Area wide insecticide resistance management strategies for fall armyworm in corn in Puerto Rico

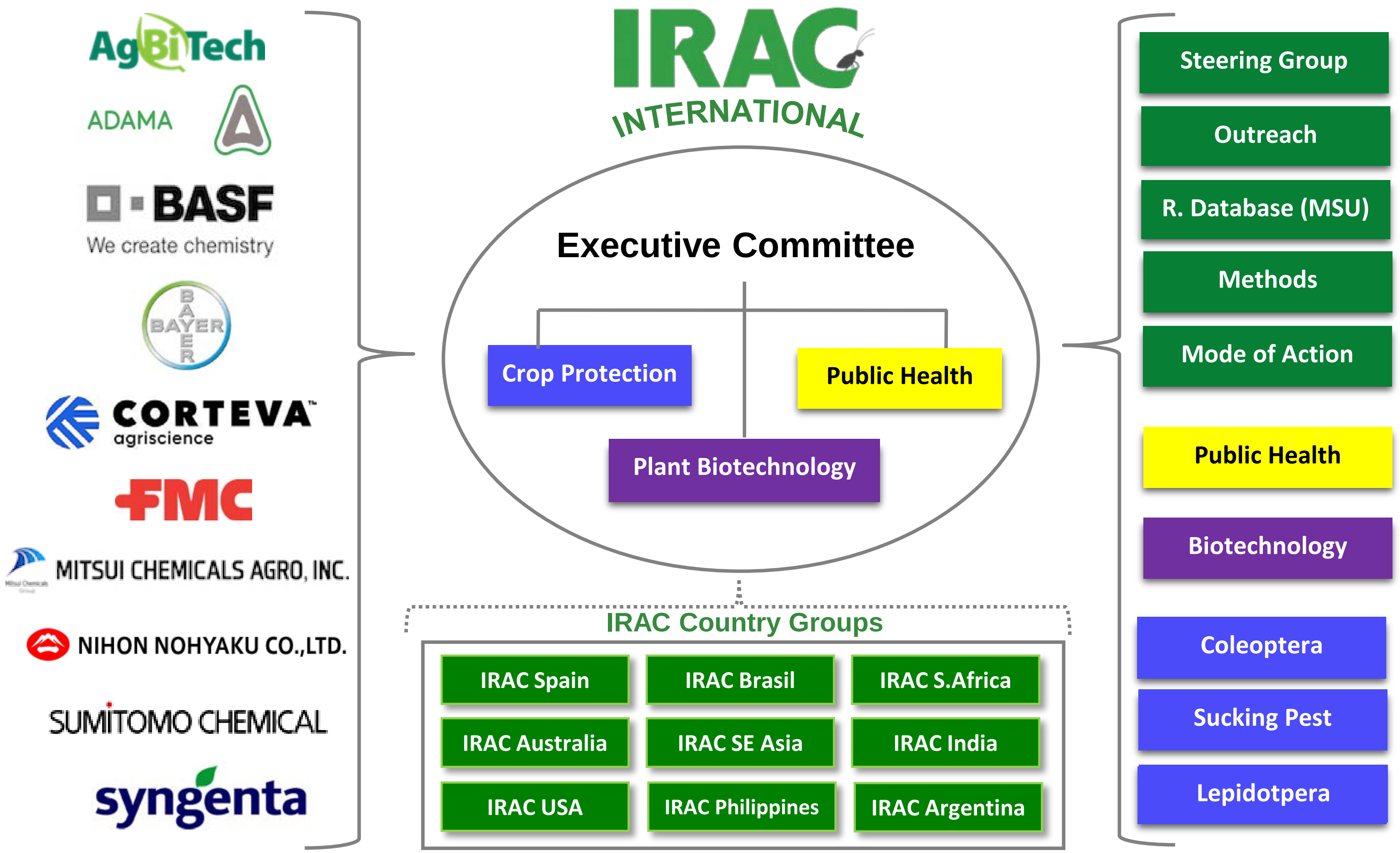
Hector E. Portillo[1], Henry Teran Santofimio[2], Caydee Savinelli[3], Anthony Burd[4], Jaime Sanchez[2], Sol Rosado-Arroyo[5], Jim Johnson[6], Graham P. Head[7], Rodney N. Nagoshi[8], David Mota-Sanchez[9] and Christian Salcedo[10]

1FMC Agricultural Solutions, Newark, DE, 2Corteva AgriScience, Salinas, PR, 3Syngenta Plant Protection, Greensboro, NC, 4Syngenta Crop Protection, Greensboro, NC, 5BASF Puerto Rico, Guanica, PR, 6Syngenta Crop Protection, Perry, MI, 7Bayer Crop Science, Chesterfield, MO, 8USDA - ARS, Gainesville, FL, 9Michigan State University, East Lansing, MI, 10Syngenta, Vero Beach, FL

IRAC Insecticide Resistance Action Commitee

PRABIA Puerto Rico Agricultural Biotechnology Industry Association

Charter: Champion principles that reduce insecticide selection pressure on pest populations to sustain agriculture. Lead industry experts in sponsoring research and educational outreach on Insecticide Resistance Management.



CropLife INTERNATIONAL

IRAC-US Member Companies

- ADAMA
- Amvac
- BASF
- Bayer CropScience
- Corteva
- FMC
- ISK Biosciences
- Nichino
- Nisso America
- Syngenta
- Valent

www.irac-online.org

IRAC
Insecticide Resistance Action Commitee

PRABIA
Puerto Rico Agricultural Biotechnology Industry Association

PRABIA Member Companies

AgReliant Genetics

BASF We create chemistry

Bayer CropScience

Corteva agriscience Agriculture Division of DowDuPont™

Illinois Crop Improvement Association

RiceTec

syngenta

Photos courtesy of Henry Teran, Corteva

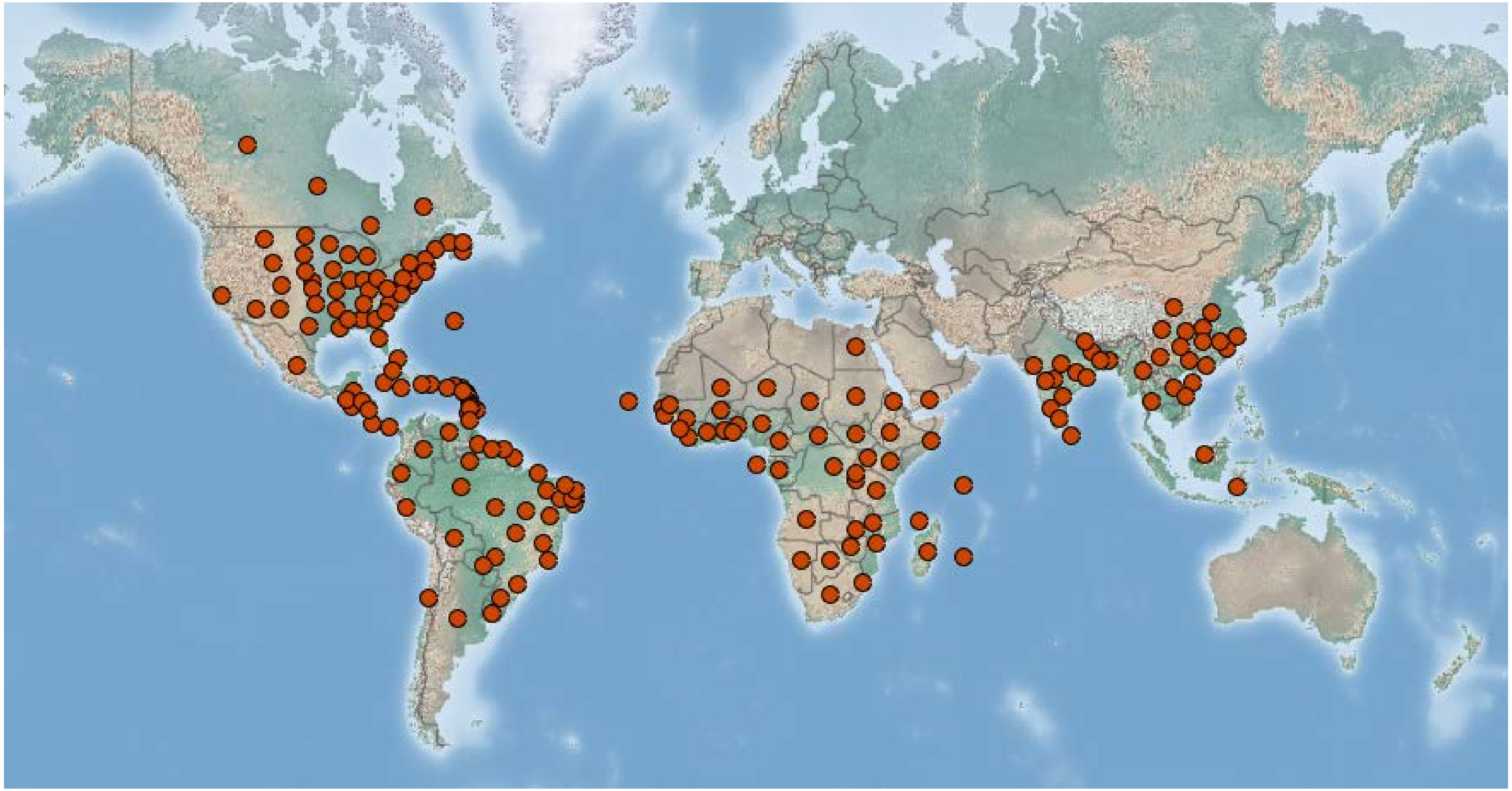
Photos courtesy of Andres Garcia Montero, FMC Mexico

Fall Armyworm as Pest in Puerto Rico

- Tropical island with favorable weather for crops and pest development
- Year round corn seed production, host crop availability
- Isolated Island Populations, 12 generations per year possible
- Rapid development of resistance:
  - Cry1F corn was introduced in 2003 in Puerto Rico, resistance in *S. frugiperda* documented in late 2006. (Storer et al., 2010 JEE 103:1031-1038).
  - Resistance or reduced susceptibility to many of the available insecticides reached a crisis in 2007-08
- Developing IRM and IPM strategies to manage fall armyworm was identified as critical for sustainable and continued profitable seed production

Fall Armyworm Becoming a Global Pest

Prior to 2016 only established in the America's



Source: www.cabi.org/isc

FAW COIB haplotype distribution in the Western Hemisphere

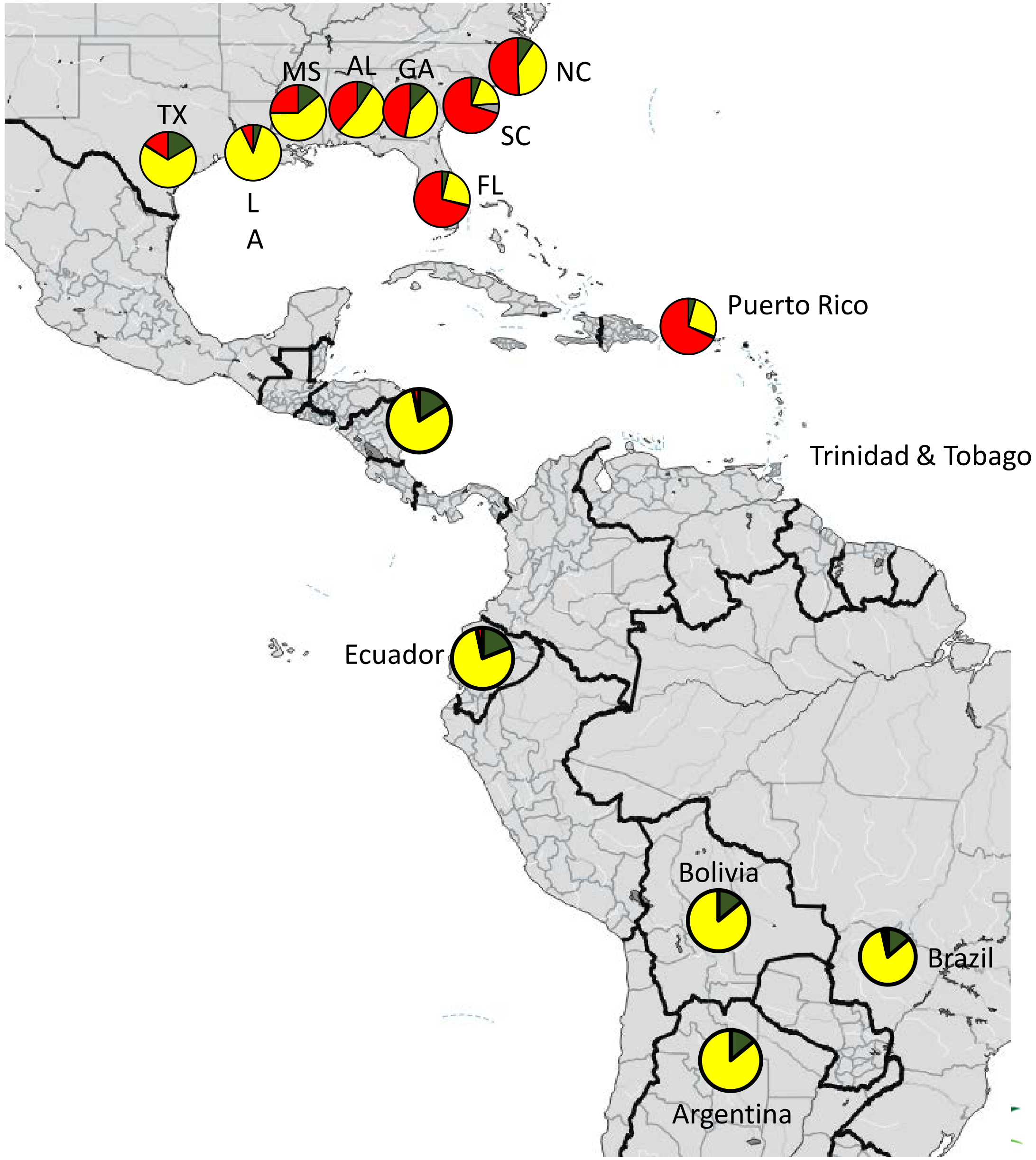
IRAC
Insecticide Resistance Action Commitee

PRABIA
Puerto Rico Agricultural Biotechnology Industry Association

Sequence analysis of segments from the presumptive coding region of the mitochondrial *Cytochrome Oxidase Subunit I* (*COI*) gene indicate that the h2 haplotype predominates in S. America, TX, and LA.

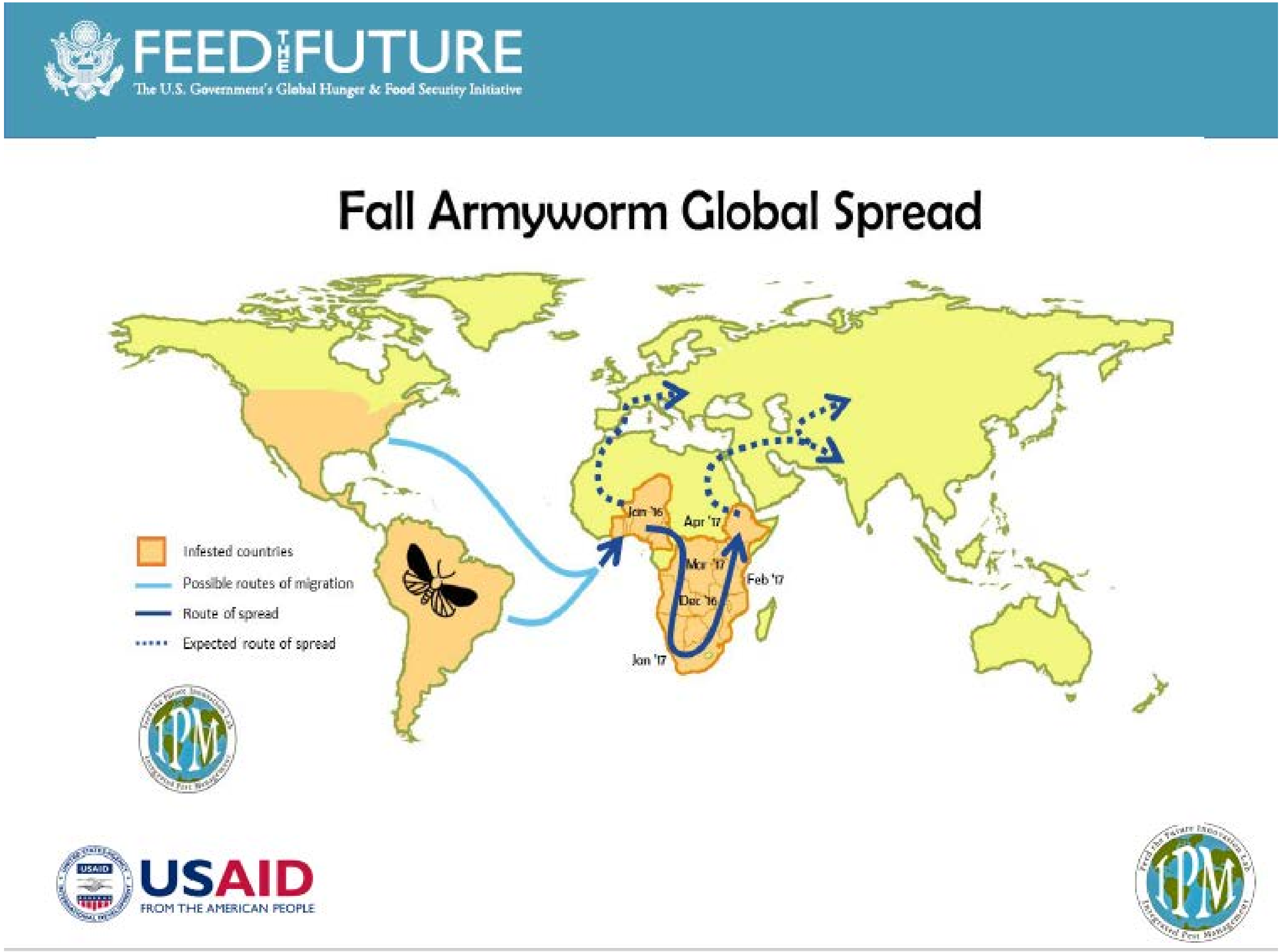
h4 is the majority form in Puerto Rico, Florida and U.S. east coast.

AL and GA are a mixture of migrants from TX and FL.



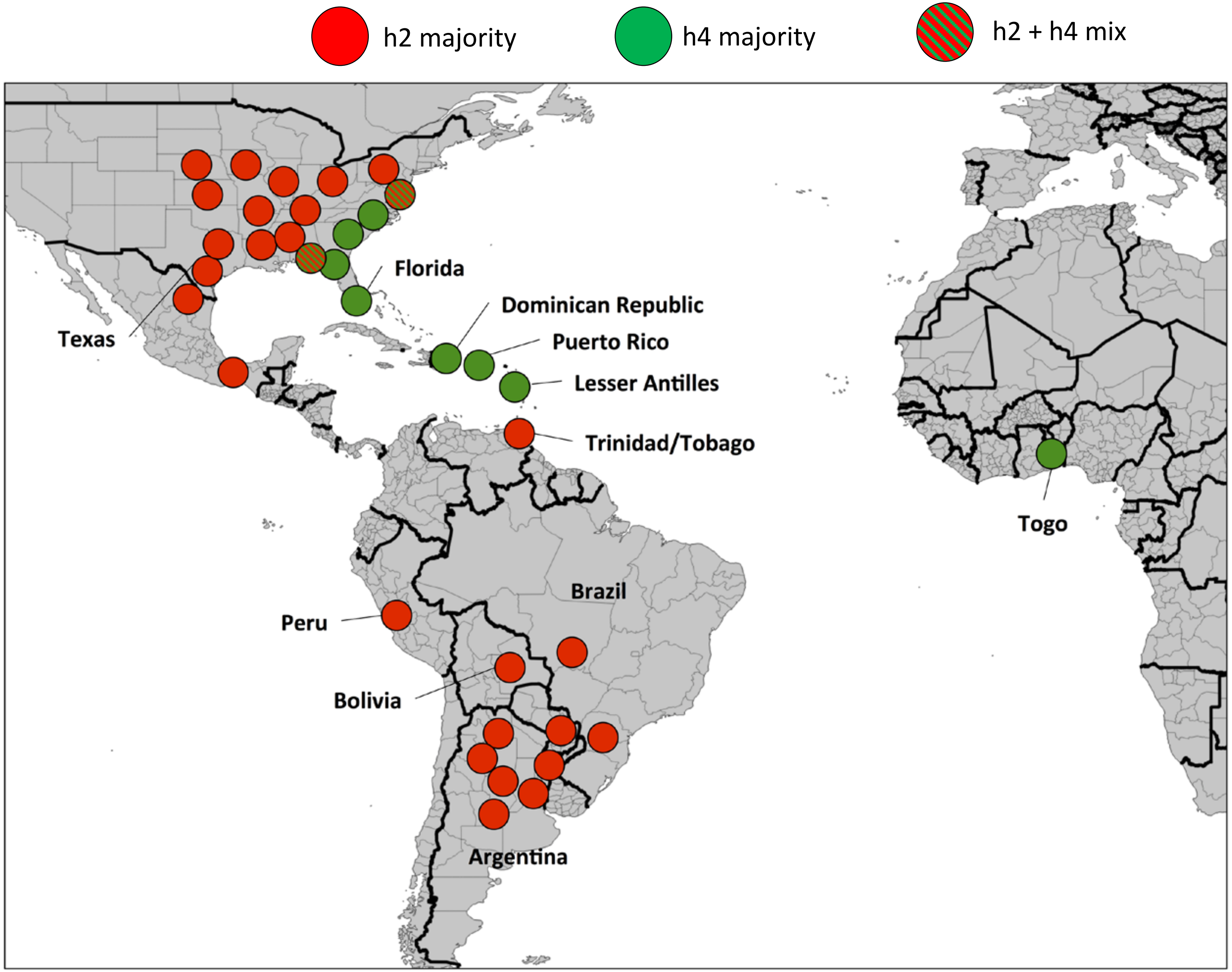
Nagoshi et al., SCIENTIFIC **REPOrTS** | *(2018) 8:3710* |

Putative Origin of FAW Invasion to Africa?



JaspreetSidhu
RangaswamyMuniappan
Virginia Tech

Summary of FAW COIB haplotype distribution



Genetic marker studies indicate that Florida-Caribbean are the likely source of the Africa FAW

The migratory patterns of FAW have implications on impact of control practices and selection of resistance, thus this is an important project beyond Puerto Rico

Nagoshi et al., SCIENTIFIC **REPOrTS** | *(2018) 8:3710* |

Seven Critical Workstreams Identified for the successful implementation of an area wide Resistance Management program in PR

1. **Product efficacy and registration in corn**
2. **Development and maintenance of rotational program**
3. **Scouting and thresholds practices**
4. **Spraying techniques**
5. **Training**
6. **Resistance Monitoring**
7. **Communication**

1. Product efficacy and registration in corn

IRAC Insecticide Resistance Action Commitee

PRABIA Puerto Rico Agricultural Biotechnology Industry Association

INSECTICIDE MOAS USEFUL FOR CONTROLLING LEPIDOPTERAN PESTS

Nerve and Muscle Targets – These insecticides are generally fast acting.

Group 1 Acetylcholinesterase (AChE) inhibitors
Inhibit AChE, causing hyperexcitation. AChE is the enzyme that terminates the action of the excitatory neurotransmitter acetylcholine at nerve synapses.
1A Carbamates (e.g. Methomyl, Thiodicarb) *1B* Organophosphates (e.g. Chlorpyrifos)

Group 2 GABA-gated chloride channel blockers
Block the GABA-activated chloride channel, causing hyperexcitation and convulsions. GABA is the major inhibitory neurotransmitter in insects.
2A Cyclodiene Organochlorines (e.g. Endosulfan) *2B* Phenylpyrazoles (e.g. Fipronil)

Group 3 Sodium channel modulators
Keep sodium channels open, causing hyperexcitation and, in some cases, nerve block. Sodium channels are involved in the propagation of action potentials along nerve axons.
3A Pyrethrins, Pyrethroids (e.g. Cypermethrin, λ-Cyhalothrin)

Group 4 Nicotinic acetylcholine receptor (nAChR) competitive modulators
Bind to the acetylcholine (ACh) site on nAChRs causing a range of symptoms from hyperexcitation to lethargy & paralysis. ACh is the major excitatory neurotransmitter in the insect central nervous system.
4A Neonicotinoids (e.g. Acetamiprid, Thiacloprid, Thiamethoxam)

Group 5 Nicotinic acetylcholine receptor (nAChR) allosteric modulators – Site I
Allosterically activate nAChRs, causing hyperexcitation of the nervous system.
Spinosyns (e.g. Spinosad, Spinetoram)

Group 6 Glutamate-gated chloride channel (GluCl) allosteric modulators
Allosterically activate glutamate-gated chloride channels (GluCls), causing paralysis. Glutamate is an important inhibitory neurotransmitter in insects.
Avermectins, Milbemycins (e.g. Abamectin, Emamectin benzoate, Lepimectin)

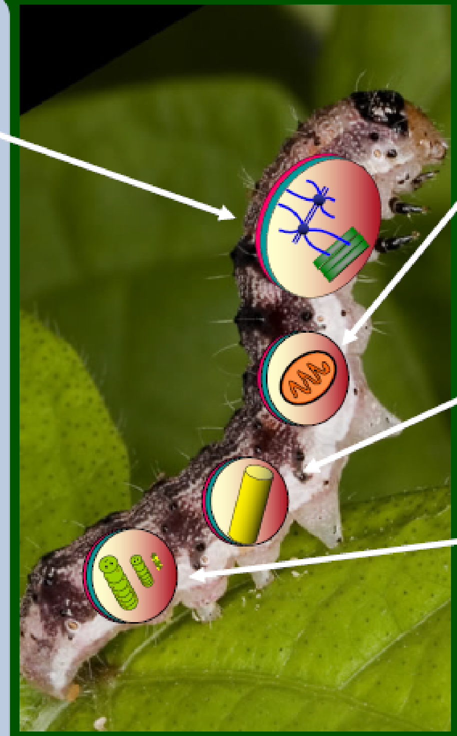
Group 14 Nicotinic acetylcholine receptor (nAChR) blockers
Block the nAChR ion channel, resulting in nervous system block and paralysis.
Bensultap, Cartap

Group 22 Voltage-dependent sodium channel blockers
Block sodium channels, causing nervous system shutdown and paralysis. Sodium channels are involved in the propagation of action potentials along nerve axons.
22A Indoxacarb *22B* Metaflumizone

Group 28 Ryanodine receptor modulators
Activate muscle ryanodine receptors, leading to contraction and paralysis. Ryanodine receptors mediate calcium release into the cytoplasm from intracellular stores.
Diamides (e.g. Chlorantraniliprole, Cyantraniliprole, Cyclaniliprole, Flubendiamide, Tetraniliprole)

Group 30 GABA-gated chloride channel allosteric modulators
Allosterically block the GABA-activated chloride channel, causing hyperexcitation and convulsions.
Meta-diamides (e.g. Broflanilide, Fluxametamide, Isocycloseram)

Group 32 Nicotinic acetylcholine receptor (nAChR) allosteric modulators – Site II
Allosterically activate nAChRs, causing hyperexcitation of the nervous system.
GS-omega/kappa HXTX-HV1A peptide



Key to Targeted Physiology
Nerve & Muscle · Growth & Development · Respiration · Midgut · Unknown or Non-specific

Respiration Targets
Mitochondrial respiration produces ATP, the molecule that energizes all vital cellular processes. In mitochondria, an electron transport chain uses the energy released by oxidation to charge a proton gradient battery that drives ATP synthesis. Several insecticides are known to interfere with mitochondrial respiration by the inhibition of electron transport and/or oxidative phosphorylation. Insecticides that act on individual targets in this system are generally fast to moderately fast acting.

Group 13 Uncouplers of oxidative phosphorylation via disruption of the proton gradient
Protonophores that short-circuit the mitochondrial proton gradient so that ATP can not be synthesized.
Chlorfenapyr

Group 21 Mitochondrial complex I electron transport inhibitors
Inhibit electron transport complex I, preventing the utilization of energy by cells.
21A Tolfenpyrad

Midgut Targets
Lepidopteran-specific microbial toxins that are sprayed or expressed in transgenic crops.

Group 11 Microbial disruptors of insect midgut membranes
Protein toxins that bind to receptors on the midgut membrane and induce pore formation, resulting in ionic imbalance and septicemia.
11A Bacillus thuringiensis *11B Bacillus sphaericus*

Group 31 Baculoviruses
Host-specific occluded pathogenic viruses
Granuloviruses, Nucleopolyhedroviruses

Growth and Development Targets
Insect development is controlled by the balance of two principal hormones: juvenile hormone and ecdysone. Insect growth regulators act by mimicking one of these hormones or by directly affecting cuticle formation/deposition or lipid biosynthesis. Insecticides that act on individual targets in this system are generally slowly to moderately slowly acting.

Group 7 Juvenile hormone mimics
Applied in the pre-metamorphic instar, these compounds disrupt and prevent metamorphosis.
7B Juvenile hormone analogues (e.g. Fenoxycarb)

Group 15 Inhibitors of chitin biosynthesis, Type 0
Incompletely defined mode of action leading to inhibition of chitin biosynthesis.
Benzoylureas (eg. Flufenoxuron, Lufenuron, Novaluron)

Group 18 Ecdysone receptor agonists
Mimic the moulting hormone, ecdysone, inducing a precocious moult.
Diacylhydrazines (e.g. Methoxyfenozide, Tebufenozide)

Unknown Several insecticides are known to affect less well-described target-sites or functions, or to act non-specifically on multiple targets.
Azadirachtin, Pyridalyl

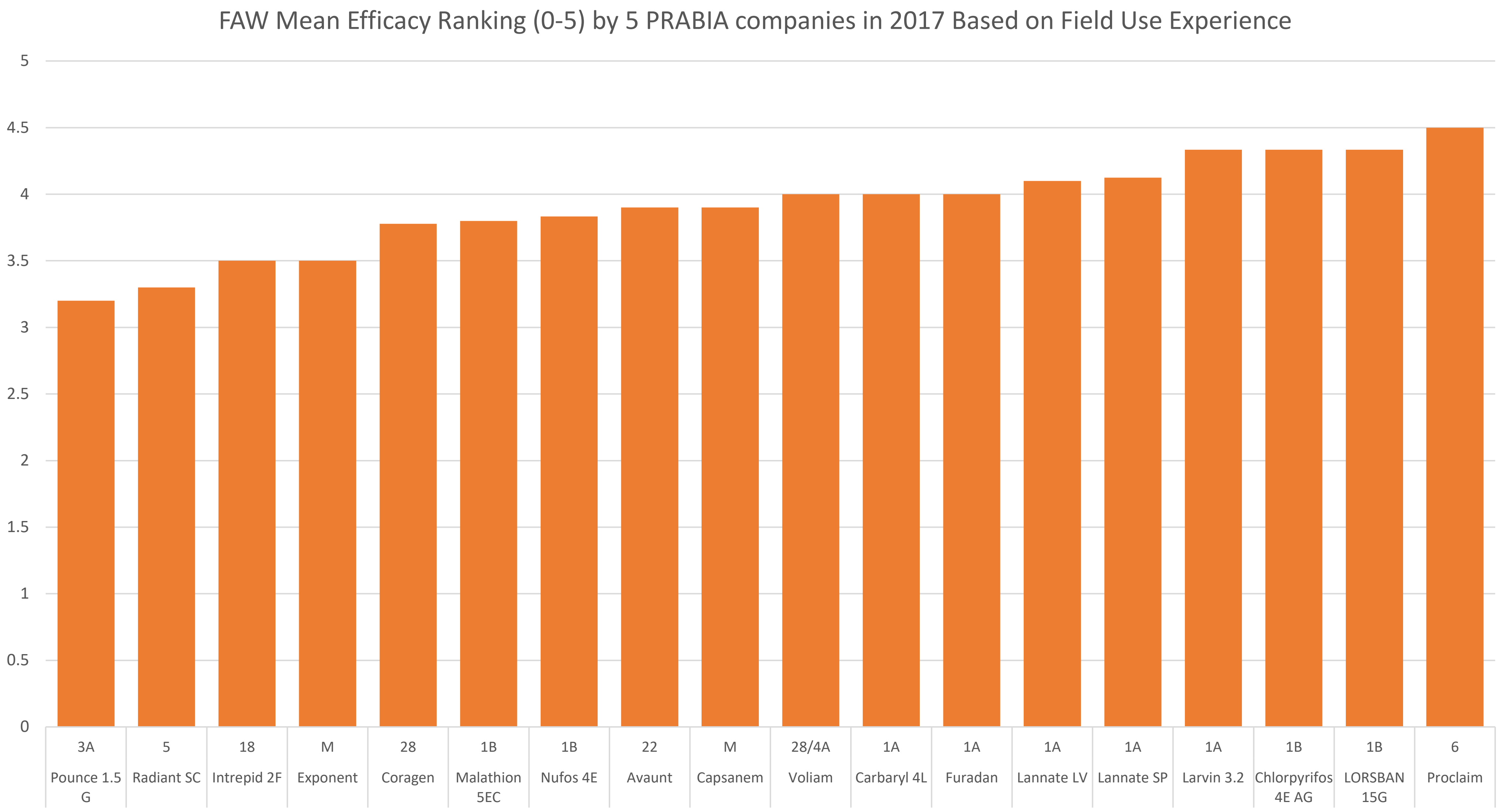
- Eight MOA available in PR
- One MOA (Group 11, Bts) not used because of previous Bt resistance to GMO crops and some GMO crops being planted, so only 7 MOAs can be used
- Group 3A (pyrethroids) partially useful due to widespread resistance of larval stage
- Others groups have varied levels of efficacy, some related to resistance

CropLife INTERNATIONAL

1. Product efficacy and registration in corn

MOA ranking:

1. Group 6
2. Group 1A/1B
3. Group 28+4A
4. Group22
5. Group 28
6. Group 18
7. Group 5
8. Group 3A



1. Product efficacy and registration in corn

Potency of Insecticides Registered for Control of FAW

Active ingredient	MOA	year	n	LD_{90} (ug/ul)	Label max rate (oz/A)	Estimated rate to kill 90% (oz/A)
Spinetoram *Radiant*	5	2016	375	0.15	6	3.1
Emamectin benzoate *Proclaim*	6	2016	300	0.01	4.8	0.2
Permethrin *Permastar*	3A	2013	250	0.15	6	1.0
Methomyl *Lannate*	1A	2015	600	0.50	24	4.4
Carbaryl	1A	2015	298	6.41	64.0	34.2
Chlorpyrifos *Nufos 4E*	1B	2016	154	1.60	32	8.5
Chlorantraniprole *Coragen*	28	2016	420	0.42	5	**5.4**
Methoxyphenozide *Intrepid*	18	2015	300	1.49	16	**15.9**
Flubendiamide *Belt*	28	2014	300	1.33	3	**7.1**
Bifenthrin *Brigade*	3A	2015	300	0.67	6	**7.2**
Zeta-cypermethrin *Mustang Maxx*	3A	2015	300	0.20	4	**5.4**

- Lab potency (field FAW population) data available for 6 MOAs, indoxacarb (Group 22) was not labeled until late 2017

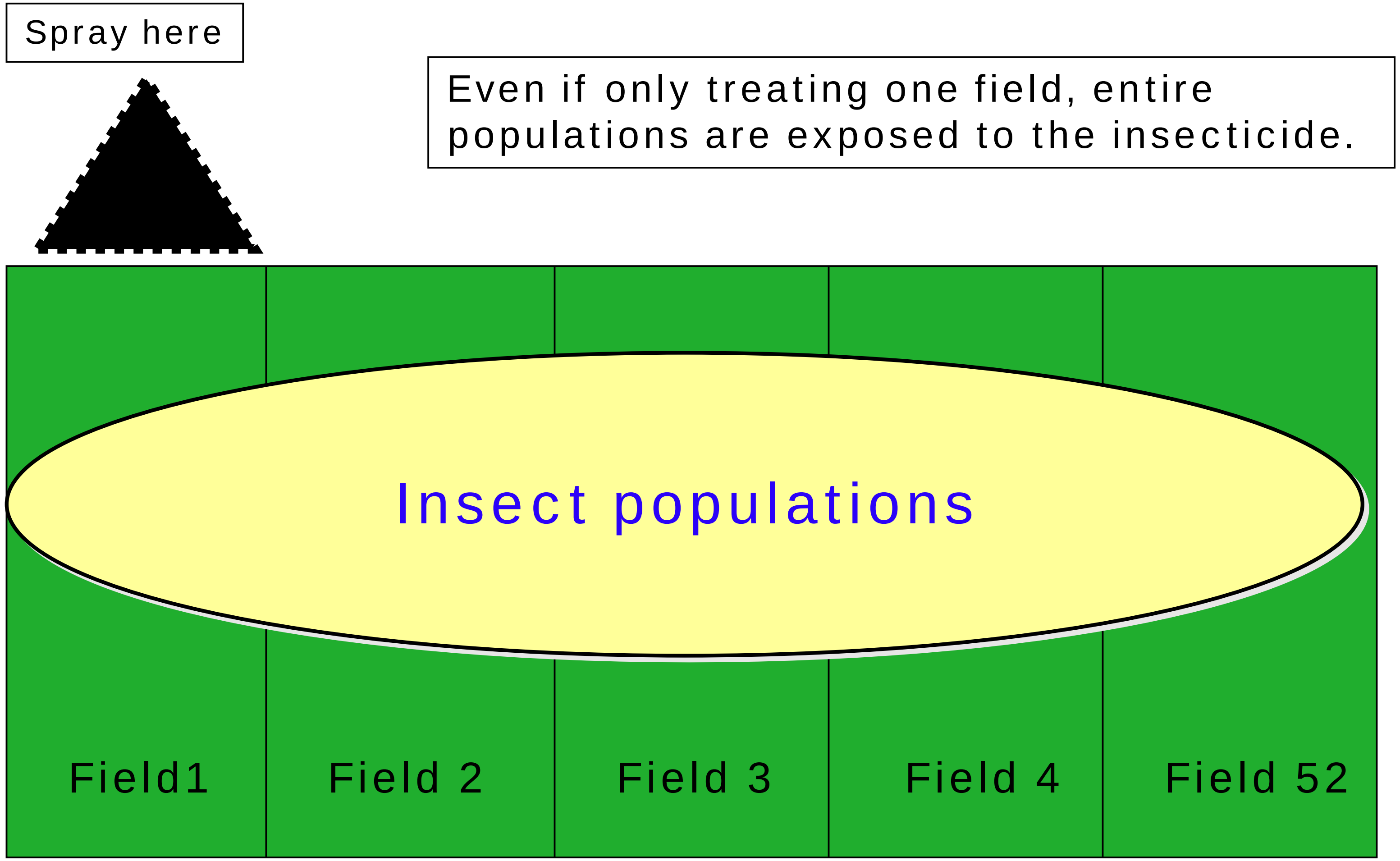
- Note that lab dose for multiple MOAs is close to or greater than what is labeled in the field in most cases

MOA ranking based on lab bioassay:

1. Group 6
2. Group 5
3. Group 3A (permethrin only)
4. Group 1A/1B
5. Groups 28, 18, 3A

2. Development and maintenance of rotational program

Effect of strip cropping and adjacent farms on populations



MOAs Rotation in time and space vs only space most likely to limit selection pressure

Possibility for exposure to every generation all year long

2. Development and maintenance of rotational program

Month	Corn Acres Grown-2016	FAW Damage
January	157.6	High
February	101.61	Medium
March	87.95	Medium
April	68.74	Medium
May	20.33	Low
June	33.77	Low
July	31.13	Low
August	27.71	Low
September	8.15	Low
October	162.75	Medium
November	358.27	High
December	431.09	High

Crop intensity and pest severity analysis was used to consider which MOs would fit best within a window

2. Development and maintenance of rotational program

Month	MOA	Products	# Applications
October / November	28	Coragen®	2
	1A / 1B	Lannate® LV / Lorsban-4E®	2
	5	Radiant® SC	3
	18	Intrepid® 2F	3
	BIO	Capsanem®	2
December / January	3A	Perm Up® 3.2 EC / Brigade® 2EC / Baythroid® XL / Mustang Maxx®	4
	6	Proclaim®	3
	22	Steward® EC	2
	BIO	Capsanem®	3
February / March	28	Coragen®	2
	1A / 1B	Lannate® LV / Lorsban-4E®	2
	5	Radiant® SC	3
	18	Intrepid® 2F	3
	BIO	Capsanem®	2
April / May	3A	Perm Up® 3.2 EC / Brigade® 2EC / Baythroid® XL / Mustang Maxx®	4
	6	Proclaim®	3
	22	Steward® EC	2
	BIO	Capsanem®	3
June / July	28	Coragen®	2
	1A / 1B	Lannate® LV / Lorsban-4E®	2
	5	Radiant® SC	3
	18	Intrepid® 2F	3
	BIO	Capsanem®	2
August / September	3A	Perm Up® 3.2 EC / Brigade® 2EC / Baythroid® XL / Mustang Maxx®	4
	6	Proclaim®	3
	22	Steward® EC	2
	BIO	Capsanem®	3

Corn Window Rotation Program 2019/2020 Season

- 2nd year program is in place
- MOAs rotated on a 2 month window in 2nd year vs 1 month window in 1st year
- Factors considered:
  - MOA
  - Efficacy level
  - Pest pressure/scouting/timing
  - Total ai registered/crop season
  - Spray intervals, REI, PHI
  - Special labels requested: Proclaim (Group 6, emamectin benzoate) and Steward (Group 22, indoxacarb)

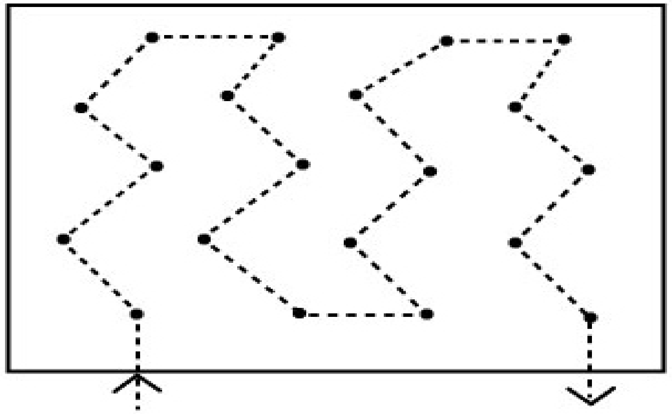
3. Scouting and thresholds practices

Standardized scouting and Reporting and Thresholds

Field size	# sample sites	# plants per site	# total plants/field
< 1 acre	4	15	60
≥ 1 < 5 acres	8	15	120
≥ 5 acres	10	15	150

Observation	Site 1	Site 2	Site 3	Site 4
# Plants with larvae	5	3	7	0
# plants without larvae	10	12	8	15
Total	15	15	15	15

% incidence = {(5 + 3 + 7 + 0) / (15 + 15 + 15 + 15)} * 100
= (15/60) * 100 = 25%



Pest identification, scout for adults, eggs, larvae and damage

Photos courtesy of Andres Garcia Montero, FMC Mexico

4. Spraying techniques

- Timing: 1-2nd instar most susceptible life stage
- Once larvae gets in the whorls it is difficult to reach
- Proper calibration and choice of application equipment
- Nozzle selection for coverage and or penetration into the whorl
- Water volume and pressure, 200-300 L/ha minimum
- Use of adjuvants that aid in product movement into the whorl

Photos courtesy of Andres Garcia Montero, FMC Mexico

5. Training

Multiple training sessions have been provided to PRABIA personnel by IRAC members as well as University experts since 2008 to cover relevant pest management topics with emphasis on IPM and IRM such as:

Insecticides mode of action training

Pest biology/pest management

IPM/IRM

Photos courtesy of Henry Teran, Corteva. PRABIA, IRAC and Michigan State University personnel attending training on May 15-17, 2019

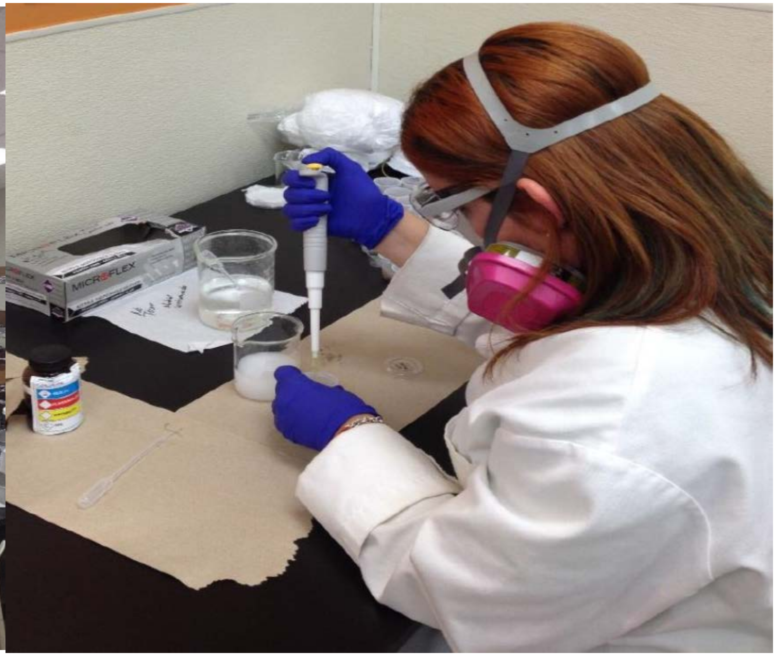
5. Training

Most recently, May 15-17, 2019, a training-workshop was held at Corteva Agriscience, Salinas Puerto Rico where 22 employees from companies belonging to PRABIA working in IPM programs (BASF, Bayer, Corteva, ICIA, Rice Tec and Syngenta) were trained by Michigan State University and IRAC on bioassay methods to conduct resistance monitoring, including:

- Bioassay techniques to monitor resistance:
- leaf disc (IRAC Method No. 007) and insecticide diet incorporation (IRAC Method No. 020)

- Evaluation of the larval mortality

- Use of Probit procedure from SAS and/or POLO program to analyze mortality data of the laboratory bioassays



Photos courtesy of Henry Teran, Corteva

6. Resistance Monitoring

IRAC Insecticide Resistance Action Commitee

PRABIA Puerto Rico Agricultural Biotechnology Industry Association

Bioassays on FAW field populations in 2019 showed the following

- Only 2 MOAs showed low/no resistance: Groups 6 and 1A
- Group 28 and Group 22 insecticides provide control in the field, but lab bioassay data show moderate to high levels of resistance
- While Groups 3A and 18 provide some control in the field, lab bioassay data show high levels of resistance
- These data is consistent with bioassays from previous years
- While Group 5 was not tested, some levels of resistance to this MOA have been observed in the past

Insecticide	Bioassay method	Dose (ppm) in diet or as overlay	FAW mortality %	
			Field Population	Lab Strain
Coragen (chlorantraniliprole Group 28)	Diet incorporation	58	33	100
		92	45	100
		108	81	100
		125	89	100
		0	0	4
Steward (indoxacarb, Group 22A)	Diet incorporation	75	58	100
		108	69	100
		125	77	100
		141	88	100
		0	0	4
Lannate LV (methomyl, Group 1A)	Diet incorporation	288	98	100
		432	100	100
		504	98	100
		575	100	100
		0	0	0
Intrepid (methoxyfenozide, Group 18)	Diet overlay	100	48	94
		150	67	92
		175	54	92
		200	58	100
		0	6	0
Mustang Maxx (zeta-cypermethrin, Group 3A)	Diet overlay	32	63	100
		36	58	100
		38	75	100
		40	56	100
		0	2	0
Proclaim (emamectin benzoate, Group 6)	Diet overlay	30	100	100
		45	100	100
		52	100	100
		60	100	100
		0	0	0
Evergreen (permethrin, Group 3A)	Diet overlay	13	0	4
		46	2	21
		63	0	88
		80	0	100
		0	0	0

7. Communication

- This is a critical task and includes the following:
  - Compile and distribute the annual IRM manual that includes a description of the program, the insecticide rotations per window, scouting techniques and other information
  - Organize meetings
  - Email members regarding any updates: new information on product efficacy, resistance monitoring bioassay results, pest pressure etc.
  - Other

Conclusions

- An area wide insecticide rotation program is the best long term option to prolong efficacy of available insecticides for FAW management in Puerto Rico
- Developing and implementing area wide programs requires a lot of effort and coordination
- Area wide programs are a hard sell, getting 100% compliance on a voluntary basis not easy
- Enforcing a fallow period may be necessary as rotation alone may not be enough to restore or maintain the efficacy of available MOAs
- Use of other management tools, i.e., cultural and biological control, need to be incorporated into the program
- This program benefits Puerto Rico/PRABIA, but it also has implications in other places given the migratory patterns of this pest

IRAC
Insecticide Resistance Action Commitee

PRABIA
Puerto Rico Agricultural Biotechnology Industry Association

Thank You!

CropLife INTERNATIONAL