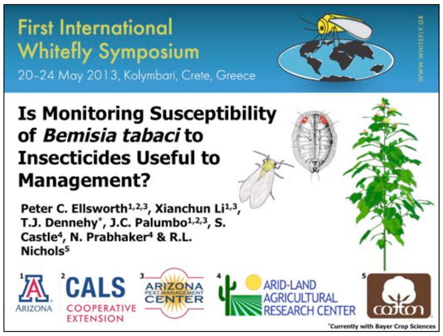
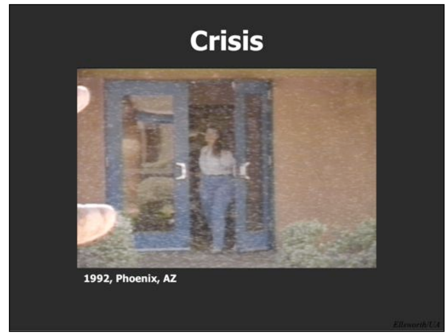
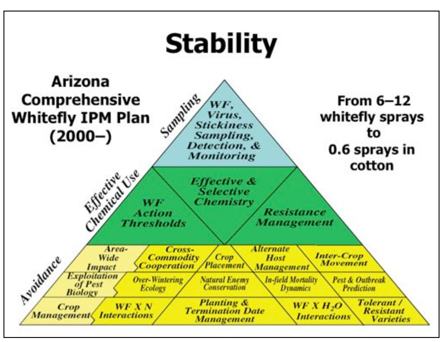


At previous whitefly symposia, either Steve Naranjo or myself have presented various aspects of the "Arizona Whitefly Story". Today, I will focus on an area that we have not discussed before. This is part of a large collaboration that has formed to address this rather broad question within the specific context of the Arizona experience. Ralf Nauen has introduced the topic of resistance & resistance management earlier in this session and Steve spoke about our current efforts to further integrate Biological Control into IPM decision-making in the keynote lecture presented in the previous session.

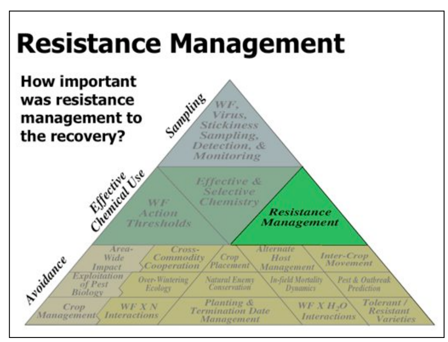
First International Whitefly Symposium, ca. 200 people, Kolymbari, Crete, Greece. (15 min.)



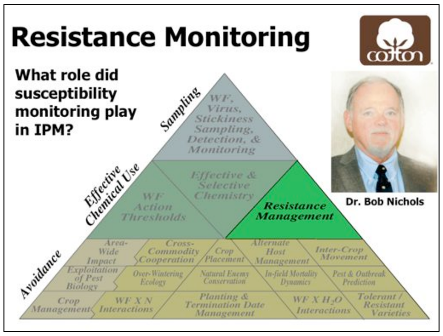
This was the scene we were facing when the invasive B-biotype came to Arizona; a system in crisis. The numerical pressure was overwhelming and impacting not only agricultural areas, but also Arizona's largest city, Phoenix, as seen here on the campus of a local college. Pedestrians and bikers of the time would wear surgical masks to protect themselves from swallowing whiteflies.



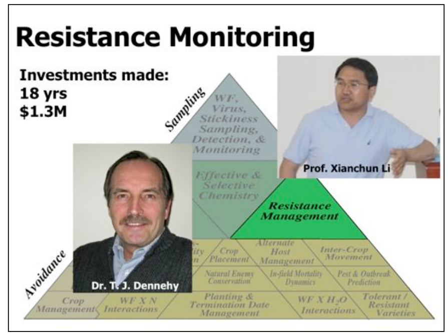
In the span of just a few short years, growers dramatically reversed the trend, and by 2000, they had achieved some critical cross-commodity agreements among cotton, vegetable and melon producers that helped our IPM plan to become fully formed into a what it is today. Most of all, it brought us to a level of stability where we now deploy, on average, just 0.6 sprays / season to control whiteflies (2006–2011) where we once invested 6–12 sprays per season (1992–1995).



Any time such a dramatic success is achieved, it is generally instructive to ask questions about which elements have been driving that success. In fact, I have heard many others looking from the outside speculate on what those factors were. However, the IPM plan is by definition an integration of multiple tactics, well-balanced into a strategy where each tactic supports the other. Still, one can ask how important was resistance management to the recovery we experienced?



Even more specifically, Dr. Bob Nichols, Research Director at Cotton Incorporated, challenged this group to think about this broad topic and address the specific question of what role did susceptibility or resistance monitoring play in our IPM system?



He asked this question because starting in the mid-1990's, his organization and the cotton growers of our state began to support Dr. Tim Dennehy's establishment and operation of a statewide resistance monitoring infrastructure. Tim operated this system for many years until he left the University of Arizona to join industry (2008) and Dr. Xianchun Li took over the responsibility for this project of statewide resistance monitoring of Bemisia in cotton and other crops.

So in total, we are reviewing — in this still ongoing project analysis — over 18 years of resistance monitoring data and information and grant investment of $1.3M in this activity.

So our question is this…

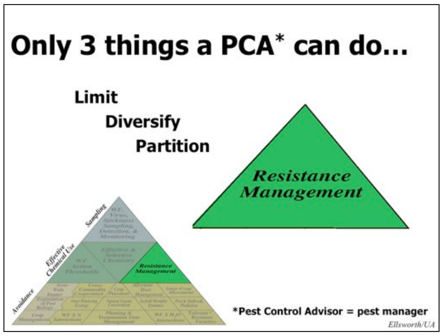
We wish to establish whether there are linkages between these activities & actual grower uptake & deployment of changed practices as a result. Many factors can incentivize a grower to change his/her practices, and we need to better understand all possible factors that drive change in a system if we wish to sustain or even replicate the success we have enjoyed.

While we will address the even larger issue, for now & today's presentation, it is given that resistance research & monitoring are intrinsically valuable to the advancement of science & understanding of resistance, resistance development and dynamics. Arguably this is enough to justify the investment & activity. However, we wish to specifically understand grower processes that contribute to their enormous success.

However, before we examine the impact of resistance "monitoring" on the practice of IPM, we need to acknowledge there are other pathways by which growers may be stimulated to change their practices.

These include change as a result of 1) perception & learning of First Principles of resistance management, 2) perception & reaction to product performance concerns, & 3) dissemination of resistance monitoring information that signal the need for change. Each of these processes can be mediated through deployment of guidelines, demonstration & oral teachings to growers through Cooperative Extension.

First and foremost are the "First Principles" of resistance management, as I see them impacting the every day person on the ground.



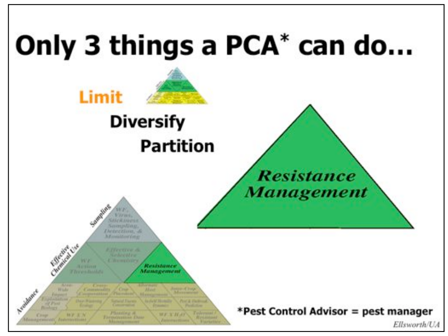
A practitioner, a PCA, can only manage resistance in one or more of three ways:

1) Limit his/her use of the chemistry to the lowest practical level, (as Ralf mentioned in his talk)

2) Diversify the modes of action used, and

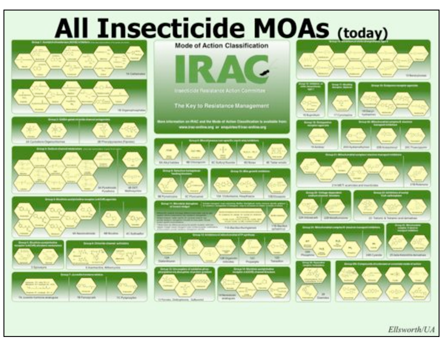
3) Partition chemistry through space or time so as to provide relief from resistance selection in certain crops or at certain times.

That's it. Practically speaking, these are the only tactics of resistance management available to the user.



…And, we know that limiting the use of pesticidal products as much as feasible is central to practicing good IPM. By doing so, you are already employing a suite of avoidance and prevention tactics and observing action thresholds that help limit the number of sprays made. This was one of Ralf's major points of his keynote lecture of this session.

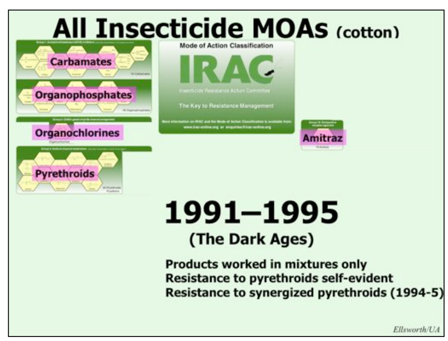
As such, IPM and resistance management or IRM are nested within each other, each a primary tactic of the other.



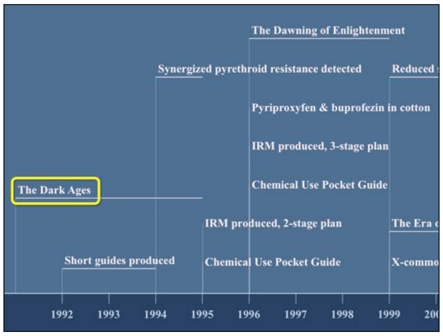
Ralf Nauen also reviewed IRAC and this classification system of Modes of Action. The industry has developed many potential modes of action and products to assist us in the management of all insect and mite pests around the world.

There are just 28 different modes of action identified to combat all insects (and mites) worldwide.

On the surface, this is a rich palette from which to base resistance management practices…



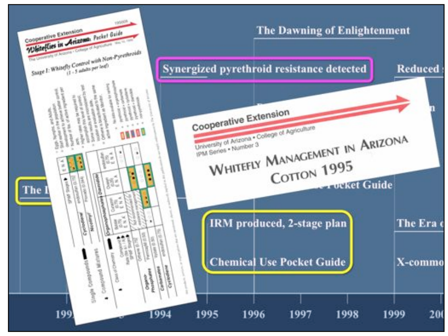
…However, during the period that I will call "the Dark Ages" of whitefly management in Arizona, we really only had arguably 4 or 5 modes of action. And these were very old pieces of chemistry that were broadly toxic to arthropods and neurotoxic to humans. Furthermore, they worked in mixtures only because of a priori resistance to the pyrethroid class of chemistry, and even then resistance developed quickly to the synergized pyrethroids as documented by Tim's work in 1994 and 1995.



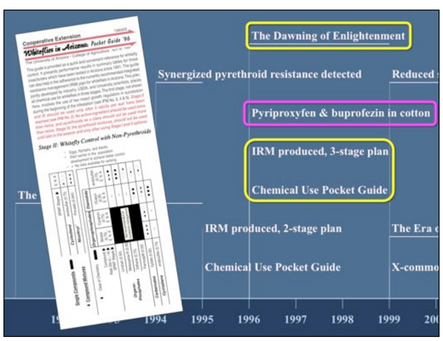
I have prepared a timeline that details the major findings and facts on the ground about resistance, and that reviews our responses in terms of the development of key resistance management information and guidelines that became the basis of our Extension and outreach campaigns of the time.

We start in the Dark Ages of the early 1990s as the B-biotype (MEAM1) of Bemisia tabaci invaded Arizona.

We had few options for chemical control.

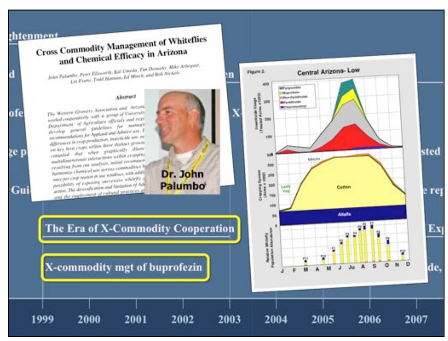


Synergized pyrethroids were already declining in efficacy and resistances were detected by monitoring conducted by Tim Dennehy's lab. In response, we constructed guidelines that included a 2-stage resistance management plan, primitively based in and cobbled by a limited range of chemistry we had available, and a chemical use guide that gave advice to delay the use of synergized pyrethroids until later in the season, using non-pyrethroid mixtures earlier in the season, and rotating tank mix partners as much as was possible.



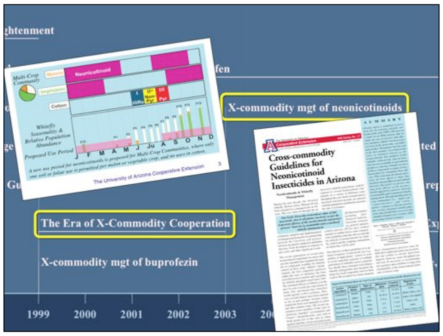
By 1996, we were at "The Dawning of Enlightenment" in large measure because of a successful petition of US-EPA for a Section 18 Emergency Exemption for the limited use (1 spray per season only of each) of pyriproxyfen and buprofezin (Knack & Applaud), the key insect growth regulators (IGRs) which have great selectivity and safety benefits in our system.

We deployed new guidelines that included a 3-stage IRM plan that emphasized the use of these much "softer" agents earlier in the season prior the need for any other chemistry. We produced a laminated chemical use pocket guide that was widely distributed in a comprehensive set of grower trainings that were mandatory under the Section 18 rules that the growers consented to and promoted at the time.



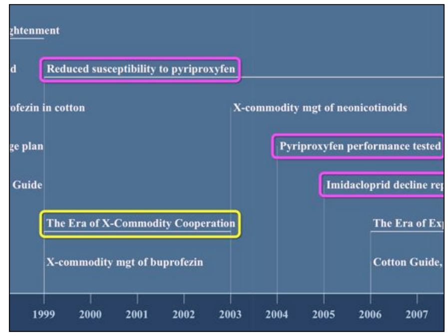
By 1999, we entered the "Era of Cross-Commodity Cooperation" starting with discussion and agreements among growers of cotton, melons and vegetables under the leadership of Dr. John Palumbo, our Vegetable IPM Entomologist. The focus of these first discussions was the sharing of the key active ingredient, buprofezin, as its label was expanding to include on other non-cotton crops (e.g., cucurbits).

This was very much a grass-roots effort starting with discussions among growers informed by 1st Principles of resistance management and other input from University, USDA, and industry scientists.

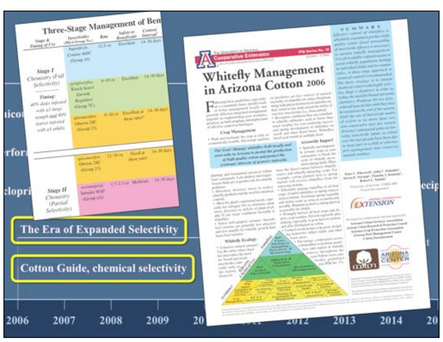


This later expanded in 2003 with landmark agreements for the neonicotinoid class where growers cooperate to voluntarily share and constrain neonicotinoid usage in each cropping system.

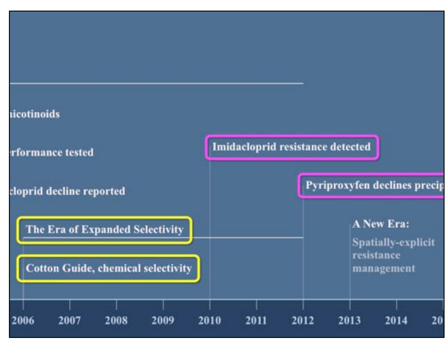
Once again, this was a grass-roots effort among growers and pest managers (PCAs) to help understand our system of chemical use and design lower risk approaches to the use of this valuable class of chemistry in all crops.



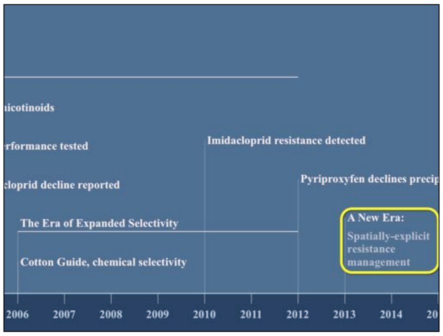
Over this same period, Tim Dennehy's resistance monitoring detected the first shifts in susceptibility to pyriproxyfen (Knack IGR) in 1999 and again in 2003. Thereafter, we conducted joint, detailed field performance and susceptibility testing in a 4-year study that confirmed the field performance of pyriproxyfen in cotton, functionally no different than at the time of pyriproxyfen introduction in 1996. Then starting in 2005, growers were noting a decline in the efficacy of imidacloprid (Admire) in vegetables and melons, even though there were no conclusive results from the resistance monitoring.



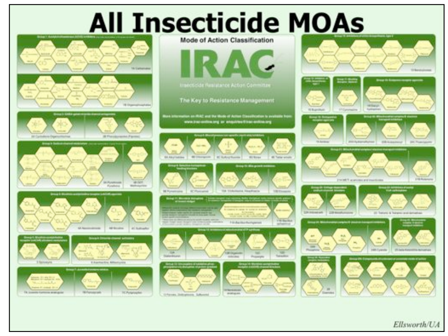
By 2006, we had entered the "Era of Expanded Selectivity" where we installed selective controls for our complete key pest spectrum with the introduction of flonicamid (Carbine) for Lygus control (the key mirid pest in our cotton system). This had been accompanied by guidelines and teachings that highlighted not just the efficacy of Bemisia chemistry but the selectivity or safety to beneficials of each product. So all chemical tools were organized around stages of fully selective, partially selective, and broad spectrum materials. This helped us to even further expand the role of conservation biological control programs that have been key to the long-term recovery from the Bemisia crisis 20 years ago.



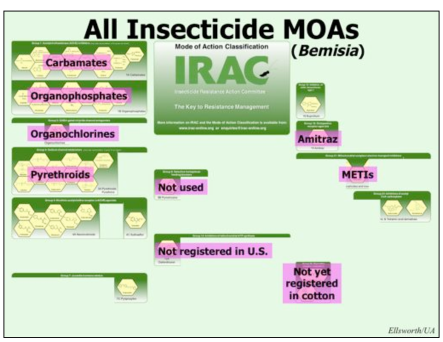
During this time, in 2010, the resistance monitoring program finally detected reduced susceptibilities to imidacloprid (Admire), a full 5 years after growers had already begun to modify their practices as a result of reduced efficacy of this key product. Also, starting just last year, we received our first, limited, grower complaints about field performance of pyriproxyfen (Knack IGR), even though it has continued to perform extraordinarily well in screening and monitored commercial trials (2012).



Finally, today, I hope to introduce you to a new period that I hope will be thought of as the era of "spatially-explicit resistance management".

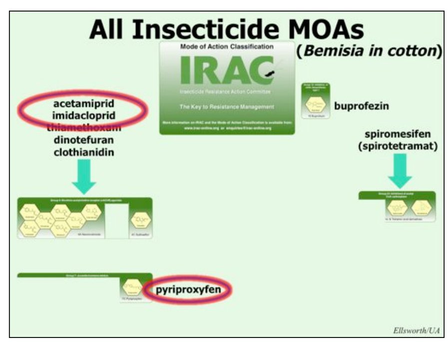


This is where we are today with regards to all MOAs for arthropod control.



These MOAs are active against whiteflies, perhaps just 12 MOAs, and not all of these are equally effective or useful.

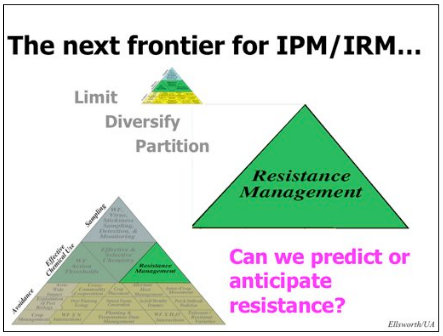
We wish not to use any of the original 5 MOAs as they are broadly toxic and disruptive to our system (and some have since been removed from the market; i.e., endosulfan and amitraz, and some OPs). A couple are not used because they do not provide adequate commercial level control in our system (METI's & selective homopteran feeding blockers). One is not registered in the U.S. and never will be (difenthiuron), and another is yet to be registered in U.S. cotton (as of 2013; diamides).



This leaves us with perhaps just 4 available MOAs, which has been the case since 2005 with the registration of spiromesifen (Oberon). [Note we lost all uses of endosulfan in 2012].

We have two modes of action, neonicotinoids group 4A [especially acetamiprid (Intruder) & imidacloprid (Admire)] and pyriproxyfen (Knack) each threatened by advancing resistances. And some of the new chemistry is not yet registered in cotton [spirotetramat (Movento)].

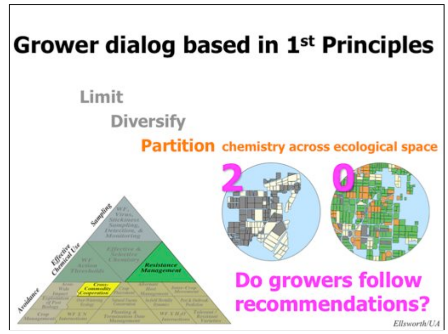
Right now (2012), we have only 2 modes of action that are relatively safe from resistance and are fully effective on whiteflies [buprofezin (Courier) & spiromesifen (Oberon)].



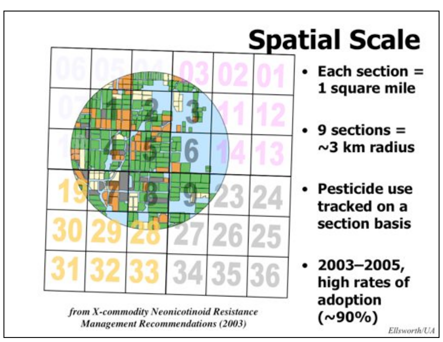
The next frontier for IPM and IRM is to get beyond the resistance retrospectives that are tantamount to the coroner arriving on the scene of a tragic accident hours later and pronouncing the "patient" dead.

We have to ask, are there ways that we can predict or anticipate resistance?

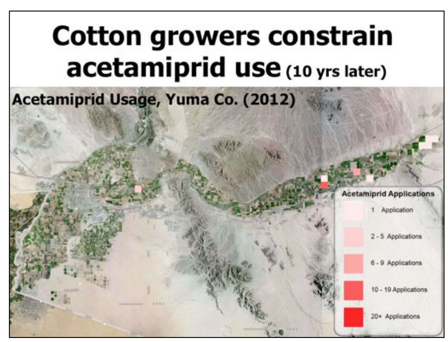
As new tools become available, we need to challenge this branch of pest management science to provide solutions that do more than document resistance changes in populations.



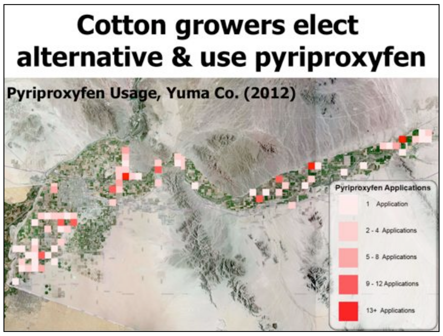
In fact, we can do so through First Principles with the simple assumption that we are always at risk of resistance. Therefore we must make use of resistance management 1st principles at all times with or without specific monitoring information. That's what growers did in 2003 when they established a dialog among growers of melons, vegetables & cotton around the idea of sharing the neonicotinoid MOA by partitioning chemistry across ecological space. As part of a larger framework, these growers consented to curtail usage of the neonicotinoid MOA to just 2 non-consecutive uses in cotton in simple systems of cotton-intensive regions and zero uses in the more complicated multi-crop production systems that included melons & vegetables where imidacloprid was already keystone to their pest management system. But, do growers follow these recommendations?



To understand this question we need to examine the ecological unit of resistance management that was defined at the time. Based on whitefly movement biology & ecology, we believed that whiteflies were functionally reproducing within a spatial context of a 3 km radius from a subject field. In the western U.S., land is organized around sections that are about 1 mile square. 9 sections taken on a 3 x 3 grid are roughly representative of this 3km community. We have access to pesticide records which are tracked on a section basis. Through analyses of these records, we could show that between 2003 and 2005, in complex systems of multiple whitefly managed host crops, growers adopted and followed these voluntary guidelines 90% of the time in cotton. I.e., they elected not to use the newly available foliar neonicotinoids.

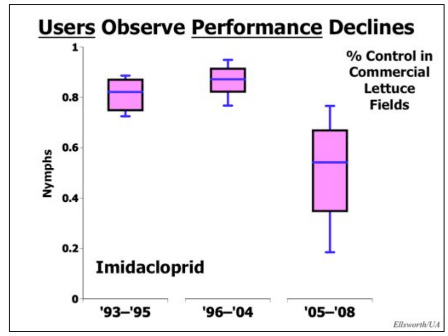


What is striking is to re-visit this question 10 seasons later and examine pesticide use patterns in areas where guidelines suggest they should still be constraining neonicotinoid usage in cotton. In this map of Yuma County where these more complex multi-cropping systems exist, we have mapped the usage of acetamiprid (Intruder) by section. Each section shows the intensity of usage of this very popular product as deeper shades of red. You can see a very limited usage of the product mainly in the eastern part of the County. This tells us that they are still constraining the use of this product as set forth in the voluntary guidelines, because there was a much greater need to control whiteflies than indicated in this map (i.e., they used alternatives; see next).



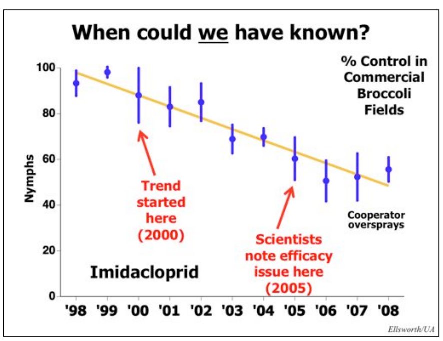
This map shows that they in fact do still need to control whiteflies in these communities and are doing so with the alternatives available to them such as pyriproxyfen (Knack) shown here.

So this tells us that changed grower practices is possible through the pathway of teaching/learning 1st principles of resistance management, even in the absence of specific resistance monitoring data. Recall that we did not have specific "intelligence" about any problems with the neonicotinoid class during this period of time 2000–2005 when these guidelines were first developed and disseminated.



Growers may also elect to voluntarily change their practices when they notice reduced efficacy in their fields.

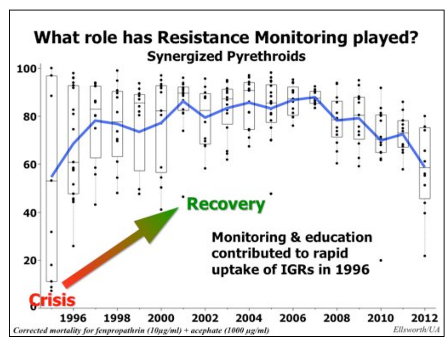
In fact, starting in 2005, they did notice reduced efficacy of imidacloprid. At the same time, John Palumbo had been doing annual assessments of imidacloprid (Admire) in commercial lettuce fields in very detailed and carefully controlled performance field assays. His work confirmed that this period starting in 2005 was faced with much reduced efficacy of imidacloprid, which by the way had continued to be used and is used still today despite this apparent resistance. It remains useful for immature control during the 1st 30 days of vegetable and melon crop establishment. Adult control & long residuals (>30 d) have been compromised, however.



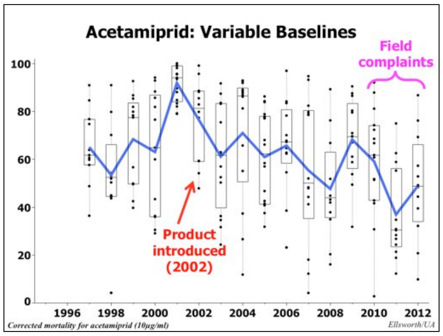
John also did these commercial assessments in broccoli, and today with 20/20 hindsight, we can easily see the halving of efficacy of imidacloprid (Admire) in this system over a 10-yr period.

He, too, first noted this decline in 2005. The question is could we or should we have known sooner? Could we have known that the larger variation of response shown in 2000 was really the beginning of a resistance-related performance decline? These are the vexing questions in resistance management. We wish to be "doctors" not "coroners" in resistance management.

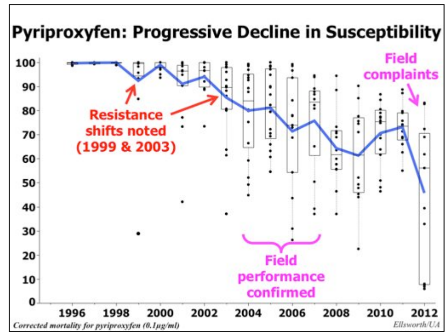
So growers can change practices in response to 1) 1st principles of resistance management or 2) to control difficulties. But what about in response to 3) resistance monitoring information itself?



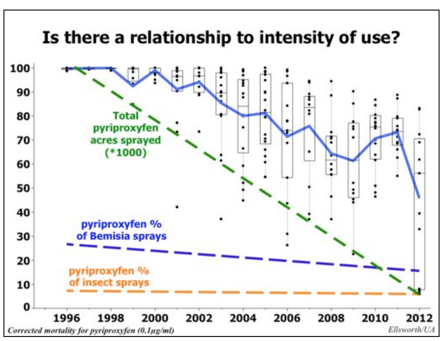
These data show statewide resistance monitoring at one dosage for a synergized pyrethroid in box plots that depict the variation of responses of populations collected from different locations around the state. Tim Dennehy's data show a wide variation of responses in 1995 that are indicative of a serious resistance in some populations (e.g., those that suffered nearly zero mortality at this dosage). This was during the crisis and these data along with education helped stimulate rapid adoption by growers of the IGRs [buprofezin (Applaud) & pyriproxyfen (Knack)] that came available in 1996. So in this sense, resistance monitoring contributed to changed practices by growers, which in turn led to a significant recovery in the susceptibility of populations to synergized pyrethroids.



The data for acetamiprid (Intruder), a key neonicotinoid, are less definitive, in part because of widely variable baselines measured prior to the introduction of this product in Arizona (1997–2001). While declines in susceptibility appear to have taken place, no specific changes were made in guidelines after 2003. Field complaints received from growers started in 2010. The industry, in response (2012), petitioned USEPA for a Special Local Needs (SLN) registration in AZ cotton of a maximum rate increase by 50%. Commercial-scale evaluations showed that this higher rate was sufficient to kill Bemisia very well, as well or better than at any other time.



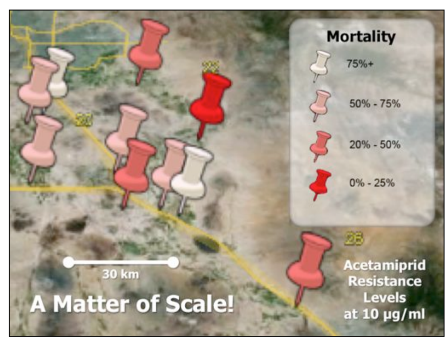
Pyriproxyfen (Knack IGR), in hindsight, shows an extremely consistent & progressive decline over time in susceptibility of Bemisia. The dosage that killed 100% of whiteflies in 1996–1999 has been killing substantially fewer whiteflies progressively over time. Tim Dennehy noted the 1st decline in 1999, but no specific action was taken. He noted another shift in 2003 & this prompted additional research into field performance of pyriproxyfen in 2004–2007. The conclusion was that pyriproxyfen was working as well as it had ever been, despite the apparent shift in susceptibility, a testament to pyriproxyfen's dependence on the biological activity of conserved natural enemies & other natural forces that we refer to as "bioresidual". We have received a limited number of field complaints starting in 2012, 17 seasons after introduction of this MOA. A large step-wise shift in the resistance monitoring data occurred in 2012, too.



In such a striking trend over time, one would expect that selection pressures [i.e., pyriproxyfen (Knack IGR) usage] had progressively increased over time. However, that is not the case at all. Actual usage in total acres sprayed statewide has declined progressively over this same period. Even if we examine pyriproxyfen sprays as a % of Bemisia sprays made or of all insect sprays made, we note a declining or neutral trend, certainly not an increasing one.

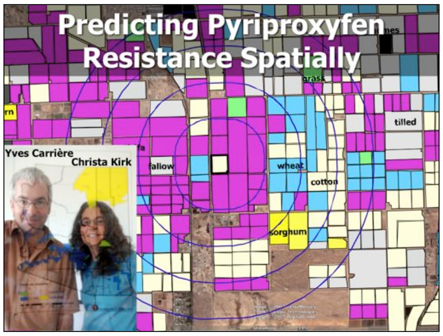
This makes it difficult to understand how to advise clientele and predict when and where they should expect to see declines in susceptibility and possible reductions in performance.

It should be noted here that pyriproxyfen has always been constrained to just 1 spray per cotton season.



This appears to be a matter of scale. The former data displays trends averaged over all populations throughout the state. These data for another compound, acetamiprid (Intruder), for example, show that populations we would expect to be highly resistant (dark red) can be located fairly close to populations that test out as quite susceptible.

2010 Acetamiprid resistance levels

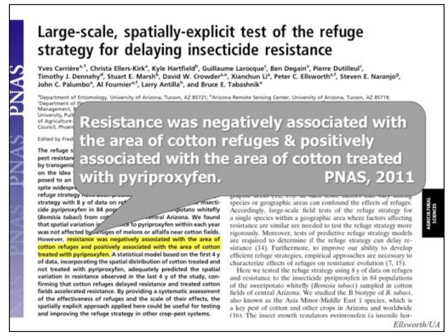


Prof. Yves Carrière of the University of Arizona led a collaboration to examine patterns of pyriproxyfen (Knack) usage relative to resistance monitoring data collected over many years.

The answer we believed may be in examining more local dynamics of the system. Can we predict pyriproxyfen (Knack) resistance spatially just by knowing something more about the local practices?

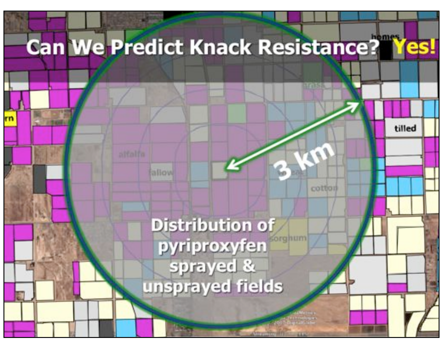
The answer was yes.

[2007 FF#47]



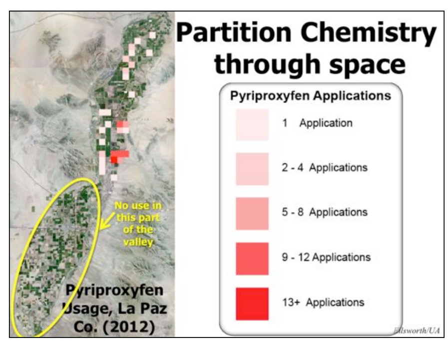
In 2011, we published a paper in the Proceedings of the National Academy of Sciences where he analyzed the spatial relationships of pyriproxyfen-sprayed and pyriproxyfen-unsprayed cotton within local areas using a ring analysis. We concluded that in fact you could predict relative levels of pyriproxyfen (Knack IGR) resistance with information about how much of the cotton was being treated with Knack and how much was not being treated with Knack within a local area.

The question was over what scale does this relationship hold true?

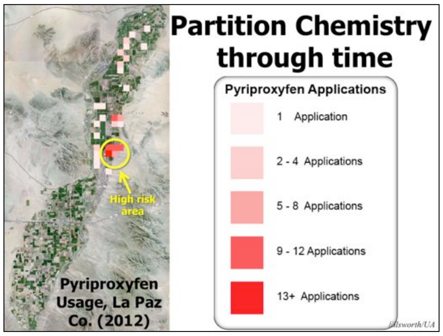


The information needed to predict risks of pyriproxyfen (Knack IGR) resistance locally can be found within 3 km of the cotton field of interest, coincidentally the same "resistance management" unit we taught growers about 10 years earlier in our cross-commodity guidelines. We surmise from this that in fact the resistance management unit of interest over which whiteflies interact & develop resistance to all chemistry may be ~ 3km radius around a subject field. In essence, our statewide surveys & pesticide usage were too coarse a measure to conclude things definitively about when & where pyriproxyfen resistance might develop. But this showed us that in a community where some growers depend on and use Knack in every cotton field every year, all growers are at greater risk of having Knack resistance affect them even if they had never used Knack there before!

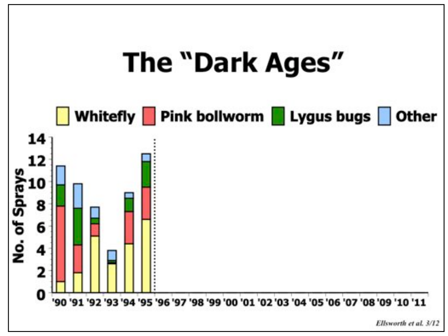
[2007 FF#47]



Now with chemical use maps that show recent trends of use such as this one of Parker Valley for pyriproxyfen (Knack IGR) usage in 2012, we can begin to arm growers with information that permits them to partition chemistry, locally, through space. In this example, growers in the northern valley used pyriproxyfen sometimes intensively in some areas. But growers in the southern part of the valley, for whatever reason, did not use pyriproxyfen. This effectively has partitioned the chemistry over space & could become a directed management practice by these growers in the future.

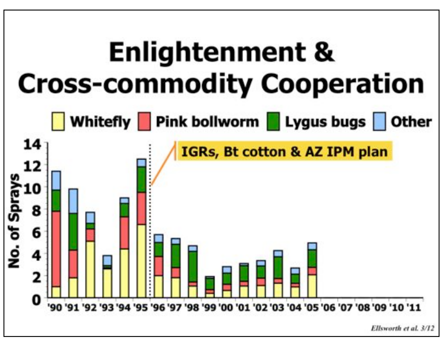


And, in some local "communities", areas defined by a 3x3 section grid or a 3km radius, we can advise a grower who has intensively used pyriproxyfen that his/her area will be subject to high risks for pyriproxyfen resistance in the next year. The advice would be to partition chemistry through time, or in this case, to forgo the use of pyriproxyfen here in 2013 after having used it intensively in 2012. Effectively this grower needs to skip a year of use for pyriproxyfen.

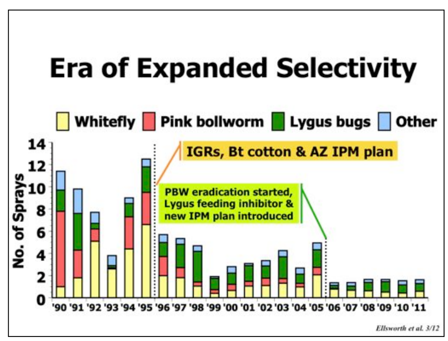


Steve Naranjo reviewed some of these trends in his keynote talk earlier in the bio-control / IPM session.

So let's review the history quickly starting with the whitefly "Dark Ages" when we were spraying 6–12 times for all insect pests of cotton on a statewide basis, and most of this increasing trend was because of whiteflies.

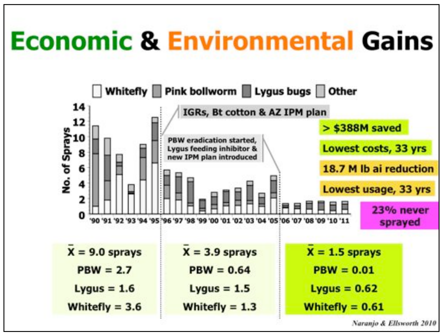


In the era of "enlightenment" and cross-commodity cooperation that followed, we helped growers to properly make use of the selective IGRs & Bt cotton as part of a complete IPM plan with a comprehensive outreach campaign that consisted of extensive grower and pest manager education. The results were striking. Insecticide use was cut at least by 50% over this period.



Then, as we advanced out system into the era of "expanded selectivity", growers deployed a selective Lygus (a mirid pest) feeding inhibitor [flonicamid (Carbine)] along with a major pink bollworm eradication campaign and an IPM plan was taught to growers and pest managers throughout the state.

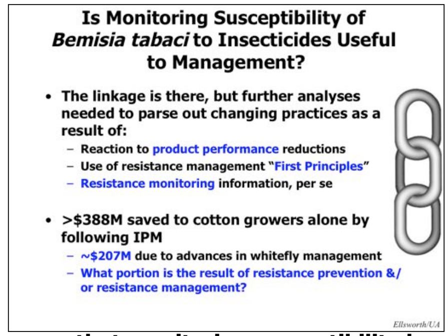
Adapted from Naranjo & Ellsworth 2009 & Ellsworth, unpubl.



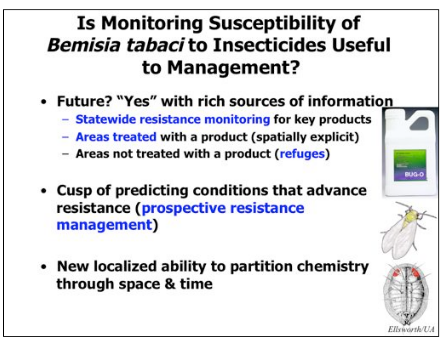
If we draw out information from these critical periods, we can see rather dramatic declines in overall insecticide use, as well as huge declines in PBW, Lygus and whitefly sprays made by growers.

At one time, we averaged 9 sprays. Our 1996 programs cut that by more than half to ca. 4 sprays, and our 2006 programs have cut this by more than half again to just 1.5 sprays. In the process we have the lowest foliar insecticide control costs in history, we are spraying less than at any time in history, and growers have saved cumulatively over $388M in 2011 constant dollars and prevented nearly 19M lbs of insecticide ai from reaching the environment.

On average today, ca. 23% of our acreage is never sprayed for arthropods, something we never thought would be possible on a single acre 20 years ago.



So can we say that monitoring susceptibility has contributed to changed practices or other improvements to management? Our work is not complete, but there is some linkage there. Our collaboration is continuing to analyze these & other data to determine what were the stimulants to changing practices by growers. Was it a reaction to poor product performance? Was it related to learning and using First Principles of resistance management? Or, was it directly related to the resistance monitoring information that was routinely made available to growers? Either way, this success has saved growers nearly $400M to date with more than half that directly due to advances in whitefly management. A further challenge of this collaboration will be to attempt to identify what portion of these savings were due to resistance prevention or improved resistance management practices?



We can extend this question into the future, and more hopefully say "yes" to our question. This rich source of information when combined with other strategic information, mapping resources, and education, we should be able to develop something better than 20/20 hindsight: prospective resistance management that empower growers with a new ability to locally partition chemistry through space and time as a key tactic to preserving the longevity of these valuable modes of action. This is where resistance management needs to go in the next decade, and if our hunch is right — that a 3 km radius is the effective unit of resistance management, then we should be able to help growers help themselves and practice sound resistance management as part of their IPM programs.

Thanks to the many growers, pest control advisors and others who have collaborated & supported this project. Specific thanks to the USDA-NIFA Extension IPM program, to Cotton Incorporated, and to the Arizona Cotton Growers Association.

The Arizona Pest Management Center (APMC) as part of its function maintains a website, the Arizona Crop Information Site (ACIS), which houses all crop production and protection information for our low desert crops, *(http://cals.arizona.edu/crops),* including a copy of this presentation.

Photo credit: J. Silvertooth