13.5 Chronicling the Socio-economic Impact of Integrating Biological Control, Technology, and Knowledge over 25 Years of IPM in Arizona

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Integrated Pest Management (IPM) in Arizona cotton over the last 25 years has depended on the successful integration of biological and chemical controls along with other insect management knowledge and technologies. Contemporaneous measurement systems enabled economic evaluations with long-term datasets to examine economic outcomes and impacts, as well as durability of adopted technology (Ellsworth *et al.*, 2007). Despite devastating outbreaks of pink bollworm, *Pectinophora gossypiella* (Saunders) (Lepidoptera: Gelechiidae), and an invasive whitefly, *Bemisia tabaci* (Gennadius) (Middle East Asia Minor 1; Dinsdale *et al.*, 2010) [= *B. argentifolii* (Bellows *et al.,* 1994)] (Hemiptera: Aleyrodidae), in the early 1990s, major economic losses to the plant bug, *Lygus hesperus* Knight (Hemiptera: Miridae), in the late 1990s, and continuing pest threats throughout the last two decades, cotton growers in Arizona have saved >US$500 million through uptake and adoption of technology, and knowledge to implement developed IPM plans that include conservation biological control (CBC) as a major component.

CBC as a tactical component of IPM was specifically developed for and directly supports the integrated management of whiteflies (Ellsworth and Martinez-Carrillo, 2001; Ellsworth *et al.,* 2006; Naranjo and Ellsworth, 2009a,b). However, integrated use of CBC has also prevented pest resurgences of other key pests and outbreaks of many secondary pests. CBC, as an actively considered practice by pest managers, became possible only through the successful discovery, development and implementation of selective control tactics that were effective against each of the three key pests of this system. Cotton genetically engineered to express a lepidopteran-active toxic protein from *Bacillus thuringiensis* Berliner (Bacillicaeae) was successfully introduced in 1996 for the direct control of pink bollworm (Naranjo and Ellsworth, 2010; Tabashnik *et al.*, 2010). At the same time, two whitefly-specific insect growth regulators (IGRs, buprofezin and pyriproxyfen) were introduced along with key knowledge domains (e.g., stage specific sampling, thresholds, chemical use and resistance management plans) that enabled selective control of whiteflies. Ten years later, a *Lygus*-specific feeding inhibitor (flonicamid) was introduced for the selective control of this third key pest (Ellsworth and Barkley, 2005), and grower collaboration to eradicate the pink bollworm was initiated.

CBC is an integral component of a larger multi-pest IPM system, making the parsing out of its effect on the system challenging. Moreover, uptake by producers is largely governed by the successful adoption of host plant resistance and chemical controls

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that permit CBC to function optimally. Thus, calculation of the economic savings due to these hard technologies, Bt cotton in 1996, whitefly IGRs in 1996, and *Lygus* feeding inhibitor in 2006, can be estimated more directly by examining pre- and post-introduction data for those respective periods (pre-/post-1996 or pre-/post-2006). For example, gains in foliar insecticide costs and in saved yield related to pink bollworm technologies pre- and post-1996 and pre- and post-2006 were US$100/ha and US$63/ha after the introduction of Bt cotton and pink bollworm eradication program efforts, respectively. These changes together with all other advances in key and other pest control also contributed to the > 90% reduction in broad-spectrum insecticide use in Arizona cotton since 1996.

This major change in insecticide use patterns enabled opportunities for generalist predators and other natural enemies to thrive and estimating their value is based on examining the remaining changes not directly associated with the introduction of one of the previously mentioned hard technologies. In 2006, US$91/ha was saved in whitefly management, despite there being no specific or major additional hard technologies introduced during this period targeting whitefly. This gain was likely due to the higher functioning of CBC and natural control of whiteflies after the remaining broad-spectrum controls in the system were replaced by the selective *Lygus* feeding inhibitor in 2006. Likewise, there were savings of US$26/ha after 1996 in management of all "other" secondary pests, even though there were no specific hard technologies deployed against them during this period. This, too, was likely due to the CBC enabled by the replacement of broad-spectrum chemistries previously used against pink bollworm and whiteflies. Thus, the cumulative benefit of increased CBC during this 20 year period can be placed conservatively at US$117/ha ($26 + $91). This represents economic gains that approach half of the total measured savings to growers since 1996 (total through 2016 = US$274/ha inclusive of trait technology grower costs) and is closely aligned with other Arizona pest manager estimates of the value of biological control in their cotton system (US$108/ha; Naranjo *et al.*, 2015).

The Arizona IPM model resulted in broad-scale improvements to the environment and the economy. CBC enabled by strategic deployment of critical hard technology (Bt cotton, whitefly IGRs, *Lygus* feeding inhibitor) and soft technology (knowledge gains in sampling, thresholds, resistance management, each part of the Arizona IPM strategy) have produced a highly selective, safe, and economically and ecologically sustainable IPM system.

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