

# Biology and Management of the Mexican Rice Borer (Lepidoptera: Crambidae) in Rice in the United States

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## Abstract

The Mexican rice borer, *Eoreuma loftini* (Dyar), is an invasive pest of rice, *Oryza sativa* L., in the Gulf Coast region of the United States. This pest also damages sugarcane, *Saccharum* spp. hybrids; corn, *Zea mays* L.; and sorghum, *Sorghum bicolor* (L.) Moench, and feeds on weedy noncrop grasses. Multiple aspects of integrated pest management including use of pheromone traps, manipulation of planting dates, harvest cutting height, stubble management, noncrop host management, soil fertility management, host plant resistance, use of insecticides, and biological control have been studied for Mexican rice borer management. However, the current management strategy in rice primarily relies on the use of chlorantraniliprole insecticide seed treatments. This profile addresses Mexican rice borer biology and management in rice in the United States.

## Resumen

El barrenador mexicano del arroz [*Eoreuma loftini* (Dyar)] es una plaga invasora de arroz (*Oryza sativa* L.) en la región de la Costa del Golfo de Estados Unidos. Esta plaga también afecta híbridos de caña de azúcar (*Saccharum* spp.), maíz (*Zea mays* L.), sorgo [*Sorghum bicolor* (L.) Moench], y se alimenta de malezas gramíneas. Múltiples aspectos del manejo integrado de plagas incluyendo el uso de trampas con feromonas, la manipulación de las fechas de siembra, la altura del corte durante la cosecha, el manejo de rastrojos, el manejo de hospederos alternos, el manejo de la fertilidad del suelo, la resistencia de la plantas, el uso de insecticidas y el control biológico han sido estudiados para el manejo del barrenador mexicano del arroz. Sin embargo, la estrategia de actual de manejo en arroz se basa principalmente en el tratamiento químico de la semilla con el uso del insecticida clorantraniliprol. Esta revisión se enfoca en la biología y manejo del barrenador mexicano del arroz en los Estados Unidos.

**Key words:** *Eoreuma loftini* (Dyar), integrated pest management, *Oryza sativa* L., stem borer

The Mexican rice borer, *Eoreuma loftini* (Dyar) (Lepidoptera: Crambidae), is an invasive pest of rice, *Oryza sativa* L.; sugarcane, *Saccharum* spp. hybrids; corn, *Zea mays* L.; and sorghum, *Sorghum bicolor* (L.) Moench, in the Gulf Coast region of the United States (Reay-Jones et al. 2008, Showler et al. 2012, VanWeelden et al. 2015, Wilson et al. 2015a). After a first detection in south Texas in 1980, the insect quickly became the most damaging pest of sugarcane in the Lower Rio Grande Valley (Johnson 1984). The insect has also become a serious pest of rice in southeast Texas, requiring insecticidal protection to minimize yield losses (Reay-Jones et al.

2007a, Espino and Way 2014). In Louisiana, where Mexican rice borer adults were first collected in 2008 (Hummel et al. 2010), larval infestations in rice have reached damaging levels (Wilson et al. 2015a). Annual economic losses in rice may approach \$45 million when the insect becomes fully established in Louisiana (Reay-Jones et al. 2008).

The recent establishment of the Mexican rice borer in Texas and Louisiana rice production areas has triggered studies to develop management strategies (Reay-Jones 2005, Beuzelin 2011, Wilson et al. 2015a). This profile addresses Mexican rice borer biology and

management in rice in the United States. The sugarcane agroecosystem, which has been the focus of Mexican rice borer research for three decades, and the sugarcane borer, *Diatraea saccharalis* (F.) (Lepidoptera: Crambidae), which is a stem borer pest with comparable crop host range in the Gulf Coast region (Bessin and Reagan 1990), are mentioned when relevant in the context of Mexican rice borer biology and management in rice.

## Taxonomy

The Mexican rice borer was first described by Dyar (1917) from specimens collected in Arizona. Two new distinct species, *Chilo loftini* and *Chilo opinionellus*, from sugarcane and wheat, *Triticum aestivum* L., respectively, were originally described. Bleszynski (1967) moved *C. loftini* into the genus *Acigona* Hübner. Klots (1970) showed *C. loftini* and *C. opinionellus* were conspecifics and moved them into the genus *Eoreuma* Ely.

## Geographic Distribution

The Mexican rice borer has been reported to occur in areas of the western coast of Mexico, and in southern Arizona and California (Johnson 1984). In the mid-1970s, the Mexican rice borer expanded its range to eastern Mexico and was first observed in south Texas in the Lower Rio Grande Valley in 1980 (Johnson and Van Leerdam 1981). By 2005, populations had spread north and east through southeast Texas at an average rate of 23 km/yr (14 miles/yr; Reay-Jones et al. 2007c). In December 2008, Mexican rice borer moths were detected in pheromone traps for the first time in southwest Louisiana near the town of Vinton (Hummel et al. 2010). In March 2012, a Mexican rice borer moth was caught at a mercury vapor light for the first time in Florida in Goethe State Forest (Hayden 2012). By early 2015, the Mexican rice borer had spread into eight parishes in southwest Louisiana (Wilson et al. 2015a), and moths had been collected in four counties in central Florida (University of Florida 2015), confirming establishment of the pest in both states.

## Host Range

Van Zwaluwenburg (1926) stated that the Mexican rice borer “attacks practically all the grasses large enough to afford it shelter within the stalk.” Mexican rice borer crop hosts include rice, sugarcane, corn, and sorghum (Osborn and Phillips 1946, Showler et al. 2011). Feeding on wheat and barley, *Hordeum vulgare* L., has also been reported (Dyar 1917, Osborn and Phillips 1946).

Major weedy hosts include two common perennial grasses, johnsongrass, *Sorghum halepense* (L.) Pers., and vaseygrass, *Paspalum urvillei* Steud., as well as two common annual grasses, brome, *Bromus* spp., and ryegrass, *Lolium* spp. Larvae and evidence of larval development completion (i.e., exit holes, pupae, empty pupal skins) have been observed in additional weedy and forage grasses, including sudangrass [*Sorghum bicolor* (L.) Moench ssp. *drummondii* (Nees ex Steud.) de Wet & Harlan], Amazon sprangletop [*Leptochloa panicoides* (Presl) Hitch], Angleton bluestem [*Dichanthium aristatum* (Poir.) C.E. Hubbard], hairy crabgrass [*Digitaria sanguinalis* (L.) Scop.], and barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.] (Beuzelin et al. 2011a,b; Showler et al. 2011). In addition, Mexican rice borer larvae have been reported to feed on *Panicum* spp., *Echinochloa* spp., yellow bristle grass [*Setaria pumila* (Poir.) Roem. & Schult. subsp. *pumila*], lemongrass [*Cymbopogon citratus* (DC. ex Nees) Stapf], wild millet

[*Pennisetum glaucum* (L.) R. Br.], Uruguayan pampas grass [*Cortaderia selloana* (Schult. & Schult. F.) Asch. & Graebn.], and bermudagrass [*Cynodon dactylon* (L.) Pers.] (Van Zwaluwenburg 1926, Osborn and Phillips 1946, Johnson 1984, Browning et al. 1989). Feeding on plants in the family Cannaceae (*Canna* spp.) and Cyperaceae (*Cyperus* spp., *Scirpus validus* Vahl) has been reported (Osborn and Phillips 1946, Beuzelin et al. 2011a).

## Life Cycle and Morphology

### Egg Stage

Mexican rice borer eggs are globular and cream-colored, typically laid in clusters of ≤100 eggs (Browning et al. 1989, Reay-Jones et al. 2007b, Beuzelin et al. 2013). On rice and major noncrop hosts, the majority of eggs are laid in folds on dry plant material, leaves or leaf sheaths (Fig. 1; Beuzelin et al. 2013). However, eggs can also be found on green leaves, leaf sheaths, and stems (Reay-Jones et al. 2007b). Rice is preferred over johnsongrass and vaseygrass for oviposition (Beuzelin et al. 2013). The egg stage lasts 14 and 5 d at 20 and 32°C (68 and 90°F), respectively, in the laboratory (Van Leerdam 1986).

### Larval Stage

Neonate larvae move to green parts of the plant and start feeding on leaf sheaths. After the second or the third molt, larvae begin to burrow into the culm (Browning et al. 1989). Larvae pack their tunnels with frass in sugarcane stalks, but this behavior is only occasionally observed in rice culms (Browning et al. 1989). Larvae are whitish, have an orange-brown head capsule, and bear four parallel purple-red stripes along their dorsal side (Fig. 2; Legaspi et al. 1997b). Last instars are 19–25 mm (0.75–1 inch) in length (Osborn and Phillips 1946, Browning et al. 1989). When reared in the laboratory, larvae undergo four to six molts. However, the number of larval stadia is affected by sex, being lower in males than in females, with five and



Fig. 1. Mexican rice borer eggs laid between a johnsongrass stalk and leaf sheath.

six stadia, respectively (Van Leerdam 1986). Also, six stadia are observed at 23°C (73°F), but five at 29°C (84°F). The larval stage on artificial diet in the laboratory lasts an average of 78 and 21 d at 20 and 32°C (68 and 90°F), respectively. Larval development at 29°C (84°F) on rice between panicle exertion and maturity is approximately 38 d in the greenhouse, and 71% longer on johnsongrass and vaseygrass (Beuzelin et al. 2013). Males generally develop faster than females (Van Leerdam 1986).

### Pupal Stage

Pupation occurs in the culm (Browning et al. 1989). Mexican rice borer pupae are yellowish to brown, cylindrical and slender, and 16 to 20 mm (0.6 to 0.8 inch) in length (Fig. 3; Legaspi et al. 1997b). They bear small tubercles at the posterior end of the abdomen (Legaspi et al. 1997b). Female and male pupae collected from rice grown in a greenhouse study weighed 26 and 18 mg ( $0.92 \times 10^{-3}$  and  $0.65 \times 10^{-3}$  ounces), respectively, on average (J.M.B., unpublished data). The duration of the pupal stage in the laboratory is 21 and 7 d at 20 and 32°C (68 and 90°F), respectively (Van Leerdam 1986).

### Adult Stage

Adults are straw-colored moths without markings, but sometimes a tiny (<1 mm or 0.04 inch) dark spot in the center of each forewing can be observed (Fig. 4). Adults have a conical frons (Klots 1970), a morphological character often used for rapid identification in the field. However, examination of male genitalia is needed to confirm species identification (Agnew et al. 1988). Adult longevity is 6 to 14 d (Van Leerdam 1986). Females reared on artificial diet in the laboratory lay an average of 29 to 64 eggs per day between 20 and

32°C (68 and 90°F), respectively, with oviposition usually peaking 2 d after adult eclosion (Van Leerdam 1986). Fecundity in the laboratory attains a maximum of 400 eggs per female at 26°C (79°F) and declines to approximately 350 eggs per female between 29 and 32°C (84 and 90°F).

### Seasonal Activity

Four to six overlapping generations annually occur in south Texas (Legaspi et al. 1997b), with a generation lasting 45 to 50 d under summer conditions (Browning et al. 1989). Cage studies in south Texas showed a peak of Mexican rice borer moth emergence in the spring, between late March and early May (Browning and Smith 1988). Monitoring of flight activity for 2 yr using pheromone traps adjacent to rice fields at three locations spanning 240 km (150 miles) in southeast Texas confirmed increased flight activity in the spring (Beuzelin et al. 2011b), with a peak in March-April 2008 at the southernmost location and a peak in March-April 2009 at the three locations. A substantial peak in flight activity also occurred between September and November in both years at the three locations (Beuzelin et al. 2011b).

Weedy grasses likely play an important role in Mexican rice borer population seasonal abundance. In a 2-yr study in southeast Texas, Mexican rice borer densities in noncrop habitats adjacent to rice fields averaged 1.2 larvae and pupae per square meter (0.1 larvae and pupae per square foot) in April and increased threefold throughout the year to reach a maximum in October-December



Fig. 2. Mexican rice borer larva in a rice culm.



Fig. 3. Mexican rice borer pupa.



Fig. 4. Mexican rice borer adult resting on a johnsongrass leaf.



Fig. 5. Mexican rice borer-caused whitehead in rice.

(Beuzelin et al. 2011a). Major weedy grass hosts in those noncrop habitats include brome and ryegrass during the spring, and johnsongrass and vaseygrass throughout the year (Beuzelin et al. 2011a). Vaseygrass harbors a large proportion of the Mexican rice borer population during the winter, with as much as 62% of larvae and pupae observed in noncrop habitats near rice fields (Beuzelin et al. 2011a).

All life stages of Mexican rice borer can be found at any time of the year throughout the Gulf Coast region of Texas (Johnson 1985; Van Leerdam et al. 1986; Meagher et al. 1994, 1996; Beuzelin et al. 2011a). However, Browning and Smith (1988) reported that larvae can enter diapause during fall and winter months, with diapausing larvae exhibiting reduced activity, supernumerary molts, and fat body accumulation. Browning and Smith (1988) also reported that as much as 30% of the larval population was in diapause during the fall in south Texas and that this proportion increased through the winter. In addition, diapausing and nondiapausing larvae would feed on warm days in the winter (Browning and Smith 1988). Mexican rice borer larvae can survive freezing temperatures, with an 80% survivorship observed when nondiapausing larvae are placed at 0°C (32°F) for 6 d (Rodriguez-del-Bosque et al. 1995). In the same study, 40% of the larvae survived after 1 d at -5°C (23°F) and 10% of the larvae survived after 6 h at -10°C (14°F), but 0% survived after 3 h at -15°C (5°F).

### Injury to Rice and Yield Loss

Mexican rice borer injury during rice vegetative stages can kill the growing point of a tiller, resulting in a “deadheart” symptom (Browning et al. 1989). Although a tiller injured during rice reproductive stages usually remains green before heading, injury to the vascular tissue can kill the panicle and the developing grain, resulting in a “whitehead” symptom (Fig. 5). When injury occurs during

ripening, the maturation of a panicle suffers from a lack of uniformity in grain development and increased grain mortality. A mature panicle may also be lost because larval injury to the topmost node can cause the culm to break (Browning et al. 1989, Way 2003).

Rice plants have the ability to compensate for injury from stem borers, including the sugarcane borer (Rubia et al. 1996, Islam and Karim 1997, Lv et al. 2008). Injured plants can increase their number of reproductive tillers and compensation is greater when injury occurs early in rice development, during vegetative stages and panicle differentiation (Lv et al. 2008, 2010). Rice plant compensatory responses to Mexican rice borer injury have not been studied. However, injury to young plants, including deadhearts, is generally not a concern relative to yield loss because of compensation (Lv et al. 2008, 2010).

The relationships between infestation level, injury, and yield have not been determined for Mexican rice borer infesting rice. These relationships have been determined for the sugarcane borer in three rice cultivars at three plant stages (Lv et al. 2008) but might be different for the Mexican rice borer because of its specific larval feeding behavior. Injury location within the culm impacts the severity of yield losses (Lv et al. 2010), and the majority of Mexican rice borer larvae are found 20 cm (8 inches) or above from the base of the culm, whereas the majority of sugarcane borer larvae are found less than 20 cm from the base of the culm (Beuzelin et al. 2012). Nevertheless, Reay-Jones et al. (2007a) determined that each whitehead per square meter caused by mixed infestations of Mexican rice borer and sugarcane borer was associated with a 2.3% decrease in yield. Whitehead densities associated with Mexican rice borer infesting rice without insecticidal protection in southwest Louisiana attained 4.8 and 12.7 whiteheads per square meter (0.4 and 1.2 whiteheads per square foot) in 2012 and 2013, respectively (Wilson et al. 2015a). Thus, yield losses may have exceeded 11 and 29% in 2012 and 2013, respectively. For reference, yield losses of 1.0 and 4.2% have been reported for each unit increase in percent whiteheads caused by a complex of stem borers in Asia (Pathak 1968, Muralidharan and Pasalu 2006).

## Mexican Rice Borer Management

### Mexican Rice Borer: Status in the Rice Stem Borer Complex in the United States

The Mexican rice borer, sugarcane borer, and rice stalk borer, *Chilo plejadellus* Zincken (Lepidoptera: Crambidae), form the stem borer complex that attacks rice in the United States (Way 2003). Sugarcane borer larvae (Fig. 6) are yellowish-white with a brown head capsule, and possess brown spots on each body segment during the summer, whereas winter forms lack spots (Holloway 1928, Legaspi 1997b). Sugarcane borer larvae are therefore easy to distinguish from Mexican rice borer larvae. Rice stalk borer larvae (Fig. 6) are yellowish-white with a dark brown head capsule, and bear four parallel brown stripes along their dorsal side. Rice stalk borer larvae therefore somewhat resemble Mexican rice borer larvae, and inspection of thoracic setae may be needed to confirm species identification (Fig. 7; Solis 1999).

The Mexican rice borer has become a consistent pest and represents the main stem borer threat to rice in the Gulf Coast region of the United States (Beuzelin et al. 2012; Way and Pearson 2013, 2014; Wilson et al. 2015a), whereas the sugarcane borer has remained a sporadic rice pest, despite being abundant and damaging in certain years and areas (Castro et al. 2004, Beuzelin et al. 2012). The rice stalk borer is considered a sporadic and minor stem borer



Fig. 6. Three stem borer species infest rice in the Gulf Coast region: the (A) Mexican rice borer, (B) sugarcane borer, and (C) rice stalk borer.

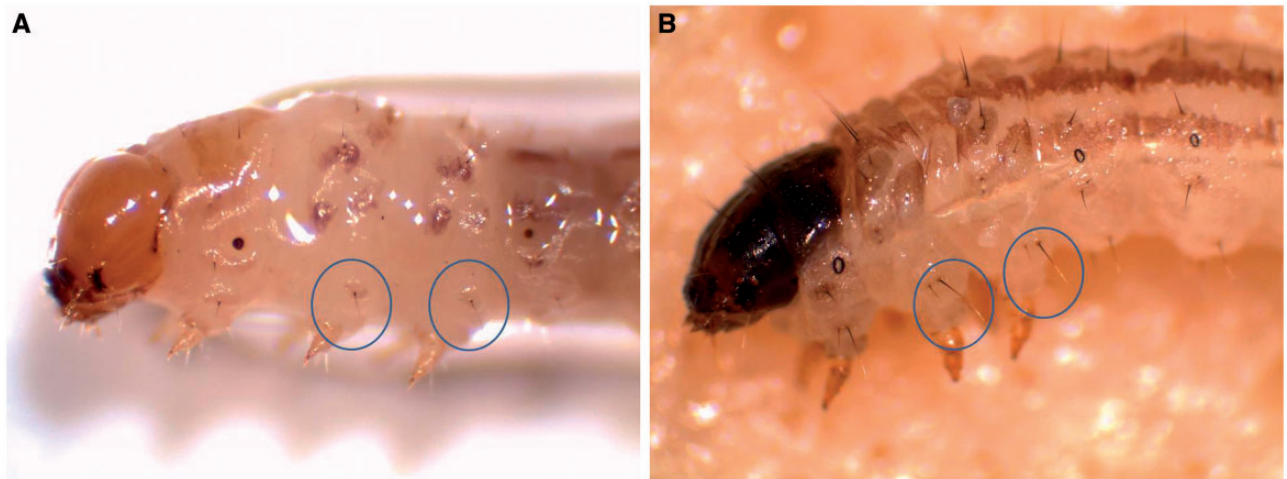


Fig. 7. Close-up of the head and thorax of (A) Mexican rice borer and (B) rice stalk borer larvae. Mexican rice borers have one subventral seta on the meso- and metathorax, whereas rice stalk borers have two subventral setae.

pest of rice in the Gulf Coast region of the United States. Thus, management of stem borers in rice must focus on the Mexican rice borer, and on the sugarcane borer to some extent. Management of the rice stalk borer is generally not needed and is not addressed in this article.

The Mexican rice borer and sugarcane borer are two crambid stem borers but are not interchangeable rice pests. Unlike the sugarcane borer, the Mexican rice borer prefers laying eggs in cracks and folds on the rice plant, typically on older, senesced leaves (Reay-Jones et al. 2007b, Hamm et al. 2012, Beuzelin et al. 2013). Larval tunneling behaviors of the two species differ, with the majority of

Mexican rice borer larvae feeding on the upper portion of rice culms, whereas the majority of sugarcane borer larvae feed on the lower portion of rice culms (Beuzelin et al. 2012). In addition, seasonal activities of the two species differ, with Mexican rice borer populations active and abundant year-round, whereas the majority of sugarcane borer populations overwinter as large larvae (Rodriguez-del-Bosque et al. 1995, Beuzelin et al. 2011a, 2011b). Data in Beuzelin et al. (2011a) also suggest that the Mexican rice borer uses noncrop grass hosts to a greater extent than does the sugarcane borer in rice agroecosystems. Thus, whereas tactics developed for Mexican rice borer management may assist in managing

the sugarcane borer, and vice versa, because of comparable life histories, some tactics may assist in managing only one stem borer species.

The Mexican rice borer and sugarcane borer can co-exist in the same rice field or even plant (Beuzelin et al. 2012), and field studies addressing Mexican rice borer management have sometimes been conducted under natural mixed infestations of the two stem borer species. Consequently, the efficacy of certain management tactics against the Mexican rice borer or sugarcane borer, specifically, is sometimes difficult to distinguish in field studies. In the following sections, research results supporting management recommendations for Mexican rice borer only, or in combination with the sugarcane borer, in rice are addressed.

### Use of Synthetic Pheromones

Brown et al. (1988) demonstrated the existence of a sex pheromone in female Mexican rice borer adults. The pheromone blend has been identified as (Z)-13-octadecenyl acetate, (Z)-11-hexadecenyl acetate, and (Z)-13-octadecenal, in the approximate ratio 8:1:1.3 (Shaver et al. 1988). Pheromone traps baited with the Mexican rice borer synthetic pheromone have been extensively used to monitor population dynamics and document geographical range expansion (Shaver et al. 1991, Reay-Jones et al. 2007c, Wilson et al. 2015a). In addition, trap catches are correlated with levels of larval injury in rice fields, and the use of pheromone traps might facilitate scouting for Mexican rice borer larval infestations (Wilson et al. 2015a). The efficacy of mating disruption using the synthetic pheromone was evaluated for Mexican rice borer management in sugarcane in south Texas (Shaver and Brown 1993); however, the tactic was inefficient (Spurgeon et al. 1997, Legaspi et al. 1999) and has never been implemented in sugarcane or rice cropping systems.

### Cultural Practices

#### Planting Date

Rice grown in the Gulf Coast region of the United States is usually planted in March-April and harvested in July-August (Blanche et al. 2009, Dou and Tarpley 2014). A second crop, or ratoon crop, developing from main crop stubble is sometimes produced and harvested in October-November (Harrell et al. 2009). A field experiment conducted in southeast Texas with rice planted in mid-March, mid-April, and mid-May showed that the heaviest Mexican rice borer and sugarcane borer infestations occurred in the main crop of the late planting dates and in the ratoon crop from the early planting date (M.O.W., unpublished data). Late-planted main crop rice and ratoon crop rice are thought to provide abundant host plants at stages of development attractive for oviposition when Mexican rice borer populations are relatively high. Thus, early planting is recommended.

#### Harvest Cutting Height and Stubble Management

A 2-yr field study in southeast Texas showed that reducing rice main crop harvest cutting height from a conventional 40 cm (16 inches) to 20 cm (8 inches) decreased Mexican rice borer infestations in the stubble by 70 to 81% (Beuzelin et al. 2012). In addition, main crop stubble, whether or not managed to produce a ratoon crop, can be a late growing season and overwintering host for Mexican rice borer larvae. Beuzelin et al. (2012) observed that Mexican rice borer densities in rice stubble decreased by 77 to >99% between late October and late March, but could remain more than five immatures per square meter (0.5 per square foot) under high pest pressure and conditions conducive to stubble growth or volunteer rice development.

Thus, reduced harvest cutting height and stubble destruction in the fall are recommended.

### Noncrop Host Management

Amazon sprangletop is a common weedy grass in rice fields that is very attractive to and suitable for the Mexican rice borer. In a study exposing potted plants to natural Mexican rice borer infestations for 4 to 7 wk, between 44 and 78% of Amazon sprangletop plants were infested with at least one larva or pupa, which was comparable with or greater than infestations observed in rice plants (Beuzelin et al. 2011b). Thus, appropriate weed management in rice fields can assist with Mexican rice borer management.

Weedy grasses in noncrop habitats adjacent to rice fields are thought to play a role in Mexican rice borer population overwintering and build-up (Beuzelin et al. 2011a). Destruction of johnsongrass and vaseygrass along field margins and ditch banks is therefore recommended in the fall and early spring to reduce overwintering populations. However, the contribution of noncrop habitats to Mexican rice borer populations infesting rice has not been quantified.

### Soil Fertility Management

The impact of soil fertilization on Mexican rice borer injury and associated yield losses in rice has not been studied. However, increasing levels of nitrogen (N) fertilization increase Mexican rice borer injury in sugarcane and sorghum (Showler 2015, VanWeelden et al. 2016). In rice, increased levels of N fertilization are generally conducive to increased stem borer infestations (Jiang and Cheng 2003). Because high levels of N fertilization likely increase Mexican rice borer infestations and can increase infestations of the rice water weevil, *Lissorhoptrus oryzophilus* Kuschel (Coleoptera: Curculionidae) (Way et al. 2006b), applying N at rates higher than suggested in fertilization recommendations is discouraged.

Amending soils with silicon (Si) increases rice resistance to stem borers (Sidhu et al. 2013). Silicon increases plant resistance directly, augmenting the mechanical resistance of plants to feeding (Reynolds et al. 2009). In addition, recent studies strongly suggest that Si amplifies plant chemical defenses and primes plants for greater responsiveness via a jasmonic acid-mediated pathway (Reynolds et al. 2009, Ye et al. 2013). Silicon may also alter plant defenses in ways that increase the effectiveness of natural enemies (Reynolds et al. 2009). A field study in southeast Texas suggests that applying Si might reduce the number of whiteheads and increase yield under Mexican rice borer natural infestations (M.O.W. and M.J.S., unpublished data). Thus, although the effects of Si on Mexican rice borers attacking rice need to be confirmed, Si soil amendments could play a role in a refined Mexican rice borer management strategy.

### Host Plant Resistance

The development of rice cultivars resistant to insect pests in general, and to the Mexican rice borer in particular, has not been a priority of modern breeding programs in the United States (Way et al. 2006a). Douglas and Ingram (1942) observed that the sugarcane borer was more abundant in rice plants with a larger culm. This is consistent with observations for the Asiatic rice borer, *Chilo suppressalis* (Walker) (Lepidoptera: Crambidae) (Patanakamjorn and Pathak 1967). In addition, tight internode-wrapping leaf sheaths (Patanakamjorn and Pathak 1967) and thick layers of sclerenchymatous or lignified tissues under the epidermis (Chaudhary et al. 1984) have been associated with decreased susceptibility of rice to stem borers in Asia. These host plant traits conferring resistance to stem

borers ecologically and taxonomically close to the Mexican rice borer are expected to confer resistance to this species. However, resistance to one stem borer species is not always associated with resistance to another stem borer species. For example, in sugarcane, cultivar 'HoCP 85-845' is considered resistant to the Mexican rice borer and sugarcane borer, whereas cultivar 'HoCP 04-838' is considered resistant only to the sugarcane borer (White et al. 2008, Hale et al. 2012, Wilson et al. 2015b).

A 4-yr field study in southeast Texas evaluated 20 rice cultivars under natural mixed infestations of Mexican rice borer and sugarcane borer (Way et al. 2006a). Stem borer injury level, as measured by the number of whiteheads per unit area, and yield loss were recorded. 'Priscilla', an inbred (~100% homozygous line), was the most susceptible cultivar with the highest injury levels in the main crop and the greatest yield losses over 3 yr. Despite varying levels of susceptibility among the years, the inbred 'Cocodrie' was considered moderately susceptible. Hybrid cultivars, which generally sustained injury levels and yield losses lower than in inbred cultivars, were considered moderately resistant. The hybrid 'XL8' sustained relatively low levels of injury (Way et al. 2006a); however, XL8 is more attractive for Mexican rice borer oviposition than Cocodrie (Reay-Jones et al. 2007b), suggesting that resistance in this hybrid cultivar might be associated with tolerance to injury or negative effects on larval performance.

The high tillering potential of hybrid cultivars is thought to impart greater tolerance to stem borer injury than that of inbred cultivars (Horgan and Crisol 2013). For example, Tan et al. (1983) found that a hybrid cultivar had both higher Asiatic rice borer larval counts and higher tolerance during the heading and ripening stages than an inbred cultivar. Luo (1987) showed higher compensation in hybrids to attack by the Asiatic rice borer through increased head and grain weights. Although current commercial inbred and hybrid cultivars are considered susceptible to the Mexican rice borer (Espino and Way 2014), they exhibit varying levels of susceptibility to the pest. Thus, as results of ongoing cultivar evaluations conducted in the Gulf Coast region of the United States become available, adoption of the more resistant cultivars will be recommended.

## Insecticides

Foliar applications of pyrethroids have historically been the only chemical control option for Mexican rice borer management in rice produced in the Gulf Coast region of the United States. Two pyrethroids are currently registered for foliar applications (Table 1). In addition, the diamide chlorantraniliprole is registered as a seed treatment (Table 1).

Foliar applications of tebufenozide and novaluron successfully reduce Mexican rice borer and sugarcane borer injury in sugarcane (Beuzelin et al. 2010a, Wilson et al. 2012). However, these two insect growth regulators and two related active ingredients, methoxyfenozide and diflubenzuron, have lacked efficacy in rice when

compared with pyrethroids (Reay-Jones et al. 2007a). Foliar applications of chlorantraniliprole and another diamide, flubendiamide, effectively reduce Mexican rice borer injury in sugarcane (Beuzelin et al. 2010b, VanWeelden et al. 2013). However, the efficacy of foliar applications of diamides has not been evaluated in rice.

Economic thresholds for Mexican rice borer management in rice have not been developed. Lv et al. (2008) established relationships between sugarcane borer infestation level, injury, and yield for three rice cultivars at three plant stages. Only limited comparable data exist for the Mexican rice borer, but results from a 4-yr field study in a region of southeast Texas with high Mexican rice borer pest pressure have helped to better time insecticide applications (Reay-Jones et al. 2007a). Pyrethroids applied twice during rice reproductive stages caused the greatest decrease in whiteheads and yield losses, and generally increased economic benefits for producers (Reay-Jones et al. 2007a). However, the effects of insecticide applications on yield losses were highly variable.

Current recommendations for Mexican rice borer management with foliar insecticides suggest scouting rice fields starting at the panicle differentiation stage and through the boot stage (Espino and Way 2014, Anonymous 2015). Scouting efforts should be directed toward detecting early larval feeding signs, which include discoloration and window-paning of leaf sheaths (Fig. 8), because the presence of concealed egg masses is practically impossible to detect. Foliar insecticides should be applied when Mexican rice borer larvae are feeding in the leaf sheaths, before penetrating the culm. Insecticides should not be applied once whiteheads are observed because larvae have already penetrated the culm and caused yield losses. However, because economic thresholds have not been developed, the decision to apply foliar insecticides is ultimately based on planting date, crop potential, decision to produce a ratoon crop, producer experience, and perceived levels of Mexican rice borer infestations. Under heavy treatable infestations, pyrethroid foliar applications at the 1-2-inch panicle stage and at the late boot or early heading stage have provided the greatest level of yield protection (Reay-Jones et al. 2007a, Espino and Way 2014, Anonymous 2015).

Pyrethroids can effectively manage Mexican rice borer infestations (Reay-Jones et al. 2007a), but foliar applications are associated with negative nontarget effects where crawfish, *Procambarus* spp. (Decapoda: Cambaridae), are produced near rice fields (Barbee et al. 2010). In addition, it is difficult for rice producers to make informed decisions in the absence of thresholds. Chlorantraniliprole seed treatments are effective against the Mexican rice borer (Way and Pearson 2013, 2014; Wilson et al. 2015a), with possible reductions of 85 and 74% in whitehead density in the main and ratoon crop, respectively (Way and Pearson 2014). These seed treatments are primarily used to protect against rice water weevil infestations and have been widely adopted since the late 2000s, with over 60% of rice producers using chlorantraniliprole in Louisiana in 2012 (Blackman et al. 2014). Chlorantraniliprole seed treatments also have limited nontarget effects on crawfish (Barbee et al. 2010).

**Table 1.** Insecticides registered for Mexican rice borer management in rice in the United States

| Active ingredient   | IRAC mode of action <sup>a</sup>  | Rate in g ai/ha (lb ai/acre)   | Trade name            | Application method |
|---------------------|-----------------------------------|--------------------------------|-----------------------|--------------------|
| Gamma-cyhalothrin   | Sodium channel modulator (3A)     | 17–22 (0.015–0.020)            | Declare               | Foliar treatment   |
| Lambda-cyhalothrin  | Sodium channel modulator (3A)     | 35–47 (0.03–0.04)              | Karate Z <sup>b</sup> | Foliar treatment   |
| Chlorantraniliprole | Ryanodine receptor modulator (28) | 67–91 (0.06–0.08) <sup>c</sup> | Dermacor X-100        | Seed treatment     |

<sup>a</sup>Insecticide Resistance Action Committee Mode of Action (IRAC 2015).

<sup>b</sup>Formulations of generic lambda-cyhalothrin are available.

<sup>c</sup>Rates based on rice seed weight will vary with seeding rate to achieve desired rates on a per unit area basis.



Fig. 8. Mexican rice borer larval feeding signs on a rice leaf sheath.

Thus, in areas where an insecticide seed treatment is recommended for rice water weevil management and where the Mexican rice borer is a concern, chlorantraniliprole seed treatments should be used.

### Biological Control

The majority of the work addressing biological control of the Mexican rice borer has been conducted for management in sugarcane in south Texas with hymenopteran and dipteran parasitoids (Legaspi et al. 1997a, Showler and Reagan 2012). In rice, Mexican rice borer parasitism from five parasitoid species was studied in field cages (Pfannenstiel and Browning 1995). *Allorhogas pyralophagus* Marsh and *Alabagrus stigma* Brullé (Hymenoptera: Braconidae) parasitized 45.0 and 11.5% of the available Mexican rice borer larvae, respectively. *Goniozius natalensis* Gordh (Hymenoptera: Bethyridae) parasitized 8.5%. However, the use of biological control agents for Mexican rice borer management has not been the focus of recent research efforts.

### Conclusions

In conclusion, multiple aspects of integrated pest management including use of pheromone traps, manipulation of planting dates, harvest cutting height, stubble management, noncrop host management, soil fertility management, host plant resistance, use of insecticides, and biological control have been studied for Mexican rice borer management in rice grown in the Gulf Coast region of the United States. The current management strategy, however, primarily relies on the use of chlorantraniliprole seed treatments targeting the rice water weevil and Mexican rice borer (Blackman et al. 2014). To encourage the adoption of additional tactics, researchers and extension specialists will have to further improve the efficacy of proven individual tactics, as well as assess the efficacy and economic return of potential management tactics. Future Mexican rice borer

management research is therefore expected to focus on the development of sampling protocols and a threshold for foliar insecticide applications, the evaluation of conventional and hybrid cultivars for resistance, the evaluation of the role of N and Si fertilization, and the determination of the efficacy of stubble and noncrop host management. Research for new insecticide modes of action and refined use of seed treatments is also anticipated. The efficacy of transgenic rice, which is not currently produced in the United States, might be investigated because transgenic corn expressing *Bacillus thuringiensis* Berliner (Bt) proteins that target common corn lepidopteran pests also control the Mexican rice borer in Texas and Louisiana (Showler et al. 2013, J.M.B., unpublished data). Finally, further differentiating Mexican rice borer management from sugarcane borer management in rice, and adapting management tactics developed for other major crop hosts like sugarcane, will be important long-term refinements for Mexican rice borer integrated pest management in rice.

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### References Cited

- Agnew, C. W., L. A. Rodríguez-del-Bosque, and J. W. Smith, Jr. 1988. Misidentifications of Mexican stalkborers in the subfamily Crambinae (Lepidoptera: Pyralidae). *Folia Entomol. Mex.* 75: 63–75.
- Anonymous. 2015. Rice, pp 30–35. 2015 Louisiana insect pest management guide. LSU AgCenter Publication 1838, Baton Rouge, LA.
- Barbee, G. C., W. R. McClain, S. K. Lanka, and M. J. Stout. 2010. Acute toxicity of chlorantraniliprole to non-target crayfish (*Procambarus clarkii*) associated with rice-crayfish cropping systems. *Pest Manag. Sci.* 66: 996–1001.
- Bessin, R. T., and T. E. Reagan. 1990. Fecundity of the sugarcane borer (Lepidoptera: Pyralidae) as affected by larval development on gramineous host plants. *Environ. Entomol.* 19: 635–639.
- Beuzelin, J. M. 2011. Agroecological factors impacting stem borer (Lepidoptera: Crambidae) dynamics in Gulf Coast sugarcane and rice. Ph.D. dissertation, Louisiana State University, Baton Rouge, LA.
- Beuzelin, J. M., W. Akbar, A. Mészáros, F. P. F. Reay-Jones, and T. E. Reagan. 2010a. Field assessment of novaluron for sugarcane borer, *Diatraea saccharalis* (F.) (Lepidoptera: Crambidae), management in Louisiana sugarcane. *Crop Prot.* 29: 1168–1176.
- Beuzelin, J. M., W. Akbar, A. Mészáros, B. E. Wilson, T. E. Reagan, and M. O. Way. 2010b. Small plot assessment of insecticides against the Mexican rice borer, 2009. *Arthropod Manag. Tests* 35: F50.
- Beuzelin, J. M., A. Mészáros, T. E. Reagan, L. T. Wilson, M. O. Way, D. C. Blouin, and A. T. Showler. 2011a. Seasonal infestations of two stem borers (Lepidoptera: Crambidae) in non-crop grasses of Gulf Coast rice agroecosystems. *Environ. Entomol.* 40: 1036–1050.



- Beuzelin, J. M., T. E. Reagan, M. O. Way, A. Mészáros, W. Akbar, and L. T. Wilson. 2011b. Potential impact of Mexican rice borer Mexican rice borer non-crop hosts on sugarcane IPM. *Intl. Sugar J.* 113: 660–665.
- Beuzelin, J. M., A. Mészáros, M. O. Way, and T. E. Reagan. 2012. Rice harvest cutting height and ratoon crop effects on late season and overwintering stem borer (Lepidoptera: Crambidae) infestations. *Crop Prot.* 34: 47–55.
- Beuzelin, J. M., L. T. Wilson, A. T. Showler, A. Mészáros, B. E. Wilson, M. O. Way, and T. E. Reagan. 2013. Oviposition and larval development of a stem borer, *Eoreuma loftini*, on rice and non-crop grass hosts. *Entomol. Exp. Appl.* 146: 332–346.
- Blackman, B., T. Autin, N. A. Hummel, A. Mészáros, M. O. Way, M. J. Stout, and D. Davis. 2014. Management practices of Louisiana and Texas rice growers. *LA. Agric.* 57: 14–15.
- Blanche, S., D. L. Harrell, and J. K. Saichuk. 2009. General agronomic guidelines, pp. 3–15. In *Louisiana Rice Production Handbook*. Louisiana State University Agricultural Center Publication 2321, Baton Rouge, LA.
- Bleszynski, S. 1967. Studies on the Crambinae (Lepidoptera). Part 44. New neotropical genera and species. Preliminary check-list of neotropical Crambinae. *Acta Zool. Cracov.* 12: 39–110.
- Brown, H. E., L. T. Wood, T. D. Shaver, and J. Worley. 1988. Behavioral responses of male *Eoreuma loftini* (Lepidoptera: Pyralidae) to ovipositor extracts. *J. Econ. Entomol.* 81: 184–188.
- Browning, H. W., and J. W. Smith, Jr. 1988. Interim progress report of the Mexican rice borer research program. Texas Agricultural Experiment Station Report 1988, College Station, TX.
- Browning, H. W., M. O. Way, and B. M. Drees. 1989. Managing the Mexican rice borer in Texas. Texas Agricultural Experiment Station Publication B-1620, College Station, TX.
- Castro, B. A., T. J. Riley, B. R. Leonard, and J. L. Baldwin. 2004. Borers galore: Emerging pest in Louisiana corn, grain sorghum and rice. *LA. Agric.* 47: 4–6.
- Chaudhary, R. C., G. S. Ksush, and E. A. Heinrichs. 1984. Varietal resistance to rice stem-borers in Asia. *Insect Sci. Appl.* 5: 447–463.
- Dou, F., and L. Tarpley. 2014. Planting dates pp. 9–10. In 2014 Texas Rice Production Guidelines. Texas A&M AgriLife Extension Service Publication B-6131, College Station, TX.
- Douglas, W. A., and J. W. Ingram. 1942. Rice-field insects. U.S. Department of Agriculture Circular 632.
- Dyar, H. G. 1917. Seven new crambids from the United States. *Insecturor Inscitiae Mentruus* 5: 84–87.
- Espino, L., and M. O. Way. 2014. Insect management pp. 59–82. In 2014 Texas Rice Production Guidelines. Texas A&M AgriLife Extension Service Publication B-6131, College Station, TX.
- Hale, A. L., W. H. White, E. O. Dufrene, T. L. Tew, M. P. Grisham, Y.-B. Pan, and J. D. Miller. 2012. HoCP 04-838 – a new sugarcane variety for Louisiana. *J. Am. Soc. Sugar Cane Technol.* 32: 84–85.
- Hamm, J. C., J. K. Sidhu, M. J. Stout, N. A. Hummel, and T. E. Reagan. 2012. Oviposition behavior of *Diatraea saccharalis* (Lepidoptera: Crambidae) on different rice cultivars in Louisiana. *Environ. Entomol.* 41: 571–577.
- Harrell, D. L., J. A. Bond, and S. Blanche. 2009. Evaluation of main-crop stubble height on ratoon rice growth and development. *Field Crops Res.* 114: 396–403.
- Hayden, J. E. 2012. Mexican rice borer, *Eoreuma loftini* (Dyar) (Lepidoptera: Crambidae) in Florida. *Pest Alert* Nov 13, 2012. Florida Department of Agriculture and Consumer Services, Division of Plant Industry, FL.
- Holloway, T. E., W. E. Halley, U. C. Loftin, and C. Heinrich. 1928. The sugar-cane borer in the United States. U.S. Department of Agriculture Technical Bulletin 41.
- Horgan, F. G., and E. Crisol. 2013. Hybrid Rice and Insect Herbivores in Asia. *Entomol. Exp. Appl.* 148: 1–19.
- Hummel, N. A., T. Hardy, T. E. Reagan, D. K. Pollet, C. E. Carlton, M. J. Stout, J. M. Beuzelin, W. Akbar, and W. H. White. 2010. Monitoring and first discovery of the Mexican rice borer *Eoreuma loftini* (Lepidoptera: Crambidae) in Louisiana. *Fla. Entomol.* 93: 123–124.
- (IRAC) The Insecticide Resistance Action Committee. 2015. Mode of action classification brochure, Fourth Edition (4.1) – June 2015, (<http://www.irc-online.org/documents/moa-brochure/?ext=pdf>) (accessed 30 October 2015).
- Islam, Z., and A. N. M. R. Karim. 1997. Whiteheads associated with stem borer infestation in modern rice varieties: An attempt to resolve the dilemma of yield losses. *Crop Prot.* 16: 303–311.
- Jiang, M. X., and J. A. Cheng. 2003. Interactions between the striped stem borer *Chilo suppressalis* (Walk.) (Lep., Pyralidae) larvae and rice plants in response to nitrogen fertilization. *J. Pest Sci.* 76: 124–128.
- Johnson, K. J. R. 1984. Identification of *Eoreuma loftini* (Dyar) (Lepidoptera: Pyralidae) in Texas, 1980: Forerunner for other sugarcane boring pest immigrants from Mexico? *Bull. Entomol. Soc. Am.* 30: 47–52.
- Johnson, K. J. R. 1985. Seasonal occurrence and insecticidal suppression of *Eoreuma loftini* (Lepidoptera: Pyralidae) in sugarcane. *J. Econ. Entomol.* 78: 960–966.
- Johnson, K. J. R., and M. B. Van Leerdam. 1981. Range extension of *Acigona loftini* into the Lower Rio Grande Valley of Texas. *Sugar y Azucar* 76: 34.
- Klots, A. B. 1970. North American Crambinae: Notes on the tribe Chiloini and a revision on the genera *Eoreuma* Ely and *Xubida* Schaus (Lepidoptera: Pyralidae). *J. NY Entomol. Soc.* 78: 100–120.
- Legaspi, J. C., B. C. Legaspi, Jr, E. G. King, and R. R. Saldaña. 1997a. Mexican rice borer, *Eoreuma loftini* (Lepidoptera: Pyralidae) in the Lower Rio Grande Valley of Texas: Its history and control. *Subtrop. Plant Sci.* 49: 53–64.
- Legaspi, J. C., R. R. Saldaña, and N. Roseff. 1997b. Identifying and managing stalkborers on Texas sugarcane. Texas Agricultural Experiment Station Publication MP-1777, College Station, TX.
- Legaspi, J. C., B. C. Legaspi, Jr, and R. R. Saldaña. 1999. Evaluation of a synthetic pheromone for control of the Mexican rice borer (Lepidoptera: Pyralidae) in south Texas. *Subtrop. Plant Sci.* 51: 49–55.
- Luo, S. 1987. Studies on the compensation of rice to the larval damage caused by the Asian rice borer (*Chilo suppressalis* (WK)). *Sci. Agric. Sin.* 20: 67–72.
- Lv, J., L. T. Wilson, and M. T. Longnecker. 2008. Tolerance and compensatory response of rice to sugarcane borer (Lepidoptera: Crambidae) injury. *Environ. Entomol.* 37: 796–807.
- Lv, J., L. T. Wilson, J. M. Beuzelin, and T. E. Reagan. 2010. Rice tillering and yield as affected by artificial and sugarcane borer (Lepidoptera: Crambidae) culm injury. *Environ. Entomol.* 39: 528–534.
- Meagher, R. L., Jr, J. W. Smith, and K. J. R. Johnson. 1994. Insecticidal management of *Eoreuma loftini* (Lepidoptera: Pyralidae) on Texas sugarcane: a critical review. *J. Econ. Entomol.* 87: 1332–1344.
- Meagher, R. L., Jr, L. T. Wilson, and R. S. Pfannenstiel. 1996. Sampling *Eoreuma loftini* (Lepidoptera: Pyralidae) on Texas sugarcane. *Environ. Entomol.* 25: 7–16.
- Muralidharan, K., and I. C. Pasalu. 2006. Assessments of crop losses in rice ecosystems due to stem borer damage (Lepidoptera: Pyralidae). *Crop Prot.* 25: 409–417.
- Osborn, H. T., and G. R. Phillips. 1946. *Chilo loftini* in California, Arizona, and Mexico. *J. Econ. Entomol.* 39: 755–759.
- Patanakamjorn, S., and M. D. Pathak. 1967. Varietal resistance to Asiatic rice borer *Chilo suppressalis* (Walker) in rice and its association with various plant characters. *Ann. Entomol. Soc. Am.* 60: 287–292.
- Pathak, M. D. 1968. Ecology of common insect pests of rice. *Annu. Rev. Entomol.* 13: 257–294.
- Pfannenstiel, R. S., and H. W. Browning. 1995. Field evaluations of parasitoids of larval stalkborers against *Eoreuma loftini* (Lepidoptera: Pyralidae) in rice. *J. Entomol. Sci.* 30: 406–414.
- Reay-Jones, F. P. F. 2005. Integrated pest management of the Mexican rice borer in Louisiana and Texas sugarcane and rice. Ph.D. dissertation, Louisiana State University, Baton Rouge, LA.
- Reay-Jones, F. P. F., M. O. Way, and T. E. Reagan. 2007a. Economic assessment of controlling stem borers (Lepidoptera: Crambidae) with insecticides in Texas rice. *Crop Prot.* 26: 963–970.
- Reay-Jones, F. P. F., L. T. Wilson, A. T. Showler, T. E. Reagan, and M. O. Way. 2007b. Role of oviposition preference in an invasive Crambid impacting two graminaceous host crops. *Environ. Entomol.* 36: 938–951.
- Reay-Jones, F. P. F., L. T. Wilson, M. O. Way, T. E. Reagan, and C. E. Carlton. 2007c. Movement of the Mexican rice borer (Lepidoptera: Crambidae) through the Texas rice belt. *J. Econ. Entomol.* 100: 54–60.

- Reay-Jones, F. P. F., L. T. Wilson, T. E. Reagan, B. L. Legendre, and M. O. Way. 2008. Predicting economic losses from the continued spread of the Mexican rice borer (Lepidoptera: Crambidae). *J. Econ. Entomol.* 101: 237–250.
- Reynolds, O. L., M. G. Keeping, and J. H. Meyer. 2009. Silicon-augmented resistance of plants to herbivorous insects: A review. *Ann. Appl. Biol.* 155: 171–186.
- Rodriguez-del-Bosque, L. A., J. W. Smith, Jr, and J. Martinez. 1995. Winter mortality and spring emergence of corn stalkborers (Lepidoptera: Pyralidae) in subtropical Mexico. *J. Econ. Entomol.* 88: 628–634.
- Rubia, E. G., K. L. Heong, M. Zalucki, B. Gonzales, G. A. Norton. 1996. Mechanisms of compensation of rice plants to yellow stem borer *Scirpophaga incertulas* (Walker) injury. *Crop Prot.* 15: 335–340.
- Shaver, T. N., and H. E. Brown. 1993. Evaluation of pheromone to disrupt mating of *Eoreuma loftini* (Lepidoptera: Pyralidae) in sugarcane. *J. Econ. Entomol.* 86: 377–381.
- Shaver, T. N., H. E. Brown, H. J. Williams, L. T. Woods, and J. Worley. 1988. Components of female sex pheromone of *Eoreuma loftini* Dyar. *J. Chem. Ecol.* 14: 391–399.
- Shaver, T. N., H. E. Brown, J. W. Bard, T. C. Holler, and D. E. Hendricks. 1991. Field evaluations of pheromone-baited traps for monitoring Mexican rice borer (Lepidoptera: Pyralidae). *J. Econ. Entomol.* 84: 1216–1219.
- Showler, A. T. 2015. Effects of compost and chicken litter on soil nutrition, and sugarcane physiochemistry, yield, and injury caused by the Mexican rice borer, *Eoreuma loftini* (Dyar) (Lepidoptera: Crambidae). *Crop Prot.* 71: 1–11.
- Showler, A. T., and T. E. Reagan. 2012. Ecology and tactics for control of three sugarcane stalk-boring species in the Western Hemisphere and Africa, pp. 1–15. In J. F. Goncalves and K. D. Correia (eds.), *Sugarcane: Production, Cultivation and Uses*. Nova Science Publishers, Inc, Hauppauge, NY.
- Showler, A. T., J. M. Beuzelin, and T. E. Reagan. 2011. Alternate crop and weed host plant oviposition preferences by the Mexican rice borer (Lepidoptera: Crambidae). *Crop Prot.* 30: 895–901.
- Showler, A. T., B. E. Wilson, and T. E. Reagan. 2012. Mexican rice borer (Lepidoptera: Crambidae) injury to corn greater than to sorghum and sugarcane under field conditions. *J. Econ. Entomol.* 105: 1597–1602.
- Showler, A. T., S. C. Cook, and V. Abrigo. 2013. Transgenic Bt corn varietal resistance against the Mexican rice borer, *Eoreuma loftini* (Dyar) (Lepidoptera: Crambidae) and implications to sugarcane. *Crop Prot.* 48: 57–62.
- Sidhu, J. K., M. J. Stout, D. C. Blouin, and L. E. Datnoff. 2013. Effect of silicon soil amendment on performance of sugarcane borer, *Diatraea saccharalis* (Lepidoptera: Crambidae) on rice. *Bull. Entomol. Res.* 103: 656–664.
- Solis, M. A. 1999. Key to selected Pyraloidea (Lepidoptera) larvae intercepted at U.S. ports of entry: revision of Pyraloidea in “Keys to some frequently intercepted Lepidopterous larvae” by Weisman 1986. *Proc. Entomol. Soc. Wash.* 101: 645–686.
- Spurgeon, D. W., J. R. Raulston, P. D. Lingren, and J. M. Gillespie. 1997. Mating disruption of Mexican rice borers (Lepidoptera: Pyralidae) in Lower Rio Grande Valley sugarcane. *J. Econ. Entomol.* 90: 223–234.
- Tan, Y. C., J. M. Zhou, and M. C. Lin. 1983. Development of the striped stem borer on hybrid rice. *Acta Entomol. Sin.* 26: 114–116.
- University of Florida. 2015. Mexican rice borer...an introduction. ([http://erc.ifas.ufl.edu/mexican\\_rice\\_borer/index.shtml](http://erc.ifas.ufl.edu/mexican_rice_borer/index.shtml)) (accessed 28 November 2015).
- VanWeelden, M. T., B. E. Wilson, T. E. Reagan, and J. M. Beuzelin. 2013. Aerial insecticidal control of the Mexican rice borer in sugarcane, 2012. *Arthropod Manag. Tests* 38: F71.
- VanWeelden, M. T., B. E. Wilson, J. M. Beuzelin, T. E. Reagan, and M. O. Way. 2015. Yield response to Mexican rice borer (Lepidoptera: Crambidae) injury in bioenergy and conventional sugarcane and sorghum. *J. Econ. Entomol.* 108: 2296–2304.
- VanWeelden, M. T., B. E. Wilson, J. M. Beuzelin, T. E. Reagan, and M. O. Way. 2016. Impact of nitrogen fertilization on Mexican rice borer (Lepidoptera: Crambidae) injury and yield in bioenergy sorghum. *Crop Prot.* 84: 37–43.
- Van Leerdam, M. B. 1986. Bionomics of *Eoreuma loftini*, a pyralid stalk borer of sugarcane. Ph.D. dissertation, Texas A&M University, College Station, TX.
- Van Leerdam, M. B., K. J. R. Johnson, and J. W. Smith, Jr. 1986. Ovipositional sites of *Eoreuma loftini* (Lepidoptera: Pyralidae) in sugarcane. *Environ. Entomol.* 15: 75–78.
- Van Zwaluwenburg, R. H. 1926. Insect enemies of sugarcane in western Mexico. *J. Econ. Entomol.* 19: 664–669.
- Way, M. O. 2003. Rice arthropod pests and their management in the United States, pp. 437–456. In C. W. Smith and R. H. Dilday (eds.), *Rice: Origin, History, Technology, and Production*. John Wiley & Sons, Inc. Hoboken, NJ.
- Way, M. O., and R. A. Pearson. 2013. Presidio seed treatments, pp. 25–27. 2013 Entomology research reports. Texas A & M AgriLife Research Center at Beaumont, Beaumont, TX.
- Way, M. O., and R. A. Pearson. 2014. Antonio seed treatments, pp. 51–54. In 2014 Entomology research reports. Texas A & M AgriLife Research Center at Beaumont, Beaumont, TX.
- Way, M. O., F. P. F. Reay-Jones, and T. E. Reagan. 2006a. Resistance to stem borers (Lepidoptera: Crambidae) among Texas rice cultivars. *J. Econ. Entomol.* 99: 1867–1876.
- Way, M. O., F. P. F. Reay-Jones, M. J. Stout, and L. Tarpley. 2006b. Effects of nitrogen fertilizer applied before permanent flood on the interaction between rice and rice water weevil (Coleoptera: Curculionidae). *J. Econ. Entomol.* 99: 2030–2037.
- White, W. H., R. P. Viator, E. O. Dufrene, C. D. Dalley, E. P. Richard, Jr, and T. L. Tew. 2008. Re-evaluation of sugarcane borer (Lepidoptera: Crambidae) bioeconomics in Louisiana. *Crop Prot.* 27: 1256–1261.
- Wilson, B. E., A. T. Showler, T. E. Reagan, and J. M. Beuzelin. 2012. Improved chemical control for the Mexican rice borer (Lepidoptera: Crambidae) in sugarcane: Larval exposure, a novel scouting method, and efficacy of a single aerial insecticide application. *J. Econ. Entomol.* 105: 1998–2006.
- Wilson, B. E., T. N. Hardy, J. M. Beuzelin, M. T. VanWeelden, T. E. Reagan, R. Miller, J. Meaux, M. J. Stout, and C. E. Carlton. 2015a. Expansion of the Mexican rice borer (Lepidoptera: Crambidae) into rice and sugarcane in Louisiana. *Environ. Entomol.* 44: 757–766.
- Wilson, B. E., M. T. VanWeelden, J. M. Beuzelin, T. E. Reagan, M. O. Way, W. H. White, L. T. Wilson, and A. T. Showler. 2015b. A relative resistance ratio for evaluation of Mexican rice borer (Lepidoptera: Crambidae) susceptibility among sugarcane cultivars. *J. Econ. Entomol.* 108: 1363–1370.
- Ye, M., Y. Song, J. Long, R. Wang, S. R. Baerson, Z. Pan, K. Zhu-Salzman, J. Xie, K. Cai, S. Luo, and R. Zeng. 2013. Priming of jasmonate-mediated antiherbivore defense responses in rice by silicon. *Proc. Natl. Acad. Sci. USA.* 110: E3631–E3639.