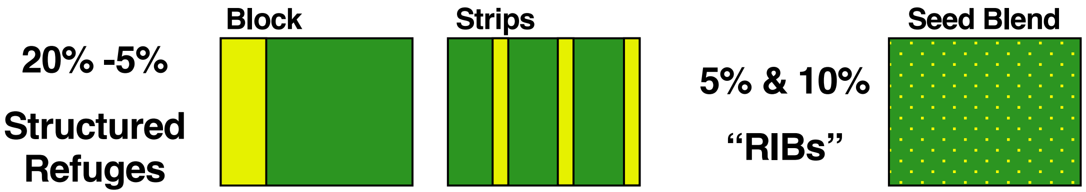
The <u>High Dose Refuge Strategy (Gould 1998)</u> would be used to delay rootworm resistance to Bt corn hybrids.

- Plant areas of non-Bt corn in or near Bt cornfields.
- Plentiful Bt susceptible beetles developing on roots of non-Bt refuge plant will disperse into nearby Bt corn where they will mate with any rare Bt-resistant beetles that developed on Bt corn.
- The 'flood' of susceptible beetles will make it unlikely that any two Bt-resistant beetles ever find each other to mate and produce resistant offspring.

Refuge strategy makes a lot of assumptions about the behavior of rootworm beetles



Gould, F. 1998. Ann. Rev. Entomol. 43:701-726.

Resistance alleles are initially rare in populations (~0.0001) –they're not; 0.10.

Bt toxin is expressed at high-dose (0.01% survivors); nope, 2.0 -5.0%

Resistance recessively inherited; nope, non-recessive.

High-dose
Refuge Strategy
for corn rootworms

Movement occurs across fields resulting in mixed-matings between adults from refuge & Bt corn.

Conclusions:

- Corn rootworm monitoring is rarely done; without data to inform pest management decisions, risk averse growers default to pyramided hybrids.
- Low WCR abundance periods were a lost opportunity to forego use of Bt.
- Locally, the practical efficacy of **Cry3** traits were lost during this period. **Cry34/35** susceptibility is steady despite broad scale use of **Cry34/35** hybrids.
- We can't do anything about the weather, but we can monitor its impact on pest abundance. When we don't, we miss opportunities to reduce both input costs and relax selection for resistance.

I am often asked "Well, what will the WCR population be like next year?" or "Do you think I need to use Bt corn next year?" With the caveat that there is no rescue treatment for larval injury in corn.

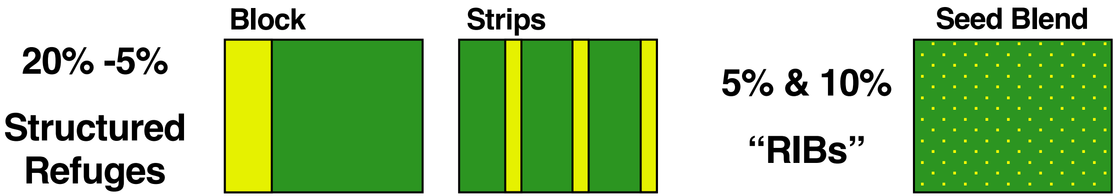
1. Between then and now many things could happen to the eggs that are present in the soil…and this is all useful if you have an idea of how many adults were present.
   a. Killing eggs by freeze/thaw crushing/grinding.
   b. Killing eggs by exposure to intense cold
      i. Was there snowcover during the cold?
         1. Insulates soil during extreme cold.
   c. Killing Larvae due to saturated soils and standing water (floods)
      i. Eggs do fine under water…embryos and developing larvae can get oxygen from the water through their egg shell, they can even hatch under water.
      ii. Neonate CRW larvae are sensitive to water.
         1. Use soil pores to find roots via CO2.
         2. Neonates are more sensitive as they use soil pore to move toward CO2 from metabolizing corn roots, if pores are saturated with water they are blocked and will not find food.
         3. This can impact injury on a small scale in fields; corn in wet spots will have less WCR injury—avoid these if you are digging roots to look at damage.
      iii. Older larvae are *less* sensitive to flooding.
         1. WCR can switch to aerobic metabolism briefly, 50% of 3rd instarts died after submersion for 25h, 50% of 2nd Instars died after submersion for 56h. Survival goes down in warm water.
         2. When feeding in roots, 2nd -3rd larvae may be able to get O2 from root tissues?
   d. Extremely dry conditions can reduced egg viability; eggs must absorb some water before they can complete development and be ready to hatch.
   e. Larvae cannot survive without host plant roots.
      i. Late Planting: Damp weather that delays planting may mean that significant proportions of larvae hatch before corn is planted or before there are lots roots for them to feed on.
         1. Only a portion of the larvae that were present will survive on late corn.
         2. However, late corn (relative to nearby fields) will draw in adults from all around, potentially setting that field up for much greater than typical local WCR pressure during the following year…important to monitor abundance.
         3. Concentrated adult populations on late corn silks can lead to silk clipping and reduced pollination leading to yield losses.

Will WCR numbers stay low or will they rebound?

The <u>High Dose Refuge Strategy (Gould 1998)</u> would be used to delay rootworm resistance to Bt corn hybrids.

- Plant areas of non-Bt corn in or near Bt cornfields.
- Plentiful Bt susceptible beetles developing on non-Bt refuge plant roots will disperse into nearby Bt corn where they will mate with any rare Bt-resistant beetles that developed on Bt corn.
- Flood Bt corn with susceptible beetles and make it unlikely that any two Bt-resistant beetles ever find each other to mate and produce resistant offspring.

- **Structured Refuges** were first deployed as in-field or adjacent blocks or strips @20%-5%.
- Refuge & Bt seed were also mixed in the bag as a **seed blend** with proper percentages of each seed (@5-10%) (integrated refuges or **RIBs**).



Gould, F. 1998. Ann. Rev. Entomol. 43:701-726.

Highlights of WCR biology, w/ pictures?

Historical CRW – Forbes and others study **<u>NCR</u>** to make 1st recommendations

Historical CRW – WCR moved east in 1930s->70s; resistance issues 1940s->

FOCUS???

Historical WCR –(2) resistance, return to Crop rotation, rotation resistance…RR is a case of the WCR beating us, later Bt resistance is a case of beating ourselves!

Bt corn for WCR is a product of rotation resistance that began HERE in IN & IL.

Will changing climate affect WCR pest pressure?

Yes, wetter and warmer by midcentury

Rootworm Resistance to Bt Traits

- 2009: first evidence of field-evolved resistance to Cry3Bb1 in western corn rootworm
  - Gassman et al. 2011 PLOS One 6 (7)
- Cross-resistance among Cry3Bb1, mCry3A, and eCry3.1Ab
- 2016-2018: confirmed reports of field-evolved resistance to Cry34/35Ab1 in Iowa
  - Gassmann et al. 2019 Pest Management Science DOI: 10.1002/ps5510
  - Gassman et al. 2016 Journal of Economic Entomology DOI: 10.1093/jee/tow110
- 2019: confirmed reports of field-evolved resistance to Cry34/35Ab1 in North Dakota WCR & NCR!
  - Calles-Torrez et al. 2019 Journal of Economic Entomology DOI:

National Climate Assessment

Mid-century projections (2041-2070); compared to 1971-2000 Averages

https://nca2014.globalchange.gov/report/regions/midwest

Current Corn Rootworm Management Recommendations

- Implement rootworm management where needed, based on monitoring of adult numbers during the previous year
  - While overall numbers are currently low, there are “hot spots”.
  - Make the decision based on local populations, not just overall trends and commodity prices.
  - Don’t forget about northern corn rootworms (NCR #s are growing in N. Illinois).

- Where rootworm management is justified, a pyramided Bt corn hybrid is still the most effective option.
  - Soil insecticides are still viable.
  - When possible, rotating to soybean is the most effective way to manage a high field population.

- Evaluate trait (and insecticide) performance on your farm
  - Best interpreted if you have an assessment of the previous year’s adult population
  - Look for changes over time
  - Leave check strips

- Where unexpected damage is observed and/or resistance is expected:
  - Best option: rotate field to soybean (kills all WCR larvae in the soil at hatch)
  - Next best: rotate to a soil insecticide
  - Unexpected damage (EPA definition):
    - ½ node pruned, pyramided hybrid
    - 1 node pruned, single-trait hybrid