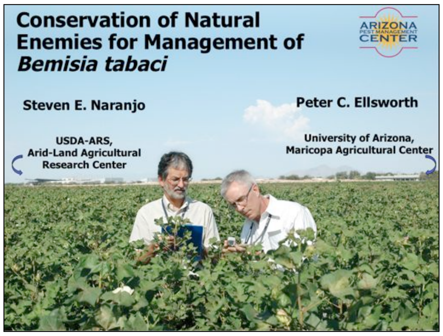
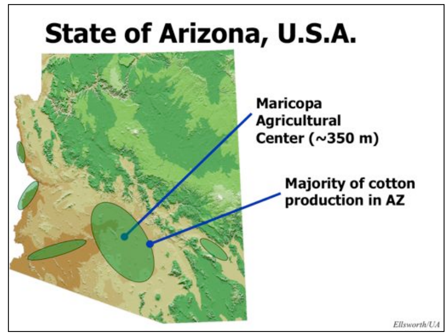
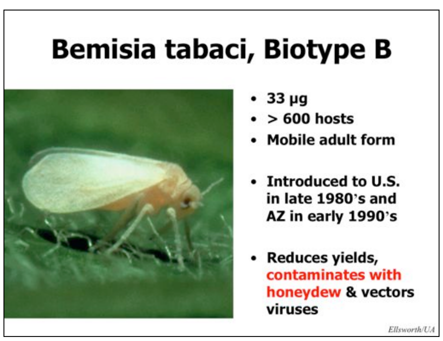


This presentation is dedicated to the topic of natural enemy conservation for management of Bemisia tabaci. I will review work that Steve Naranjo and I have collaboratively developed over the last 15–20 years. We are both located in Maricopa, AZ, he with the USDA-ARS, ALARC facility and myself with the University of Arizona Maricopa Agricultural Center. Our collaboration has resulted in or is at least coincident with a rather stunning recovery of an industry threatened by this pest insect.

Invited presentation at the European Whitefly Symposium, 80 people in attendance.



My location is in the center of ca. one quarter million acres of cotton in the central part of the state. Pinal County, where we are located, has one of the highest concentrations of cotton in the country. Arizona produces the highest yielding cotton in the world with very high fiber qualities sought after by buyers around the world. This is a desert, very arid environment where some host of Bemisia tabaci is growing year round.



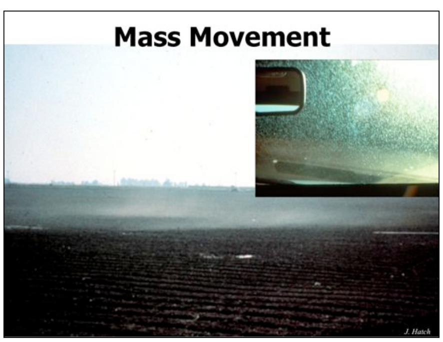
This biotype of Bemisia tabaci was introduced to the U.S. in the late 1980's and invaded AZ in the early 1990's. The B-biotype or MEAM1 was devastating, reducing yields and contaminating agricultural products with honeydew.

The problem starts with the insect, but the driver of this system is what is shown in this micrograph of a cotton thread. While yield losses have always been a potential problem, the real problem is the deposition of honeydew on exposed cotton lint that then is processed, if it can be processed at all, and spun into a thread loaded with these defects. So a 100 million dollar problem starts with honeydew dropping on leaves, and cotton fibers, and finishes with knotted fabrics or yarns. Costly shutdowns of mills for cleaning motivates the marketplace. Marketers play it safe by avoiding buying fiber from whole areas where previous episodes of sticky cotton have occurred. This has a chilling effect on cotton prices locally. [Photo credits: International Textile Center (Lubbock, TX), upper left, Lynn Jech (inset), USDA (wf), pce (remaining)].

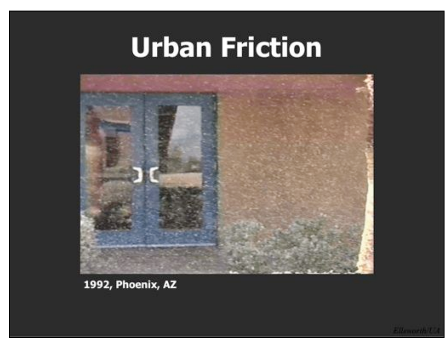
Our largest challenge was to protect the major summer crop, cotton, from unacceptable losses of quality due to honeydew and sooty mold contamination. In 1992, when this was shot, we had little to control these whiteflies, depending on pyrethroids, organophosphates and endosulfan.

This "new" pest attacked many different crops. Here, adults cover the surface of a cotton leaf, and the immobile immatures (eggs and nymphs) encrust the leaf underside.

And, we were facing an a priori resistance in that the invading whiteflies were already insensitive to pyrethroids as well as organophosphates.

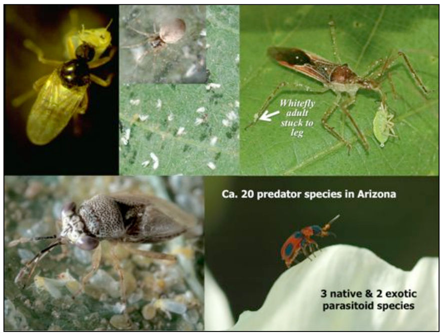


This is a mobile insect, as is evident in this now famous slide showing "clouds" of whiteflies moving across a newly planted vegetable field in the Imperial Valley of California in the early 1990s. Pressures were so extreme at that time that driving through the valley would actually cloud up your windshield.



This was the scene we were facing when the invasive B-biotype came to Arizona. 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.

The urban friction caused was substantial, where residents had to wear masks just to jog or ride a bike in the fall of 1992.

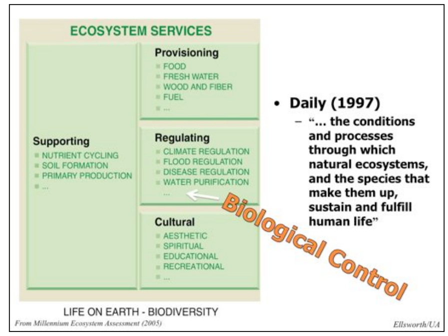


Whilst on this was happening, we already had a large complement of potential generalist predators. Since that time Hagler and Naranjo immunologically confirmed the predatory roles of some 20 species, just a few pictured here.

We also have 5 parasitoids currently.

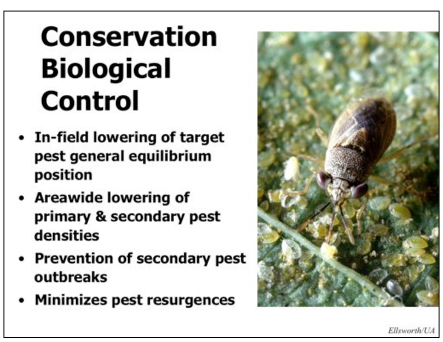
However, this complex alone was not sufficient to overcome the sorts of numbers shown in the previous videos. But their impact was and is important in our very successful management system of today and the last 15 years.

Encarsia sophia and Eretmocerus nr. emiratus (exotics), which replaced Eret. eremicus; other natives: Enc. meritoria and Enc. luteola.



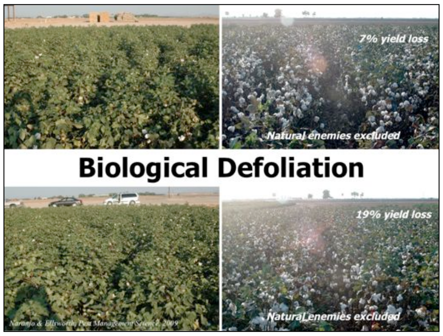
Gretchen Daily at Stanford was instrumental in the development and popularization of the concept of "ecosystem services." Ecosystem services are quite simply defined as those things contained in our ecosystems that sustain our life. Daily's original definition focused on "natural" systems; however, the concept has expanded appropriately to encompass the interrelationships between natural and managed ecosystems.

These services are often broken down into categories. Biological control or pest population regulation services provided by natural enemies is a key "regulating" ecosystem service.



Conservation biological control (CBC) can function to lower the general equilibrium position of the target pest in the field under management Practiced widely enough, it should lead to an areawide lowering of both primary and secondary pests. CBC is often critical to prevention of secondary pest outbreaks and minimization of pest resurgences.

Peter Asiimwe, our current graduate student, is trying to understand the relative contribution of NEs and irrigation to the control dynamics of ***Bemisia***. In this work, we had plots where NEs were chemically excluded by using a common Lygus insecticide. These broad-spectrum sprays released whiteflies from the natural control possible in the right-hand figure. The result was very sticky and sooty cotton. The left side was never sprayed at all.

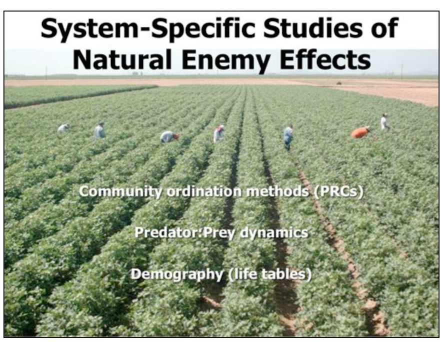


The potential role that NE's play is graphically shown in these photo contrasts. There were major losses to whiteflies where NEs were chemically excluded. These paired pictures were shot on the same day (2 weeks after the ones shown on the previous slide) and show cotton that was biologically defoliated by this sucking pest. The cotton on the left was never sprayed for any pest and also had commercially unacceptable whitefly levels but at much lower densities than in the exclusion plots.

This example stresses the interactions of our control systems for Lygus and whiteflies. That is, no matter how selective our control system is for whiteflies, if growers are spraying for Lygus or other pests with broad-spectrum materials, selective advantages may be lost.

So it has been long enough now since these terrible scenes that there are growers and pest managers who are too young to recall the situation. So I now use this video to show to them and pose the question, "In what year was this video shot?" Invariably several people will guess 1992, 1995 or early 1990's.

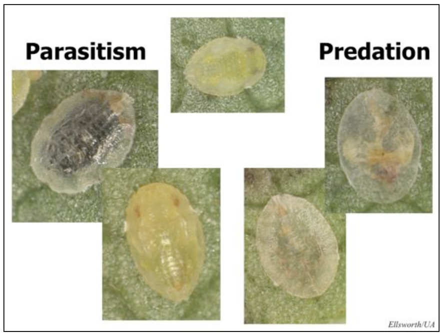
However, this was shot in September 2010 in plots where we made a set of bad decisions. This emphasizes that 1992-like conditions can be "created" in any year or in any location where inappropriate decision-making takes place.



Over many years, Naranjo and I along with students, post-docs and plenty of technical help have conducted ecosystem-specific studies and used various approaches to identify the presence and function of natural enemies and the impact of all mortality factors.

These include community ordination methods that permit the analyses of whole NE communities and construction of Principal Response Curves (PRCs); exhaustive surveys of canopy arthropods and whitefly densities to develop predator:prey ratios; and demography. From these data, we constructed life tables that tell us what mortalities are operational and which ones are most influential in population regulation.

This is not easy work, but is made easier by the fact that this animal has two immobile life stages, the eggs and the sessile nymphs. By marking the specific locations of eggs and nymphs in the field, we are able to track and document the timing and type of death experienced by each whitefly, as well as those that do manage to survive.



Examples of NE activity can be found and identified in the field.

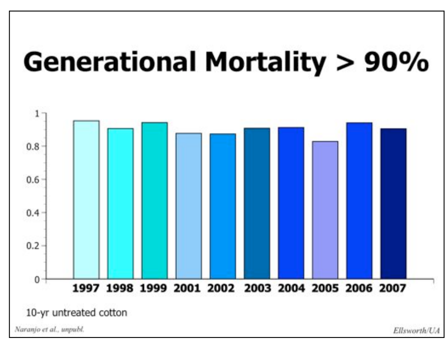
Eretmocerus nr emiratus, Encaria sophia.

Encarsia sophia and Eretmocerus nr. emiratus (exotics), which replaced Eret. eremicus; other natives: Enc. meritoria and Enc. luteola.

Feeding by Orius (incomplete evacuation of cadaver contents) and Geocoris (complete evacuation).

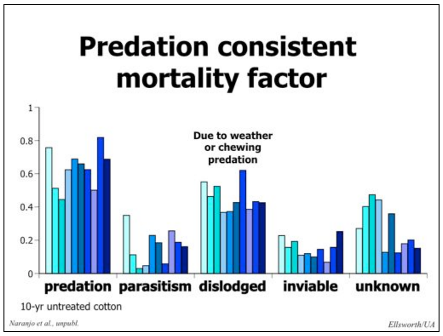
We are also able to identify mortality associated with significant weather events like these dry dust storms that travel over our landscape during the monsoon season. These haboobs carry with them dust and high winds that can abrade leaf surfaces that remove whitefly eggs and nymphs. However, the distribution and timing of these haboobs and monsoon rains are very difficult to predict and can be very localized.

Some of you may have seen the international reports of a large haboob that traveled from the south to the north through urban Phoenix last July.



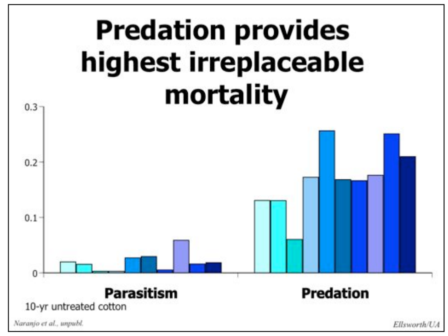
2011 was the first year since 1996 that Steve and I did <u>not</u> conduct life table studies in the field. Here are 10 years of results for untreated cotton. What is striking is how uniform the results are, ca. > 90% mortality is common in cotton.

(These are apparent mortalities for 2–6 generations of whiteflies on untreated cotton for each year.)



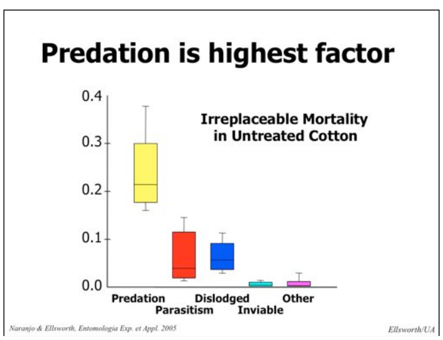
Teasing this mortality out and looking specifically at marginal mortality rates, which attempt to account for the contemporaneous processes of mortality, we can see right away that predation by generalist, usually sucking, predators is quite high and consistent over time. It is especially high when one considers that chewing predation is tied up in the "dislodged" category with weather. That is whiteflies that disappear during the course of the life table are lost either to the physical effects of weather (the haboobs) or to removal by chewing predators who leave no trace of a cadaver.

(These are marginal mortalities by source factor in untreated cotton.)

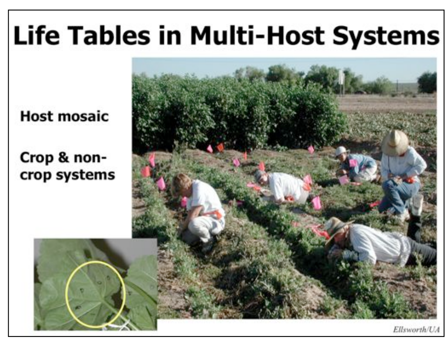


Irreplaceable mortality estimates the amount of mortality that would fail to occur if not for the operation of a given factor.

In this analysis, it shows how important predation is and how much higher it is than the irreplaceable mortality supplied by parasitoids.



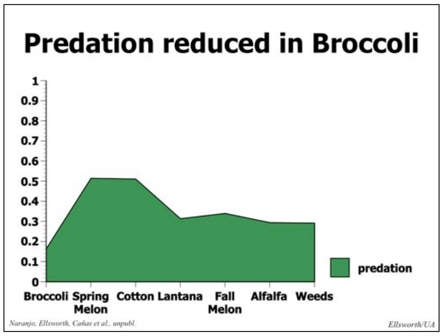
These are irreplaceable mortalities over 14 generations in box-whisker plots. Predation is by far the most important mortality factor. The remaining factors are not nearly as important. Incidentally, despite major changes, if not, wholesale species replacements over the last decade, parasitoids exert very little irreplaceable mortality. Here, too, a portion of 'dislodged' is due to chewing predation (& part to haboobs).



We also conducted life table studies in multi-host systems where crop and non-crop hosts were arranged in a field mosaic. Here the crew is marking the locations of a new cohort under study in a fall weed system.

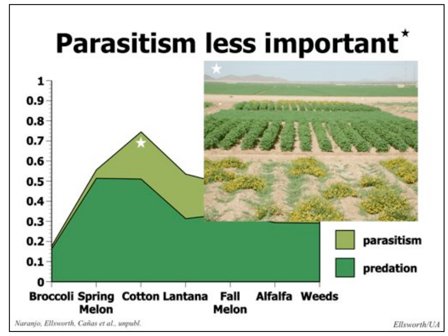
Individuals are marked on the undersides of leaves and then revisited regularly to determine the fate of each insect.

Crew establishing a *B. tabaci* cohort in *Sonchus asper*.

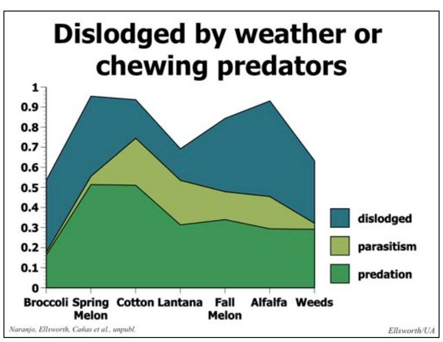


Hosts are arranged roughly according to season, starting with broccoli in the winter, spring melon in the spring and summer, cotton in summer, Lantana and fall melon in summer and fall, and alfalfa and weeds in late summer, fall and winter.

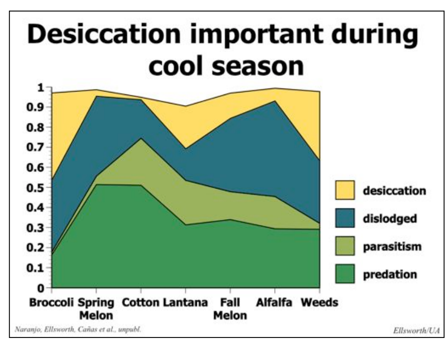
These are distribution of k-values by factor and host in untreated systems, and show that there is a significant impact of predation in all systems though predation is reduced in broccoli.



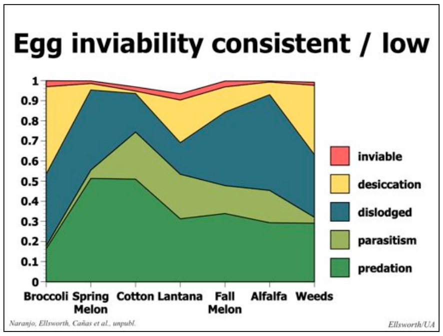
Parasitism in general across all host types is less important and almost non-existent in the broccoli and weed systems. Despite this, this is the highest amount of parasitism that we have measured in cotton, and perhaps this is because of the relatively close association of so many other host plants in this small mosaic (see photo).



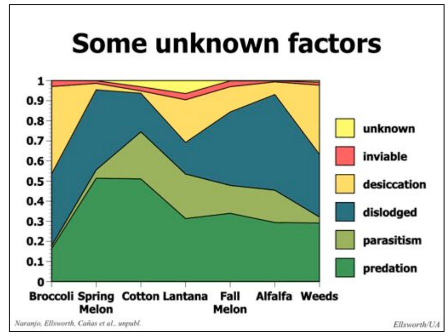
Dislodged mortality is rather consistent across the host systems, though somewhat higher in alfalfa.



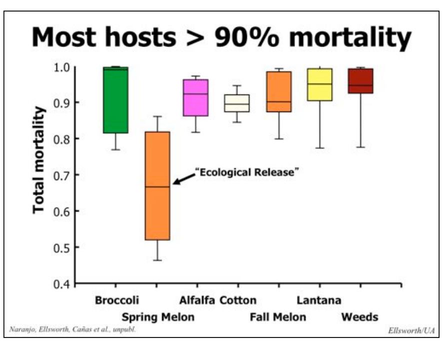
Desiccation sometimes related to leaf quality and senescence, and often associated with lower temperatures is noticeably higher in the cool season generations. These were conducted in broccoli, Lantana, fall melons, alfalfa and weeds.



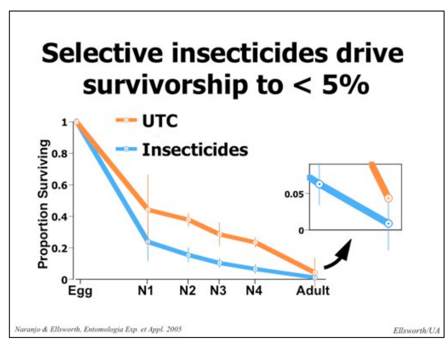
Egg inviability was consistently low across all hosts with no obvious pattern of importance.



Then there remain the few unidentifiable mortality factors, which seem to be restricted to the summer generations of cotton and Lantana.



High rates of natural mortality are obvious in cotton; however, what is striking here is how consistently high natural mortality is in a wide array of (and otherwise very different) crop systems. More striking perhaps is that spring cantaloupes are subject to much less natural mortality than any other host system. As a result spring melons serve as an "ecological release" of Bemisia in our system, and we do have a large and widely dispersed spring melon production in Arizona.



From our life table studies, we can construct survivorship curves. In untreated systems, whiteflies survived to adult at what appear to be very low rates. Rates that belie the explosive potential of this pest.

When we compare this to systems managed with these selective insecticides, we see what appears to be only a subtly different outcome.

There is a difference in survivorship: the orange line represents an out-of-control growing population, while the blue represents a well-managed system with collapsing populations. Thus, we are trying to leverage, on average, only about a 4% absolute or irreplaceable change in survivorship by using insecticides.

Integrated Control

"*Applied pest control which combines and integrates biological and chemical control.* Chemical control is used as necessary and in a manner which is least disruptive to biological control."

Stern, Smith, van den Bosch & Hagen 1959, Hilgardia

Ellsworth/UA

Stern, Smith, van den Bosch & Hagen more than 50 years ago developed the conceptual underpinning and precursor to modern day IPM. At a time when DDT usage was at an all time high, when Stern was studying spotted alfalfa aphid outbreaks in alfalfa, when that system was completely dependent on parathion sprays, they proposed the combination and integration of biological and chemical controls as key to achieving "Integrated Control".

Integrated Control

"Integrated control is most successful when sound economic thresholds have been established, rapid sampling methods have been devised, and selective insecticides are available."

Stern, Smith, van den Bosch & Hagen 1959, Hilgardia

Ellsworth/UA

They also identified the specific steps for realizing the Integrated Control Concept:

You need economic thresholds, rapid sampling methods, and selective insecticides.

Selective Insecticide

"Chemical control should act as a complement to the biological control."

Chemical and biological control... "with adequate understanding, can be made to augment one another."

"An insecticide which while killing the pest individuals spares much or most of the other fauna, including beneficial species, either through differential toxic action or through the manner in which the insecticide is utilized (formulation, dosage, timing, etc.)."

Stern et al. 1959. Ellsworth/UA

At the heart of Stern's paper, they make several important, simple, and straight-forward statements about chemical control. Namely, chemical control should complement biological control; and the two tactics should be made to augment one another. Within the ICC there is this pervasive idea that an insecticide should kill the target but spare most everything else. Given the times, and given the tools available at the time (DDT, toxaphene), these ideas were rather controversial especially within the agricultural community. Also, much of Stern's hopes for selective insecticides were pinned on the development of new organophosphate and carbamate insecticides!

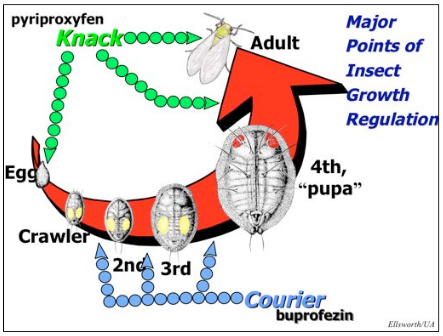
Bioresidual

"Combined contribution of all natural mortality factors ...that allow for lowering of the general equilibrium position of the target pest and long-term pest control following the use of selective insecticides."

Naranjo & Ellsworth. Biological Control, 2009 Ellsworth/UA

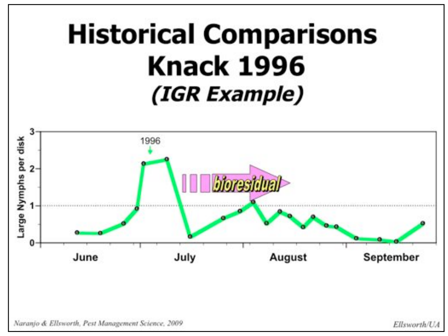
We coined the term "bioresidual" as a means to better describe and communicate to growers about the importance of integrated natural controls with selective insecticides.

In teaching this concept to growers, I used a familiar icon as a metaphor, the IGR jug. In essence, our work showed that about half of the control interval could be directly attributable to the toxic growth-regulating effects of the IGR, while the other half was due to the biological or ecological sources of mortality that are in place already but are made more effective by the selective reduction of the previously "out of control" host, the whiteflies.

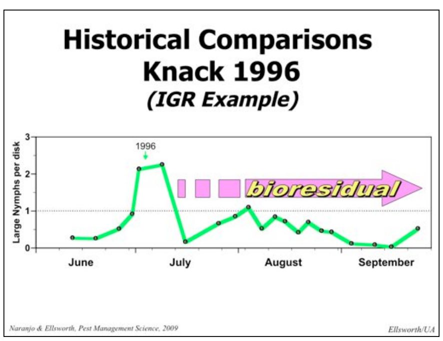


When the B-biotype first invaded, we only had pyrethroids, OP's/carbamates, and endosulfan. With an EPA Emergency Exemption in hand in 1996, we had access to two new insect growth regulators first used against whiteflies in Israel. Pyriproxyfen is a juvenoid, a juvenile hormone mimic, that does not kill adults outright -- neither IGR does this -- however, Knack sterilizes adult females and developing eggs prior to blastokinesis. Knack may also prevent metamorphosis. Buprofezin is entirely different chemistry structurally and functionally. It is a chitin inhibitor and as such interrupts the molting of each nymphal instar.

Both of these IGRs are selective in our system, ultimately killing only our target pest, the whitefly.

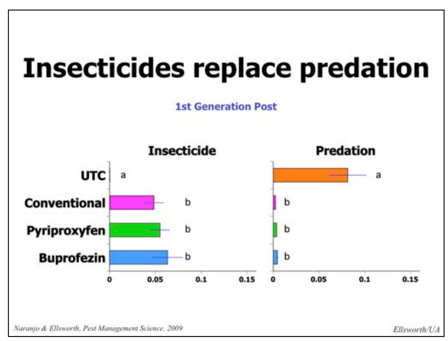


Our IGRs are the classic example of selectivity in action. We've been running commercial scale demos for years, starting in 1996 with the whitefly IGRs. In this one example with Knack in 1996, we can see that we reached threshold (1 large nymph per disk or 40% infested disks), sprayed, densities continued up for a time, and then the population collapsed. We know from our studies that the chemical effects of Knack last only a few weeks at best, but…



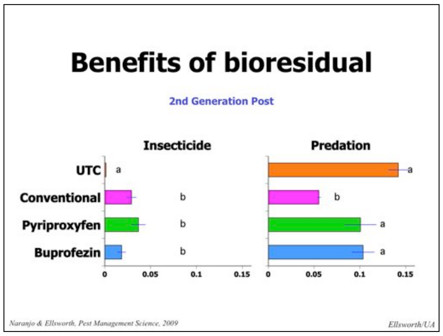
… through the action of predators especially, and other natural sources of mortality, the whitefly population is maintained below threshold well beyond the known period of chemical residual. We term this extended suppressive interval present in a selective system, "bioresidual". We coined this term to better communicate with growers and to accommodate all the mortality processes present in a selective system, not just those related to conservation biological control.

The duration of the bioresidual is indefinite as one would expect in a biological system that is impacted by an array of dynamic factors.



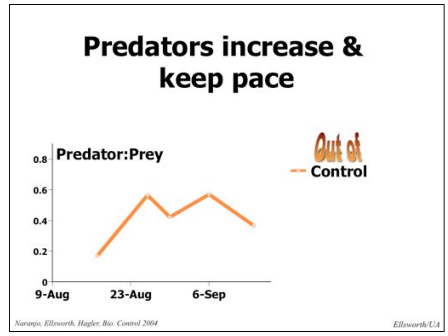
We examined patterns of irreplaceable mortality in selective vs. conventional systems. The two major sources of mortality are "insecticide" and predation. No insecticide-related mortality was measured in the UTC, but similar levels for each compound used in the first generation exposed to the sprays. Predation, however, was significantly higher in the UTC. Even though predation is present in the IGR regimes, it is less irreplaceable because of the insecticidal action of the IGRs.

If we advance our time step to the next generation, ca. 3-6 weeks later…



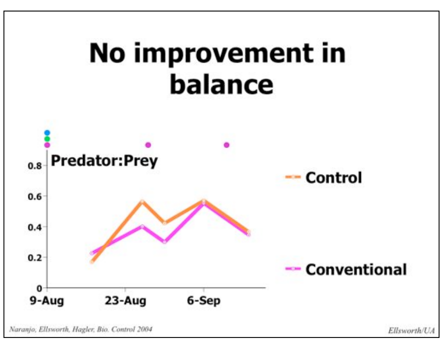
Looking at the next time course, i.e., the 2nd generation after initiating sprays, we see that rates of insecticidal mortality are still present where insecticides are used, but lower than before. Residues are diminished. Irreplaceable mortality due to predation, however, grows substantially in the IGR regimes, but much less so in the conventional regime. These levels of irreplaceable mortality in the IGR regime are very similar to what can be seen in the UTC.

Thus, the bioresidual effect is starting to exert influence over the population, because predators in particular were selectively conserved in the IGR system.



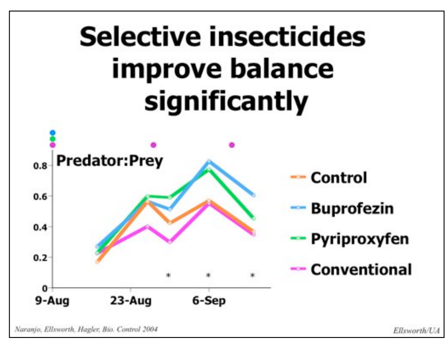
We can also examine Predator : Prey ratios. In this example, all predators captured in 50 sweeps compared to all whiteflies per leaf in cotton. Here we see that predator numbers increase and stay level relative to prey numbers, which are increasing through this time period.

This "Control" is producing out-of-control whitefly populations.



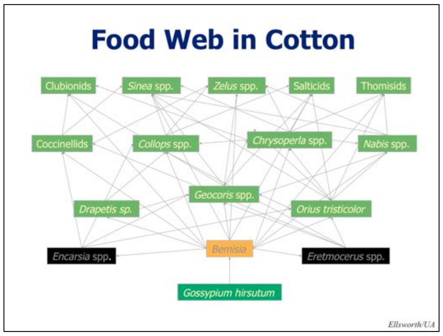
Conventional sprays served to lower prey densities, but predator densities as well. Thus, there is no improvement in the balance.

Whiteflies are in fact well-controlled by conventional chemistry but required 3 sprays to do so in this example.

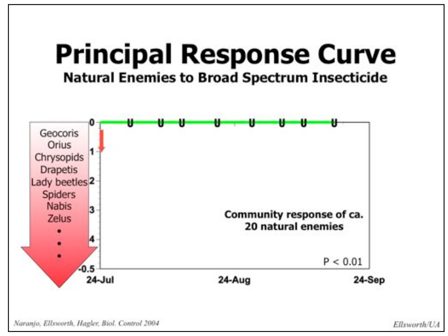


IGRs on the other hand not only reduce prey numbers, they conserve existing predator numbers and create a more favorable balance of predators to prey resulting in a more efficient control system that creates collateral benefits in regulation of other pests in the system as well. Only 1 IGR spray was needed.

So this tells us that there are predators serving an important role in the biological control of this pest when selective insecticides are used. However, it does not tell us which species are important in these dynamics.

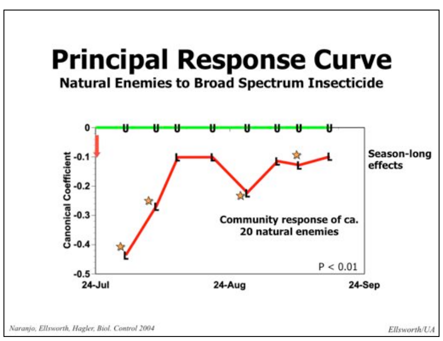


The food web in cotton is complex and dynamic. How one determines which species are driving the system has historically been a difficult problem to deal with. Experimentally, people have tried caged systems that exclude all predators or confine one or a few species with fixed numbers of prey, and even then usually only the target pest as the prey item. These are highly artificial conditions. Survey work has sometimes focused on one or a few species and failed to identify consistent patterns and relationships. These problems faced us as well; however, we applied some multivariate approaches to our data, which help us understand the complex dynamics that are operational when selective insecticides are used.

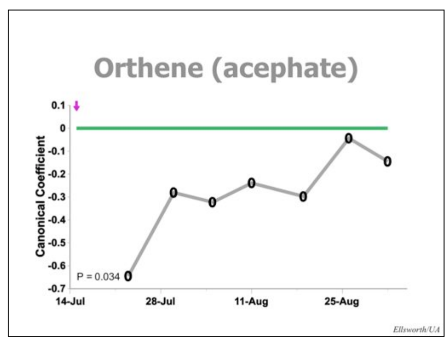


We used a multivariate, time-dependent, analytic approach that is represented graphically in Principal Response Curves. In this example we can see the green 'U' line representing the UTC as a baseline from which we compare other treatments. Departures from the baseline may be interpreted as density changes in this natural enemy community. In our case, we track densities on ca. 20 different species or species groups. The red arrow indicates the timing of a single, very broad spectrum insecticide sprayed to control Lygus in a study that we did several years ago…

U = UTC = Untreated check

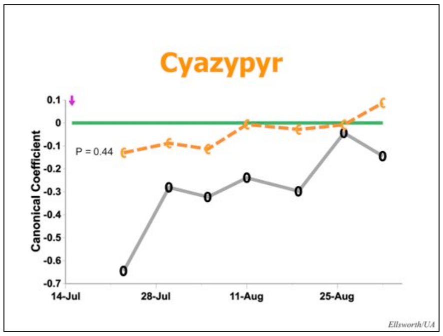


…What we see is a dramatic and immediate lowering of the density of these natural enemies in comparison to the UTC. What is more sobering is the duration and significance of this effect, all the way out to 7 weeks post-treatment. These season-long effects have grave consequences in the control of many other primary and secondary pests. Each PRC is accompanied by a table of species weights for each species represented (not shown). We have shown in past analyses that both buprofezin and pyriproxyfen are fully selective in our cotton system. We have extended this approach to examine candidate, novel compounds so that we can properly advise growers on how to exploit selectivity and biological controls.

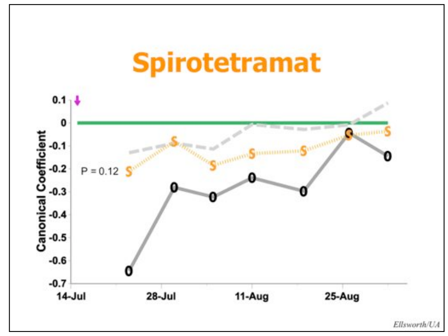


In this recent example, acephate was used as our standard broad-spectrum insecticide.

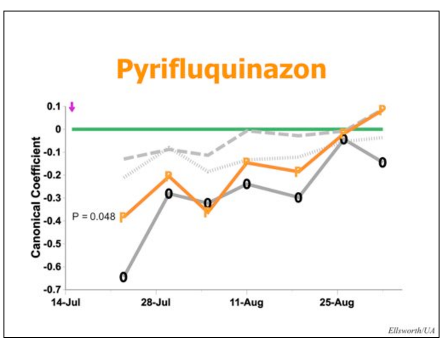
Orthene when used just once is highly destructive to the NE community present in our cotton system.



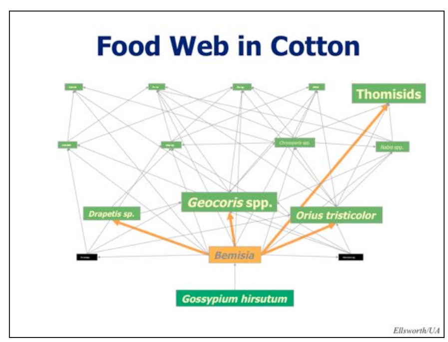
Cyazypyr, under development by DuPont, is not significantly different from the untreated check, suggesting excellent safety for our NE community.



Spirotetramat or Movento also appears to be quite safe to our NE community.



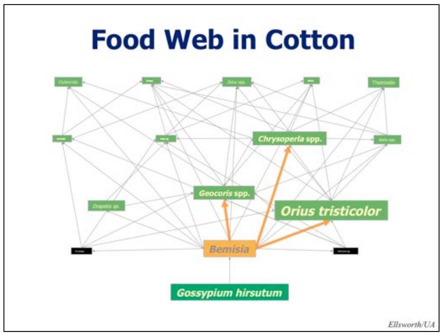
Pyrifluquinazon, while very effective against *Bemisia* whiteflies, appears to be more damaging to the NE community, though not as much as acephate (Orthene). These negative impacts appear to be driven largely in the first 3 weeks post-application.



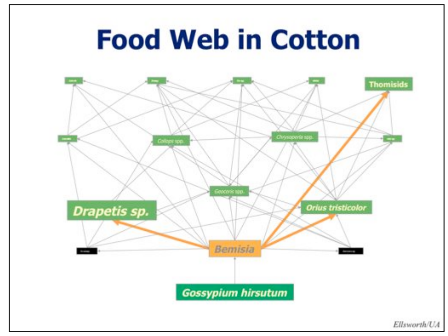
Different species dominate the relationships measured in different years or locations in AZ cotton and is a remarkable testament to the complexity of the food web. Certain conditions may favor certain pathways in certain years and other pathways in other years. Yet the same, generally, level of natural mortality in whiteflies is expressed if the system is not disrupted with broad spectrum insecticides.

This representation attempts to show important drivers of the PRC on a scale of size, roughly equivalent to their species weights in the analysis.

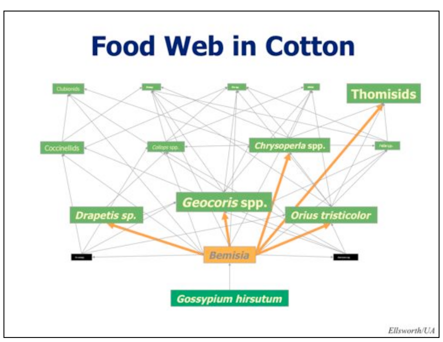
Note these are mostly generalist predators that spend time feeding on each other as well as on pest insects. Four predators dominated the PRC in this year.



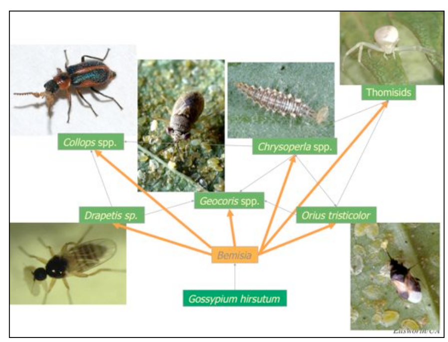
Three species in this year.



And a different set of 3 species in this year.



And 5 species dominated the PRC this year.



Over many years of intensive field study, Naranjo and I have found that most often one or more of these six predators dominated the relationship between whiteflies and their predation.

A small empidid fly that feeds on whitefly adults (not eggs or nymphs).

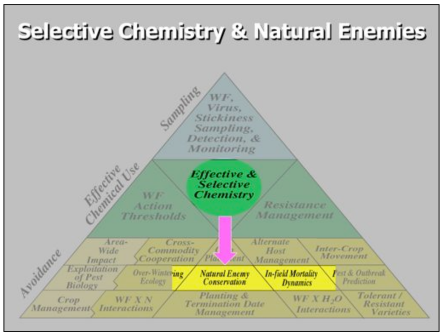
Collops beetle.

Big-eyed bugs.

Lacewings.

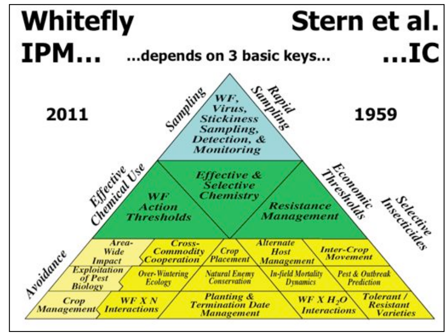
Crab and other spiders.

Minute Pirate bugs.



So our management system has evolved into a highly refined system of management where remedial chemical controls should be both effective and selective. In AZ, we have shown that when selective options are available and effective, 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 the these specific and selective chemical controls in our system.

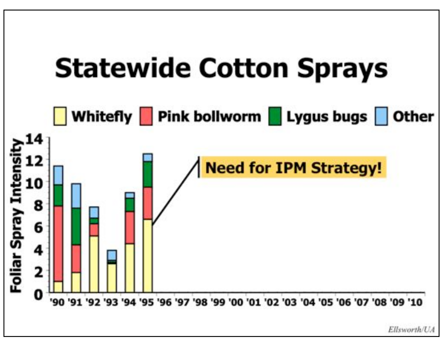
And this combination of tactics, chemical and biological control, was exactly what was suggested by Stern and colleagues over 50 years ago.



Our whitefly IPM program for cotton depends on three basic keys…

Sampling, Effective Chemical Use, all laid on a broad foundation of Avoidance or prevention practices.

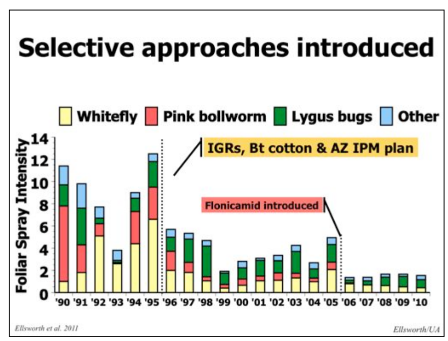
I focused today on the role that natural enemies play in our cotton-whitefly system. In addition, we can draw parallels to the original Integrated Control Concept of Stern et al., where they suggested that rapid sampling, economic thresholds and selective insecticides were needed to achieve IC.



The need was great; the situation dire. Cotton growers were spraying 5-15 times to control an array of pests. Whitefly, Pink Bollworm, and Lygus bugs are our 3 key pests of cotton in AZ.

There was a critical need for an IPM strategy, especially after the whitefly outbreak of 1995 precipitated in part by a resistance episode.

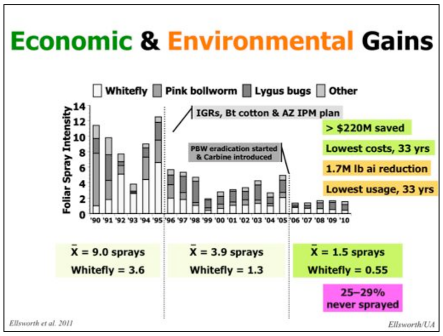
Statewide average cotton foliar insecticide spray intensity by year and insect pest (Ellsworth et al., 2011).



The results have been striking. A watershed of change occurred in 1996 with the introduction of very safe and selective Insect Growth Regulators for whitefly control, and transgenic Bt cotton, along with an IPM plan for whitefly management.

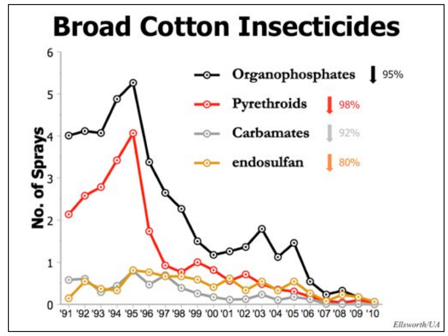
Flonicamid, a feeding inhibitor and very first fully selective compound for Lygus control was also first introduced in 2006.

The reduction in insecticide inputs is obvious.



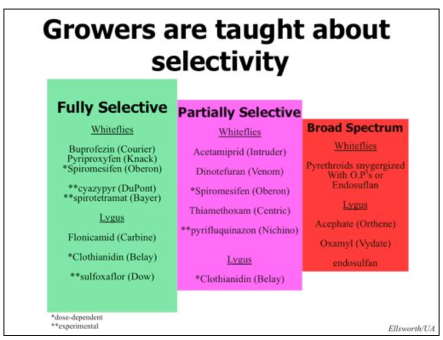
Looking at these critical periods in our history, we can see rather dramatic declines in overall insecticide use, as well as huge declines in whitefly sprays made by growers. Compared to 1995, we estimate that cotton growers have saved cumulatively over $220 million during this period. The cost of their foliar insecticide control budget over the last 5 years is the lowest it has ever been on record (33 yrs). During this same period, we have witnessed an annual insecticide reduction of ca. 1.7M lbs active ingredient used in cotton and the lowest overall usage in 33 years.

We spray whiteflies just ca. 0.5 times per season now. And growers now report between ¼ and 1/3 of their fields as going unsprayed with insecticides at all! This was inconceivable 15 and 20 years ago.



In collaboration with the state Department of Agriculture, we maintain a 20-yr database of pesticide use records within the state for all crops. Broad spectrum cotton insecticides have gone down dramatically nearing zero in most cases.

Comparing the last 5 years to our all-time peak year of 1995, organophosphates have declined 95%, pyrethroids by 98%, carbamates by 92% and endosulfan by 80%.



So we teach growers not only the efficacy of key insecticides but their selectivity in our system. We place all chemistry into one of three boxes and encourage growers to use fully or partially selective insecticides, if needed and whenever possible.

Thank you for your attention.

Thanks, too, to the many growers, pest control advisors and others who collaborate to make this such a successful program. We also thank our respective institutions, Univ. Arizona & USDA-ARS, ALARC, as well as numerous funding agencies that have supported our research and outreach over the years.

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.