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Frequency and Abundance of Selected Early-Season Insect Pests of Cotton

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Abstract

The use of insecticides at planting has been a common crop management practice in cotton for several decades. Historically, U.S. cotton growers relied on in-furrow applications of insecticides, such as aldicarb, to control early-season insect pests. In-furrow applications have largely been replaced with insecticide-treated seed. Since 2012, more than 60% of the U.S. cotton crop is planted with seed treated with insecticide, primarily the neonicotinoids imidacloprid or thiamethoxam. Several insects or insect groups are included on the labels of these neonicotinoids for use as seed treatments. An increased understanding of the risks associated with economically injurious populations of insect pests is needed to optimize use of early-season insecticides and reduce over-reliance on them in cotton, especially when initial decisions for insect control before planting have subsequent influence on future pest abundance. Existing literature pertaining to these early-season cotton insect pests was examined to identify factors favoring their distribution and abundance and the importance of insect control tactics used at planting. The relative importance of some of these pests is dependent on the cotton-growing region and impacted by local production practices. Thrips (predominantly *Frankliniella* spp.) (Thysanoptera: Thripidae) are the most prevalent early-season insect group in cotton across the United States and the primary target of initial insect control. Other targeted insects include the black cutworm, *Agrotis ipsilon* (Hufnagel) (Lepidoptera: Noctuidae), aphids (predominantly *Aphis gossypii* Glover) (Hemiptera: Aphididae), plant bugs (Hemiptera: Miridae), and wireworms (Coleoptera: Elateridae).

Key words: cotton insect, *Gossypium hirsutum*, risk factor, neonicotinoid, cotton seedling pest

Treatment of seed with a neonicotinoid insecticide is now commonplace for many crops in American agriculture (Douglas and Tooker 2015). This includes cotton, where 60 to 80% of the crop has been planted with treated seed since 2012 nationally (Williams 2013, 2014, 2015, 2016) and over 90% since 2010 in the Midsouth region (Williams 2011) (Fig. 1). Increased use of seed treatments for cotton is evident in all regions, with over 90% adoption in the Southeast since 2012 (Williams 2013) and over 50% in the West in 2015 (Williams 2016). Douglas and Tooker (2015) estimated that neonicotinoid seed treatments accounted for 29% of the total insecticide applied to cotton during 2010–2013. The neonicotinoids being used on seed—principally clothianidin, imidacloprid, and thiamethoxam—provide systemic protection to the seedling for the first few weeks after germination from several early-season insect pests. Five insects or insect groups are listed on the labels of neonicotinoid seed treatments for cotton: wireworms (Coleoptera: Elateridae), cutworms (Lepidoptera: Noctuidae), thrips (Thysanoptera: Thripidae), aphids (Hemiptera: Aphididae), and plant bugs (including fleahoppers) (Hemiptera: Miridae).

Although thrips' infestations are highly probable in many production systems, the early-season economic risk some of these pests pose to a specific field or farm is difficult to predict several months in advance at time of seed purchase. In-season rescue treatments with foliar or soil insecticides may not be an option for some pests. The perceived risk of crop pests and the aversion to this risk are major factors in determining whether a farmer adopts a certain pest management strategy (Norgaard 1976). In general, with higher degrees of uncertainty about pest damage, there will be more frequent use of insecticides (Feder 1979), and it is not surprising that many cotton growers find investing in a preventative seed treatment against insect pests an attractive option.

The benefits of preventative seedling protection in the face of unknown pest risk are counterbalanced by the resulting overuse of neonicotinoid seed treatments, which has raised a number of

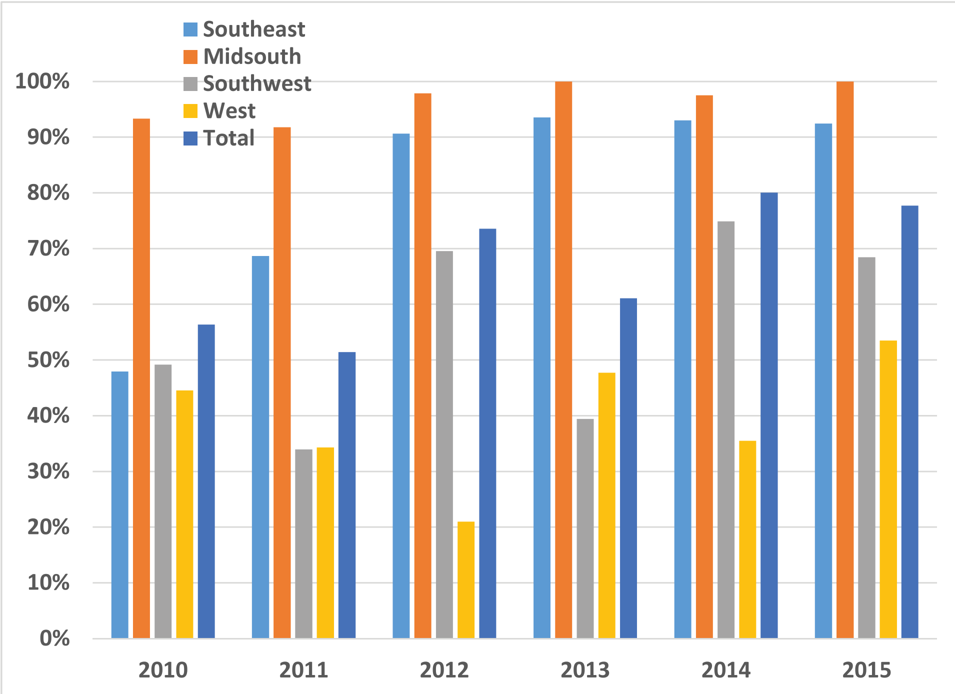

Fig. 1. Percent of cotton acreage in the Southeast, Midsouth, Southwest, and West regions of the U.S. Cotton Belt planted with insecticide-treated seed during the period 2010–2015 (Williams 2011, 2012, 2013, 2014, 2015, 2016).

concerns. Possible negative nontarget effects, including insect mortality or sublethal effects impacting normal function, especially on honey bees, *Apis mellifera* L. (Hymenoptera: Apidae), and other pollinators, are the subject of much recent research (Stewart et al. 2014, Krupke and Long 2015, Baron et al. 2017). In addition, the expanded use of neonicotinoid seed treatments has increased the exposure of early-season cotton pests to this class of insecticide, which has contributed to decreased susceptibility in one of the main targets, tobacco thrips, *Frankliniella fusca* (Hinds) (Thysanoptera: Thripidae) (Huseth et al. 2016). Declining efficacy of neonicotinoid seed treatments against thrips can force farmers to change early-season management tactics, including the use of foliar insecticides.

The purpose of this study was to review the literature on the insect pests listed on the labels of neonicotinoid seed treatment products. Specifically, our goal was to garner as much information as possible about the agronomic, environmental, geographic, and other factors that increase or decrease risk of an economic infestation in a field. Although we are interested in recent studies and management recommendations, we also purposely reviewed information in publications from decades past, before neonicotinoid seed treatments were available or common. Pest dynamics under production practices in use when some of these older papers were published may not be wholly transferable to those under current production systems in the various cotton-growing regions of the United States. Nevertheless, they still provide relevant information toward understanding the potential occurrence, abundance, and risk factors associated with these insect groups. Companion reviews in our series on sporadic early-season pests of corn (Sappington et al. 2018), soybean (Hesler et al. 2018a), and wheat (Hesler et al. 2018b) were conducted with the same purpose in mind (Papiernik et al. 2018). However, cotton production and early-season pest management present challenges that are in many ways quite different than those typically encountered in these other crops, and it is important to be cognizant of them.

Cotton production in the United States is challenged by a diversity of arthropod pests. All parts of the plant are attacked, including the roots, stems, leaves, and fruiting structures (Matthews and Tunstall 1994, Leigh et al. 1996). The seasonal sequence of pest abundance and potential damage follows crop phenological development (Leigh et al. 1996, Luttrell et al. 2015). Timely development and early maturity of cotton depend on optimum set and retention of early-season fruit. At the initiation of fruiting (Square Node Development Stage), usually 35 to 65 d after planting, cotton is extremely attractive to a number of fruit-feeding insects, including several species of plant bugs (mirids), bollworm, *Helicoverpa zea* (Boddie) (Lepidoptera: Noctuidae); tobacco budworm, *Heliothis virescens* (F.) (Lepidoptera: Noctuidae); aphids; spider mites; and several defoliating caterpillars. Even when the fruit is not attacked directly, stress from injury elsewhere on the plant often results in fruit abscission or ‘shedding’. Significant damage to the cotton crop at this stage delays effective fruit set and forces crop managers to intensify late-season control actions against bollworm, tobacco budworm, and a complex of hemipteran pests (Luttrell et al. 2015). Wireworms; black cutworm, *Agrotis ipsilon* (Hufnagel) (Lepidoptera: Noctuidae); and thrips are primarily pests of early-season cotton production (prefruiting cotton), while aphids and plant bugs can be pests throughout the development of the cotton plant. Even if populations of the latter two pests are too low to cause immediate economic injury during the seedling stage, population growth from an early infestation may result in economic losses inflicted later in the season. Thus, management decisions on early-season insect control in cotton are important not only because they impact the initial populations of colonizing species, but also subsequent populations of pests and predator species (Scott et al. 1986, Luttrell et al. 1997, Smith et al. 2013).

Cotton production in the United States has a long history of using insecticides at planting to provide preventative protection against early-season insect pests. Reports of soil-applied or insecticide-treated seed for the control of early-season insect pests in cotton, mainly using organophosphates, go back at least 60 yr (Ivy et al. 1950, 1954; Parencia et al. 1957; Hanna 1958). Since the widespread deployment of transgenic cotton varieties expressing genes for *Bacillus thuringiensis* (Bt), which protect the plant from certain lepidopteran pests, and implementation of a boll weevil eradication program, there has been a reduction in foliar insecticide applications on cotton and an overall change in the allocation of control costs for insects in the crop. The control costs allocated to foliar insecticides were 70% of total costs in 1997 (Williams 1998), but only 7.8% in 2015 (Williams 2016). At-planting costs accounted for about 10% of all control costs in 1997 but now account for more than one-third (Williams 1998, 2016). Prior to 2010, aldicarb and several organophosphorus insecticides were primarily applied at planting for control of seedling thrips (King et al. 1996), but since 2010, U.S. cotton growers have reduced use of these insecticides applied in-furrow at planting (Fig. 2). Instead, thrips control is primarily achieved using seed treated with imidacloprid or thiamethoxam (neonicotinoid) or additional foliar applications of insecticides. Growers in different regions have adopted these practices to different degrees, but use of insecticide-treated seed has been adopted as a replacement for in-furrow applications of aldicarb and aggressive early-season foliar sprays.

In our effort to assess the likelihood of and factors contributing to economic infestations, we reviewed published accounts of early-season insect pests of cotton targeted by neonicotinoid seed treatments. For each pest, we specifically highlight: 1) aspects of its ecology, biology, behavior, and life cycle that impact early-season colonization of cotton; 2) the nature and severity of damage it can cause, with an emphasis on seedling cotton up to initial fruit set; 3) the frequency and severity of early-season infestations to be expected in the absence of control measures; and 4) general management options in the absence of neonicotinoid seed treatment. The following pest profiles are presented in the typical order of their appearance during early-season development of cotton.

Wireworms

Wireworms are the larvae of click beetles (Coleoptera: Elateridae), a diverse group of insects with nearly 10,000 described species (Traugott et al. 2015). They are generalist feeders found worldwide in soil, litter, or dead wood, where they feed on plants, animals, or decaying matter (Thomas 1911, Thomas 1940, Traugott et al. 2015). Some wireworm species prefer to oviposit in particular crops but can damage nonpreferred crops planted in a field in which the larvae are already present (Eagerton 1914, Nash and Rawlins 1941, Hawkins et al. 1958). There are both semivoltine and multivoltine species of wireworms. Multivoltine species can overwinter as both larvae and adults, resulting in overlapping generations (Willis et al. 2010).

Various species of wireworm inhabit cotton fields in the United States. The sand wireworm, *Horistonotus uhlerii* Horn, was described by Tenhet and Howe (1939) as a serious pest of corn, cotton, cowpea, and other crops in the coastal plain of South Carolina and other restricted parts of the country since at least 1914. Early research bulletins supply detailed information about this pest, particularly

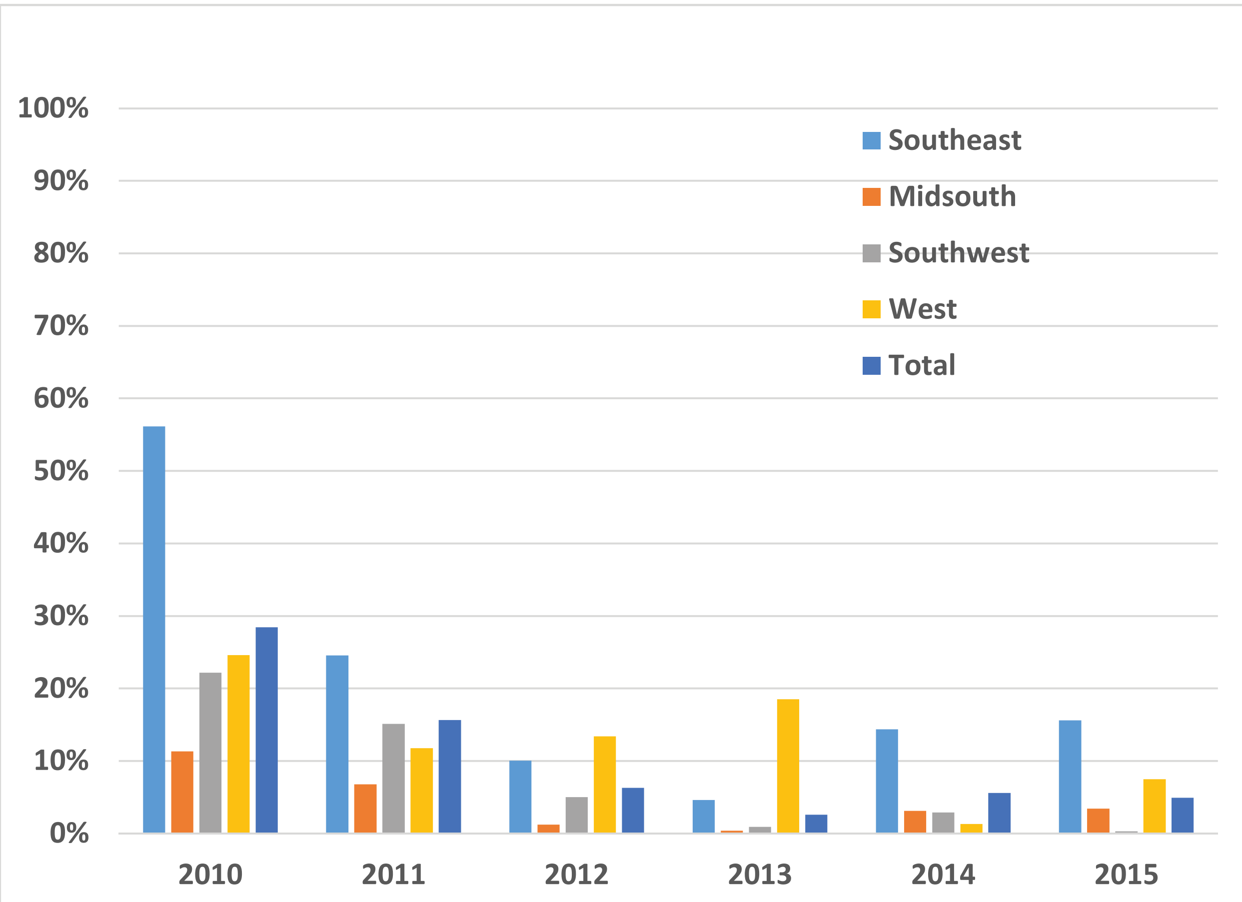

Fig. 2. Percent of cotton acreage in the Southeast, Midsouth, Southwest, and West regions of the U.S. Cotton Belt receiving in-furrow applications of insecticide (not including insecticide-treated seed) during the period 2010–2015 (Williams 2011, 2012, 2013, 2014, 2015, 2016).

in South Carolina (Thomas 1911, Conradi and Eagerton 1914, Tenhet and Howe 1939). More recently, surveys of wireworms in cotton fields in Georgia and North Carolina reported the presence of *Conoderus scissus* Schaeffer, *Conoderus rudis* (Brown), *Conoderus lividus* (De Geer), *Conoderus vespertinus* (Fabricius), and *Melanotus communis* Gyllenhal (Seal et al. 1992, Willis et al. 2010). In Texas, wireworms may include the genera *Aeolus*, *Conoderus*, *Limonius*, *Hemicrepidus*, *Agriotes*, and *Melanotus* (Anon. 2016). Wireworm pests in California include the Pacific Coast wireworm, *Limonius canus* LeConte, and the western field wireworm, *Limonius infuscatus* Motschulsky (Leigh and Goodell 1996).

Injury caused by wireworms is sometimes difficult to detect or differentiate from that caused by other pests. They may feed on germinating seeds and the roots of seedlings and transplants, causing stunting or death (Thomas 1940). Wireworms inflict their greatest damage in cotton by feeding on and destroying germinating seeds (Tenhet and Howe 1939, Leigh and Goodell 1996). In cases of severe infestation, the seed may be attacked as soon as it begins to germinate, and young plants are killed before they reach the soil surface (Tenhet and Howe 1939). Wireworms can feed on roots throughout the year but are seldom abundant enough to cause economic damage to established plants (Leigh and Goodell 1996). There are reports of severe damage caused by wireworm infestations in cotton, but recent studies are lacking. In heavily infested fields, Tenhet and Howe (1939) reported corn and cotton yields reduced by 50–100% by the sand wireworm.

Sand wireworm was reported as one of the most destructive soil-inhabiting insects in Louisiana during the late 1940s (Floyd 1949). Most infestations were in sandy upland fields, with no injury apparent on low, compact bottom lands (Conradi and Eagerton 1914). Control of this insect was readily achieved with soil-applied insecticides (Floyd 1949, Lange et al. 1949), which may have led to its absence as an economic pest in the literature since the mid-twentieth century. Wireworms are more common in cotton fields recently taken out of pasture or alfalfa; in cotton planted after grain crops, fallow or on weedy ground; and in systems of reduced tillage (Leigh and Goodell 1996, Anon. 2016). In Texas, wireworms are primarily a pest of cotton in the High Plains region (Anon. 2016).

Historically, wireworms have been difficult to manage because they are subterranean and occur irregularly in space and time (Finney 1946). Populations of larvae can be estimated through soil sampling or use of bait stations (Barsics et al. 2013, Anon. 2016). Existing infestations can be minimized through clean cultivation and planting in warm conditions, which allow seeds to germinate rapidly (Anon. 2016). There are no rescue treatments for wireworms, and, if they are present at planting, a preventative seed treatment may be useful (Godfrey et al. 2015, Anon. 2016).

Thrips

A few species of thrips (Thysanoptera: Thripidae) are annual economic pests of cotton, especially seedling cotton during the first 7 to 10 d after plant emergence (Layton and Reed 2002). The most important thrips pest of U.S. cotton is the tobacco thrips. The western flower thrips, *Frankliniella occidentalis* (Pergande); flower thrips, *Frankliniella tritici* (Fitch); soybean thrips, *Neohydatothrips variabilis* (Beach); and onion thrips, *Thrips tabaci* Lindeman, are also common and cause similar injury. Leigh et al. (1996), Cook et al. (2003), Reed et al. (2006), Albeldano et al. (2008), Cook et al. (2013), Stewart et al. (2013), and Wang et al. (2018) provide recent reviews of the diversity of thrips species attacking cotton in the United States. Western flower thrips and soybean thrips are known predators of spider mites but primarily feed on plants. Most thrips pests of cotton lay eggs singly beneath the plant epidermis (Bournier 1994), usually in tender new plant tissue like that of recently emerged cotton seedlings. Reproduction by parthenogenesis is known in thrips including the *Frankliniella* species that attack cotton (Layton and Reed 2002). There are two larval stages before entering a nonfeeding prepupal stage. Adults are capable of short directed flight, but prevailing wind has a major influence on dispersal. Thrips may overwinter as adults, as larvae on winter host plants, or as prepupae in the soil (Layton and Reed 2002). Thrips are highly polyphagous and are found on numerous crop and weed species that may be present near cotton (Cook et al. 2011). They begin feeding on alternate hosts early in the spring and may complete one or more generations before moving into cotton.

Adults rapidly colonize emerging cotton seedlings from weeds or other nearby crops. They feed by injecting saliva to lyse cells and then use their pharyngeal pump to suck up the contents (Bournier 1994, Layton and Reed 2002). Heavy feeding results in significant damage to the terminal bud, stunted growth, delayed fruiting, and reduced stands under some conditions (Layton and Reed 2002). Leaves become distorted, malformed, and leaf margin areas can curl upward (Telford and Hopkins 1957). While this injury can often be compensated, the delayed plant development can have important impacts on crop maturity. Slowed canopy development and stunted plants coupled with adverse weather conditions and other crop stress factors, such as drift from postemergence herbicide sprays, and cultivation damage reduce the ability of plants to fully compensate (Gaines 1934, Dunham and Clark 1937, Newsom et al. 1953, Race 1961, Gaines 1965, Burris 1980, Burris et al. 1989). Cook et al. (2013) and Stewart et al. (2013) provide recent reviews and updated synthesis of information on thrips damage to cotton.

Thrips are entirely an early-season pest of cotton. Plants are most vulnerable to damage between emergence and the 3- to 4-leaf stage (Layton and Reed 2002). In the presence of suboptimal growing conditions and multiple plant stressors, plants are very vulnerable to thrips injury. Conversely, healthy plants with vigorous plant growth may sustain little or no damage from high densities of thrips. Usually, by the time cotton plants are 6- to 7-wk old, they have outgrown any visible injury caused by thrips (Hawkins et al. 1966). The most serious effect of thrips feeding is when it occurs with other plant stresses to delay timely fruit set and optimum management of crop development (Luttrell et al. 2015). However, a degree of uncertainty related to the economic damage posed by a particular thrips infestation exists.

Cook et al. (2011) reviewed the impact of thrips on delayed maturity and damage to cotton. Some researchers have reported relatively little delay in cotton maturity (Newsom et al. 1953, Leigh 1963, Harp and Turner 1976), while others have reported delays of 2 wk or more (Gaines 1934, Dunham and Clark 1937, Watts 1937, Bourland 1992). The ability of cotton plants to compensate and recover from early-season thrips injury is largely dependent on environmental growing conditions, which complicates estimates of damage (Sadras and Wilson 1998).

Given the polyphagy of these pests and their presence on many weed hosts and crops, the probability of cotton infestation is high. Over the past 10 yr (2007–2016), thrips were estimated to infest between 70 and 95% of total U.S. cotton acreage (Williams 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017). Early planting and proximity of cotton to other crops or wild hosts supporting high densities of thrips increase the likelihood of damaging infestations (Greenberg et al. 2009, Toews et al. 2010, Cook et al. 2013, Stewart et al. 2013). Movement of high densities of thrips from maturing winter wheat is common in the southern United States (DuRant et al. 1994). A recent model that incorporates information including geographical location, temperature, and rainfall to predict thrips infestations has been developed (Kennedy et al. 2017).

Standard production practices have long included at-planting use of insecticides to protect young cotton plants from thrips damage (Ivy et al. 1954, Parencia et al. 1957, Hanna 1958). Use of systemic insecticides at planting is widely accepted because seedling stress develops quickly, environmental conditions are difficult to predict, and thrips are almost always present in the system when cotton emerges. Supplemental foliar treatments are used in addition to at-planting insecticides when environmental conditions slow the growth of cotton plants, which allows a longer period of susceptibility to thrips damage (Cook et al. 2011). Tillage practices have been reported to impact population densities of thrips. Thrips population densities were lower in no-till plots compared with plots receiving conventional tillage (All et al. 1993, Leonard 1995). Management of thrips in cover-cropped systems has also been explored. Higher densities of thrips were reported in areas that had native winter vegetation compared with a cover crop of winter wheat (All et al. 1993). Toews et al. (2010) reported no differences in thrips densities between three different cover crops.

Cutworms

A number of different cutworm (Lepidoptera: Noctuidae) species have been reported to feed on cotton including: the granulate cutworm, *Feltia subterranea* (Fabricius); black cutworm; pale-sided cutworm, *Agrotis malefida* Guenée; *Agrotis vetusta* (Walker); and variegated cutworm, *Peridroma saucia* (Hübner) (Crumb 1929). The black cutworm feeds on numerous cultivated and wild hosts (Crumb 1929, Busching and Turpin 1977) and is one of the most common cutworms that injure cotton. It is found throughout the continental United States, southern Canada, and Mexico (Showers 1997). Moths are capable of long-range migration, which distributes insects into regions where they cannot overwinter. Capture of black cutworm adults marked with exotic pollen or dye demonstrated the capacity to migrate over 1,000 km (Showers et al. 1989, Hendrix and Showers 1992). Blacklight trap captures of males and mated females in Crowley, LA, from January through May (Sappington and Showers 1992) indicate adults are present and active in the southern cotton-growing region of the United States at the time of cotton planting. Eggs are deposited singly or in clusters of a few eggs on the underside of leaves and stems of host plants (Crumb 1929, Metcalf et al. 1962). Maxwell-Lefroy and Ghosh (1908) noted that up to approximately 30 eggs may be deposited together. Eggs may be deposited on vegetation in or around cotton fields and developing larvae may already be present when cotton plants emerge (Gaylor 1989, Leonard et al. 1993).

Black cutworm larvae damage their host plants by severing seedling plants or feeding on stalks, roots, bulbs, or tubers (Sherrod et al. 1979). Young cotton plants are often destroyed when larvae feed on the stem, but larvae can also feed on leaves (Folsom 1932). Black cutworms are entirely an early-season pest of cotton. Young plants at the one-node stage are most susceptible to injury, and susceptibility decreases with increasing age of the plant. In a greenhouse study with black cutworm, fourth and fifth instars cut the greatest number of one-node plants (4.6–5.8 plants per larva), decreasing to 1.6 plants per larva for sixth instars on 5-node cotton. By the time cotton plants had seven nodes, they were nearly resistant to cutworm injury (Foster and Gaylor 1987). Economic injury results from plant stands reduced below levels necessary to produce optimum yields (Leonard et al. 1993) and, occasionally, when damage to seedling cotton necessitates replanting (Folsom 1932).

Cutworms are considered only occasional pests of seedling cotton (Gaylor 1989, Leonard et al. 1993, Stewart 2010). Cutworms were estimated to infest between 2 and 8% of the total U.S. cotton acreage from 2007 to 2016 (Williams 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017), with higher populations east of the Mississippi River. Several factors may increase the probability of cutworm infestation in cotton. Black cutworms were reported more frequently in cotton planted in clay soils in the Lower Rio Grande Valley of Texas compared with sandy soils (Schuster and Boling 1973). Risk of cutworm damage is higher in systems of reduced tillage and when cotton is planted after winter cover crops (Gaylor et al. 1984, Leonard et al. 1993). Cutworms already present in fields with reduced tillage at the time of planting move to seedling cotton when weeds are destroyed (Gaylor et al. 1984, Leonard et al. 1993).

Proper cultural or chemical control of weeds before planting cotton is the major management tactic to reduce the potential for cutworm damage in cotton. Gaylor and Foster (1987) advocated tillage a few weeks before planting to reduce the risk of stand reduction by cutworms. Leonard et al. (1993) reported significantly lower stand reduction in plots treated with herbicides 4–6 wk before planting compared with plots treated 1–2 wk before planting. Also, tilled plots suffered lower stand reductions than plots treated with herbicide, regardless of application timing. Application of a pyrethroid insecticide in a narrow band behind the planter will typically prevent infestations of cutworm from causing economic damage if vegetation has not been destroyed by 3 wk before planting (Stewart 2010).

Aphids

There are at least eight species of aphid (Hemiptera: Aphididae) known to inhabit cotton in the United States, including the cowpea aphid, *Aphis craccivora* Koch; the bean aphid, *Aphis fabae* Scopoli; the cotton or melon aphid *Aphis gossypii* Glover; the corn root aphid, *Anuraphis maidiradicis* Forbes; the potato aphid, *Macrosiphum euphorbiae* (Thomas); the green peach aphid, *Myzus persicae* (Sulzer); the rice root aphid, *Rhopalosiphum rufiadominale* (Sasaki); and the bean root aphid; *Smynthurodes betae* Westwood (Stoetzel et al. 1996). Of these, the cotton aphid is considered the most common pest of cotton, as well as the most severe (Goff and Tissot 1932, Leigh et al. 1996). Most aphid species have one or two closely related host plants (Eastop 1973). The cotton aphid, in contrast, is highly polyphagous and a pest of Cucurbitaceae, including cucumbers, pumpkin, and watermelon; Malvaceae, including cotton, okra, and *Hibiscus*; Solanaceae, including potato, eggplant, and peppers; and is found in citrus orchards and on ornamental plants such as chrysanthemum (Goff and Tissot 1932, Isely 1946, Blackman and Eastop 1984, Ebert and Cartwright 1997). The generation time and number of generations per year are highly dependent on temperature. The duration of the immature stage ranges from approximately 12 d at 15°C to 5 d at 28–30°C (Isely 1946, Kersting et al. 1999). The longevity of adult females was 12.6 d at 30°C, with an average of 51 aphids produced per female (Kersting et al. 1999). More than 31 generations can occur in a year in Florida (Goff and Tissot 1932). Migration or dispersal to different hosts is achieved by winged forms of aphids (Goff and Tissot 1932). This high reproductive capacity and ability to disperse from multiple hosts contribute to the pest status of the cotton aphid in cotton.

The cotton aphid damages cotton by sucking fluids from the plant, which interferes with leaf function (Isely 1946). Leaves become distorted and discolored, and, ultimately, defoliation occurs. Honeydew excreted by the aphids may cover the upper surfaces of leaves, bolls, and lint, which may reduce yield. Most damage estimates of cotton aphids on cotton are related to mid- and late-season infestations that can reduce cotton yields by as much as 168 kg of lint per ha (150 lb/ac) when aphids exceed 50 per leaf (Fuchs and Minzenmayer 1995). Yield loss attributed to cotton aphids has been measured by determining differences between untreated plots and those treated with insecticide during the mid to late cotton-growing season (Ewing 1943, Andrews and Kitten 1989, Bagwell et al. 1991, Harris et al. 1992, Godfrey and Wood 1998). Fewer references are available regarding injury and loss of yield attributed to presquaring infestations of cotton aphids, because cotton plants can compensate for early-season feeding. Sanderson (1905) stated that aphids appear with the formation of the first true leaves of cotton in Texas but did not consider insecticide treatments to be profitable. Smith (1942) noted that early injury from cotton aphid can stunt plant growth, and high infestations can cause plant death. Rosenheim et al. (1997) reported a 58% reduction in leaf area and a 45% reduction in cotton plant biomass caused by early-season aphid infestations, but there was no reduction in lint yield. Early-season feeding did produce changes in the architecture of cotton plants, including a decrease in number of vegetative branches. Jimenez et al. (1994) reported yield losses from early-season infestations of cotton aphid on acala cotton during 1993, with the plots receiving the earliest insecticide treatments having the highest yields. Estimates of economic injury are generally related to the number of cotton aphids on a per leaf basis. Kidd and Rummel (1997) found a significant reduction in yield when >50 aphids per leaf were present for more than approximately 10 d. Kerns et al. (2015) estimated economic injury levels ranging from 66 to 272 aphids per leaf with a mean of 137 aphids per leaf.

The cotton aphid is found in all regions of the world where cotton is grown (Isely 1946). Cotton aphids infested from 30 to 63% of U.S. cotton over the past 10 yr (Williams 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017). In the southern United States, it is an annual but sporadic pest of cotton (Gore et al. 2013). Several cultural practices can affect populations in a given field. Infestations can be greater on cotton plants receiving higher inputs of nitrogen fertilizer, due in part to greater reproductive capacity of aphids (Isely 1946, Cisneros and Godfrey 2001). Populations can also be more severe in fields or areas within fields of low stand density or in fields planted in a skip-row pattern (Rummel et al. 1995). Higher populations of aphids have been noted after some insecticide applications, presumably due to elimination of natural enemies that suppress populations of aphids (Slosser et al. 1989, Chen et al. 1991).

Populations of cotton aphids are usually controlled by natural enemies, both predatory and parasitic, in spite of their reproductive capacity (Isely 1946). Epizootics of the naturally occurring entomopathogenic fungus *Neozygites fresenii* (Nowakowski) can be common in populations of cotton aphid in the mid-southern and southeastern United States during relatively dry periods (Steinkraus et al. 1991, Steinkraus et al. 1995, Steinkraus et al. 2002, Abney et al. 2008). Insecticides have been used to control high populations, but historically aphids have rapidly developed resistance to chemicals used for their control (Gore et al. 2013). Cotton aphids prefer hairy-leaf varieties of cotton, and smooth-leaf varieties offer some resistance to populations of cotton aphid (Weathersbee and Hardee 1994, Weathersbee et al. 1995). In years of moderate pressure, planting cotton earlier has been effective in reducing damage by aphid populations (Cisneros and Godfrey 2001).

Plant Bugs

Several polyphagous mirids (Hemiptera: Miridae) are economic pests of cotton. Leigh et al. (1996) and Layton (2000) considered the tarnished plant bug, *Lygus lineolaris* (Palisot de Beauvois); western tarnished plant bug, *Lygus hesperus* Knight; cotton fleahopper, *Pseudatomoscelis seriatus* (Reuter); and clouded plant bug, *Neurocolpus nubilis* (Say), to be the most important, but both recognized other mirids may be regionally important. An example of a recent regionally important pest is the verde plant bug, *Creontiades signatus* Distant, in southern Texas (Armstrong et al. 2009, Brewer et al. 2013). Mirids generally deposit eggs singly into plant tissues including cotton leaf petioles, stems, and fruiting structures (Leigh et al. 1996). Generation time is about 33 d (Bariola 1969, Fleischer and Gaylor 1988). Plant bugs are among the most polyphagous of all insects (Cleveland 1982, Snodgrass et al. 1984, Young 1986, Fleischer and Gaylor 1987, Robbins et al. 2000, Esquivel and Mowery 2007, Esquivel and Esquivel 2009, Parys 2014). Their ability to utilize a wide range of wild hosts and cultivated crops reflects their adaptability and directly influences local ecology and population growth.

The distribution and abundance of host plants in the local landscape affects the numbers of tarnished plant bugs that disperse into cotton. Late-spring and early summer wild hosts can serve as sources or sinks for cotton fleahopper and plant bug populations infesting cotton (Almand et al. 1976, Fleischer and Gaylor 1987). The proximity of cultivated crops, such as corn, in the landscape increases the number of tarnished plant bugs that develop on these hosts and subsequently move into cotton (Abel et al. 2010, Jackson et al. 2014).

Although there are subtle differences in the feeding preferences of plant bugs, and their relative importance as pests of cotton varies regionally and seasonally (Leigh et al. 1996), they all cause similar damage. Plant bugs inject salivary enzymes into the plant that cause localized injury and fruit abortion. Hanny et al. (1977), Tugwell et al. (1976), and Layton (2000) elaborately describe tarnished plant bug feeding and resulting fruit damage. The most frequent type of injury is feeding-induced abortion of young fruit (squares). Yield losses ranging from 15 to 50% have been attributed to high infestations of tarnished plant bugs feeding on cotton (Black 1973, Laster and Meredith 1974, Tugwell et al. 1976, Scott et al. 1986). Other researchers have shown no yield reductions caused by infestations of plant bugs (Jubb and Carruth 1971, Wilson 1984), although feeding resulted in delayed maturity of up to 2 wk (Wilson 1984). These studies were conducted over a range of plant bug densities and durations of feeding. The plant growth stage of cotton when plant bugs are encountered and the ability of plants to compensate for injury has an important impact on damage and potential yield loss. Holman (1996) found that cotton plants can tolerate fruit losses as high as 19% without suffering yield reductions. Black (1973) observed economic injury to cotton from 47,000 tarnished plant bugs per ha during the cotton squaring period but did not observe economic injury during flowering until nearly 350,000 plant bugs per ha were encountered.

Although plant bugs are generally noted inflicting damage to developing fruit, they can feed on cotton from plant emergence to boll formation (Pack and Tugwell 1976). Seedling cotton can be injured by tarnished plant bugs feeding in the plant terminal (Burris et al. 1997). Among other injuries, plant bug feeding on seedling cotton can result in a loss of apical dominance by plants and development of numerous secondary terminals (Wene and Sheets 1964, Scales and Furr 1968, Hanny et al. 1977). In experiments in Arizona, Wene and Sheets (1964) reported that *L. hesperus* could kill a cotton seedling within a few days of emergence by feeding on the cotyledons. Feeding on the growing points of plants caused additional injuries including: deformed plants, blank squares, and a delay in developing squares for a period of 2–4 wk. Hanny et al. (1977) reported significant reductions in plant height, weight, swollen nodes, shortened internodes, deformed leaves, and excessive branching of the main stem due to *L. lineolaris* feeding on presquaring cotton plants but no differences in lint weight or number of bolls. In this study, fruit set was only delayed an average of 4 d. Overall, the ultimate impact of early season injury is a delay in crop maturity.

The different plant bugs that are pests of U.S. cotton have relatively distinct but overlapping distributions. *L. hesperus* is found predominately in the western United States, while *L. lineolaris* is predominately in the eastern and southern United States (Tingey and Pillemar 1977). Collectively, these two insects were estimated to have infested between 38 and 61% of total U.S. cotton acreage over the last 10 yr and ranked as the number one pest in six of these years (Williams 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017). Cotton fleahoppers are pests of cotton in central and southern Texas and other parts of the southern United States (Lidell et al. 1986). Infestations of cotton fleahopper ranged between 16 and 61% of total U.S. cotton from 2007 to 2016 (Williams 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017). The clouded plant bug is found most frequently in Arkansas, Mississippi, Missouri, and Tennessee (Williams 2017), and total infestations over the past 10 yr across the entire U.S. ranged from 4 to 8% of cotton acreage (Williams 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017). These estimates are based on occurrence of these insects at any growth stage of cotton and do not reflect populations occurring only in presquaring cotton.

Foliar applications of synthetic insecticides have been widely used for control of plant bugs in cotton, and research efforts detailing economic injury levels of these insects at different cotton growth stages have been estimated (Leigh et al. 1988; Ring et al. 1993; Musser et al. 2009a,b). Earlier planting dates and earlier maturing varieties reduce total numbers of plant bugs and number of insecticide applications for their control (Adams et al. 2013). Due to the polyphagous nature, management of wild hosts can reduce populations moving into cotton. Snodgrass et al. (2005, 2006) demonstrated a reduction in overall populations of tarnished plant bug in cotton by eliminating early-season wild hosts with a herbicide application to ditch banks and other marginal areas around fields. Reducing early-season populations of these polyphagous pests relies on a better understanding of the relative importance and availability of different host plants, both wild and cultivated, to the seasonal dynamics of cotton pest populations.

Discussion

When neonicotinoid seed treatments are used for preventative protection of seedling cotton against early-season pests, pest control expenses and potential environmental costs are incurred before insect densities are known. For some pests in some production systems (i.e., thrips in the Midsouth), the probability of occurrence is high, and the probability of economic benefit is high (North et al. 2018). The compilation of existing information pertaining to targeted pests and the factors determining the likelihood of an economic infestation in a given field is an important step in helping farmers make informed decisions about whether and where to deploy these products. The pest profiles presented in this article also expose a number of knowledge gaps that would be worthy of future research.

Aphids and plant bugs can cause considerable damage, but uncertainty exists regarding the economic and yield protection gained from at-planting control tactics. Some publications describing yield loss and damage associated with these insect groups do not specify the stage of plant growth at which damaging populations were present. This situation handicaps us in assessing the relative contribution of early season injury by aphids to full season yield loss. Aphids are found on cotton throughout the United States but have been ranked among the top five insect pests only in two of the last 10 yr (Williams 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017). It is possible that early-season control measurers targeting other insect groups are reducing population buildup by suppressing early-season populations. More studies on the effects of early-season aphid infestations are needed.

The plant bug species complex includes pests with varying degrees of prominence in different states. Although pestiferous *Lygus* spp. are not present in all cotton-growing areas of the United States, collectively, they have been ranked the number one insect pest of cotton in six of the last 10 yr (Williams 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017). Again, the caveat is that we do not know the extent to which presquaring infestations specifically contribute to their overall status as a (or the) major pest of cotton.

Cutworms and wireworms are solely early-season insect pests of cotton whose prevalence varies widely among the cotton-growing regions of the United States. Because they inhabit the soil, wireworms are the only group for which no rescue option exists for treating infestations. They are not included in the annual assessment of cotton insect pests in the Proceedings of the Beltwide Cotton Conference, suggesting they are rarely a problem. Cutworms are most prominent in the southern cotton-growing region and can be controlled with foliar applications upon detecting damaged plants through a crop scouting program before plant stands are reduced to unacceptable levels.

The most prevalent early-season insect pest of cotton is the complex of thrips that can injure plants any time after plant emergence. Thrips, historically, have been the driving force of at-planting insecticide treatments in cotton. Pest surveys indicate they commonly infest more than 80% of cotton acreage (Williams 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017). Heavy infestations cause severe crop damage. Although infestations are not always associated with measurable yield loss, the economic impacts of delayed plant maturity and early growth stress are difficult to capture in direct damage or yield estimates. Delayed maturity can impact the severity of later-season insect pests, particularly some migrating Lepidoptera, and those (such as the bollworm) whose populations build on alternate hosts such as corn before moving into cotton. The impacts on these later-season pests are consequential enough that they must be considered when evaluating the risks posed by early-season pests.

In cotton production systems, assessing the value to the grower of deploying at-planting insecticides must include pest management considerations for the entire growing season, not only the few weeks after seedling emergence when they can directly affect targeted early-season pests like thrips. Cotton insect management remains a dynamic process impacted by pest adaptation and environmental interactions, and profitable cotton production remains a seasonal series of decisions balancing optimum fruit set against a changing sequence of pest threats. The interconnected nature of control measures applied early in the season to pest pressure late in the season is an extremely important aspect of cotton pest management that must be taken into account when evaluating the value of any early-season preventative or rescue insecticidal treatment strategy.

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