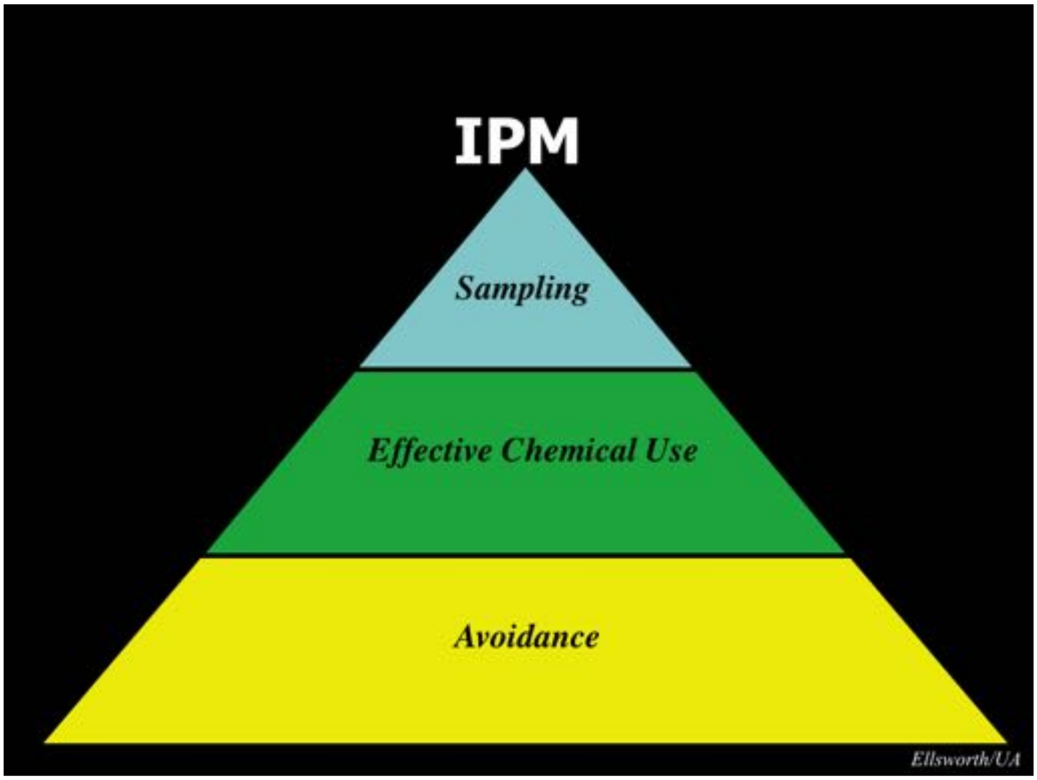
Today I would like to review the cotton IPM system of Arizona, highlighting the role that Bt cotton has played in its development and progress. At the conclusion of my talk, I will briefly share the northern Mexican cotton IPM system as a counterfactual example of IPM adoption and the critical role that "soft" technology plays in the proper integration of "hard" technologies like Bt cotton.

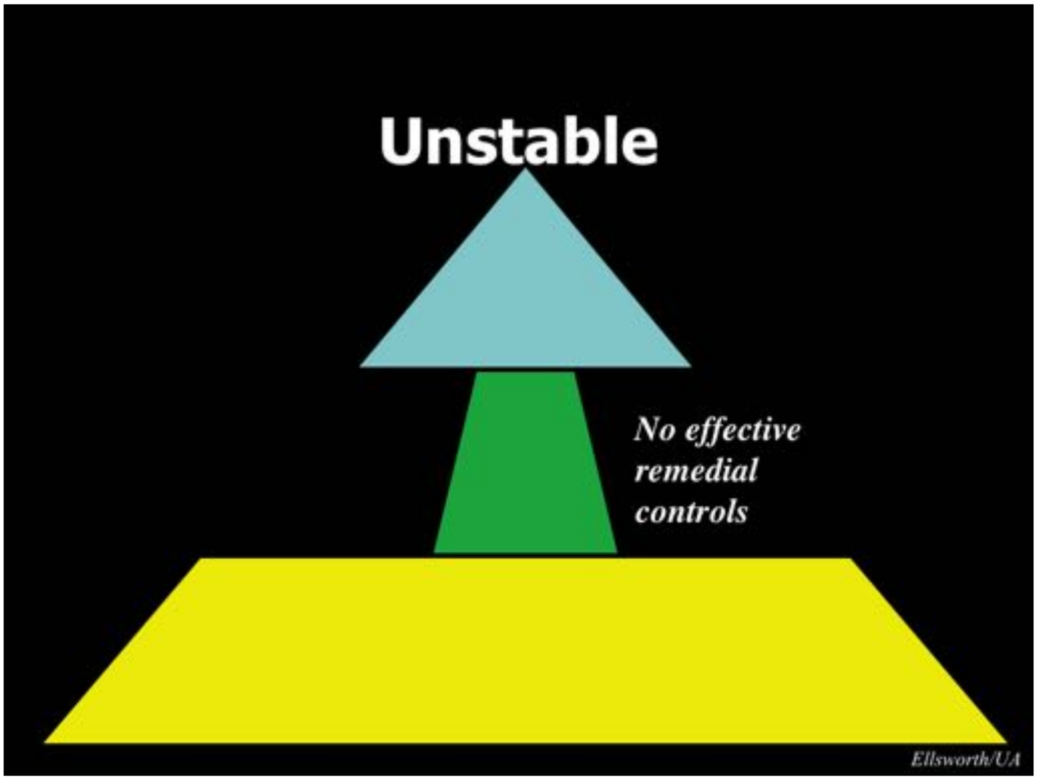
Corresponding author: Peter C. Ellsworth, peterell@cals.arizona.edu

20 minutes followed by panel; 50 people

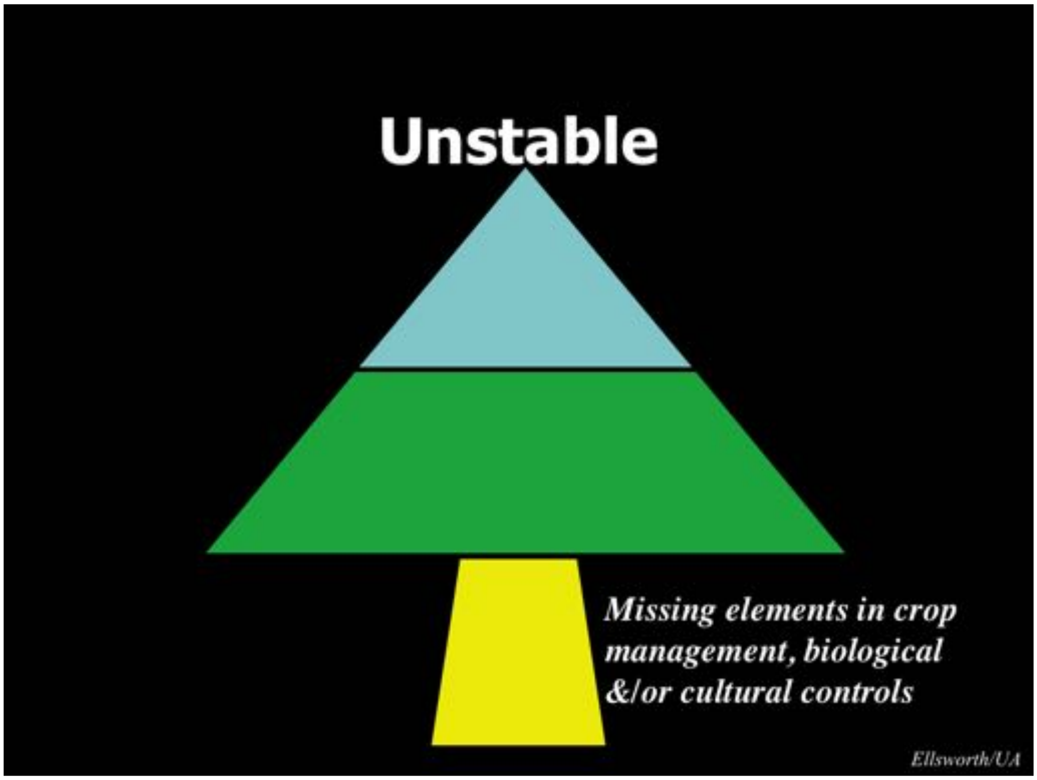


The triangle or pyramid is a convenient metaphor for distilling down the major components of IPM and communicating them quickly to stakeholders, especially growers and pest managers. I've found this to be not only a convenient representation of IPM, but a powerful way to show both the simplicity and complexity of IPM in managed plant systems.

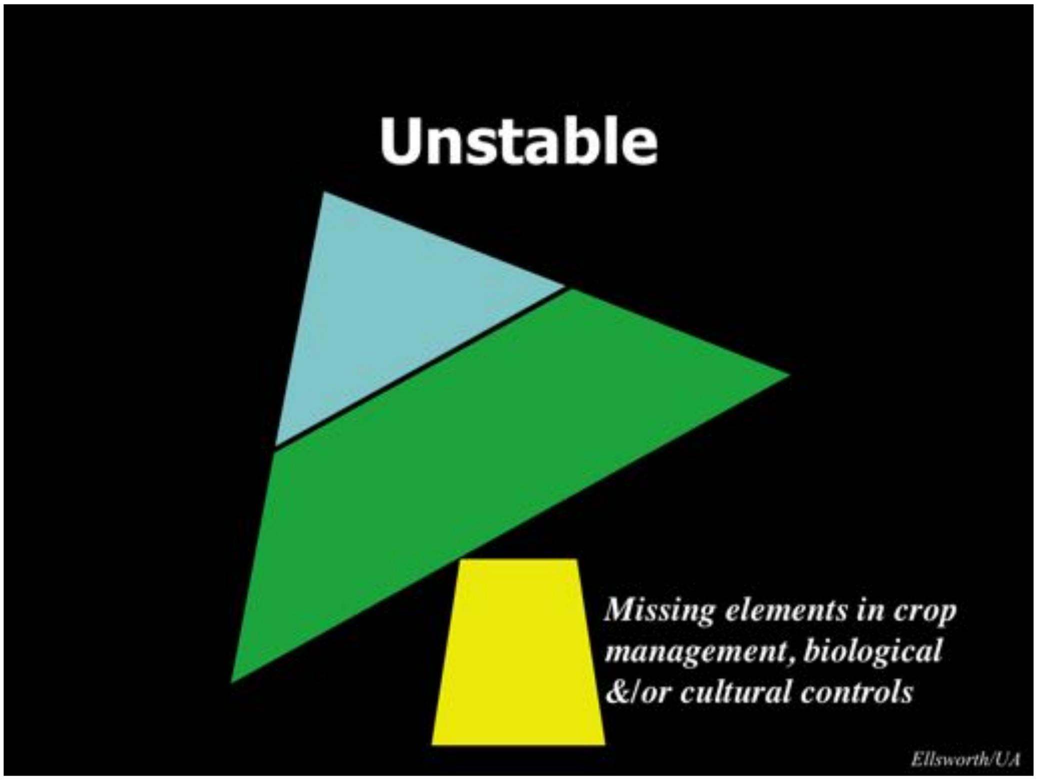
IPM for many systems can be represented by these 3 layers. They are interdependent. You must have sampling or detection systems to know when or if a pest is present as well as remedial controls, often chemical controls (even in organic systems) that can help when all other prevention or avoidance tactics fail to maintain pests below economic levels.

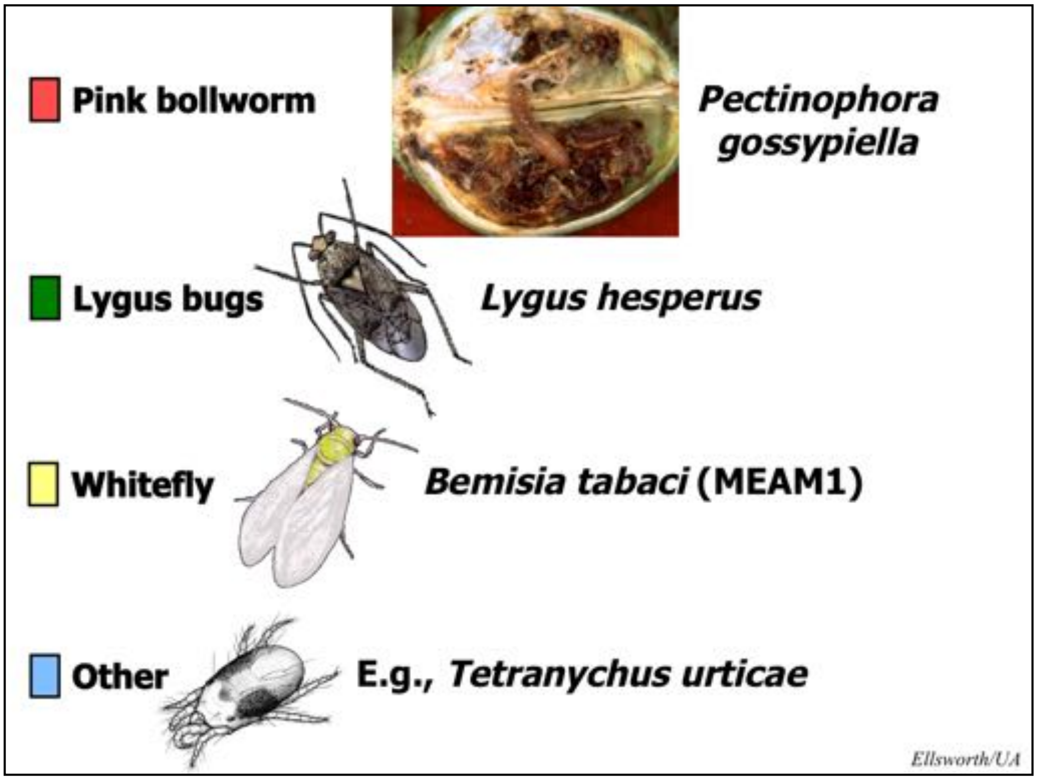


Even with the broadest and best foundation of avoidance tactics and ecological controls, there will be those scenarios where and when pests break-out and require control. If the technology arsenal is too narrow, the management becomes unstable.



Even more seriously unstable are those systems where we have become over-dependent on the chemical tools (organic, biorational, or otherwise) and where we lack the fundamental foundation of avoidance and prevention tactics of crop management, biological and cultural controls.


Unstable
Missing elements in crop management, biological &/or cultural controls
Ellsworth/UA



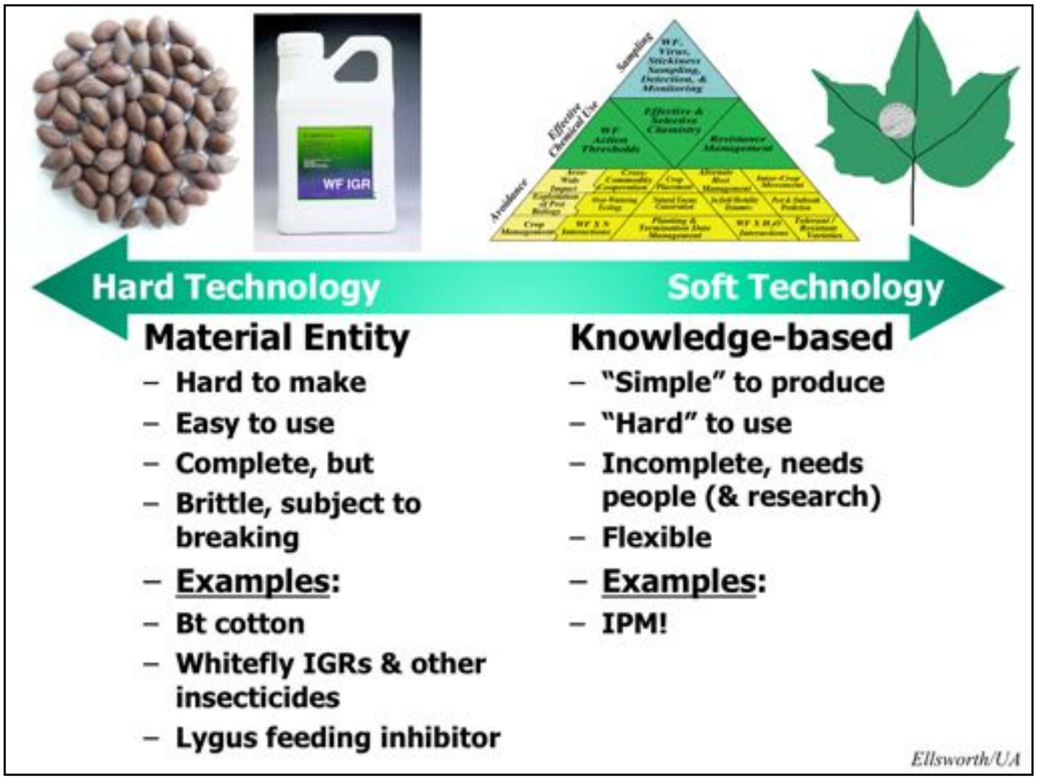
The inventory of key insect pests in the cotton system have been:

The pink bollworm, which enters the boll within hours of hatching making it a particularly difficult pest to control chemically;

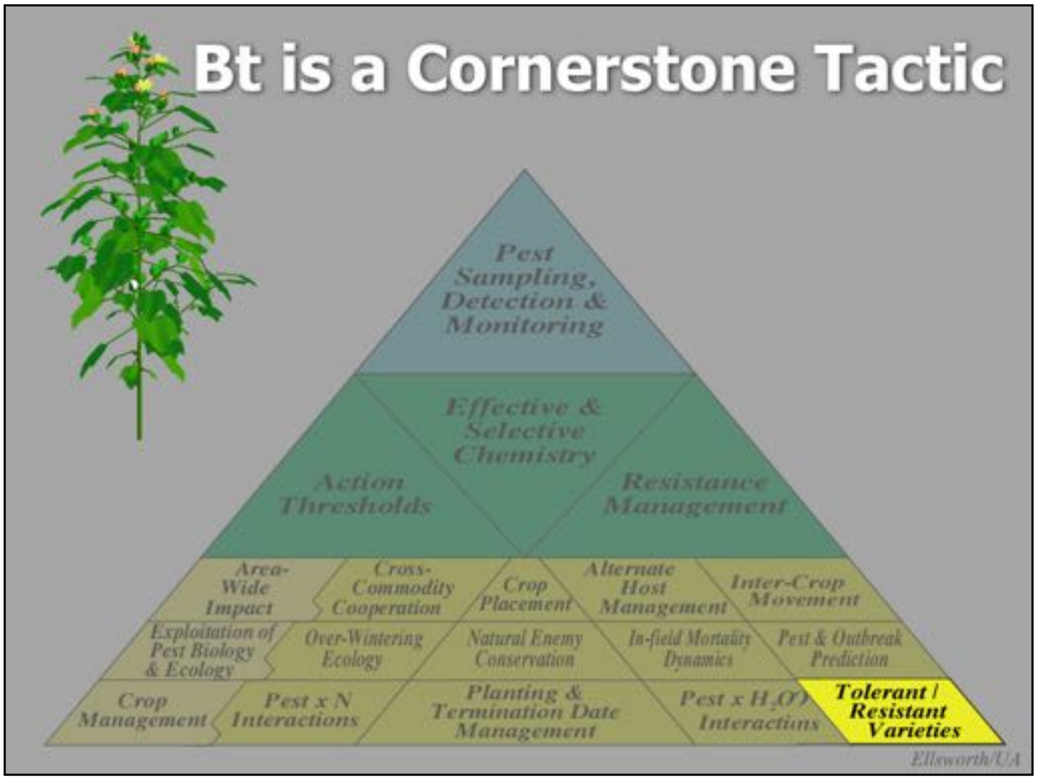
The Lygus bug, a medium sized Mirid or plant bug that attacks the developing flower bud or square causing abortion and loss of that fruiting site; and

The sweetpotato or silverleaf whitefly, which feeds on leaves and excretes sugary honeydew waste that contaminates leaves and cotton fibers.

Secondary and other pests are variable, mostly held under natural control, and best represented by the two-spotted spider mite.

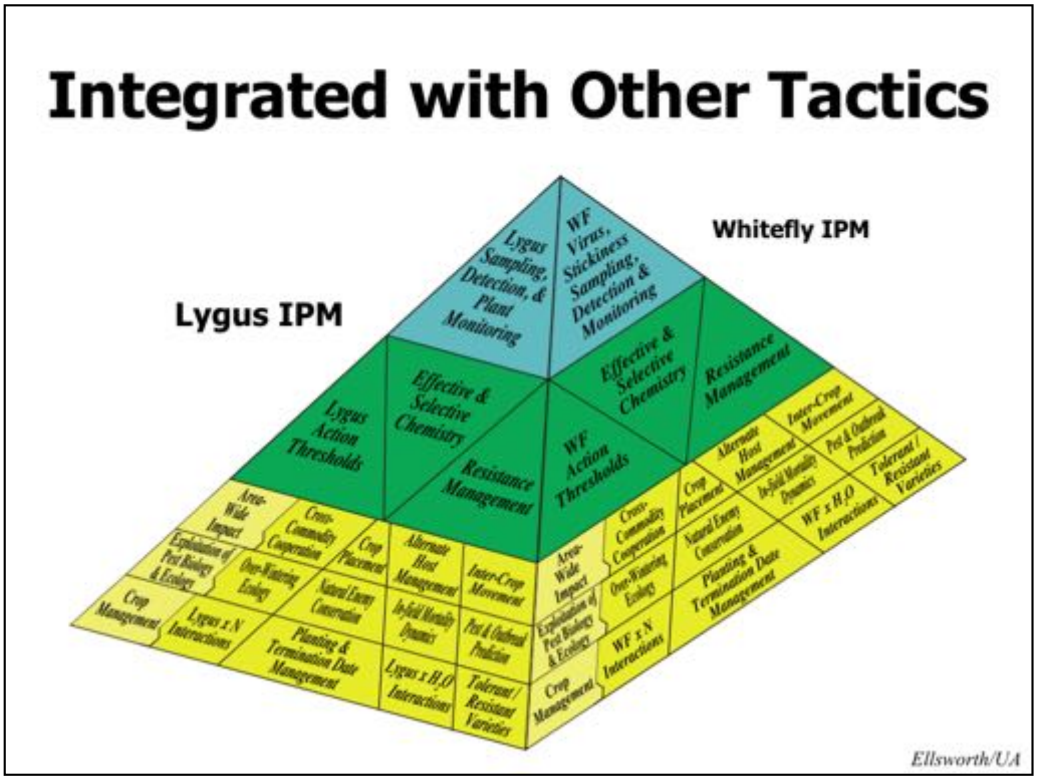


Technologies can be broadly classified as either "hard" or "soft". The dichotomy is imperfect; however, useful nonetheless, especially if everyone recognizes this as a continuum. Even hard technologies can be softened and soft technologies hardened. In general terms, a hard technology is a material entity like a seed or variety or new insecticidal product. They are hard to make, but easy to use. They are complete but subject to breaking. Soft technologies, on the other hand, are knowledge-based and therefore human-mediated. This makes them relatively "simple" to produce, though scientists will tell you that there is nothing simple about developing an IPM plan or the tactical components that make it up. Because humans are needed, they are "hard" to use and by definition incomplete. However, they are extremely flexible.



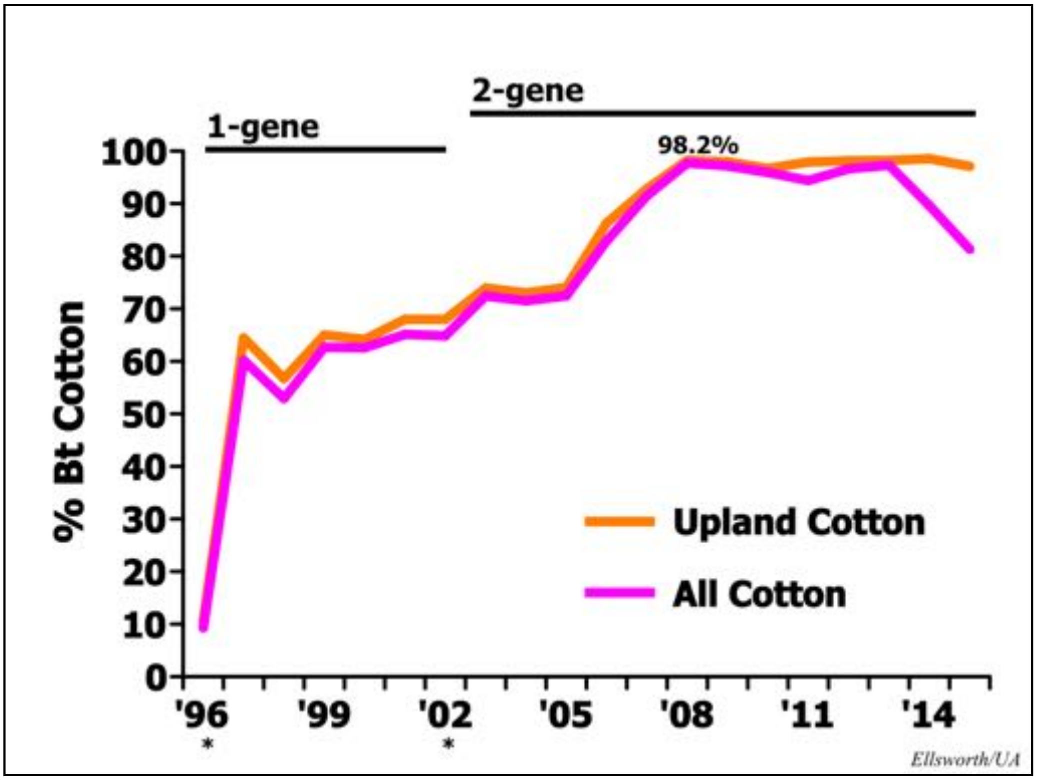
This is the more detailed overall structure of Arizona Cotton IPM. Bt cotton not only fits into the base layer of crop management, it is a cornerstone tactic. While Bt cotton directly supports the management of the pink bollworm, the key lepidopteran pest, it also indirectly supports the other IPM facets dedicated to the management of other key and secondary pests. Because of the sprays eliminated for PBW control, fewer issues arise due to system disruption and conserved natural enemies better function to suppress all potential pests.

As any student of plant breeding knows, the cornerstone to IPM is resistant varieties. It shapes the foundation for all else that we do in the production of cotton. Bt cotton for us in Arizona has been an all-important selective control tactic for pink bollworm, our key lepidopteran pest.



Think of each triangle as just a face of a larger structure that addresses the management system for each pest. It is critical in IPM to make sure all tactics are integrated and not antagonistic of each other.

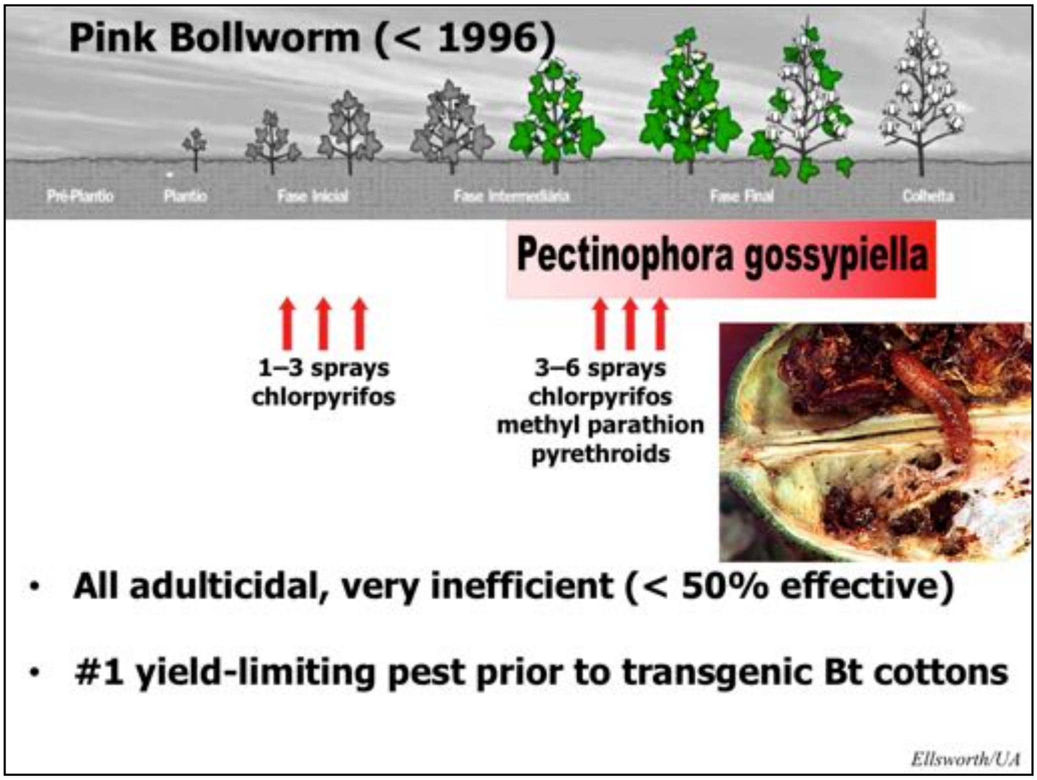
The resulting structure should be an n-dimensional, crystalline structure where tactics are compatible, interdependent, and even shared across dimensions, with each pest’s management system visually represented on a single facet.



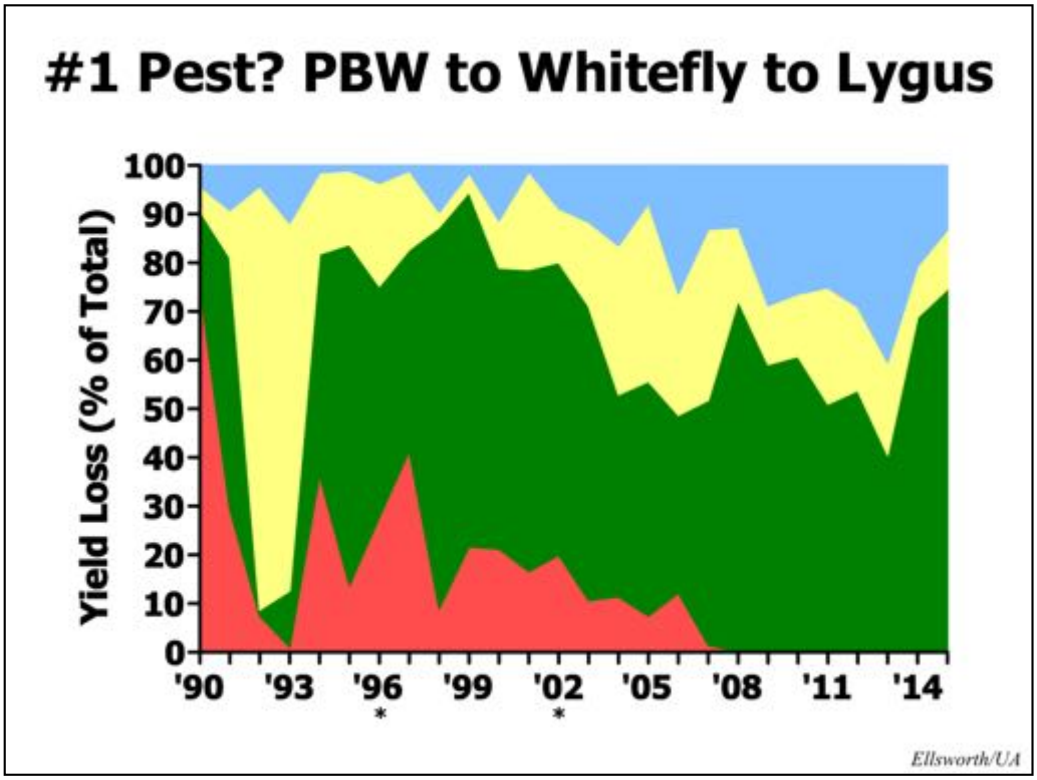
Cry1Ac-based cottons are 100% effective against the PBW. 1-gene Bt cottons were deployed in the U.S. now more than 20 years ago in 1996, followed by 2-gene Bt cottons in 2003 (and Roundup Ready Flex cottons in 2006). Starting in 2006, growers in AZ and later throughout western U.S. cotton and northern Mexico, began a cooperative program for eradicating PBW from our system, largely on the back of Bt cottons.

There have been no grower sprays against PBW since 2007 (or program sprays since 2008). The last moth recovered was in 2012.

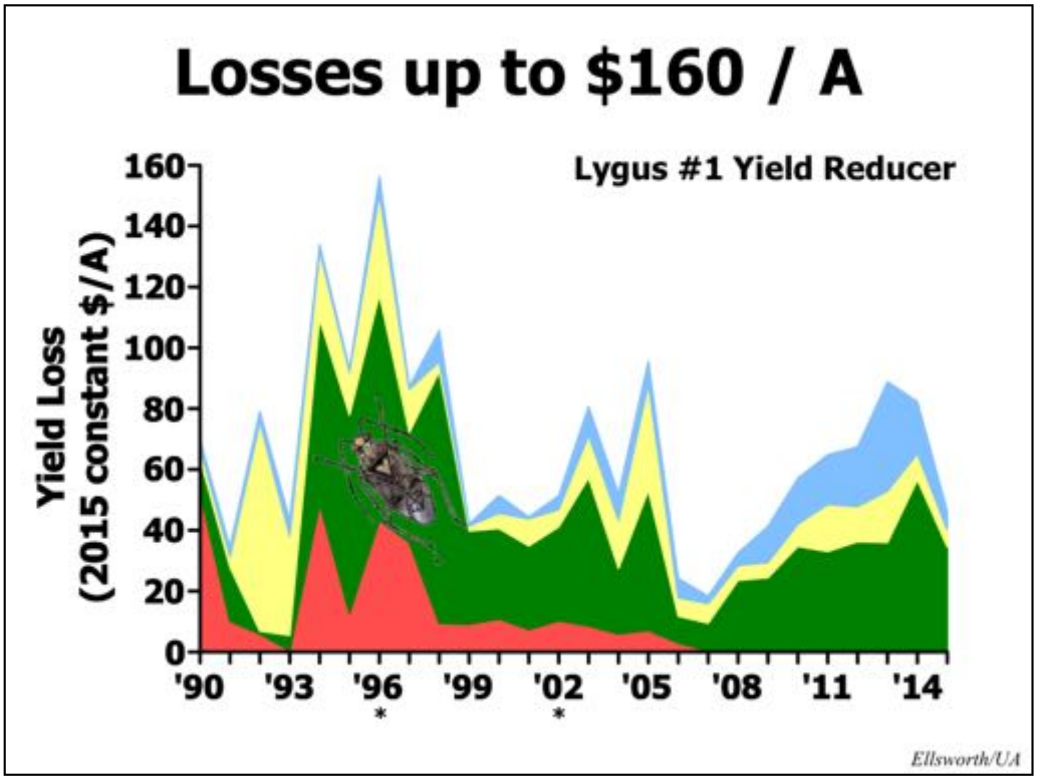
Bt uptake peaked in 2008 at more than 98% of all cotton planted (upland + Pima cotton species). Bt is not a trait available in Pima cotton and PBW pressure is one of the reasons why Pima cotton faded from the AZ landscape 20 years ago and today is returning as a result of functional eradication of PBW.



Prior to 1996, growers sprayed 3–6 times mid- to late-season, after having sprayed 1–3 times very early in the season, all in a very inefficient system to kill adult moths before they laid eggs in cotton. The materials used were all broadly toxic and very disruptive to the cotton system.

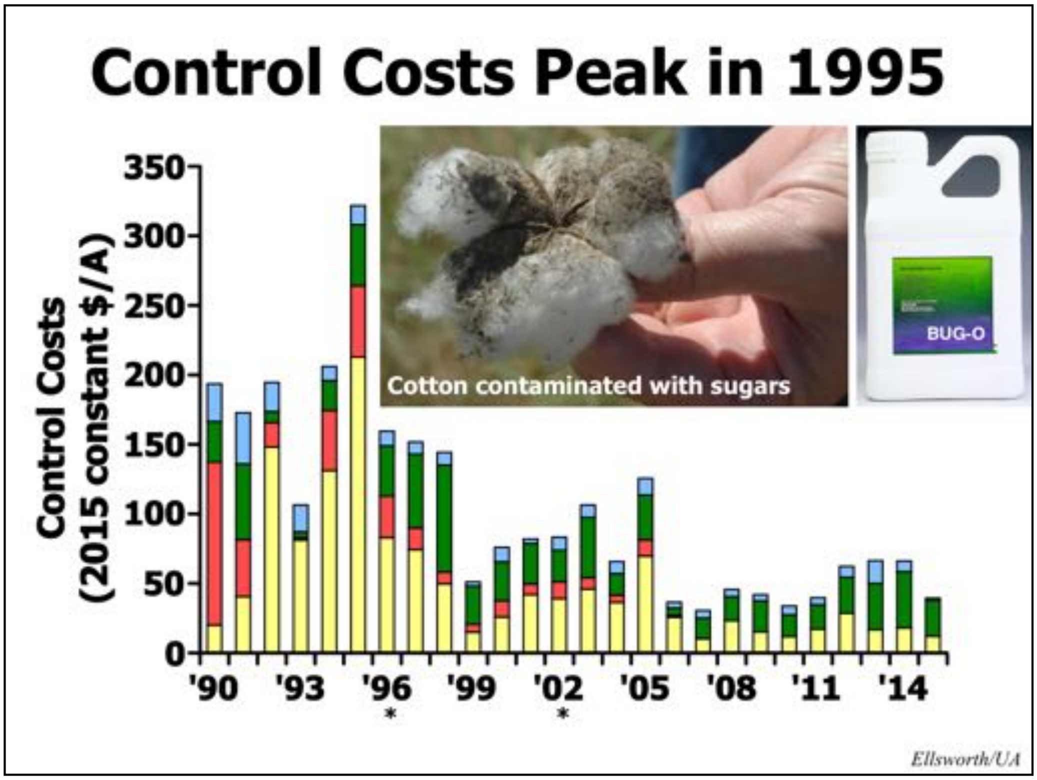


Looking at % yield loss due to arthropods, we can see that when I arrived in Arizona 25 years ago, growers had just experienced one of the worst (perhaps worst) PBW outbreaks in history (1990, pink) and there was no doubt about what was the #1 pest of Arizona cotton at that time. However, soon after, a new invasive species of whitefly [Bemisia tabaci MEAM1] invaded our state and caused catastrophic losses in our system. However, for the most part ever since, Lygus Bug [Lygus hesperus], has been our number 1 pest of Arizona cotton.

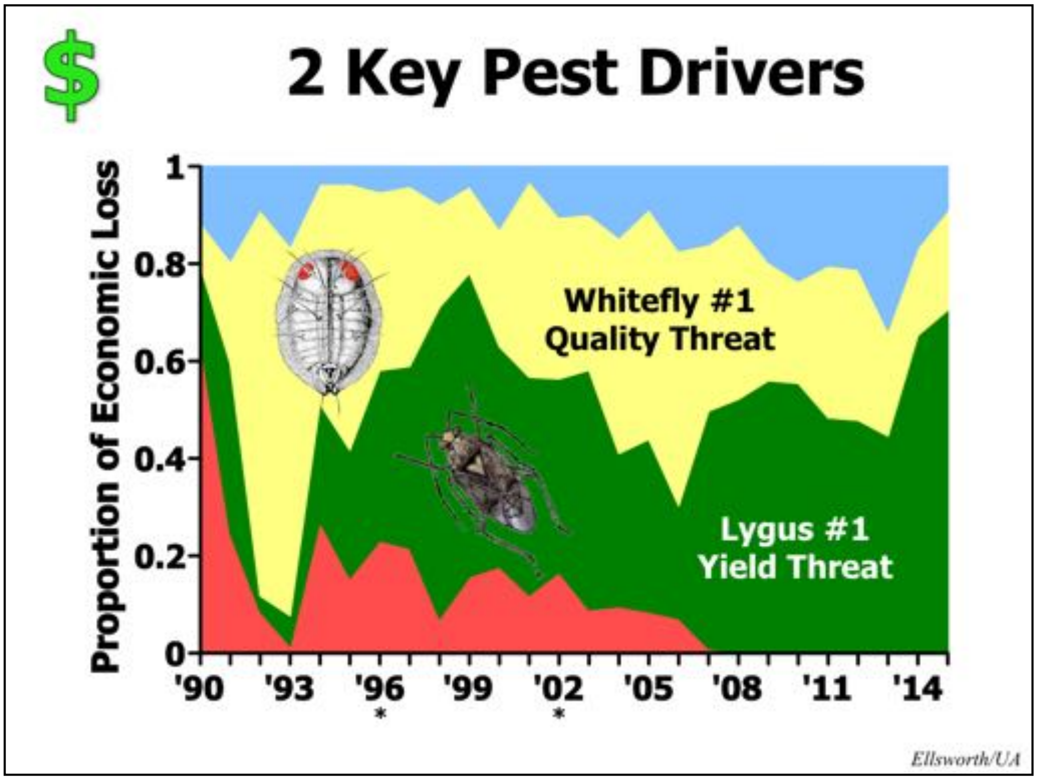


Yield loss on a per acre basis peaked in the mid-1990s at nearly $160/A and mainly due to our #1 yield reducing pest, the Lygus bug.

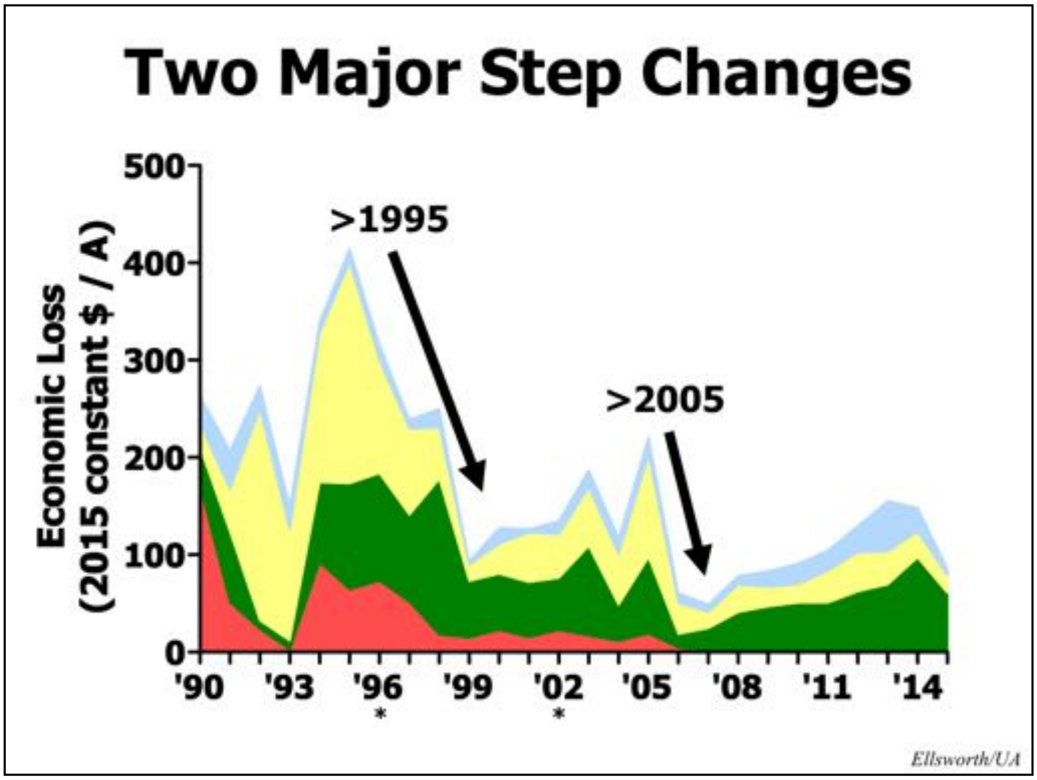
However, % yield loss is only one way in which economic loss occurs…



Economic loss also occurs in the costs incurred trying to control a given pest. Here we can see the spike in control costs in the early and mid-1990s to control whiteflies. This pest is not normally a major yield reducing pest. However, whiteflies excrete sugary honeydew that falls onto cotton fiber, which then serves as a substrate for sooty mold fungi.

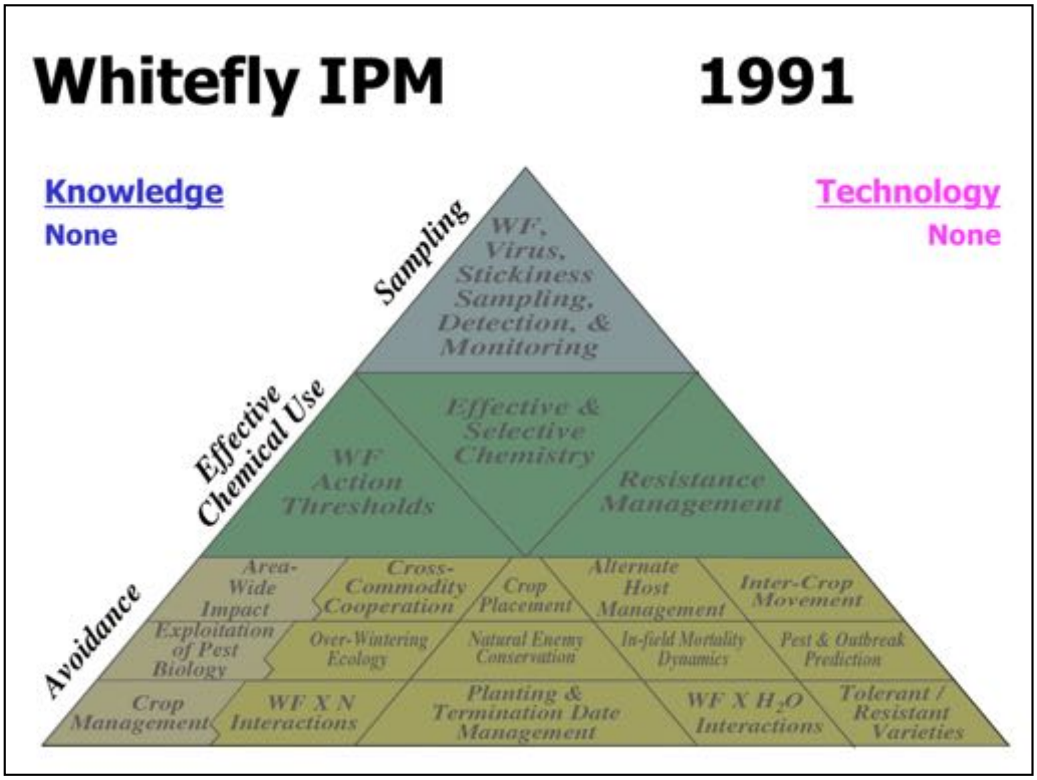


So our system has evolved to be driven by 2 key pests, one based in protection of quality, the other in protection of the yield component. And, PBW has faded from memory due to the successful eradication campaign.



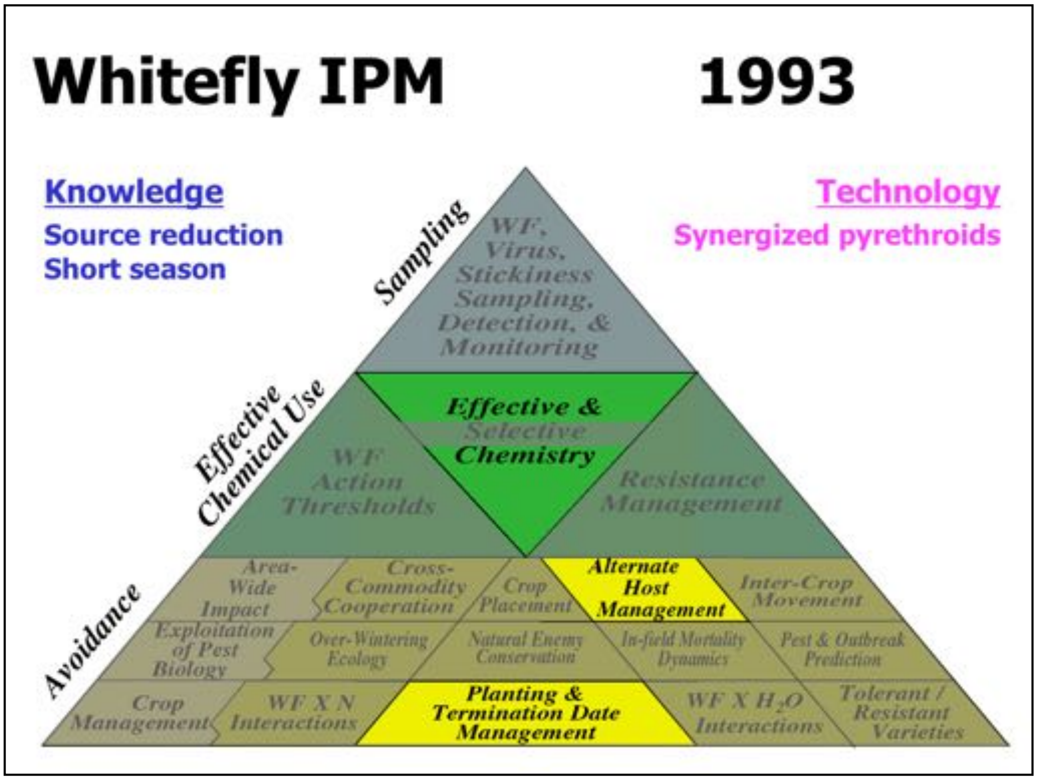
When economic loss is examined on a per acre basis, we see two major step changes in loss, one after 1995 and the other after 2005. Because of our rich dataset and contemporaneous measurement of behaviors, we have the context necessary to parse out the reasons for and infer causes of these changes.

To best understand the role that technologies play in these changes, we have to review the historical development of knowledge ('soft' technology) and products ('hard' technology). This largely, but not exclusively, can be done through examination of the development of IPM for whitefly management…



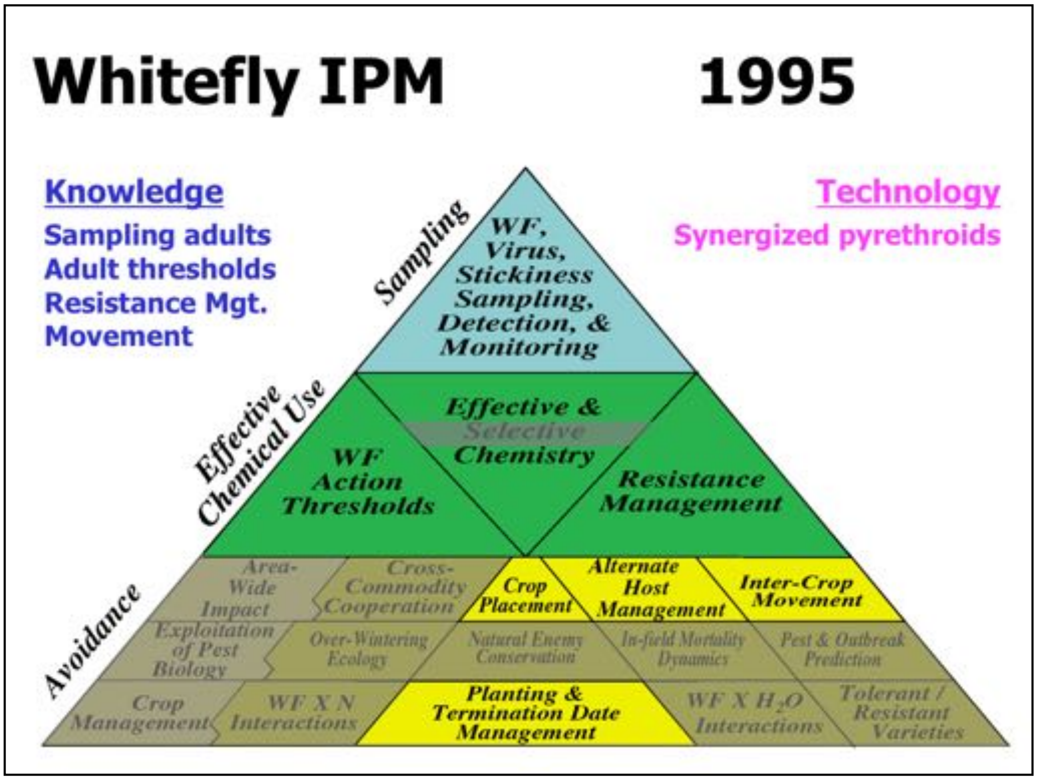
We were starting from nothing in 1991, when this new species of whitefly invaded our state.

We had almost no *a priori* knowledge ('soft', human-mediated technology) of how to cope with this invasive pest and effectively no ('hard') technology developed for its control.

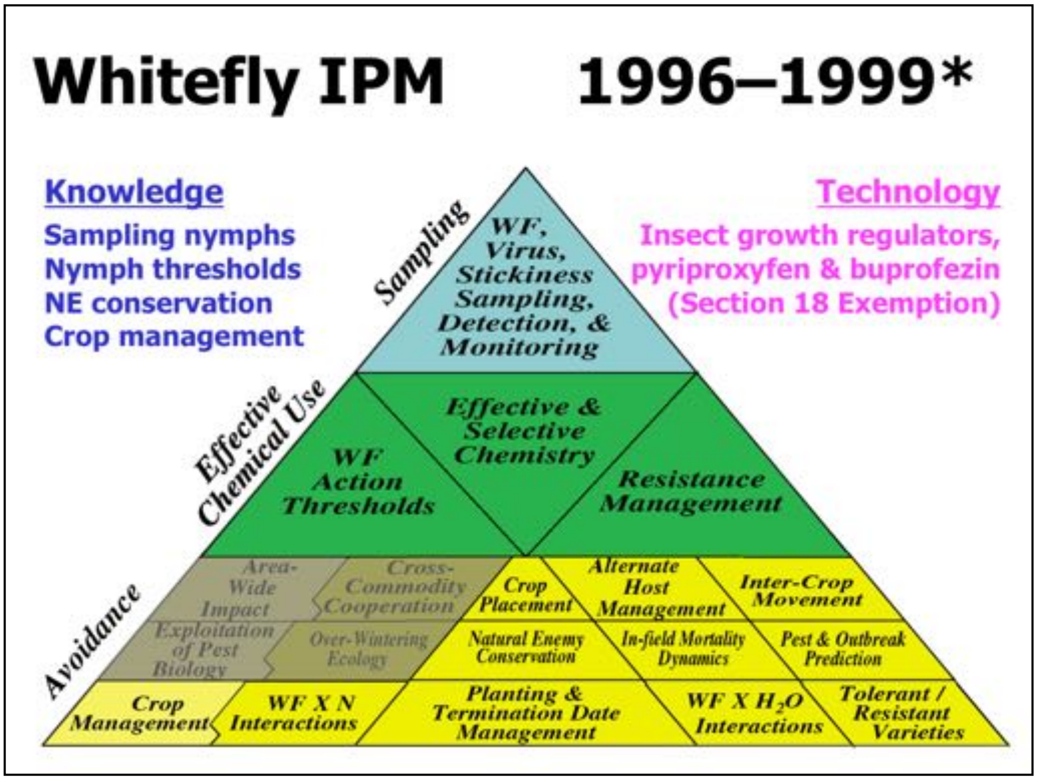


By 1993, we at least had identified some commercial chemistries that could be used to combat this problem in the form of broad spectrum pyrethroids synergized with organophosphates or other chemistries.

We had some idea of the alternate host interactions that were present in our desert agro-ecosystem and were faced with telling growers to shorten their season at all costs to avoid major damage from whiteflies. [Shortening the season had the side effect of greatly lowering yield potential.]



By 1995, we added adult sampling plans, action thresholds and more insight into resistances, and movement. No new technologies were added at this stage and chemical control was still based on broadly toxic synergized pyethroids.

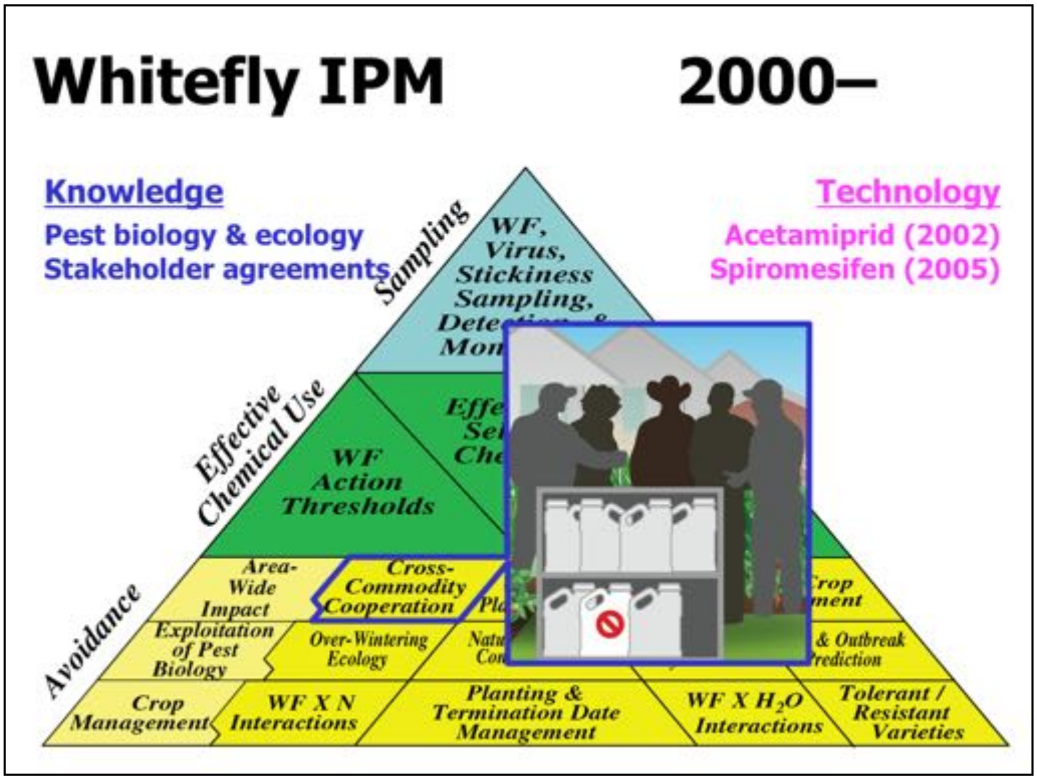


However, in 1996, we introduced some key selective chemistries, 2 IGRs for use for the first time in U.S. history, that changed everything for us. [Note this year was coincidental with the introduction of 1-gene Bt cotton, too.]

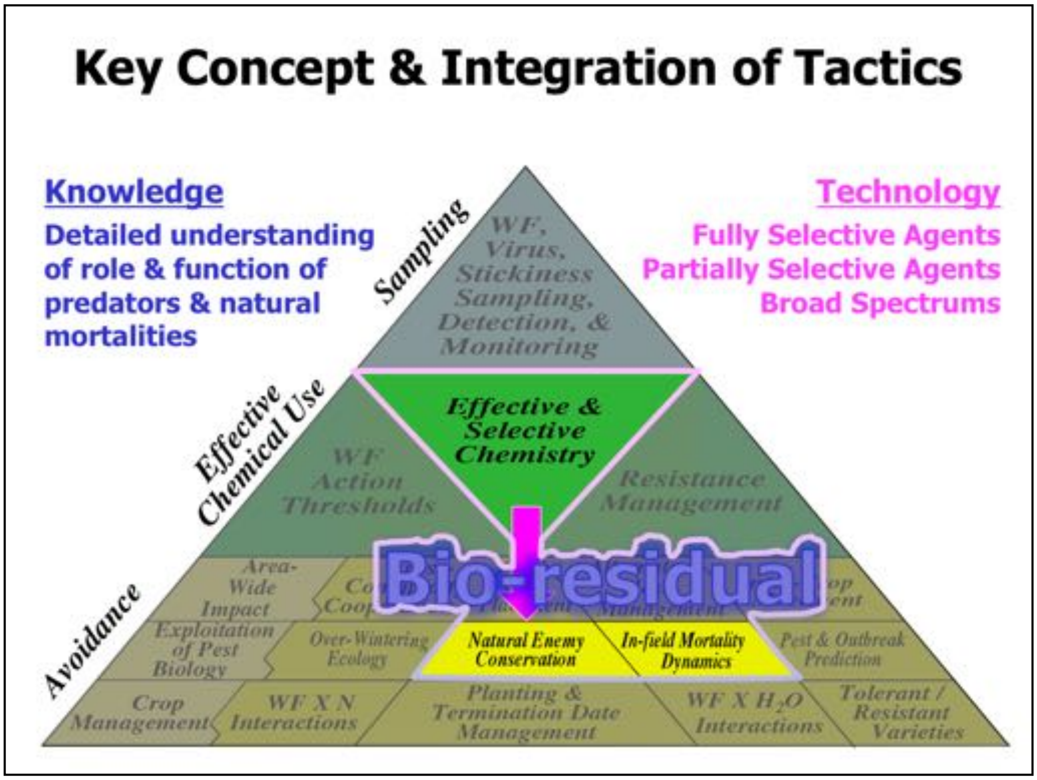
At the same time, we added nymphal sampling plans and thresholds to support the proper use of IGRs, and important information about the role of natural enemy conservation and broad crop management practices.

These soft- and hard-technologies represented revolutionary changes in thinking for our growers, who up until now were completely dependent on broad-spectrum, largely adulticidal measures for whitefly (and PBW) control.

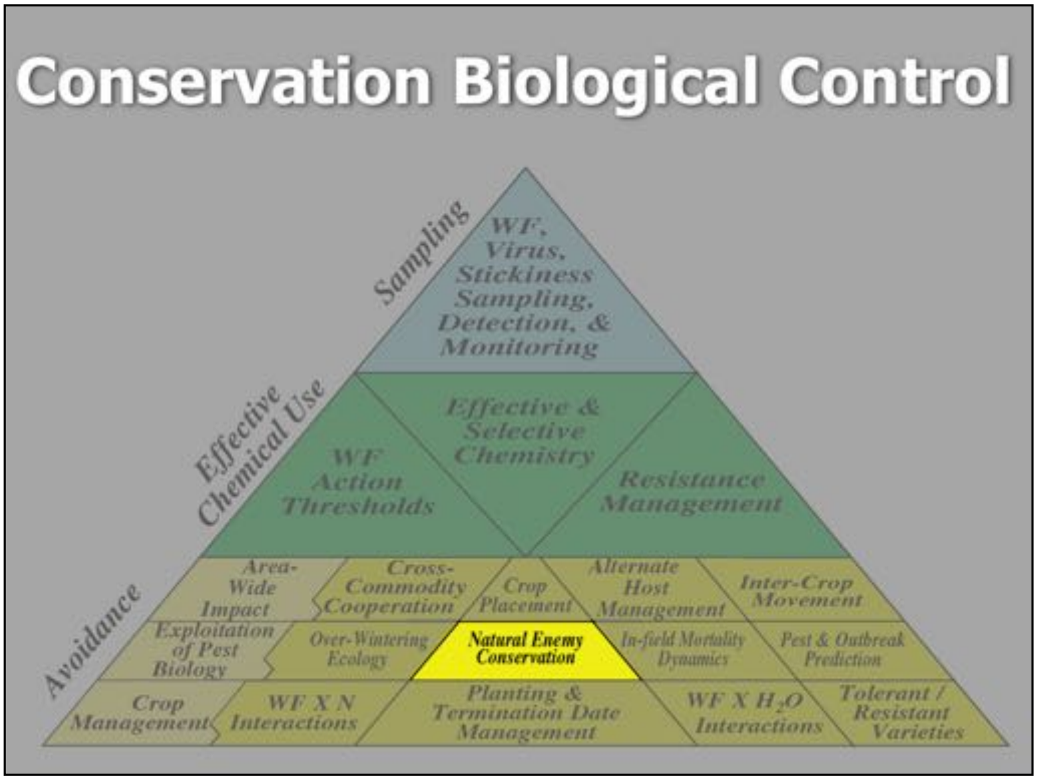
***The 1st time "Integrated Control" was accomplished, sensu Stern et al. 1959.**



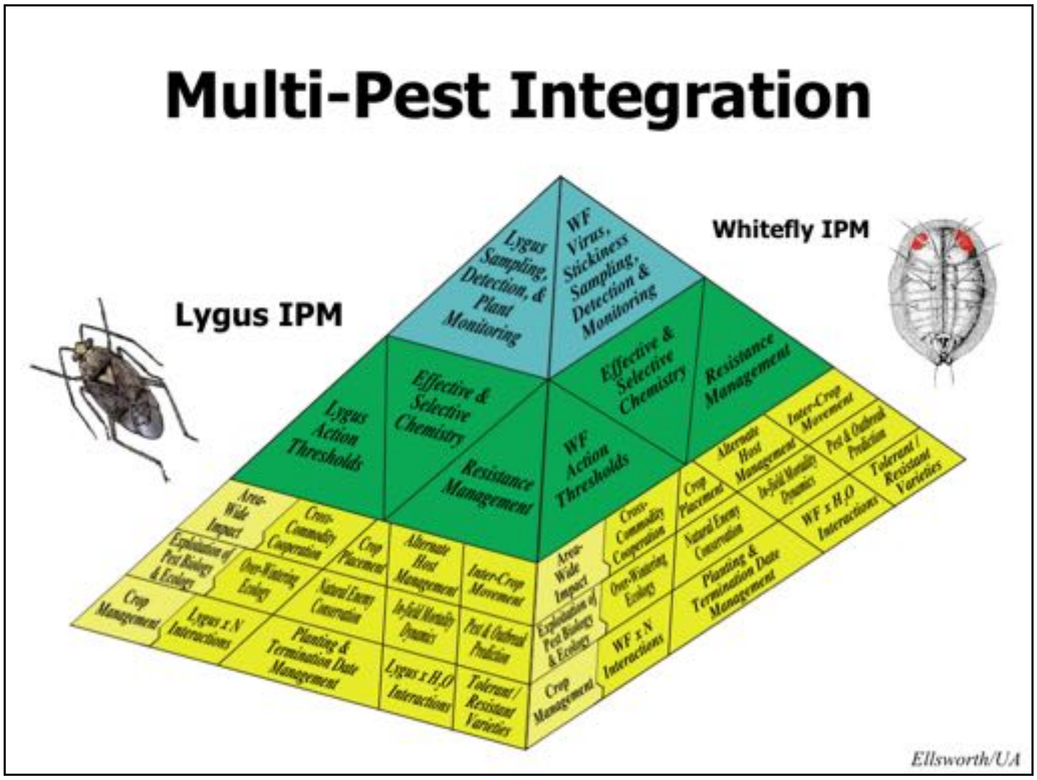
By 2000, we completed our understanding of the management system through key findings about pest biology & ecology, and we installed some critical cross-commodity agreements among cotton, vegetable and melon producers for sharing technologies across the ecological landscape, especially for the purposes of resistance management. This was first done for buprofezin, an IGR that was broadly labeled among these crops, but later this was followed by sharing agreements for neonicotinoid use. This pyramid metaphor serves as our heuristic representation of whitefly IPM in Arizona cotton. This continues to be our operational IPM plan, but has been refined still more as new technologies come on board like acetamiprid in 2002 and spiromesifen in 2005.



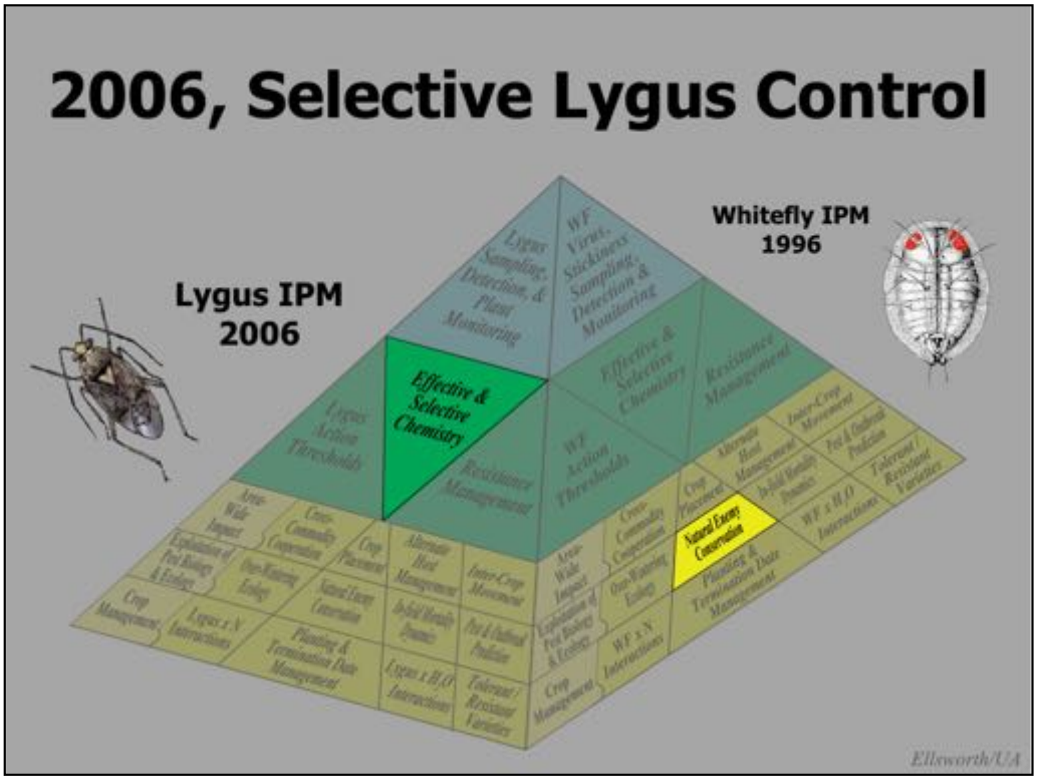
The central key concept to this effort was based in our understanding of the role and function of predators and natural mortalities in whiteflies in cotton and the integration of these mortality factors with fully selective insecticides. The two combined give us access to an extended suppressive interval known as bio-residual. "Bio-residual" as a term was very effective in explaining the efficacy of control programs based in fully selective technologies like the whitefly IGRs. Because growers are very accustomed to hearing about (and estimating) "chemical residuals", this term relays critical information to them that gives them confidence that the program will work as intended.



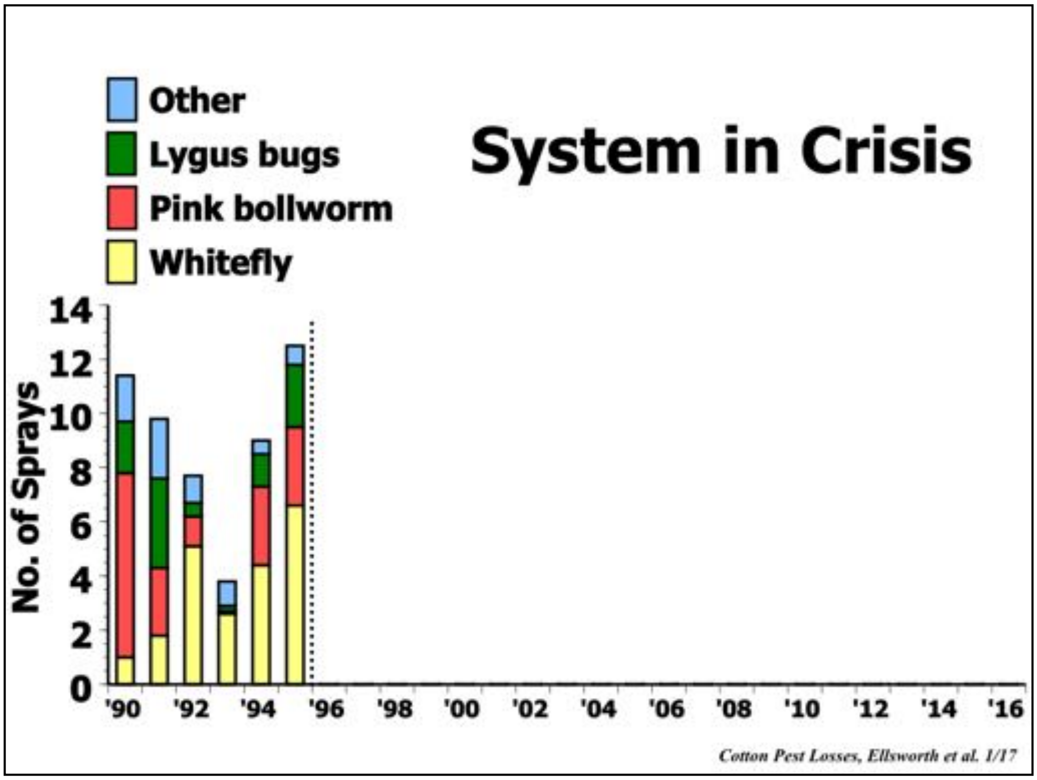
For AZ cotton, conservation biological control or those practices that foster the survival and function of the natural enemies in our system has become a key building block of our IPM system.



Natural enemy conservation was functioning better after 1996 and the introduction of both Bt cotton and whitefly IGRs. However, that critical tactic still had to be integrated with those required to control Lygus bugs.



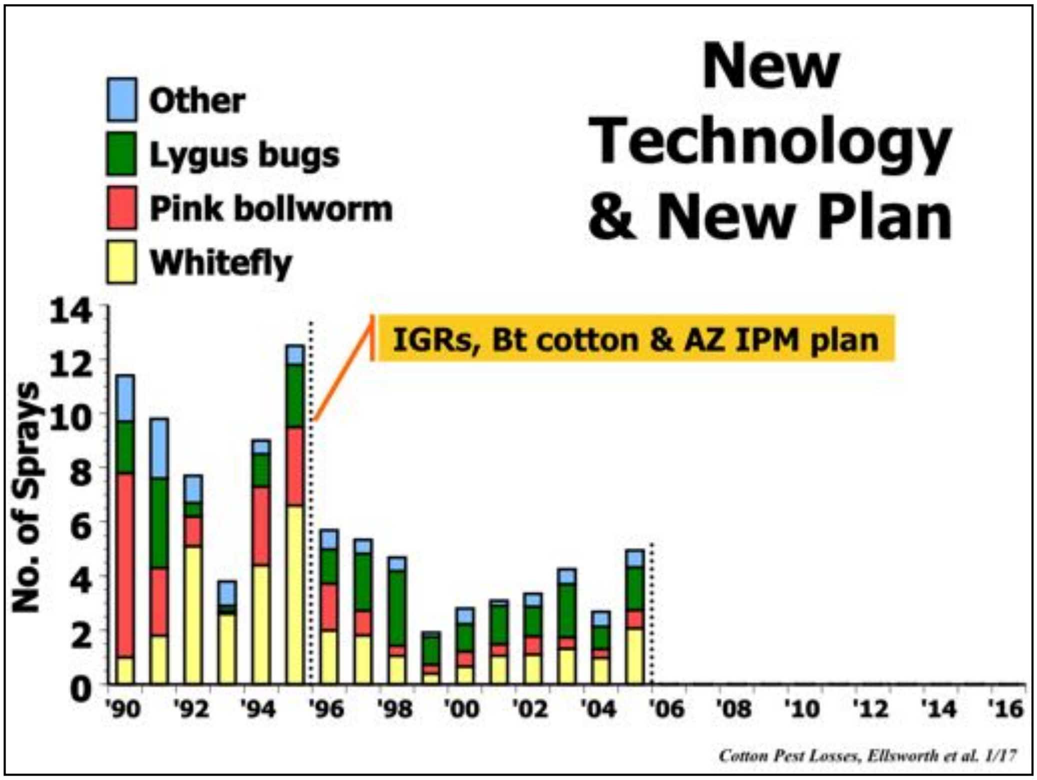
Chemical controls for Lygus prior to 2006 were all very broad spectrum and potentially damaging to the natural enemies we were seeking to conserve for whitefly management. But in 2006 after years of development, we introduced flonicamid (i.e., Carbine), a fully selective feeding inhibitor to control Lygus such that natural enemies were conserved for whitefly (and secondary) pest control. [In 2012, a second, very effective & selective Lygus control agent was introduced, sulfoxaflor or Transform, that solidified our selective approach. Sulfoxaflor was then cancelled by US-EPA in late 2015 and then restored in Arizona cotton in 2017 under a specific Section 18 emergency exemption.]



Let's review this history in terms of statewide average number of sprays.

The early 1990s was reeling after a historic PBW outbreak and the introduction of a new invasive whitefly species. This was a system in crisis. This crisis spurred much needed science by government, academic and industry scientists. However, perhaps one of the more important outcomes of having a system in crisis was creating a culture where growers and pest managers were ready and willing to listen to and implement alternatives, including the newly developed IPM plan of 1996.

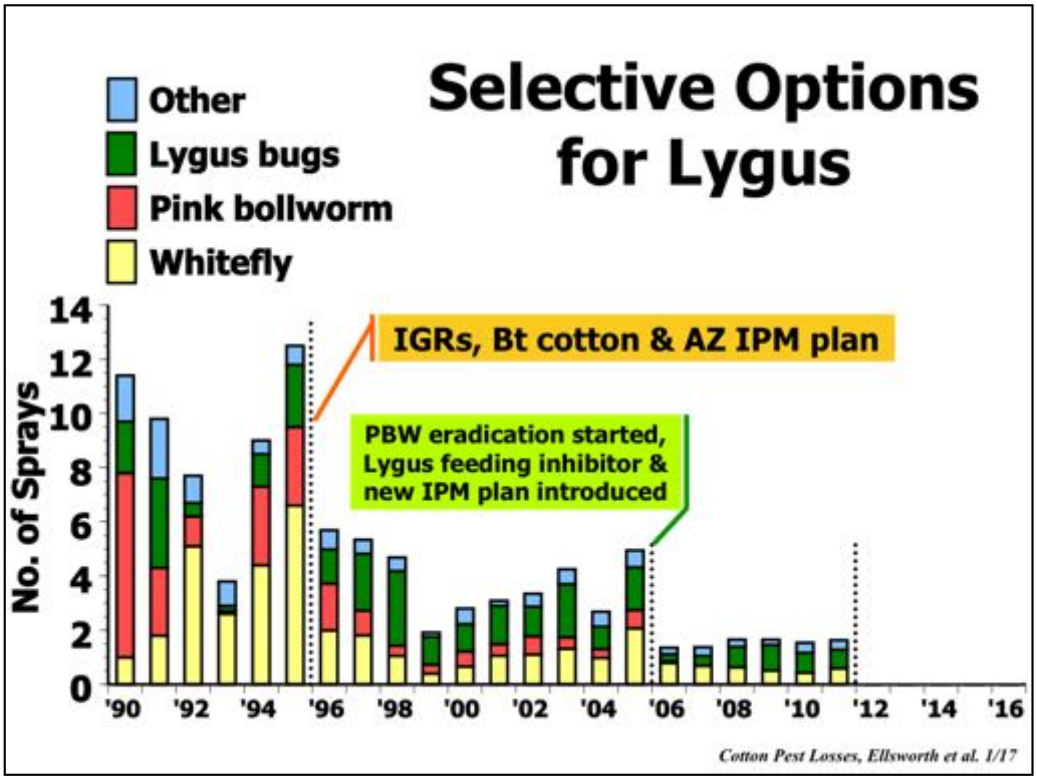
Adapted from Naranjo & Ellsworth 2009, & Ellsworth, unpubl.



In 1996, we gained IGRs for whitefly management, Bt cotton for lepidopteran control, and developed a new Arizona IPM Plan. These advances in “selective” technologies and approaches to insect pest management were based on our need to better manage and conserve the natural controls in our system, such as predators of whiteflies.

The result was a dramatic and immediate halving in the amount of spraying that was going on to control our insect pest complex.

Adapted from Naranjo & Ellsworth 2009, & Ellsworth, unpubl.



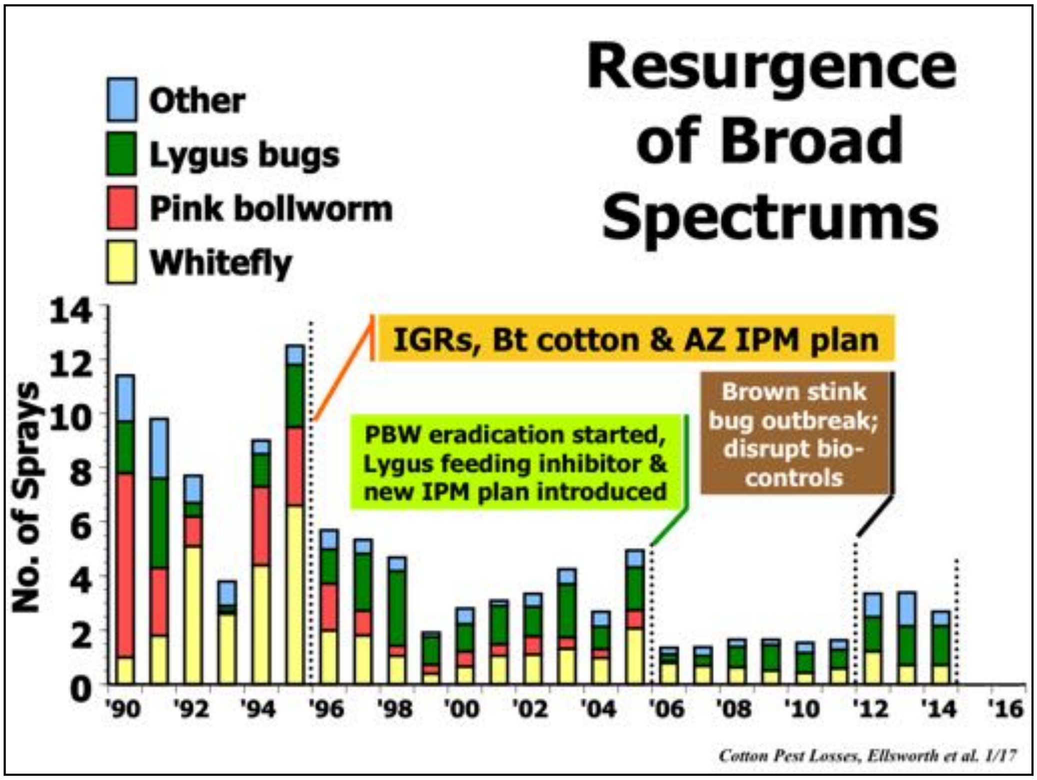
Progressive improvements to the system continued…

In 2006, we saw deployment of a selective Lygus feeding inhibitor [flonicamid (Carbine)] and the cotton industry banded together to develop a major pink bollworm eradication campaign.

Under this new IPM plan, growers and pest managers throughout the state saw a continued lowering in the need for foliar insecticides for all insect pests, halving it once again relative to the previous period.

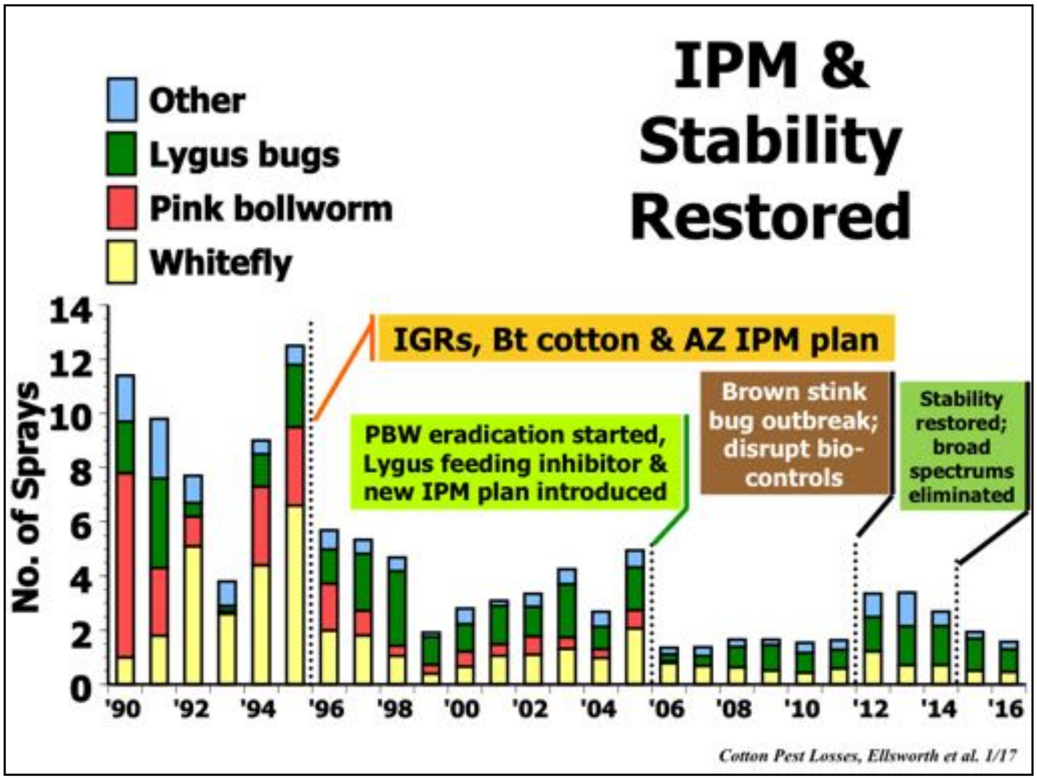
These continued advances in "selective" technologies and approaches to insect pest management completed our ability to better manage and conserve the natural controls in our system, such as predators of whiteflies.

Adapted from Naranjo & Ellsworth 2009, & Ellsworth, unpubl.



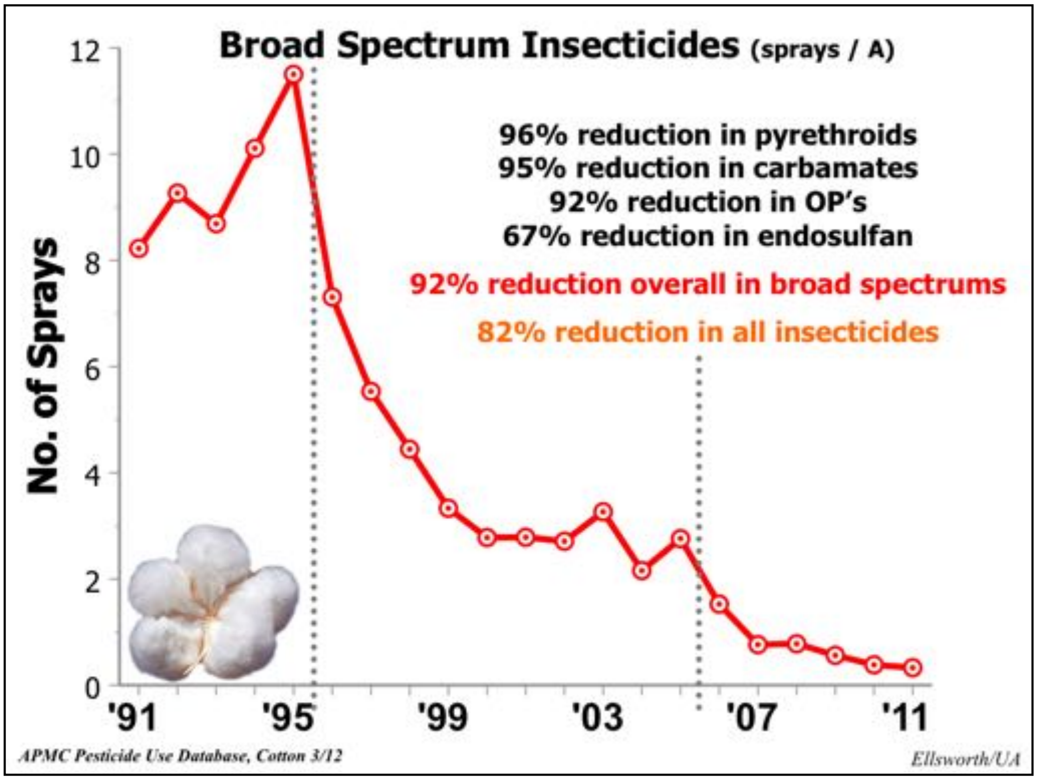
Set-backs occur, too! An outbreak of a native pest that hadn't been seen in damaging numbers since 1963. This underscores the importance of having infrastructure and capacity maintained so that rapid response is possible.

In 2012, we see an increase in the use of broad spectrum insecticides in response to elevated populations of BSB. In many areas, the use of broad spectrum insecticides disrupted biological control and led to resurgences of whiteflies and outbreaks of mites.



Once research and practice amply demonstrated the futility of chemical controls for brown stink bugs, growers eliminated their use of broad-spectrum insecticides once again and stability of the IPM system was restored.

During these periods of stability (2006–2011, 2015–2016), we average just over 1.5 sprays for the entire arthropod pest complex.

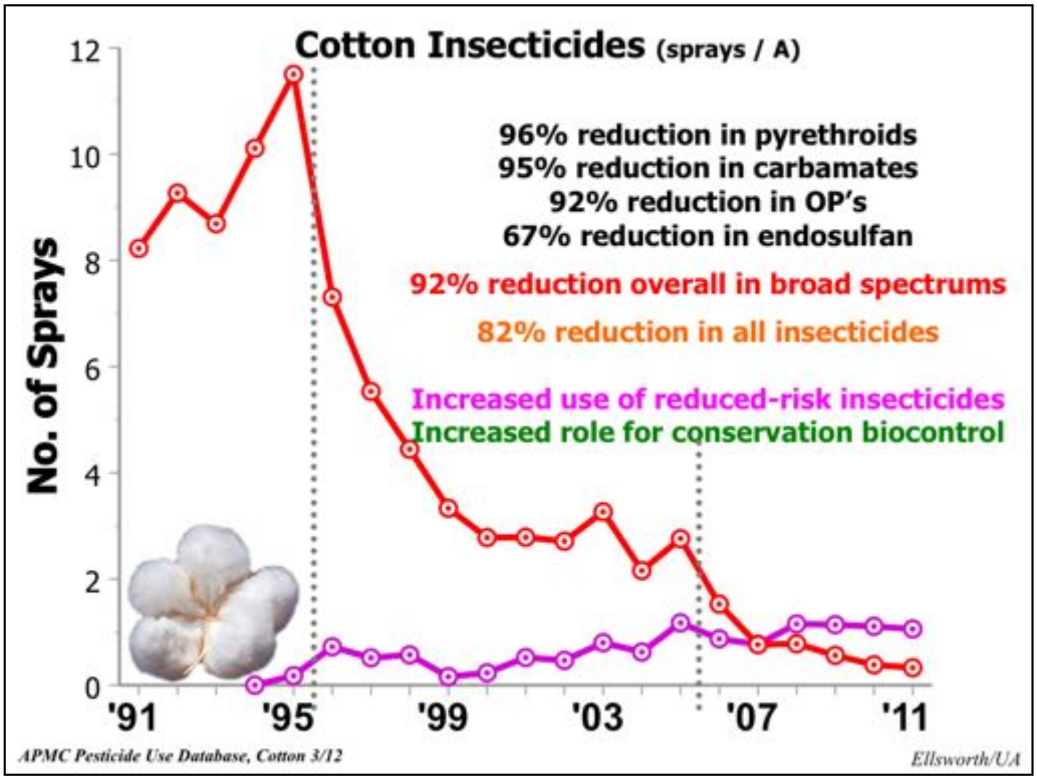


And, the character of the sprays made have changed dramatically.

We have reduced all insecticide usage by more than 80% and broad spectrum usage by more than 90%, practically eliminating pyrethroids, carbamates, organophophates and endosulfan.

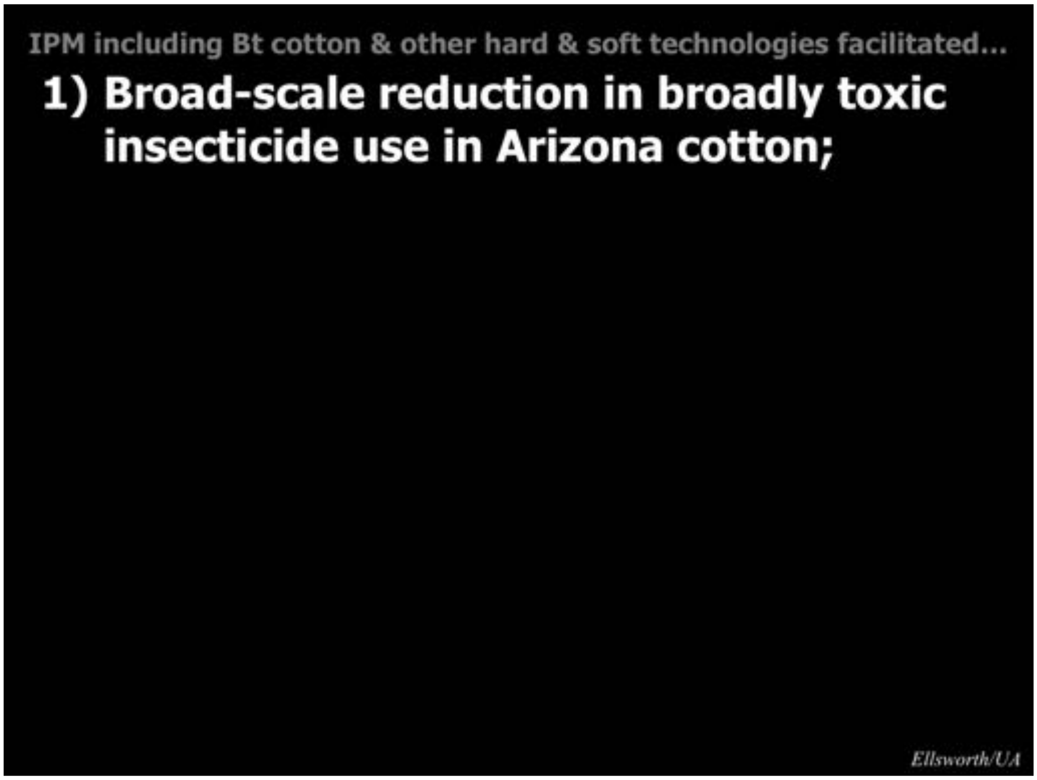
[These data on pesticide use are from an independent source collected by the State and maintained by the University's Arizona Pest Management Center. They include all pesticide use reported by applicators in the State, though not all sprays require reporting to the State.]

Reductions based on comparisons of these 2 periods, 1990-1995 v. 2006-2011



These gains were accomplished by the comprehensive IPM programs enacted in 1996 and progressively improved since with major changes to our Lygus control system in 2006. Furthermore, this was enabled by the strategic introduction of selective technologies into our system, and now we see the usage of reduced-risk insecticides (at a low frequency of use) out numbering broad spectrum insecticides. Most importantly, this has created opportunity for an ever increasing role for conservation biological control.

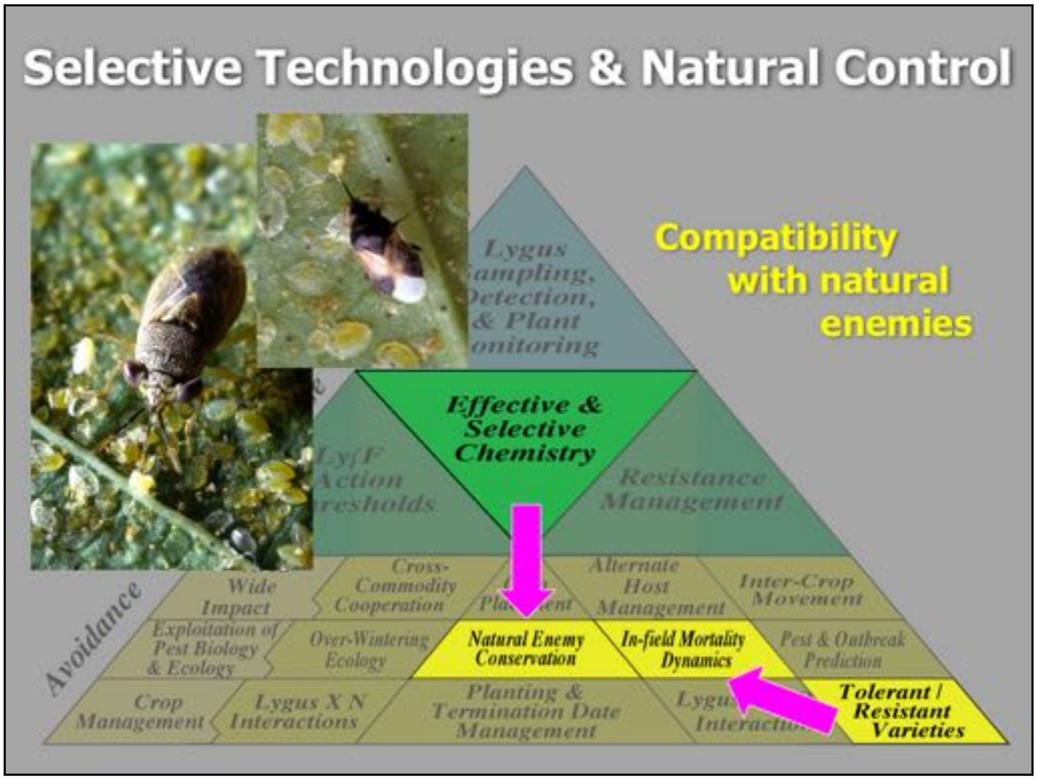
1990-1995 v. 2006-2011



I'd like to conclude with a series of comments supported by summary information and data I have to share.

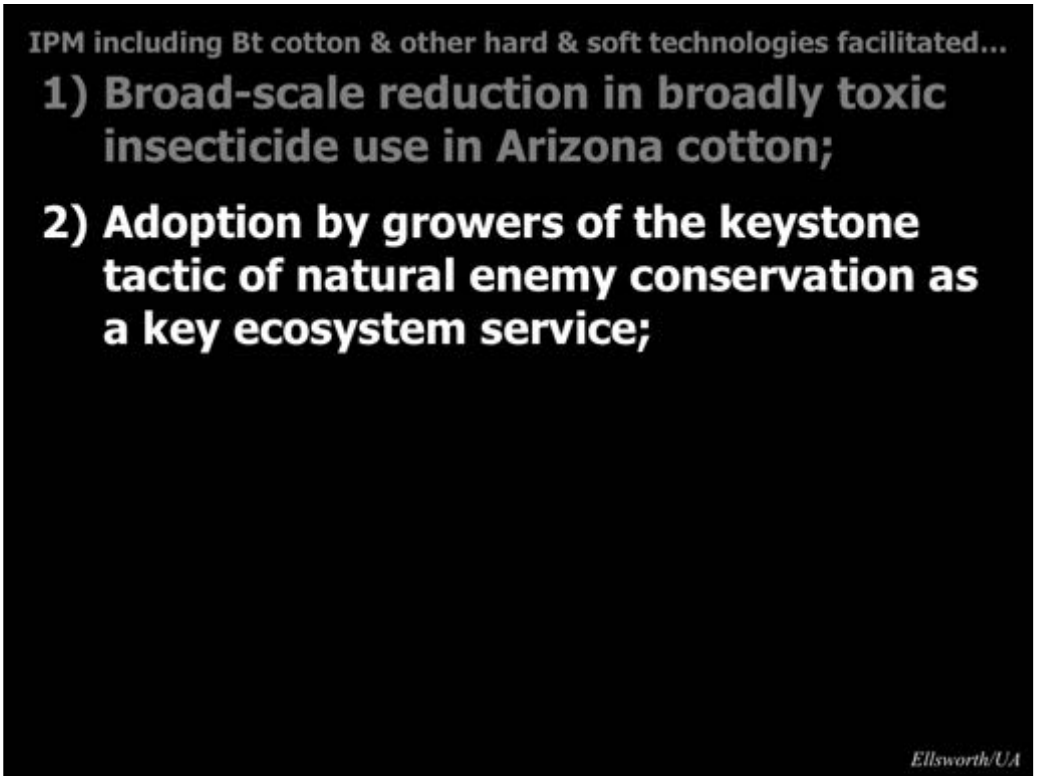
IPM, including Bt cotton and all other hard and soft technologies, has facilitated the broad-scale reduction in broadly toxic insecticide use in Arizona cotton.

While Bt cotton is a critically important, enabling technology, it is still just a singular control tactic and not an entire IPM strategy. There was and is soft technology that supports the proper use and deployment of Bt cotton and other hard technologies.

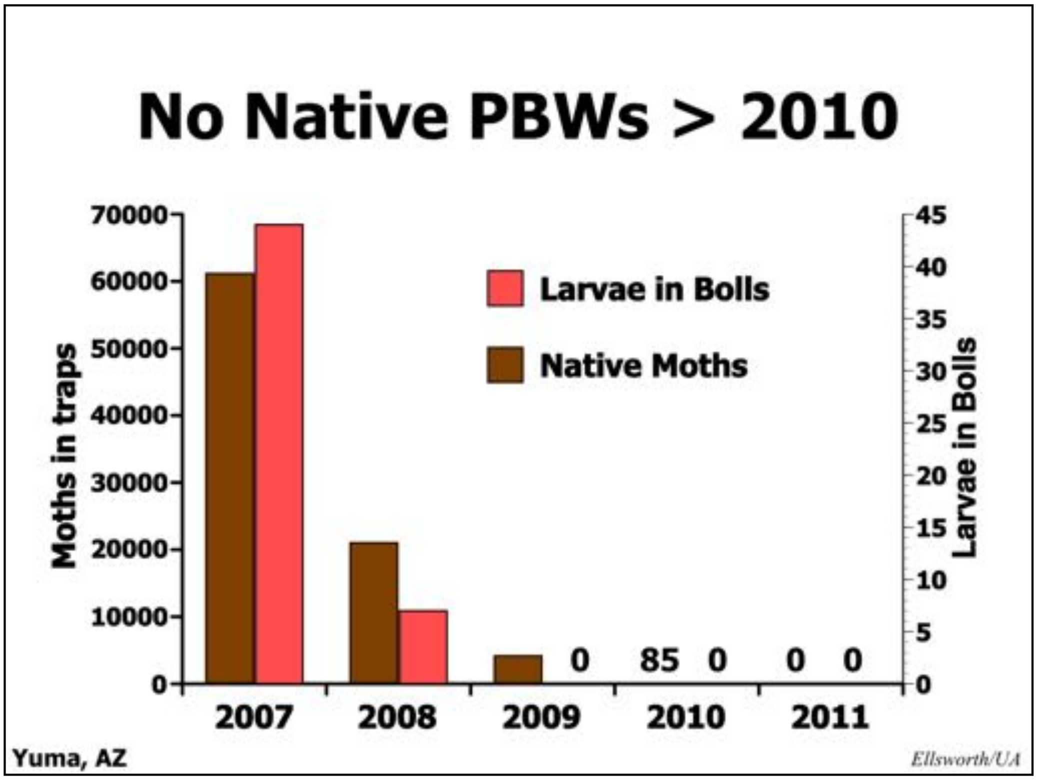


In AZ, we have shown that when selective options are available and effective (Bt cotton, whitefly IGRs, selective Lygus feeding inhibitor), huge gains in both target and collateral control can be achieved due to much better natural enemy conservation and other natural mortalities. This ecosystem service is a foundational element of "Avoidance," and one made compatible with these specific and selective controls in our system.

And this combination of tactics, chemical and biological control, was exactly what was suggested by Stern and colleagues over 50 years ago.

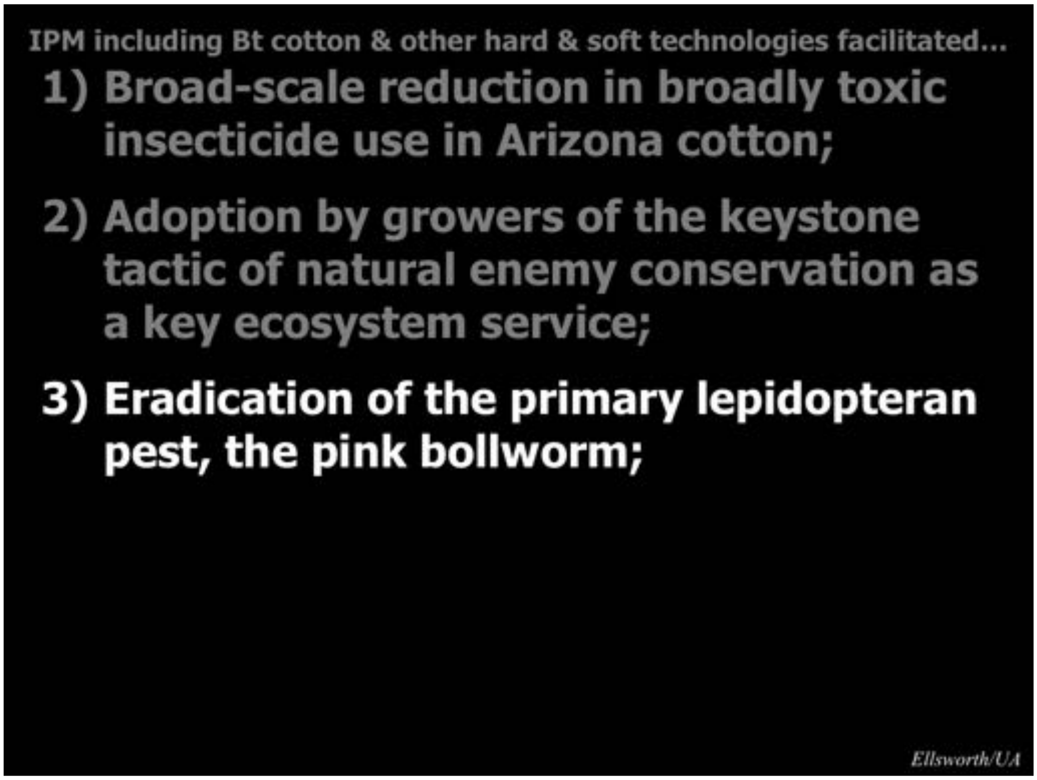


Thus, IPM has also facilitated the recognition and adoption by growers of the keystone tactic of natural enemy conservation. And this tactic is a key ecosystem service necessary to support IPM sustainably into the future.

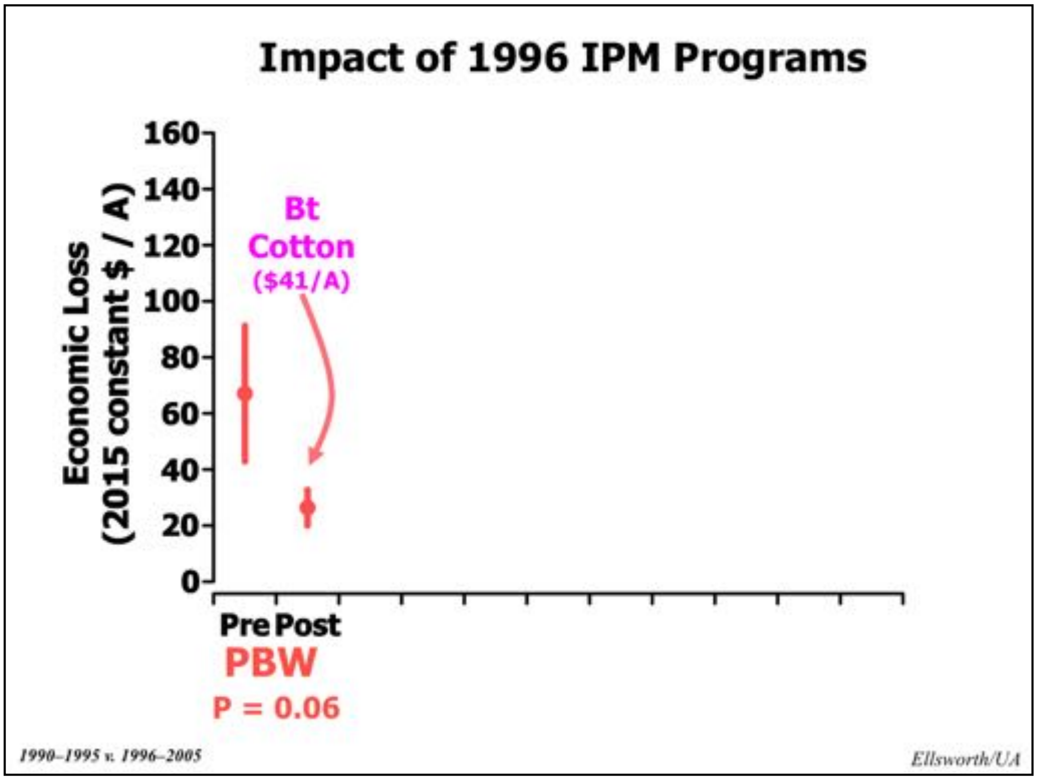


No native moth captures have been made since 2009 in Yuma and no PBW moths or larvae after 2010 over the entire 7-state region (4 U.S. states and 3 Mexican states).

Bt cotton was obviously critical to this major success.



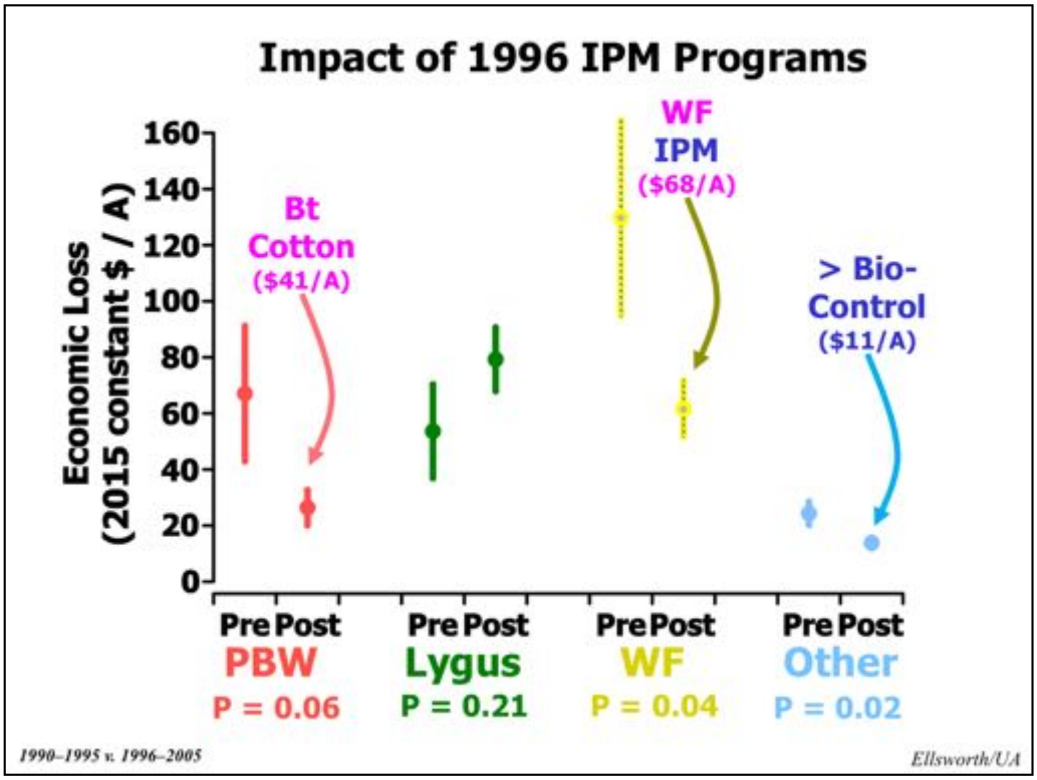
IPM, and largely through the proper deployment of Bt cotton, facilitated the eradication of the primary lepidopteran pest, the pink bollworm. It is important to note that refuge compliance pre-eradication was generally very good in Arizona and no resistances to Cry1Ac had been detected or advanced in the 10-yrs of deployment prior to the initiation of eradication program. It should also be noted that Arizona had a very aggressive plow-down requirement to assure a host-free period, with enforcement controlled by a grower-controlled organization and a gin rebate penalty for non-compliance. Once eradication was initiated, this same organization petitioned and received a Special Local Needs registration (SLN or 24c) of the Bt trait that permitted adoption of 100% Bt cotton (i.e., no planted refuge required).



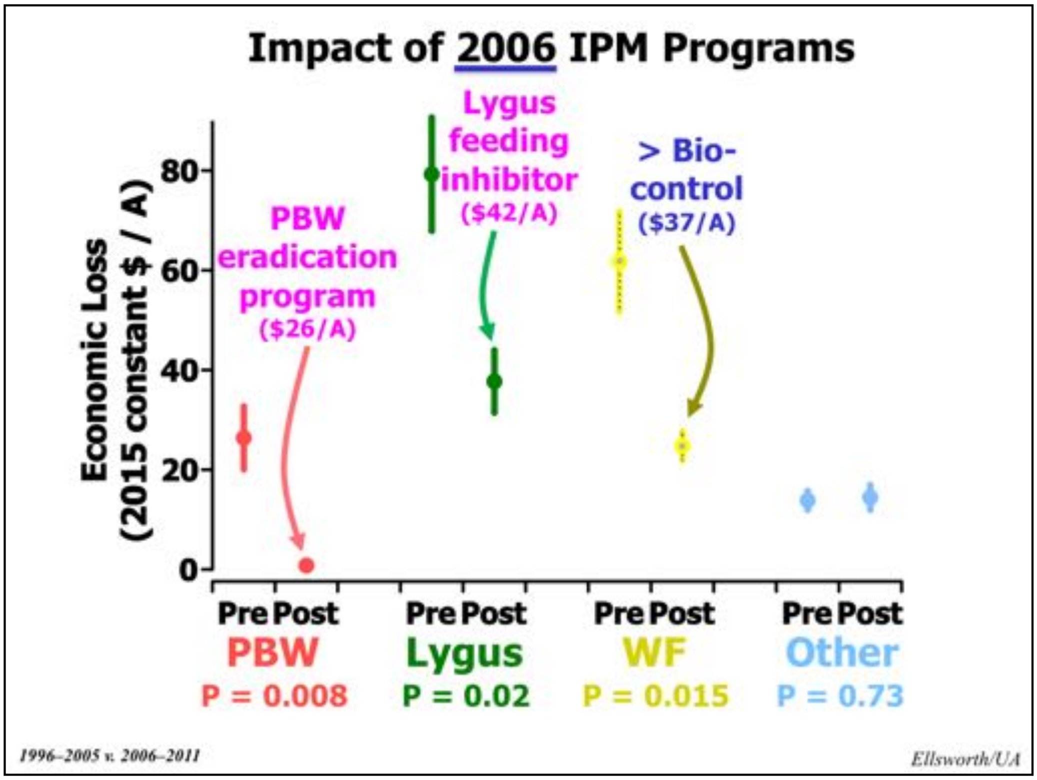
Comparing periods of time through history, we can examine each pest of cotton and ask the question of whether our IPM programs were coincident with the gains made in pest management.

This chart shows "Economic Loss" in 2015 constant dollars per acre by pest for a 6-yr period both before and after the introduction of our 1996 IPM program. There is a significant reduction in economic loss after the introduction of our IPM programs. For PBW, $41 per acre was saved in our system (but exclusive of gene/trait technology).

[No gains were made in Lygus management during this period.]



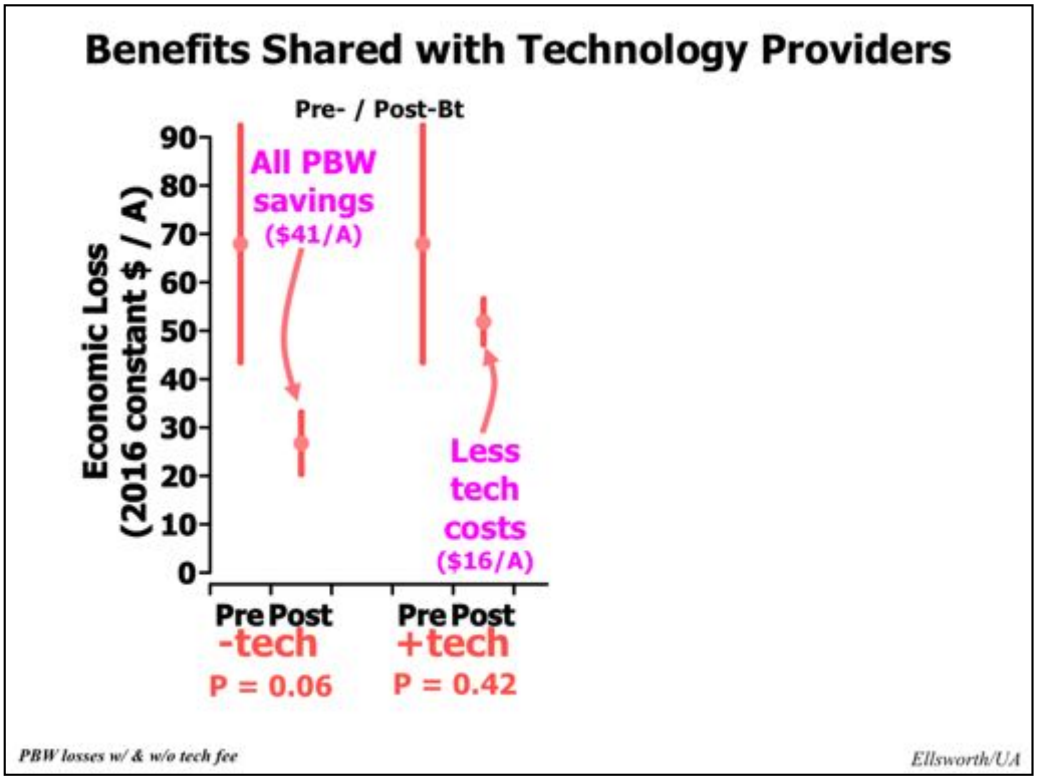
During this same period, we also see a $68/A gain to our growers in whitefly management. Again, some might point to the coincident deployment of the whitefly insect growth regulators, buprofezin and pyriproxyfen, and suggest "they" alone were responsible. However, the conservation of natural enemies made possible by the reduced / eliminated spraying for whiteflies & PBW along with the IPM plan taught to growers at the time was also contributing to these major advances in whitefly control. There were also significant economic gains in management of all other insect (and related arthropod) pests, with no associated "hard" technology deployed. Why? We suggest that this was due to the overall IPM plan, as designed, which was enabling natural forces including conservation biological control to better hold secondary pests in check.



Fast-forwarding 10 years to 2006 after progressive improvements to the system, we see additional gains made by our growers. $26/A more was gained in PBW management and some might suggest this was due to historic adoption of Bt cotton and the PBW eradication program*. $42/A more was gained in Lygus management; some would suggest that this was because of deployment of a Lygus feeding inhibitor.

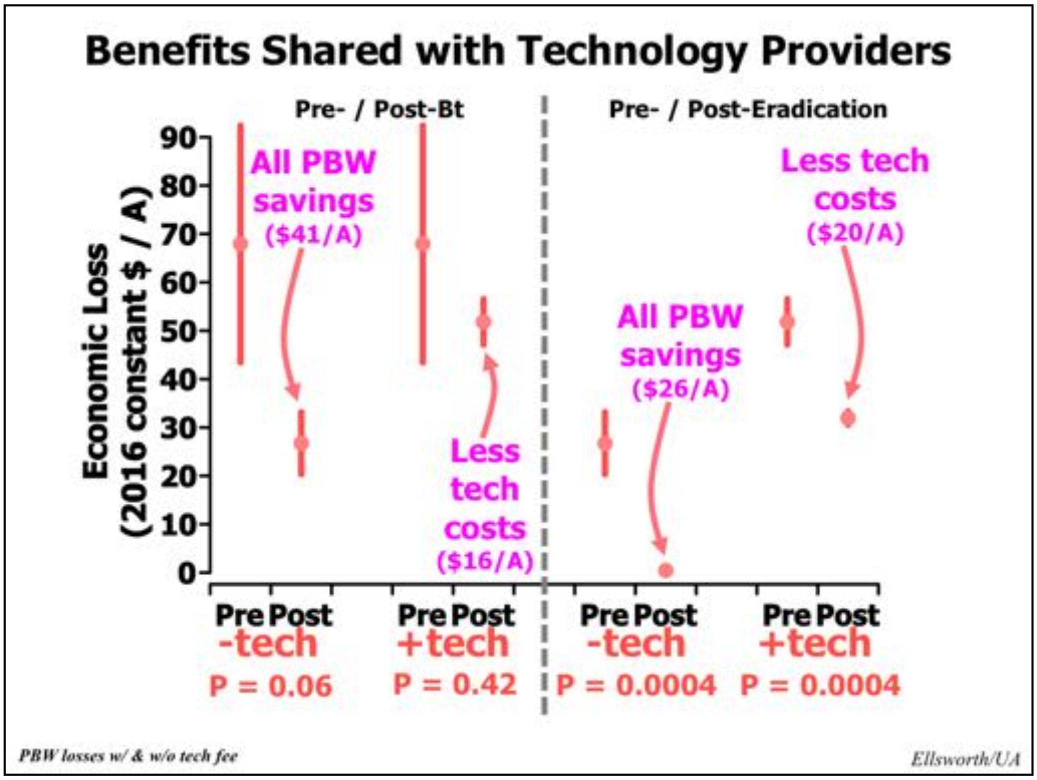
But what about whitefly management? No specific products were introduced at this time. Why then was there a gain of more than $37/A? What was the intervention made here? We suggest it is the additional biological control made possible through reduced spraying practices enabled by adoption of selective control technologies.

***Exclusive of Bt technology and eradication program costs.**



Stakeholders taken broadly have derived these economic savings; however, those savings are shared between the grower and the technology provider. This chart shows what the savings were both pre- and post-Bt cotton introduction as well as without considering the cost of the trait technology and with the trait technology. Obviously, grower savings are reduced by the amount they had to pay for the Bt technology. It appears that at least initially, Monsanto made a good estimate of the value of the Bt trait technology to growers, because they charged about what it would have cost for growers to have sprayed for PBW. However, while greater savings is desired by the grower, most had no problem adopting Bt cotton for the other benefits it provided, including conservation biological control.

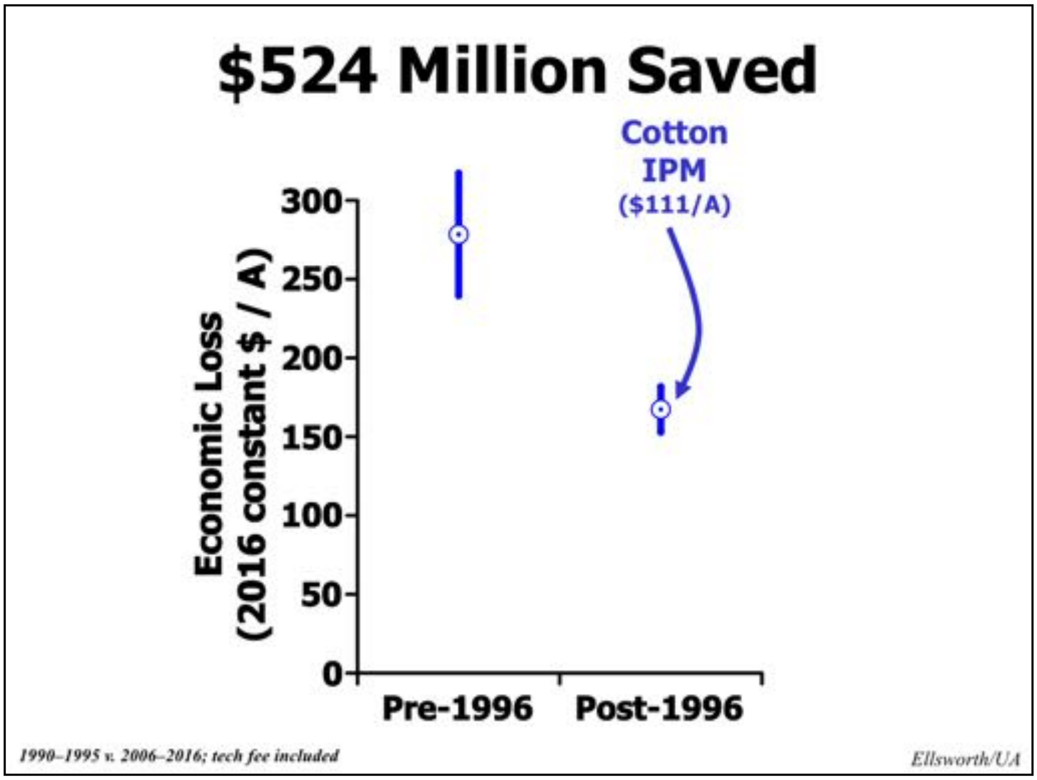
Pre = $67.94 Post =$ 26.73; Pre = $67.94 Post = $51.82



We can also look at the period just before and after the eradication program initiation. Here again, growers saved money after the eradication (exclusive of any program costs, which were on the minority of non-Bt acreages that remained, usually less than 3% of the acreage). Even when the cost of the trait technology is figured in, growers still saved money over the pre-eradication period, in part because of the yield loss and control costs that were still required on refuge acres prior to eradication.

However, what's interesting here is AZ growers are still paying for this trait technology without really gaining any direct benefit from the Bt trait itself. The primary target is gone! There are many reasons for this, not the least of which the advanced genetics are available in these same lines.

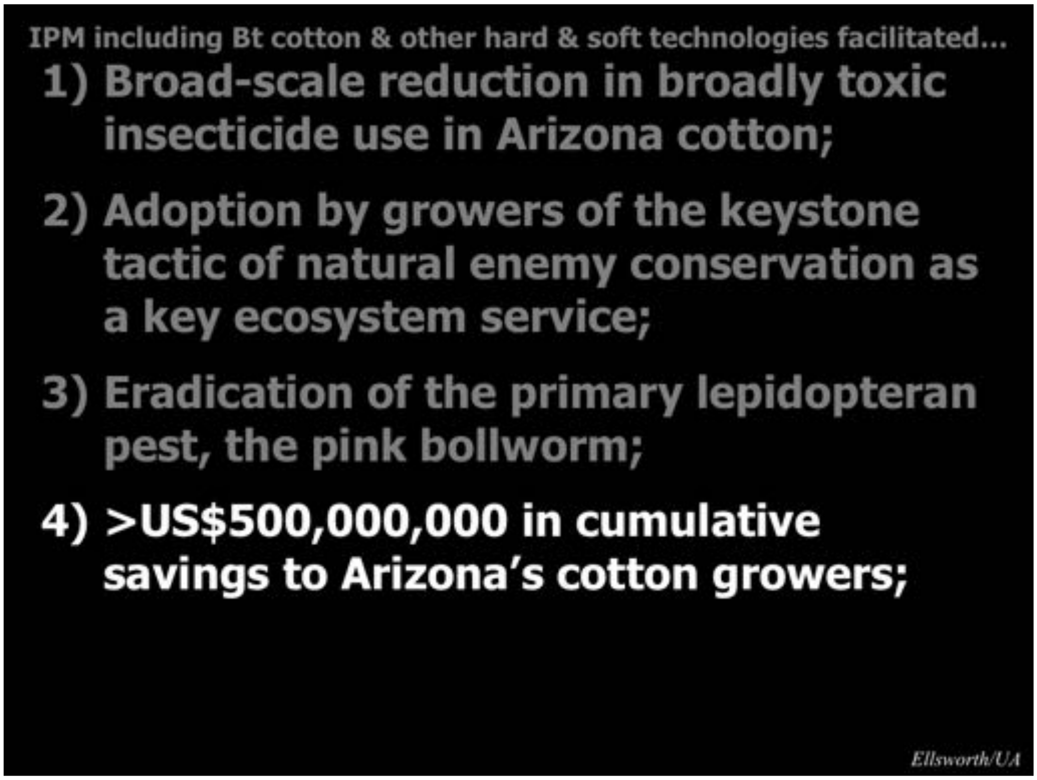
Pre = $26.73 Post = $0.44; Pre = $51.82 Post = $31.95



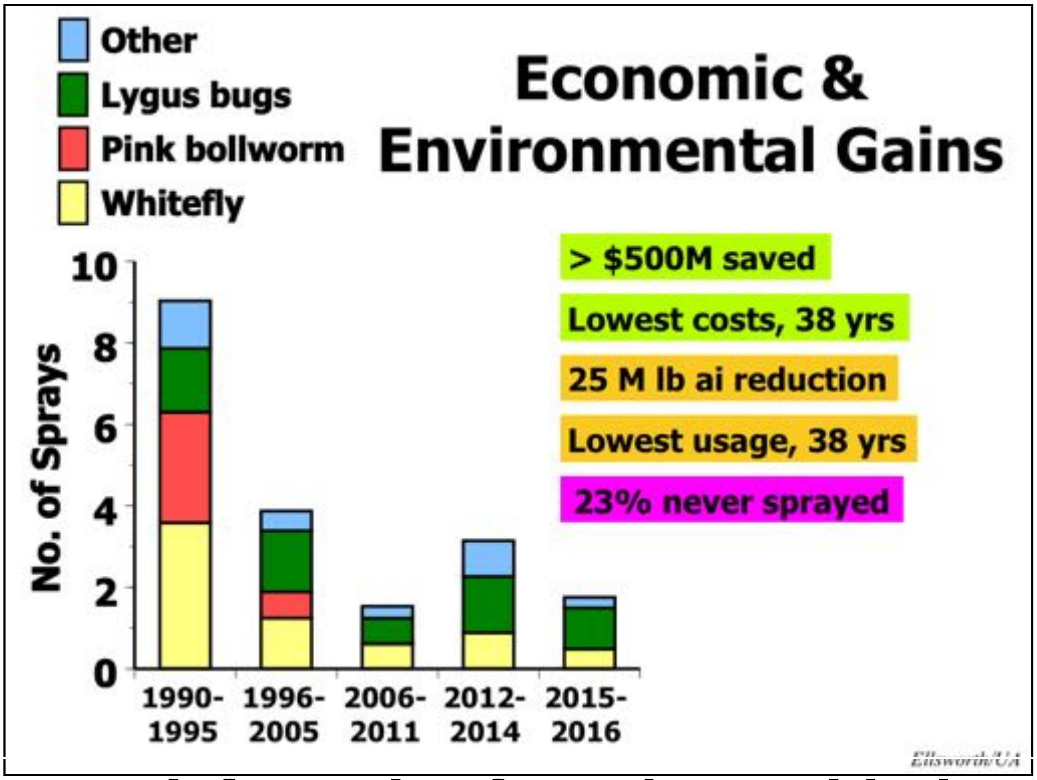
The gains through history since major adoption of both 'soft' and 'hard' technologies are very large for this industry sector. We estimate that since 1996, Arizona cotton growers have saved at least $523,533,918 through the 2016 cotton season, or ca. $111 / acre / year*.

[This estimate does not attempt to incorporate the additional benefits of preserving an economy and culture that may not have been possible if not for the advances made at the time. It also provides a low end estimate just because Pima cotton was included at Upland cotton prices which are considerably lower.]

***inclusive of costs to the grower of Bt trait technologies.**

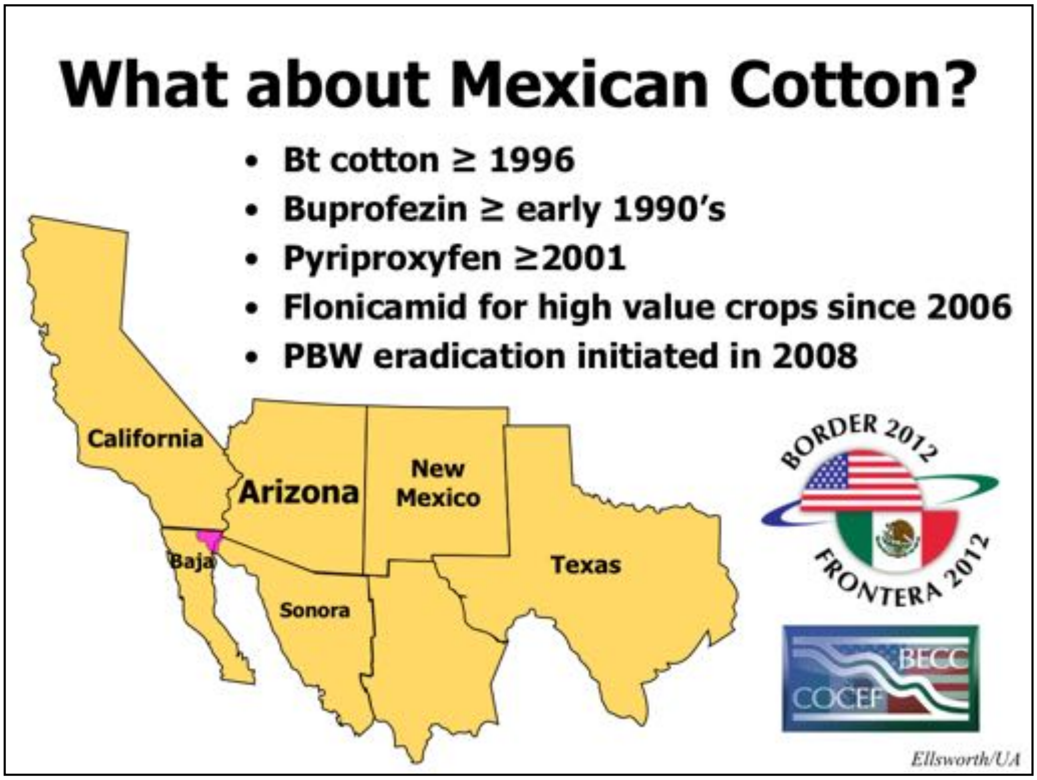


IPM facilitated cumulative savings of > half billion USD$ to Arizona cotton growers since 1996 (through the 2016 season).



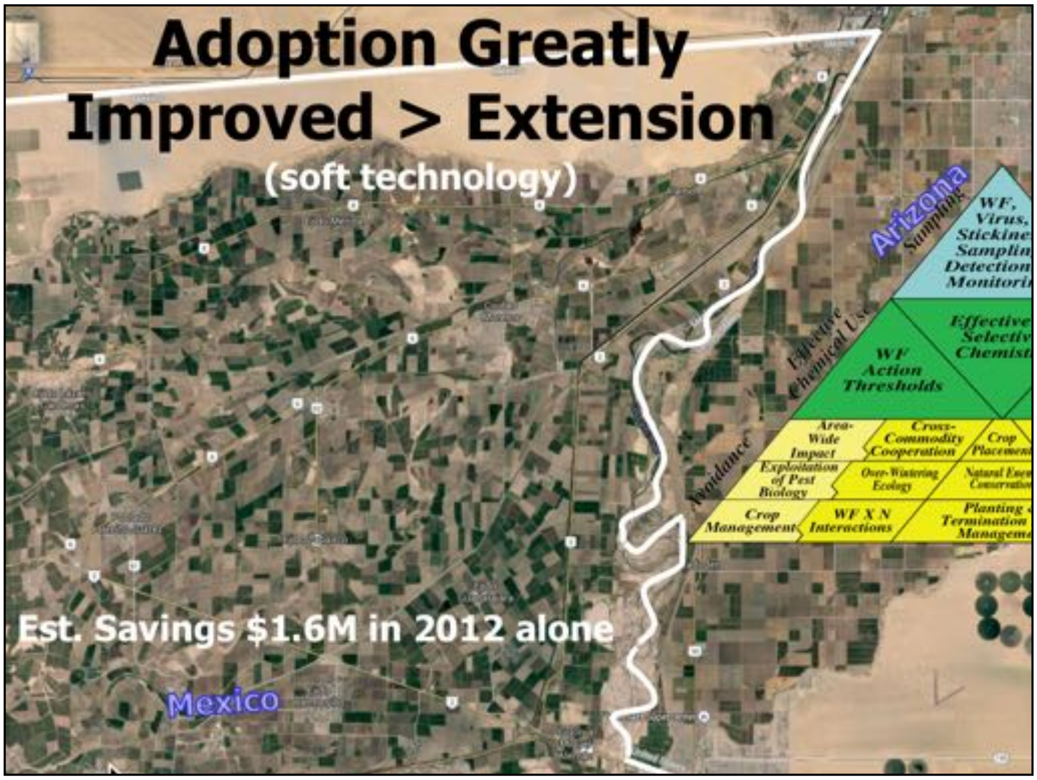
If we draw out information from these critical periods, we can see rather dramatic declines in overall insecticide use, as well as huge declines in PBW, Lygus and whitefly sprays made by growers. At one time, we averaged 9 sprays. Our 1996 programs cut that by more than half to ca. 4 sprays, and our 2006 programs have cut this by more than half again to just 1.5 sprays. In the process we are in the lowest foliar insecticide control costs in history, we're spraying less than at any time in history, and have saved growers cumulatively over $500M in 2016 constant dollars and prevented over 25M lbs of insecticide ai from reaching the environment.

Most importantly, 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. The economic value of these environmental gains have not been estimated.



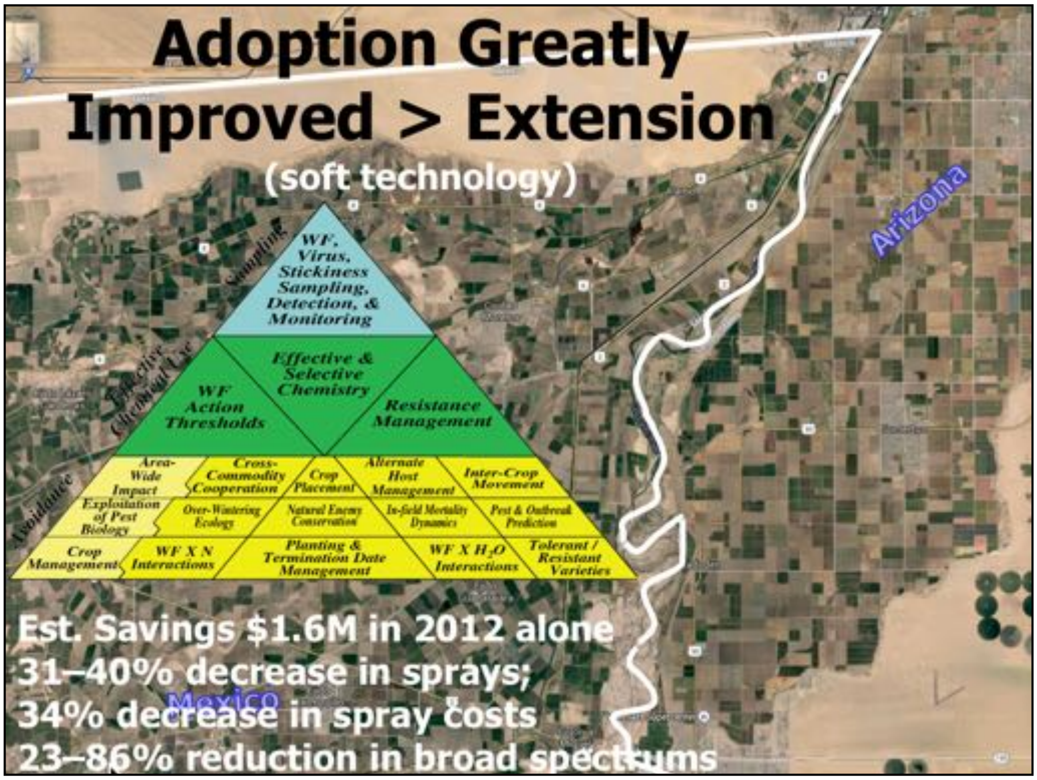
So, what about Mexican cotton throughout this period. The Mexicali and San Luis Valleys lie just south of the California and Arizona borders in the states of Baja California and Sonora and divided by the Colorado River. This is the largest cotton production region of the country and is eco-regionally similar to Arizona.

They in fact had access to much of the hard technologies that were in use in Arizona. Bt cotton, the whitefly IGRs and even PBW eradication was operational there. Yet, in 2010, growers of cotton in this region were conducting pest management as if it were 1991! While some benefits were realized – they did adopt Bt cotton and later herbicide tolerant cotton — they were spraying nothing but broadly toxic pyrethroids, organophosphates, and endosulfan.



The US-EPA's "Border 2012" program was designed in coordination with Mexican government to fund pollution prevention projects within 100 km of the U.S. – Mexican border from California to the southern tip of Texas. EPA approached me after noting the success of the Arizona cotton IPM program and asked if I could effectively extend our model to Mexico's largest cotton production region along the border with Arizona and California.

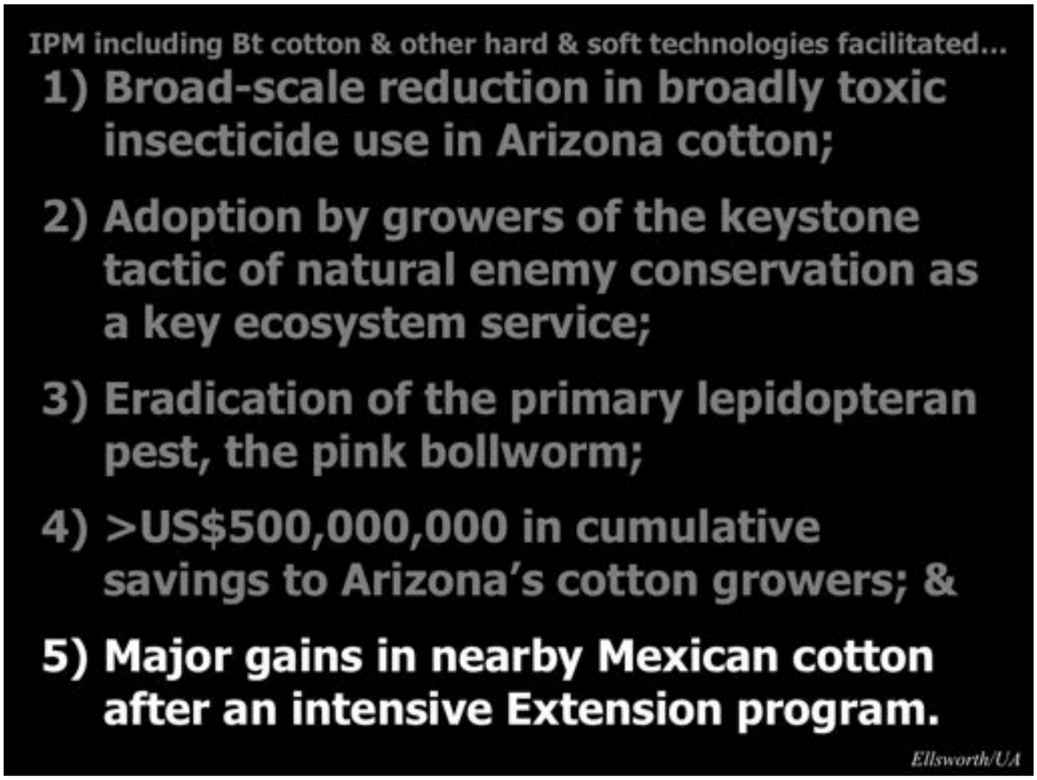
Clearly the mere existence of one or more hard and/or soft technologies was not sufficient to fuel the change needed there. The entire plan and all of its components were needed in Mexico. And despite their general and passive availability to Mexican growers previously, certain hard and soft technologies had not been introduced and taught to growers properly.



Over the next 17 months, we attempted to translate 17 years of Arizona cotton IPM progress into an improved Mexican cotton IPM program there.

Our Extension effort encompassed a broad program of activities (totaling 1214 contact hrs & 100 site visits): validation research, grower demonstration trials, newly introduced or re-introduced hard technologies (especially flonicamid for Lygus and buprofezin, pyriproxyfen & spiromesifen for whiteflies), other tools (the Arizona whitefly sampling loupe & sweepnet), new and translated IPM publications, farmer field workshops, pest manager advisor seminars (technicos) and trainings.

We estimate that we helped growers save > US$1.6M in 2012 alone, with more savings accruing and accelerating in 2013, with large reductions in numbers of sprays and in use of broadly toxic insecticides.



IPM with the requisite soft technology helped to facilitate major gains in nearby Mexican cotton, but only after an intensive Extension program.

Hopefully this presentation supports the idea of examining and analyzing a system in its entirety and discourages sole focus on a singular tactic, like Bt cotton, to the exclusion of consideration of all the interacting tactics that IPM seeks to blend and optimally deploy such that economic, environmental and human health interests are protected.

In addition, it should become clear that one reason why deployment of Bt traited crops have been only variably successful is because of variable investments in the allied hard and soft technologies needed, as well as Coopeative Extension to support the trait technology.

We thank the supporters and collaborators of our research and outreach programs, who are many and span many years!

Special thanks to the Western IPM Center for a Signature Program grant that supports our contemporaneous measurements and analyses of grower pest management behaviors through time. Also, to the US-EPA Border 2012 program that supported the 17-month Extension project in Mexico, and to the very cooperative Mexican cotton growers and technicos who assisted us during this project.

Most all we thank Dr. Ramon Cinco, formerly of Algodonera de Baja California, and his major and critical leadership on behalf of the entire agricultural industry of Mexicali and San Luis Valleys of Mexico.

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