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Evaluation of Rice Stink Bug, Oebalus pugnax (F.), Resistance to Lambda-cyhalothrin and the Economic Impact on Rice Grain Quality for Multiple Foliar Insecticides

Trevor Bradley Newkirk
University of Arkansas-Fayetteville

Evaluation of Rice Stink Bug, *Oebalus pugnax* (F.), Resistance to Lambda-cyhalothrin and the Economic Impact on Rice Grain Quality for Multiple Foliar Insecticides

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Trevor Newkirk
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Nicholas R. Bateman, PhD.
Thesis Director

Benjamin C. Thrash, PhD.
Co-Committee Chair

Gustav M. Lorenz III, PhD.
Committee Chair (ex-officio)

Jarrod T. Hardke, PhD.
Committee Member

Neelendra Joshi, PhD.
Committee Member

Abstract

Rice stink bug, (RSB), *Oebalus pugnax* (F.), (Fabricius 1775) is the major pest of headed rice, *Oryza sativa* L. in the southern rice producing states. The evaluation of current insecticides is imperative to efficient and economical RSB management for rice growers. Multiple reports of field failures with lambda-cyhalothrin have been documented since 2019. Lambda-cyhalothrin has been the standard for RSB control for the past two decades. The objective for this research was to determine if RSB is becoming resistant to lambda-cyhalothrin in Arkansas, and the most economical insecticide choice for growers with respect to RSB control and grain quality.

RSB populations were collected throughout Arkansas throughout the growing season to determine resistance levels to lambda-cyhalothrin. Increased resistance to lambda-cyhalothrin in RSB populations in Arkansas is occurring, among naturally diverse RSB populations. Lower mortality was observed for collections made in August compared to May, June, or July. Based on results from this study growers and consultants should not anticipate more than 70% control with lambda-cyhalothrin, and commonly a decrease in percent control as the growing season progresses. These assays were direct exposure, and less control should be anticipated in a field setting.

Foliar insecticide comparison trials were conducted in 2021 and 2022 at a total of 7 sites, to evaluate insecticides for efficacy and residual control of RSB, and to determine any subsequent on rice quality. Lambda-cyhalothrin provided lower control of RSB nymphs at all sampling dates, up to 14 DAT, compared to dinotefuran and thiamethoxam + lambda-cyhalothrin. Dinotefuran and thiamethoxam + lambda-cyhalothrin had less RSB damage (“peck”) compared to all other treatments excluding carbaryl. Total peck was reduced with dinotefuran and both rates of thiamethoxam + lambda-cyhalothrin across all locations, compared

to malathion, zeta-cypermethrin, and lambda-cyhalothrin. Return on investment was the highest in dinotefuran, thiamethoxam + lambda-cyhalothrin, and carbaryl treated plots compared to lambda-cyhalothrin.

Foliar timing experiments were performed in 2022 over three field sites, to establish at which time in grain maturity is treatment for RSB is most crucial to preserve grain quality. This study observed common trends between the three test locations, where RSB peck was higher in lambda-cyhalothrin treated plots compared to dinotefuran and thiamethoxam + lambda-cyhalothrin. Applications of lambda-cyhalothrin only lowered RSB peck when applied late or applied twice compared to the untreated check (UTC). No differences were observed between thiamethoxam + lambda-cyhalothrin and dinotefuran within or across application timing. Greater net returns were observed for thiamethoxam + lambda-cyhalothrin and dinotefuran, at each treatment timing compared to lambda-cyhalothrin and the UTC. A trend was observed that an application of either dinotefuran or thiamethoxam + lambda-cyhalothrin at the soft dough growth stage provided greater returns on investment than an application made during flowering or at both timings.

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Dedication

I would like to dedicate this thesis to my dad, Brad Newkirk, without him I truly would not be the man I am today. He provided my sister and I with a great life, taking us to church, and to our family farm to enjoy time with family. Growing up playing travel baseball he made sure I had the nicest cleats, best catching gear, and plenty of snacks in the dugout. He taught me that a man's word was all that he had and to always tell the truth and do the right thing even when the wrong thing might be easier. My dad taught me that a strong work ethic and good communication among coworkers was important to having a successful career, to treat everyone with respect no matter the individual's rank. He has always pushed me to be the best that I can be in whatever I was doing, even if it seemed like a meaningless task. I will forever be grateful for my dad and all the life advice he has provided me through life's twist and turns.

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Chapter I – Literature Review

Introduction

Rice, *Oryza sativa*, is the most vital crop in the world, being the staple food of about half the world's population (Dawe et al. 2010). It is grown worldwide, presumed to first be developed in China, roughly 7,000 years ago. Rice is one of the top three grown commodity, with global harvest in 2000 around 166 million ha. In 2022, global rice production provided 519.5 million tons of milled rice (FAO 2022). Global rice prices have steadily increased since 2022, high yields – have played a major role in the increase of rice prices. Utilization of rice throughout the world has grown at a high rate (2%) since 2020/21, with a re-establishment of animal feed generated from rice (FAO 2022). Rice production in the U.S., began in South Carolina in 1685 and grew rapidly throughout the U.S. in the 1990s, setting record highs in 1999 and 2001 (Livezey and Foreman 2005). In the U.S. rice is grown primarily in six states Arkansas, Louisiana, Mississippi, Texas, Missouri, and California and is a major commodity for these states. In 2022, U.S. rice growers planted 899,595 hectares and harvested 879,352 hectares (NASS 2021).

The rice stink bug, *Oebalus pugnax* (F.) (Hemiptera: Pentatomidae) is a common insect pest in all rice producing states, excluding California, on a yearly basis and is the most important pest to heading rice (Douglas 1939). Rice stink bugs damage rice by decreasing yields and grain quality, on a yearly basis, in the mid-south rice growing regions (Douglas and Ingram 1942, Bowling 1962). High field populations leads to lower rough rice yields and higher amount of damaged kernels (pecky rice) (Bowling 1963). Annual losses from rice stink bug damage in Arkansas, Texas, and Louisiana in 1930-1937, were estimated to be $473,595 (Douglas and Ingram 1942, Bowling 1963). Insecticide applications are the main control tactic for rice stink

bug management (Jones and Cherry 1986). In Arkansas, around 50% of rice acres are treated each year for RSB management (Bateman et al. 2019).

Arkansas Rice Production

W. H. Fuller moved from Ohio to Carlisle, Arkansas in 1896, and began the development of Arkansas rice production (Dethloff 2003). Fuller traveled to Louisiana to explore the rice culture he rented a farm in 1898 and planted rice, recording information, and sending it back to Arkansas. In 1902, Fuller helped his Arkansan neighbor John Morris, organize a rice crop with the help of the Arkansas Agricultural Experiment Station, but the crop failed. In 1904, the Arkansas Agricultural Experiment Station planted 395 hectares of rice on preserved prairie land in Lonoke County and averaged 3278 kg/hectare. Fuller returned to Arkansas he, and neighboring farmer John Morris had successful rice crops in 1904. In 1906, local brokers from Stuttgart invested in the development of the state's first rice mill. By 1909, rice production in the central prairie of Arkansas grew from 6327 kg to over 2.5 million kg, accounting for 3.8% of the total U.S. rice crop (Dethloff 2003).

Of the 75 counties in Arkansas, 40 of them grow rice, making rice one of the top three crop commodities in Arkansas for planted acreage, harvested acreage, and total production (Hardke 2018). Poinsett, Lawrence, and Arkansas counties produce the most rice in the state, ranking among the top five counties in the U.S. in hectares planted and kg produced. The eastern-half of Arkansas is the premier region for rice production. However, the Arkansas River Valley and the Ouachita and Red River valleys in southwest Arkansas also produce rice. In 2021, Arkansas planted 490,283 hectares, and harvested 482,995 hectares. Arkansas is responsible for 47.5% of the total rice production in the U.S., making Arkansas the number one rice growing state in the U.S. (Hardke 2022).

Arkansas rice planting usually begins in late March and runs through June, with harvest beginning in late August and ending in early November (Hardke 2022). Roughly 57% of Arkansas rice was planted using clean-tillage methods in 2021. This method involves removing previous crop matter from the field in the fall or spring, to prepare a clean seedbed for the rice seed (Hardke 2021). Arkansas growers typically plant rice with a drill in a dry-seeded, delayed flood system, but other planting methods such as broadcasting occur on a smaller amount of acreage. With the growing interest of row rice production, true no-till practices using a furrow-irrigated system have increased from 7.7% in 2018, to 16.9% in 2020. However, traditional levee systems still remain the most common practice, accounting for 49% of planted acres, with precision-leveled and zero-graded fields responsible for 37% and 13% (Hardke 2021).

Rice Development

Rice *Oryza sativa* L. is an annual grass (Gramineae) with circular, hollow, jointed culms; thin, smooth, sessile leaf blades connected to the leaf sheaths with collars; precise, sickle-shaped, hirsute auricles; thin acute or two split ligules; and terminal panicles (Moldenhauer et al. 2018). Rice life cycle varies between cultivars but usually is completed in 105-145 days from germination to grain maturity. Rice development is categorized by three separate growth phases: vegetative, reproductive, and grain filling. The vegetative phase consists of multiple stages: seed germination (S1-S3); seedling emergence (V1-V2); pre-tillering (V1-V4); tillering (V5); maximum tillering; and vegetative lag phase. During vegetative phases, increases in plant height, tillering, root length, shoot dry weight, and leaf characters or leaf area index (LAI) are observed. The amount of tillers a rice plant produce is directly related to panicle number, and panicle number is a key yield component in rice (Fageria 2007). The reproductive phase of the rice plant consists of panicle initiation (PI; R0); internode elongation (IE); panicle differentiation (PD; R1);

booting (R2); heading (R3); and anthesis (R4) (Moldenhauer et al. 2018). The reproductive growth stage is distinguished by culm prolongation, a reduction in number of tillers, booting, development of flag leaves, heading, and anthesis. This stage determines panicle size and number of spikelet's per panicle, ultimately determine crop yield potential (Fageria 2007). The reproductive stage takes roughly 30 days in common cultivars. The ripening phase is made up of the milk stage (R6), soft dough (R6), hard dough (R7-R8), and grain maturity (R9) (Moldenhauer et al. 2018). Environmental factors including drought, inadequate solar radiation, nitrogen shortage, temperature, and panicle blast can cause panicle sterility which decreases grain yield (Fageria 2007).

Rice classification in the U.S. is divided into three separate classes short-, medium-, and long grain, classed based on kernel dimensions (Cameron et al. 2008). For the past century, breeding programs in the U.S. have developed germplasm pools for medium- and long-grain varieties which produce exceptional grain quality (Mackill and McKenzie 2003). Short- and medium-grain varieties are developed from temperate *japonica* subspecies, whereas long-grain cultivars are derived from a group of tropical *japonica* types amalgamating outstanding grain quality and high yield (Mackill and McKenzie 2003).

Hybrid rice technology originated in China during in 1975 (Virmani 2003). The U.S. first commercial hybrid rice was XL6, released by RiceTec in 2000. Using hybrid technology allows rice producers to grow more rice per unit area and increases grain yields (Virmani 1996). Land-grant universities are working with private companies to improve and develop cultivars that will control pests and add other traits that will be beneficial to rice growers (Hardke et al. 2018). Over, the last decade the adoption of hybrid rice seed in the Mid-South has provided growers with an alternative option other than conventional rice cultivars. Hybrid rice has the potential to

yield ~20% higher than conventional varieties (Virmani 1996). Hybrid rice production has increased from 2% of harvested long-grain to nearly 50% in 2011 (Lyman and Nalley 2013). Higher yields and increased disease resistance are beneficial qualities of hybrid rice (Nalley et al. 2016).

Overall Pest Complex

Weeds contend with rice for sunlight, nutrients, and water which can lower rice yields (Scott et al. 2018). Weed density not only decreases yield, but also reduces the quality and grade of rice. Higher weed pressure leads to longer harvests and cleaning proficiency, higher insect and disease pressure and greater expenses, also promotes expansion in the seedbank which supports higher weed populations in future crops and enhances development of herbicide-resistant weeds (Scott et al. 2018). In Arkansas, the most problematic weeds are barnyard grass, *Echinochloa crus-galli* (L.), annual sedges, *Cyperus* spp., and *Oryza sativa* L. (weedy rice), in traditional-flooded rice, and palmer pigweed, *Amaranthus palmeri*, and sedges, *Cyperus* spp., in furrow-irrigated rice (Butts et al. 2022).

Diseases have steadily increased in Arkansas rice production over time (Wamishe et al. 2018). Diseases in rice contributes to lower yields and profits, even with advances in rice production technology. In Arkansas and other Mid-South rice producing states, sheath blight is the most detrimental disease in rice. Three main factors are responsible for plant diseases: susceptible cultivar, virulent pathogen, and favorable environment, cause severe outbreaks of disease. *Pyricularia oryza*, an airborne fungus which causes 'blast', a disease that only harms rice. The fungus *Sclerotium oryza*, a rice disease, referred to as 'stem rot' (Wamishe et al. 2018). False smut caused by *Ustilaginoidea virens*, is an important disease of rice covering all parts of a kernel with a mass of black spores (Brooks et al. 2009).

Insect pest are problematic to rice plants, feeding during immature and mature stages, with different types of feeding mechanisms can take place following planting, and continue throughout the growing season up to harvest time (Ali et al. 2021). Insect pests can be separated into two categories, minor and major. Minor pests are commonly around but are less damaging, insects that cause economic damage are termed major pests due to reducing yields or grain quality (Ali et al. 2021). Insecticides are the main control tactic for insects in rice, with Arkansas rice growers averaging 1-2 applications each year. U.S. rice production losses caused by insects was roughly 3.54% in terms of yield loss in 2019 (Bateman et al. 2019). Rice water weevil had the greatest impact on yield compared to all other insect pests, with RSB being second. Both insects cost Arkansas rice producers more to control than all other pests.

Rice Insect Complex

Rice insect pests attack all parts of a rice plant at all stages of plant growth development (Heinrichs 1994). Defoliators feed on leaves (armyworms), grain insects (RSBs) extract nutrients from developing grains, stem borers (rice billbug) feed inside the stem, sucking insects (aphids) feed on leaves and stems, and some species (rice water weevil) feed on roots (Heinrichs 1994). In the Mid-South there are only a few insects that are major pests of rice, and most can be managed with insecticide applications (Lorenz et al. 2018). Variables such as planting date, rice stand, weed control, fertilization, and water management are common cultural practices to assist in growing a rice crop, and reducing insecticide applications.

Rice Water Weevil, *Lissorhoptrus oryzophilus* F., (Coleoptera: Curculionidae) is a yearly and destructive insect pest of rice post-flood, in the United States (Saito et al. 2005). Rice water weevils overwinter as adults in perennial grasses and leaf-litter around wooded areas surrounding rice fields (Way 2003). In early spring, adults emerge and begin searching for host plants in early

morning and evening hours (Lorenz et al. 2018). Adults are snout beetles and ~2.5 – 3.5 mm long with a grayish coloration, or dark brown when wet (Way 2003, Saito et al. 2005). Adults emerge into rice fields overnight and begin swimming below the water surface moving from plant to plant. Adults feed on rice foliage creating longitudinal feeding scars, feeding does not result in yield loss. Once rice is flooded, females deposit eggs in culms underwater into the leaf sheath (Saito et al. 2005). After hatching larvae move to plant roots to feed, feeding results in root pruning, or dislodges the plant from the soil (Way 2003). Root pruning can make rice turn yellow, hinder rice growth, prolong grain maturity, and in high-infestation decrease yields (Lorenz et al. 2018). Pruning can also reduce the number of tillers, allowing greater weed pressure (Way 2003). Larval feeding on the root system inhibits plant uptake of nutrients and water (Lorenz et al. 2018). Seed treatments are the most reliable control method, however foliar insecticides can be used to control adults, but application must be timely. Insecticide seed treatments recommended are cyantraniliprole (Fortenza, Syngenta Crop Protection), thiamethoxam (CruiserMaxx Rice, Syngenta Crop Protection), chlorantraniliprole (Dermacor X-100, Corteva Agriscience), and clothianidin (Nipsit INSIDE, Valent Corporation). Insecticides labeled for foliar applications targeting rice water weevil are gamma-cyhalothrin (Proaxis & Declare, FMC Corporation), lambda-cyhalothrin (Karate Z, Syngenta Crop Protection), zeta-cypermethrin (Mustang Maxx, FMC Corporation), and chlothianidin (Belay, Valent Corporation). Cultural controls such as field draining are effective in control rice water weevil larvae, however it can be more expensive compared to seed treatments or foliar applications (Lorenz et al. 2018). After egg lay occurs, removing the permanent flood can be removed for 7 to 13 days, or until soil cracking, at this point the flood can be reapplied. If water is removed,

growers typically need to apply an additional herbicide application and potentially more nitrogen (Way 2003).

Grape colaspis, *Colaspis brunnea* F., (Coleoptera: Chrysomelidae) overwinters as larvae in the subsoil and topsoil. In the spring grubs emerge from overwintering and feed on germinating seeds, roots, and seedlings reducing rice stand and tillering (Dale 1994). Larvae move up the soil and begin feeding in early May, while pupation starts in late May and continues through late June. Pupation takes place in the soil and pupae remain in the soil for 3 to 7 days until adults emerge. Damage is commonly confined to dry-seeded fields and less compact soils (Dale 1994). Soybeans are a desired host for grape colaspis, larvae and adults are typically found in legumes such as soybeans, rice is commonly rotated with soybeans leaving rice susceptible to overwintering larvae (Lorenz et al. 2018). Larvae feed on the below-ground stem causing seedlings to turn yellow and are often stunted or wilted. Spring tillage can reduce larvae density if overwintering larvae are near the topsoil. Flooding fields and maintaining a flood for 48 hours lowers small larvae population and depose others. Insecticide seed treatments such as thiamethoxam (CruiserMaxx Rice, Syngenta Crop Protection) and clothianidin (NipsIt INSIDE, Valent Corporation) provide plant protection against grape colaspis. Foliar applications prior to rain or flushing could potentially reduce populations, mixed in with herbicides and applied at 1 to 2-leaf stage (Lorenz et al. 2018).

Periodically, rice stalk borers (Lepidoptera: Crambidae), rice billbugs (Coleoptera: Curculionidae), rice seed midges (Diptera: Cecidomyiidae), short-horned grasshoppers (Orthoptera: Acrididae), armyworms (Lepidoptera: Noctuidae), chinch bugs (Heteroptera: Lygaeidae), and aphids (Hemiptera: Aphididae) can cause damage to rice plants (Lorenz et al. 2018). Aphids damage rice in patches, inserting toxins into the plant with piercing-sucking

mouthparts (Dale 1994). Adults and nymphs extract plant sap, promoting yellowing of leaves and stunted plants. Seed midge are most common in California rice production systems, injury is caused by feeding on seedlings. Maggots feed on primary roots and shoots and hollowing out embryos, and terminating the plant (Dale 1994). In Arkansas, seed midges are problematic in water seeded planting practices (Lorenz et al. 2018). Stalk borer larvae attack by boring the inner portion of leaf sheaths, causing longitudinal yellowish white patches at the injury site (Dale 1994). Caterpillars bore themselves into the stem stimulating the central whorl to remain closed, browning, and dying. Armyworms: true armyworm (Pseudaletia unipuncta) and fall armyworm (Spodoptera frugiperda) feed on the leaves and stems of rice plants, and occasionally on grain (Lorenz et al. 2018). Depending on when defoliation occurs, or where it occurs determines the significance to the rice plant (Felts et al. 2022). Rice billbug adults and larvae attack stems and roots causing tiller death and terminate panicles (Lorenz et al. 2018). Billbugs are restricted to rice levees in traditional flood system, terming it a minor pest. However, increases in furrow-irrigated rice production, has determined rice billbug as the most important insect pest in row rice systems (Floyd et al. 2022). Growers have limited amount of control options for billbugs, combinations of insecticide seed treatments have shown to be the most promising control method, for reducing tiller damage (Floyd et al. 2022). Short-horned grasshoppers can damage freshly emerged rice panicles feeding on blooms and grain, and in serious scenarios can injure the plant by causing ‘whiteheads’ (Lorenz et al. 2018). Long-horned grasshoppers are beneficials and common in rice, targeting other insects.

Rice Stink Bug

Rice stink bug (RSB), (Hemiptera: Pentatomidae), is a common insect to the U.S. and a major insect pest to heading rice in the mid-south (Douglas and Ingram 1942, Swanson and

Newsom 1962). RSB is a polyphagous insect feeding on a diverse range of native grasses in around rice fields, along with other grain crops (Douglas 1939, McPherson 2000). RSB is found east of the Rocky Mountains and as far north as Minnesota and New York (Sailer 1944). RSBs are an occasional pest to cultivated crops such as wheat, Triticum aestivum (L.); corn, Zea mays (L.); millet, Panicum miliaceum (L.); grain sorghum, Sorghum bicolor (L.); barley, Hordeum vulgare (L.); oats, Avena spp.; and rye, Secale cereale (L.) (Douglas 1939, Awuni et al. 2015b). RSB following emergence are attracted to ryegrass and wheat, both are winter annuals that produce fruiting structures during the early spring. Overwintered RSBs, depend on ryegrass and wheat for survival, development, and reproduction (Awuni et al. 2015b). Monocotyledonous plants are the most attractive for RSBs, which are commonly present in or around rice fields (Douglas 1939, Awuni et al. 2015b). In the early summer, RSB migrates from spring hosts to native summer hosts: barnyardgrass, E. crus-galli (L.) Johnsongrass, Sorghum halepense (L.) and dallisgrass, Paspalum dilatatum Poir. (Hall and Teetes 1982, Viator et al. 1983, Awuni et al. 2015b). These native grasses are common on field levees, ditch banks, and fence rows (Douglas 1939). RSB feeding on native host plants improves fitness and fecundity prior to migrating into crop fields (Panizzi 1997, Awuni et al. 2015b). Weather and host plant plays a vital role in the maturation and stability of RSB development process (Bhavanam et al. 2021). High weed densities increase RSB populations leading to higher injury levels to rice plants (Tindall et al. 2005). Lower amounts of filled rice seeds, increases in kernel damage from RSB (pecky rice), and lower milling quality are commonly observed in rice fields with high grassy weed pressure (Tindall et al. 2005). RSB feed on a variety of native host plants throughout the summer, feeding site preference changing over the course of a growing season (Panizzi 1997). When a RSBs lands

on a host, it goes through a food-plant selection phase to determine if the plant is suitable for itself or suitable for its offspring (Thorsteinson 1960).

When rice panicles emerge RSB adults disperse from native hosts and fly to nearby rice fields (Douglas 1939). Odor and other stimuli in addition to vision contributes to direct dispersal of RSB from natural grasses to rice fields during heading (R5-R9) (Rashid et al. 2006). Feeding initiates while rice grains are green and soft providing easy penetration to extract liquid-contents from immature kernels (Swanson and Newsom 1962). Earlier infestations occur in fields with higher weed densities, prior to panicle emergence, creating a larger possibility of rice injury (Tindall et al. 2004). RSB populations are swayed by weed densities; however, RSB tend to have a larger effect on quality of rice rather than the yield. Graminaceous weeds not only increase RSB populations present, but they can also introduce pathogens that attribute to pecky rice (Tindall et al. 2005). Injured rice kernels are termed as 'pecky rice', appearing smaller in size with a circular lesion appearing black or brown. Rice kernels with peck lead to yield and quality losses, as well as marketing dockages. Undamaged rice grains weigh significantly more, than damaged grains, due to damaged grains not achieving complete development (Wang et al. 2002).

Biology of Rice Stink Bug

Females lay two rows of light-green cylindrical eggs on leaves, stems, and panicles of grass or rice plants, in an upright position on plants, each row of eggs alter position with the corresponding rows (Smith 1994, Bernhardt 2009). Females lay roughly half as many eggs on native grasses compared to egg masses laid on rice (Nilakhe 1976). The amount of eggs in a cluster varies from 8 to 44, but commonly, each cluster contains 20-40 eggs (Esselbaugh 1946). A secretion released by the female during egg lay, attaches eggs to one another by, the same secretion anchors the eggs to the plant material. Eggs are cylindrical or 'barrel-shaped', 0.78-

0.84 mm in length and 0.59-0.67 mm in diameter (Esselbaugh 1946). Prior to hatching eggs become reddish, eggs hatch in 4-8 days after oviposition (Esselbaugh 1946, Pathak and Khan 1994, Bernhardt 2009). The first visual color change in eggs is the visual of two red lines underneath the operculum. Temperature determines the development process, with a minimum and maximum temperature for egg hatching of 15°C and 37°C (Bernhardt 2009). After hatching first instar nymphs gather around empty eggshells for a 24-hour period, feeding on eggshells prior to locating a feeding site (Decoursey and Esselbaugh 1962, Pathak and Khan 1994).

RSB nymphs are active and are more roundly shaped than elongated (Esselbaugh 1946). Nymphs go through five molts or "instars", before becoming adults. Typically, in field conditions it takes approximately 21 days to complete the life cycle from egg to fifth instar (Bhavanam et al. 2021). First instars ingest water, second through fifth instar feed on developing seeds.

Early instars can be separated from later instars based on body shape, color, and size (Bhavanam et al. 2021). First instar nymphs are mainly black in coloration, with red abdomens and two or three spots on the abdomen with red antennae and 1.12-1.21 mm in length and 0.82-0.85 mm in width (Decoursey and Esselbaugh 1962). Second instar nymphs are oval to elongate oval shaped, with dark red antennae and 1.66-2.40 mm in length and 1.06-1.55 mm in width. Fourth instar nymphs are dark pale and 3.2-5.1 mm in length and 2.0-2.8 mm in width. Fifth instar nymphs are pale with black antennae, 4.7-8.6 mm in length and 3.0-4.1 mm in width. Wing pads become visible at the fourth instar and are even more prominent in fifth instars (Decoursey and Esselbaugh 1962).

Adult RSB are shielded-shaped, metallic-brown- or straw-colored insects measuring approximately 1.3 cm long, with reddish antennae and two sharply pointed shoulder spines that

face forward (Pathak and Khan 1994). RSB overwinter as adults in leaf-liter or weedy grasses near the soil surface (Douglas and Ingram 1942). RSB overwinter in a diapause state, females are unmated (Nilakhe 1976). Time of entry into overwintering sites changes based on geography, typically, depends on when cold weather arrives, or grasses become fluorescent (Pathak and Khan 1994). RSBs emerge from overwintering in April through May, depending on weather, and begin feeding on winter annuals such as wheat or oats, and multiple native varieties of grasses that are producing seeds at that time (Douglas and Ingram 1942). Males tend to emerge 10 days earlier than females, mating begins 2-3 days after female emerge (Nilakhe 1976). Breeding takes place on native grasses or winter crops, and early generations will be produced on the natural hosts (Douglas and Ingram 1942). Overwintered adults cycle out in mid-June. Males usually live approximately 39 days and females approximately 50 days (Pathak and Khan 1994). When hot temperatures occur, adults seek shade moving lower on panicles, towards the ground surface, or closer to wood lines (Douglas and Ingram 1942, Pathak and Khan 1994).

Damage

In the Mid-South, RSB is the number one pest to heading rice (Awuni et al. 2015a). RSB was first reported as a pest in rice in the 1880's (Riley 1882). RSB has piercing-sucking mouthparts composed of modified structures referred to as stylets, stylets are arranged by modified mandibles and maxillae structures (Lucini and Panizzi 2018). Stylets are slender/flexible structures and are inserted into host plant tissue during feeding. The stylet bundle is comprised of four stylets, two mandibular and two maxillary stylets, fused together by an interlocking mechanism expanding over their entire length (Lucini and Panizzi 2018). RSB mouthparts produce a salivary secretion that hardens on contact, forming a volcano shaped structure referred to as a feeding sheath which remains on the rice kernel (Bowling 1979, Hollay

et al. 1987). RSB mandibular stylets have 'small teeth' which are used to create an entrance site for the maxillary styles (Hollay et al. 1987). Sheaths are either opened or closed, open sheaths are found individually or in pairs, closed sheaths are found in groups of two or more. Open sheaths occurs whenever stylets are quickly removed, due to feeding disturbance. When stylets are retracted slowly formation of long/thin sheath tips, while sheath material is still soft, is described as closed sheaths (Hollay et al. 1987). The insertion of stylets and injection of digestive enzymes into plant tissue leads to different types of damage in vegetative and reproductive tissues (Lucini and Panizzi 2018). Stylet sheaths are tan and volcano-shaped and can be discovered on developing grains and rice panicles (Bowling 1979). The feeding activity of RSB in rice is a multiplex process due to the variability in rice development (Awuni et al. 2015a). RSB reduces rough rice hulls and caryopsis, leading to lower head rice yields (Espino and Way 2008).

The susceptibility of economic injury from insect pests usually depends on the growth stage of an individual crop (Patel et al. 2006). Damage to rice from RSB feeding in the nymph or adult stage, occurs from rice flowering through grain maturity, leading to yield losses or reduced quality (Espino and Way 2008, Awuni et al. 2015a). The flowering or anthesis stage is determined by panicle emergence (PE) and can be divided into the flowering or grain filling stage (Counce et al. 2000). RSB feeding during the flowering and milk stage injures rice panicles by subtracting nutrients from developing grains, leading to atrophied and blank kernels (Swanson and Newsom 1962, Patel et al. 2006). This type of injury equals quantitative losses due to lower amounts of filled grains and average grain weights, and ultimately lower rough rice yields (Patel et al. 2006). RSB feeding during anthesis, and the milk stage produces a higher percentage of empty grains, leading to yield losses. Rice grains become less susceptible to

quantitative injury (yield loss) by RSB as rice panicles mature. Later plant development injury promoted by RSB feeding during the dough stages, leads to quality losses due to feeding mechanisms and the introduction of microbes, either directly or indirectly (Swanson and Newsom 1962, Patel et al. 2006).

Rice panicles attacked at the soft dough stage leads to the highest amount of RSB injury "pecky rice" (Patel et al. 2006). Damaged kernels appearing chalky in color are referred to as pecky rice, a term representing rice kernels bearing spots, and leads to dockage at the selling point (Swanson and Newsom 1962). Discolored rice kernels reduce the acceptability and commercial value of rice (Lee et al. 1993). Damaged kernels are weaker and more vulnerable to breakage under mechanical stresses which occur during the milling process, lowering overall head rice. Kernels will appear light yellow or bleach and have coal black spots from puncturing and feeding, varying in shape and size (Swanson and Newsom 1962). Peck is formed from a combination of feeding and invading fungi at feeding sites (Lee et al. 1993). Fungi can use feeding sheaths as a nutritive substrate with fruiting bodies often appear on outer walls of open and closed sheaths (Hollay et al. 1987). Discolored kernels caused by RSB or disease organisms, imply that insects and pathogenic organisms should be controlled to reduce discolored rice kernels (Douglas and Tullis 1950). RSBs introduce fungi during feeding, fungi present on mouthparts can enter the seed when feeding takes place (Lee et al. 1993). Successful stylet penetration of rice hulls has fungi on the underside of the hulls and in/or around the feeding wounds (Hollay et al. 1987). Stylet penetration through the hull does not always determine successful penetration into the rice kernel. Fungal mycelia only occur inside the feeding wound of a kernel because it is either delivered on or in stylets of a RSB during feeding or enter through the hole after feeding (Hollay et al. 1987). Peck rice also, germinates at a notably lower rate than

non-pecky rice, suggesting that damage from feeding and microbes related with peck rice possibly injures embryos (Patel et al. 2006). In addition to peck rice, there is also damage called sterility where rice lacks production of developing millable kernels (Douglas 1939).

Rice Stink Bug Sampling

Decision making is major component for integrated pest management (IPM) and will continue to be a vital tactic for IPM (Binns and Nyrop 1992). Monitoring RSB populations should start at flowering and continue until 60% hard dough stage of development is achieved (Espino and Way 2008). Estimates of RSB populations are a key component for monitoring field density, determining insecticide application timing, predicting losses in rice yield and grain quality (Rashid et al. 2006). Direct observation and sweep net sampling are common methods for determining RSB density levels. A time-efficient sampling method for detecting and quantifying the migration and population density to rice fields relative to grain growth stage is vital for IPM (Rashid et al. 2006). Populations of RSB in fields may fluctuate due to adults migrating from field to field, which validates monitoring fields once or twice a week (Oliver et al. 1972). RSB are abundant in rice fields during the reproductive stages and should be closely monitored during heading and grain filling stages of panicle development (Awuni et al. 2015a). Rice fields should be sampled each week starting after 75% panicle emergence and repeating through grain maturity (30 to 35 days after 50% heading) (Lorenz et al. 2018). Samples should be performed daylight until mid-morning and the last few hours of daylight in the afternoon for accurate population assessments. RSB populations are sampled with a 38 cm sweep net. RSB sampling consists of conducting 10/1.8 m sweeps to evaluate RSB densities (Lorenz et al. 2018). Sampling series should be performed randomly throughout the field (Rashid et al. 2006). Keep a steady forward pace while sweeping side to side (6ft) with the top of the net passing 2-3 inches above

the rice heads. Research studies in 2017 and 2018, tested three different sweep lengths: .9 m (3ft), 1.8 m (6ft), and 3.5 m (180°) (Cato et al. 2019). In Arkansas, sampling recommendations were altered from 3.5 m to 1.8 m, providing easier sweeps and similar sampling practices for other crops. Having specific guidelines for sampling is important for conducting accurate evaluations of RSB populations in a field setting. Sweep net sampling provides validation for the timing of insecticide applications. Arkansas RSB economic threshold is set at 5 RSBs per 10 sweeps, at one and two weeks after 75% heading. Weeks three and four after 75% heading, the threshold is increased to 10 RSBs per 10 sweeps. Treatment recommendations are determined on the combined number of nymphs and adults, since both are damaging to rice kernels (Cato 2018).

Control Tactics

"The notion of pest management developed from the resentment of a solely insecticidal based approach for pest control in the 1950's" (Pedigo et al. 2021). Integrated pest management (IPM), IPM employs biological, cultural, host resistance, and chemicals to different levels based on environment and pest complex (Smith 1994). Successful pest management starts with an ecological outlook (Flint and Van den Bosch 2012). Artificial controls such as pesticides should be viewed as tools and used after alternative control strategies have been utilized. IPM is an ecologically based pest control strategy relying heavy on natural mortality factors such as natural enemies and weather, seeking out control factors in which reduce the disturbance of these factors. Integrated control tactics depend on combinations of biological, chemical, cultural methods and resistant varieties (Litsinger 1994). IPM, employs pesticides but only after systematic observations of pest populations and natural control factors indicates a need. The components of IPM are: prevention; identification; monitoring; assessment; planning; and

evaluation. IPM systems are dynamic, as are the ecosystems in which they are induced, and typically involve constant information collection and assessment as the resource and its corresponding physical and biological environment progress through their seasonal progressions (Flint and Van den Bosch 2012).

Cultural Control

Little attempt has been made to establish non-chemical control tactics for RSB for different reasons. Rice plants are only susceptible to RSB for a relatively a short period of time (heading to harvest, ~30 days for most varieties), the high dispersal rate of the RSB, and low economic thresholds (Patel et al. 2006, Awuni et al. 2015a). There are two types of cultural control methods for insects, primary and secondary (Litsinger 1994). Primary practices are utilized to target or control one specific insect such as removing a flood, planting a secondary crop, or transplanting seeds that are more mature. Secondary practices are utilized for crop husbandry including field cultivation, managing weeds, and fertilization to help reduce insect population growth (Litsinger 1994). Commonly, short-grain and medium-grain rice varieties have a higher percentage of damage from RSB feeding and more pecky kernels, compared to long-grain varieties (Bernhardt et al. 2004). Different grain types have the variability to be more susceptible to damage due to different rice panicle maturity rates (Bernhardt et al. 2004). RSBs use native host plants throughout the summer, managing host plants around rice fields can inhibit increased populations prior to heading (Douglas and Ingram 1942). Before planting, a precise assessment of the field environment should be evaluated (Awuni et al. 2015a). Adjusting the planting date provides insect pests with a disadvantage, due to plant growth being altered and changing the timing of preferred growth stage for feeding (Litsinger 1994).

Host Plant Resistance

Host plant resistance (HPR) is an effective, economical, and environmentally friendly method of insect control (Sharma and Ortiz 2002). Crop varieties that are high-yielding and resistant are valuable assets to growers, offering a built-in plant protection, built-in traits protect plants from the insect pests while at the same time reducing the need for applications of insecticides (Mohamad Saad et al. 2018). The objective in insect management strategies focuses on lowering insecticidal usage, not only due to chemical cost, but also to avoid beneficial insect disturbance and eliminate potential insecticide resistance (Declining et al. 1994). Insect-plant exchange may transpire at multiple different levels; interactions also take place between the insect and the resistance mechanism. Improving resistance crop cultivars by combining them with cultural control methods would benefit growers in their intent of controlling insect pests (Declining et al. 1994). Host-plant resistance is a valuable and economically friendly control tactic for pest management, combined with other control mechanisms, and reduces the usage of insecticides (Bhavanam and Stout 2022). Plant resistance can alter insect behavior decreasing the acceptability and colonization of host plants, which is termed as antiemesis. Alternatively, antibiosis, is a variety of plant resistance that affects insect biology and physiology, leading to impaired development, reproduction, and survival (Bhavanam and Stout 2022).

Insecticide Control

Rice growers and consultants have relied heavily on synthetic insecticides to control RSB (Espino and Way 2008). Applications of insecticides are the main management control tactic for RSB control in rice growing states, and pyrethroids are the primary insecticide class used (Blackman et al. 2015). Insecticide applications intended to control RSB are intended to reduce the density of RSBs, and in-turn protect rice kernels from damage (Bernhardt 2010). Labeled

insecticides for RSB control should provide swift and efficient kill and provide adequate residual to decrease reinfestation probability (Oliver et al. 1972). Applications of insecticides should not be applied prior to the population density exceeding the action threshold (Espino and Way 2008). Insecticidal applications with little to no residual activity prior to heading are not effective in control RSB (Oliver et al. 1972, Espino et al. 2007). Insecticides labeled for RSBs before 2013 consisted of pyrethroids, organophosphates, and carbamates (Blackman et al. 2015). Organophosphates and pyrethroids tend to achieve high contact mortality but lack residual control (Bernhardt 2010). Current labeled insecticides for RSB control are carbaryl (Carbaryl 4L, Drexel Chemical Company), lambda-cyhalothrin (Warrior II, Syngenta Crop Protection), zeta-cypermethrin (Mustang Maxx, FMC, Corporate), malathion (Malathion 57, FMC, Corporate), and dinotefuran (Tenchu 20SG, Belchim Crop Protection) (Lorenz et al. 2018). Insecticides should be applied in the morning or late evening, to achieve the best results. With the limited amount of different classes of insecticides, a new class of insecticide is desired to provide rice producers alternative options and help prevent insecticide resistance (Blackman et al. 2015). Endigo ZC (thiamethoxam + lambda-cyhalothrin, Syngenta Crop Protection) was granted a section 18 emergency exemption during 2021 and 2022 for Arkansas rice growers due to control issues with pyrethroids and a lack of supply of alternatives (Reynolds 2021, 2022).

Insecticide Detoxification

The toxicity of insecticidally active organophosphorus and carbamate esters to insects is correlated to their capability to inhibit acetylcholinesterase (AChE), an enzyme classification that catalyzes the hydrolysis of the neurotransmitter agent acetylcholine (ACh) (Fukuto 1990). Organophosphorus and carbamate insecticides are represented by a wide range of chemical structures utilizing different chemical and physical properties. The toxicity of these compounds

to insects is fixated by several factors that may influence the insecticides on how they are absorbed, transmitted to target site, and as they inactivate target organisms, leading to poisoning. Acetylcholinesterase is responsible for rapid hydrolytic degradation of the neurotransmitter into the inactive products choline and acetic acid. Acetylcholine is a physiologically important neurotransmitter agent utilized in transmission of nerve impulses to effector cells at cholinergic, synaptic, and neuromuscular junctions (Fukuto 1990). Organophosphorus insecticides (Ops) have acute toxic effects connected to hindrance of acetylcholinesterase (Sogorb and Vilanova 2002). The hindrance of this enzyme causes over-stimulation of nicotinic and muscarinic acetylcholine receptors. Indicators of poisoning are agitation, muscle weakness, miosis, and hypersalivation. OPs are primarily detoxified through oxidation and hydrolysis. The two primary enzyme groups involved in the hydrolysis of these compounds are phosphotriesterases (PTEs) and carboxylesterases (CbEs). Carbamate insecticides reversibly inhibit neuropathy target esterase. The primary detoxification routes of carbamate insecticides are hydrolysis and oxidation, hydrolysis by CbEs are an effective route (Sogorb and Vilanova 2002).

Since the origination of synthetic pyrethroids in 1973, they have obtained over 30% of the commercial insecticide market giving proficient cost/benefit ratio for agriculture pest control (Flannigan et al. 1985). Pyrethroids are lipophilic compounds that attack nerve toxins. They act precisely on the axon by interfering with the sodium channel gating mechanism that underlies the triggering and depolarization of each nerve impulse. Pyrethroids prompt sodium channels to close more slowly than normal, resulting in a moderately decaying inward sodium current after stoppage of membrane depolarization. Unlike other insecticides, pyrethroids have many sites for metabolic degradation. Ester cleavage is controlled by the degree of stearic hindrance, and

molecule sites are vulnerable to attacks from mixed oxidase systems. As a result, their lipophilic characteristic enhances rapid penetration to the nervous system (Flannigan et al. 1985).

Neonicotinoids are a newer class of insecticide that are quickly absorbed by plants and act quickly, at low rates, on piercing-sucking insects (Tomizawa and Casida 2005). Neonicotinoids have exclusive physical and toxicological effects compared to organic insecticides. Toxicity corresponds with agonist action and binding affinity at nACHR, main target in the insect brain. Neonicotinoids are nicotinic agonists that interact with nACHR. They have an electronegative tip that bind to specific cationic subsite on insect receptors. The chemical fate of neonicotinoids in and on crops is determined by metabolic and photochemical reactions (Tomizawa and Casida 2005). Dinotefuran, a neonicotinoid insecticide, is highly effective against a large variety of insect pests and has small mammalian toxicity (Mori et al. 2002). Dinotefuran is a tetrahydrofuran (THF) nonaromatic cyclic ether substituent, which is different from other neonicotinoids (Wakita 2011). Dinotefuran has a tetrahydrofuran ring in its structure whereas other neonicotinoids have halogenated aromatic heterocyclic rings such as chloropyridine and chlorothiazole (Mori et al. 2002). This is unique structure to dinotefuran that resulted from combining a nitroimino structure into the structure of acetylcholine. Dinotefuran's site of action is through the inhibition of the nerve conduction in insects by binding to nicotinic acetylcholine receptors (Mori et al. 2002). Dinotefuran possess stomach and contact poisoning, and characteristics of a persisting and broad-spectrum insecticide (David et al. 2007). Dinotefuran has high water solubility, allowing its use in numerous formulations and application methods (Wakita 2011).

Potential Insecticide Resistance

Resistance is a heritable modification in the responsiveness of a pest population suggested by repeated failure of a product to attain the required level of control when applied in accordance with label recommendation for a specific pest (IRAC 2022). To preserve the maximum efficacy of insecticides over a lengthy period, Insect Resistance Management (IRM) strategies for pest management should be utilized by growers. Applications should target early insect developmental stages or the most susceptible life stage of an individual organism (IRAC 2022). IRAC provides a MoA Classification Scheme to state and government agencies, consultants, advisors, growers, universities, and extension staff with guidelines on selecting insecticides to improve class rotation and mitigate resistance (Sparks and Nauen 2015).

Insecticide resistance is the most severe problem facing manager of insect pests in agricultural crops (Grafius 1997). IRM practices focuses on delaying or minimizing the development of resistance to insecticides (Sparks and Nauen 2015). Tactics of IRM such as reducing the selection pressure of an insecticide to rejuvenate a certain insecticide chemistry in which an insect pest has become immune to through genetic modification (Sparks and Nauen 2015). Lack of labeled insecticides or high prices, results in repetition of pyrethroids being overused to control RSBs (Miller et al. 2010). The cost of pesticide resistance is assumed to be around $1.5 billion USD on a yearly basis in the United States. Pest resistance to insecticides is concerning since chemical applications are an essential control strategy for RSB management and producing high quality and high-yielding crops (Miller et al. 2010). It is key to reduce the probability of resistance developing in RSB populations for current products, since alternative compounds that provide adequate control or are equally priced are unavailable (Sparks and Nauen 2015). Rotating compounds in the same Group, but in different subgroups is not preferred

unless no alternative option with different modes of action is available. Maintaining adequate efficacy for current insecticides is challenging due to the lack of alternative options for RSB control. The development of new insecticide are limited and the cost increases due to regulatory requirements, which are challenging to obtain in the agrochemical industry (Sparks and Nauen 2015).

Insecticide resistance genes have occurred in several insect species. Pyrethroid resistance genes that desensitize the sodium channel tend to be recessive (Bourguet et al. 1996). Resistance to cyclodiene through target of the GABA receptor is commonly described as codominant. When a resistance gene correlates with a detoxification enzyme, resistance is codominant to dominant. Resistance to organophosphorus (OP) or carbamate (CB) insecticides through insensitive acetylcholinesterase (AChE) is codominant to dominant (Bourguet et al. 1996). Insecticide resistance symbols a genetic change in response to selection (Feyereisen 1995). Individual insects with genetic characteristics for surviving chemically hostile environments survive and reproduce, transmitting traits to their offspring. Continued selection pressure applied by insecticides quickly increases the rate of the genetic trait in the population. There are two ways insects can become resistant: either by modifying the effective dose of the insecticide obtainable at the target site or by altering the target itself. Mechanisms of resistance such as behavioral resistance, reduced penetration or absorption, sequestration and detoxification all contribute to decrease the dose of insecticide, whereas a decreased target site sensitivity or a modification of target site number plays a role in rendering the dose of insecticide unproductivity (Feyereisen 1995). Resistance mechanisms can be separated into three classes: first is modified behavior, reducing exposure of an insect to toxic compounds; secondly physiological, consisting of altered penetration, excretion, transport or storage of insecticides by insects; thirdly biochemical, such as

insensitivity of target sites to insecticides and amplified detoxification by metabolizing enzymes (Lee et al. 2001). Molecular mechanisms of resistance are classified conforming to the essence of genetic change favored by insecticide pressure: point mutations in structural genes, or modification in the activity of genes (Feyereisen 1995). Resistance mechanisms typically rely on a single R-gene. Continued pressure with one or more insecticide may result in accumulation of several R-genes, and resistance mechanisms. In cross-resistance a single R-gene, or numerous R-genes, selected by a certain insecticide frequently extends resistance to several other insecticides (Lee et al. 2001).

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Chapter II – Evaluation of Pyrethroid Resistance in Rice Stink Bug, Oebalus pugnax F., in Arkansas

Abstract

The rice stink bug, *Oebalus pugnax,* Hemiptera: Pentatomidae, is a major pest of rice, *Oryza sativa* L., after panicle emergence in the southern United States. Synthetic pyrethroids, particularly lambda-cyhalothrin, have been the primary insecticides used to manage rice stink bugs for the past 15 years due to adequate control at a low cost. The reliance on lambda-cyhalothrin, and control issues documented in Louisiana and Texas, raises concern for resistance in Arkansas rice stink bug populations. Lambda-cyhalothrin control failures have been documented in late-season rice stink bug populations in Arkansas. Laboratory petri-dish bioassays experiments were conducted to determine and assess lambda-cyhalothrin resistance in Arkansas rice stink bug populations. Populations of rice stink bugs were collected in May, Jun, Jul, and Aug throughout the 2021 and 2022 growing season in Arkansas. Lambda-cyhalothrin was applied to petri dishes at five different rates: 8.3 g ai/ha, 16.6 g ai/ha, 33.2 g ai/ha, 66.4g ai/ha and 132.8 g ai/ha and an untreated check (water only) for comparison. Fifty-four sites were sampled over the two years of the study. Mortality was assessed at 8 and 24 h after exposure. On average the 24 h ratings had higher mortality than the 8 h rating across years, by month, and by year. Higher mortality was observed in May followed by Jul, Jun, then Aug. Increased mortality was observed as the rate of lambda-cyhalothrin was increased across all years and months, by year, and by month. Increased mortality was observed in 2021 compared to 2022 for collections made in May, however this trend was not the same for the other months. Lambda-cyhalothrin never achieved 80% mortality at the 24 h rating timing. This data suggests that there has been a major increase in tolerance to lambda-cyhalothrin for rice stink bug (Fortner et al. 2010, Plummer et al. 2014).

Introduction

The rice stink bug (RSB) *Oebalus pugnax* F., was first recognized in 1775, by J.C. Fabricius. It was first recorded as a pest of rice, in the 1880s by Charles Riley (Riley 1882), and has become the dominant pest of heading rice in the Mid-South (Douglas and Ingram 1942, Swanson and Newsom 1962, Awuni et al. 2015a). RSB nymphs and adults cause injury to rice by feeding on developing grains, leading to both yield lose and decreasing grain quality (Swanson and Newsom 1962). Rough rice yield losses occur due to the extraction of fluids from the developing rice kernel in the milk stage. Feeding during the early stages of grain development injures rice by removing the endosperm from immature kernels, resulting in non-filled seeds (Swanson and Newsom 1962). Rice in the milk and soft dough stages tend to be the most vulnerable to rice stink bug feeding with respect to quality degradation (Espino et al. 2007). During feeding RSB pierce rice grains and introduce microorganisms that lead to loses in quality or 'pecky' rice (Bowling 1963, 1979). Feeding during the later stages of grain development creates withered seeds and lessens the quality of grains, along with increasing the likelihood of breakage during the milling process (Douglas 1939, Swanson and Newsom 1962). Discolored kernels are commonly termed as peck and are either circular lesions or dark discolored spots of numerous sizes and shapes developed from RSB feeding or fungal invasions from rice stink bug damaging the hull (Lee et al. 1993).

RSB populations are commonly temporary in rice due to adults migrating from field to field in search of freshly emerged seeds (Oliver et al. 1972). Heavy adult populations frequently become problematic for insecticidal control, due to these transitory habits, which can result in large-population increases in fields that recently had no presence of RSB. Ideally, insecticides should be affordable and provide a fast initial kill and provide some residual activity to prohibit

adult RSBs from re-entering and eliminate nymphal development (Oliver et al. 1972). However, limited insecticide chemistry is currently available to rice producers for RSB management. The primary control tactic for RSB management is the use of a broad-spectrum insecticide once action thresholds are reached (Blackman et al. 2015). Synthetic pyrethroids, particularly lambda-cyhalothrin, are favored by southern U.S. rice growers to manage RSB populations due to availability and price (Blackman et al. 2015). Lambda-cyhalothrin is a synthetic pyrethroid insecticide registered by the U.S. Environmental Protection Agency (EPA) in 1988 (NPIC 2001). Lambda-cyhalothrin is one of the most common used insecticides worldwide for insect control (Saleh et al. 2021). Lambda-cyhalothrin interacts with the insect by penetrating through the cuticle and disturbing the nervous system by fluctuating sodium channels on nerve membranes. After disruption, the insect muscular control is eliminated, leading to immobility and eventually death (Saleh et al. 2021). In 2002, it was the among the top three pyrethroid insecticides applied in the U.S. with over 117,000 kg active ingredient used (Moore et al. 2009).

Insecticide resistance is a repercussion due to the repetitive exposure of a single insecticide to an individual or group of pests (Guedes 2017). Repeated applications of one insecticide allows genetic changes within an individual species with a direct response to a particular insecticide (IRAC 2022). Recently in Texas, studies have confirmed an increased tolerance of RSB populations to lambda-cyhalothrin, advocating the necessity for insecticides with alternative modes of action for rice stink bug control measures (Miller et al. 2010, Blackman et al. 2015). Pest resistance to insecticides is problematic due to insecticides playing a major role in producing high-yielding and high-quality crops. Due to the confined classes of insecticides labeled for rice stink bug management and the lack of availability of alternative products, lambda-cyhalothrin has been used repetitively and under constant selection pressure.

This problem is intensified due to rice stink bug having multiple generations on a yearly basis and many generations are being exposed to pyrethroids. Pest resistance leads to increased rates and more repeated applications of insecticides to reach sufficient control (Miller et al. 2010, Blackman et al. 2015). Control failure of an insecticide due to insecticide resistance is formed on the crucial reduction of efficacy of a commercial insecticide product applied at the recommended rate but not achieving the desired control level (Guedes 2017). Lambda-cyhalothrin control failures have been documented by extension entomologist in Arkansas since 2019 (Lorenz 2020, Newkirk et al. 2021, Newkirk et al. 2022). Resistance monitoring is essential to any resistance management program (Prabhaker et al. 1996). Constant observations of populations for differentiations in resistance frequencies provides decisions for successful management strategies (Prabhaker et al. 1996). Knowledge on labeled insecticide susceptibility levels to RSBs is required to determine changes in sensitivity that could transpire in RSB populations over time and in different areas. The objective of this study was to determine the effectiveness of lambda-cyhalothrin for RSB control throughout the growing season and rice growing regions of Arkansas.

Materials and Methods

Populations of adult RSB were collected over a total of 54 sites Arkansas in 2021 and 2022 (Table 2.1). Collections were made throughout the growing season, starting in May, and ending in Aug. Within each month, a minimum of two populations were collected. In 2021, 16 populations were collected and 38 populations in 2022 (Table 2.1). All sampled areas practiced similar agriculture practices of irrigation, fertilization, weed management, and insecticide usage. Collections were made using a sweep net (38 cm diameter), performing sweeps on native grasses, wheat fields, and rice fields, depending on time of year. Adults were transferred from

sweep nets to rearing cages and fruiting grasses were inserted into rearing cages for feeding along with water-soaked cotton balls for moisture. Approximately 450 adults were collected from each location to ensure 300 fit RSBs would be available for testing. RSBs were transported to the laboratory at the University of Arkansas System Division of Agriculture's Rice Research and Extension Center, near Stuttgart, Arkansas and held overnight at 22.2°C, to ensure healthy adults were used for bioassays.

The synthetic pyrethroid lambda-cyhalothrin (Warrior II, Syngenta Crop Protection), was applied to the inside of the top and bottom of a 10.2 cm x 10.2 cm petri dish at five different rates: 8.3 g ai/ha (0.25X), 16.6 g ai/ha (0.5X), 33.2 g ai/ha (1X), 66.4 g ai/ha (2X), and 132.8 g ai/ha (4X) with an untreated check only receiving water. Lambda-cyhalothrin was applied to the insides of petri dishes with a CO_2 backpack sprayer, using a two-row hand boom with TeeJet hollow cone tips calibrated to 37.9 L/ha at 275.8 kPa. Petri dishes were allowed to dry (1hr.) prior to infestation. After drying, five adult RSB were placed into each dish, and each treatment was replicated ten times. For each location 50 RSB were tested per treatment (n=50) for a pooled total of 300 RSB (n=300). Across all 54 locations, 2700 RSB were tested per treatment (n=2700) for a pooled total of 16,200 RSB (n=16,200). Mortality ratings were recorded at 8 and 24 h after infestation. Adults that were moribund or did not move upon nudging were considered dead. An Abbots correction for mortality was performed within each collection (Abbott 1925). Data was analyzed with PROC GLIMIX (SAS v. 9.4, Institute, Cary, NC) with an alpha level of 0.05. Individual dishes, year, and replication were considered random factors.

Results

RSB's were collected over 17 counties between 2021 and 2022 (Figure 2.1). Counties received regional designations based on geography. Analysis was performed and multiple

interactions with region occurred. This was due to the amount of collections made in the central region as compared to the other regions. Data were pooled across all regions for further analysis.

A three-way interaction was observed among year, month of collection, and rating timing ($F=5.0$, $df=3, 6012$, $P<0.01$) (Figure 2.2). In general, higher mortality was observed at the 24 h observation timing than the 8 h observation timing. Additionally, less mortality was observed for collections made in Aug. compared to the other months regardless of rating timing. Within the 8 h rating timing, collections made in 2021 had higher mortality than 2022 for all months except Jul. At the 24 h rating, a difference in year was only observed for Jun collections with respect to RSB mortality. Furthermore, an interaction was observed among year and rating timing ($F=15.5$, $df=1, 6012$, $P<0.01$) (Figure 2.3). Mortality ratings recorded at the 24 h timing in both years had higher mortality than ratings recorded at the 8 h timing. No differences were observed within rating timing. An interaction was also observed between year and month of collection ($F=9.6$, $df=3, 522$, $P<0.01$) (Figure 2.4). Only for collections made in Jun was there a difference in RSB mortality between years. Aug had the lowest RSB mortality compared to all other months.

Furthermore, an interaction was observed between year, month of collection, and rate of lambda-cyhalothrin ($F=2.8$, $df= 15, 6016$, $P<0.01$). Regression analysis was performed with year and lambda-cyhalothrin rate by collection month. For the collection month of May, less RSB mortality was observed in 2022 for the lowest four rates of lambda-cyhalothrin tested, however at the highest rate tested no difference was observed between 2021 and 2022 (Figure 2.5 A). The inverse trend was observed for the collection month of Jun. (Figure 2.5 B), where differences between years were only observed at the highest rate of lambda-cyhalothrin tested. For the collection month of Jul., all rates of lambda-cyhalothrin performed better in 2022 as compared to 2021 (Figure 2.5 C), however the opposite was observed for the collection month of Aug.

(Figure 2.5 D). When comparing collection month and rate of lambda-cyhalothrin across years ($F=13.8$, $df= 15, 6016$, $P<0.01$), similar trends were observed between each collection month (Figure 2.6). For all collection months RSB mortality increased as the rate of lambda-cyhalothrin increased. Higher mortality across all rates was observed for the month of May, followed by Jul, Jun, and lastly Aug. Even at the highest rate of lambda-cyhalothrin tested, 80% mortality was not achieved.

Overall lambda-cyhalothrin was not able to achieve adequate control (≥80%) at any rate or within any month. A general trend was observed that less mortality was observed as months progressed. May populations are the first generation of RSB coming out of overwintering, which are generally weaker than Jun, Jul, and Aug populations. Based on these data, growers should not expect greater than 70% control with lambda-cyhalothrin, and most likely much worse as the season progresses.

Discussion

In May, higher mortality was observed due to overwintered populations being tested, as the season progressed lower mortality was observed. Overwintering populations, such as RSB tested in May and early June, have not yet increased their fat bodies/fitness, and have lower immunity to insecticidal applications. The accessibility and acceptability of native host plants provide a nutritional supplement to increase fitness, development, and reproduction (McPherson 2000). RSB feeding scheme fluctuates in relation to native plants development stage, during flowering and seed development of plants are most attractive to RSBs (Awuni et al. 2014). Native hosts such as *Paspalum urvillei* (vaseygrass) was found to be the most attractive compared to 10 other tested grasses (Naresh and Smith 1983). Naresh and Smith (1983) also observed higher survivability when RSB nymphs and adults fed on rice or grain sorghum

compared to feeding on vaseygrass. Cultivated crops such as rice and grain sorghum are more beneficial than native plants, in regard of nymphal and adult weight increase and survival (Naresh and Smith 1983). Female RSBs produce roughly half as many eggs on vaseygrass and barnyard grass as on rice plants (Nilakhe 1976).

Assay results indicate the resistance/tolerance to lambda-cyhalothrin in RSB populations is growing throughout the state and has become a major concern for Arkansas rice growers. Previous research showed that two tested populations from Texas were resistant to lambda-cyhalothrin, in 2010 (Cross 2016). Cross (2016) determined that RSB populations in Arkansas, Louisiana, and Missouri are still susceptible to lambda-cyhalothrin. This study presents standard susceptibility data for numerous Arkansas RSB populations to the commonly used insecticide lambda-cyhalothrin and certifies reduced susceptibility to lambda-cyhalothrin among spatially separated populations. Blackman et al. (2015) tested RSBs from two different counties and observed higher resistance was present in Wharton County compared to tested RSB populations from the LSU research station. Changes in susceptibility levels between territorially individual populations could be a repercussion of natural genetic differences between populations, host plant differences, discrepancy insecticidal exposure, and other ecological conditions (Kole et al. 2019). Over exposure of lambda-cyhalothrin has increased resistant mechanisms to develop among RSB populations (Blackman et al. 2015). Blackman et al. (2015) also determined that higher RSB mortality was observed with dinotefuran applications, compared to lambda-cyhalothrin.

This research presents baseline data on the current responsiveness of Arkansas RSB to the synthetic pyrethroid lambda-cyhalothrin. Bioassay's confirmed reports from agricultural consultants and rice producers that RSB is becoming less susceptible to lambda-cyhalothrin. The

change in susceptibility to lambda-cyhalothrin is not surprising due to high number of applications on a yearly basis to manage RSB populations. The repeated applications and limited alternative options with different modes of action have rapidly lowered the efficacy of lambda-cyhalothrin in recent years. Other options outside of lambda-cyhalothrin, are carbaryl (Carbaryl 4L, Drexel Chemical Company), malathion (Malathion 57, FMC Corporation), and dinotefuran (Tenchu, Belchim Crop Protection). Introduction of advanced insecticides with alternative modes of action is necessary for insect pest management, helping to maintain a reliable crop protection program. Newly developed insecticides should correlate with current integrated pest management (IPM) strategies targeting the essential necessities of better toxicological and environmental profile, removing overused insecticides which are facing resistant problems in pest populations which have been targeted with the same chemistry for years in some agricultural settings (Nauen et al. 2015). New products with alternative modes of action from previous used insecticides could aid in resistance management strategies (Nauen et al. 2015). Pyrethroid resistance is a developing issue, providing information and educating Arkansas growers and consultants on sustainable insecticide resistance management is vital to the longevity of labeled insecticides.

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Table 2.1. A list of regions, counties, and number of collections by year and month for rice stink bug collections used in lambda-cyhalothrin resistance assays conducted in Arkansas during 2021 and 2022.

		2021				2022			
		Month				Month			
Region	County	May	Jun	Jul	Aug	May	Jun	Jul	Aug
Northeast	Craighead	1					2	1	1
	Jackson		1				1	1	1
	Poinsett	1		1				1	
Central	Arkansas	1	1	2			3	3	2
	Crittenden					1			
	Cross			1			1		
	Jefferson	1			1	1	1	1	1
	Lee						1		
	Lonoke						1		
	Monroe		1			1	1		
	Prairie		2		1	1	1	1	1
	St. Francis			1		1	1	1	
	White					1			
	Woodruff					1		1	
Southeast	Chicot						1		
	Desha						1		

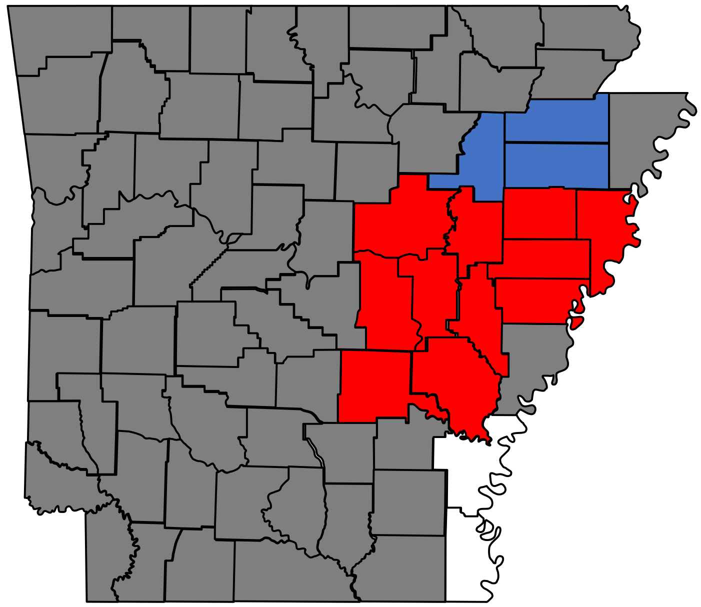

Figure 2.1. A county map of Arkansas detailing where rice stink bug collections were made in 2021 and 2022 for lambda-cyhalothrin mortality assays and their designation based on region. North Region Counties are blue; Central Region Counties are red; and South Region Counties are white.

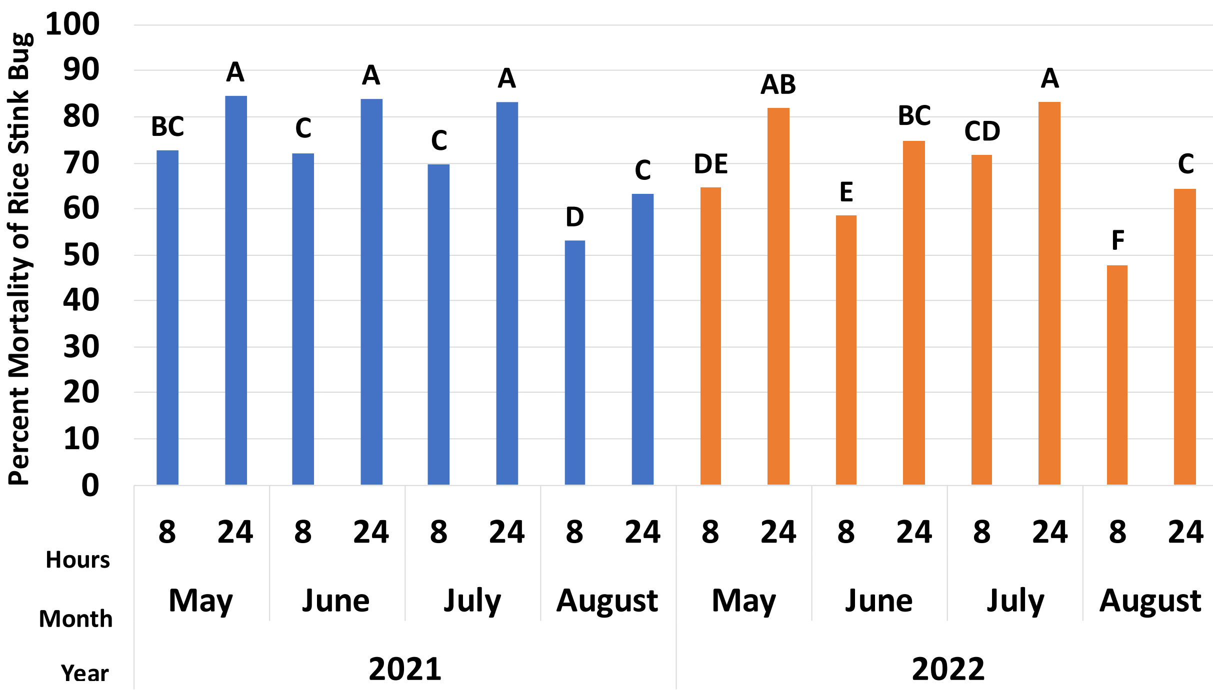

Figure 2.2. Three-way interaction between year, collection month, and rating timing for rice stink bug mortality exposed to multiple rates of lambda-cyhalothrin for collections made throughout the growing seasons of 2021 and 2022 in Arkansas.

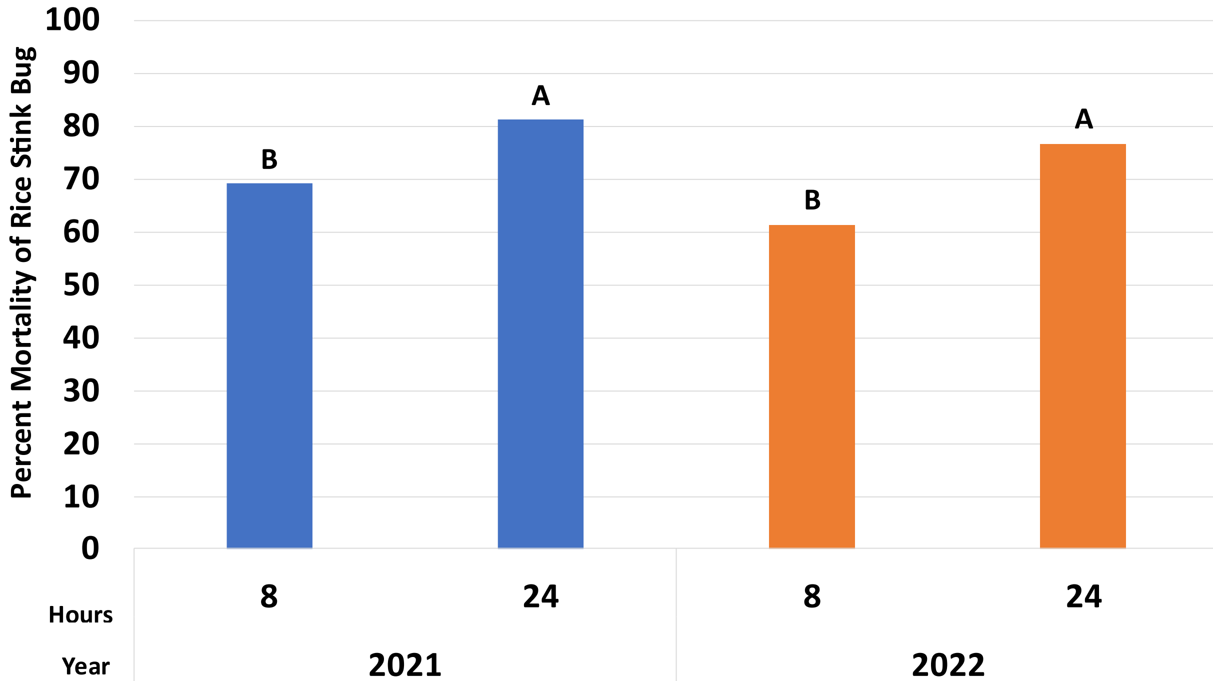

Figure 2.3. Precent mortality of rice stink bug across multiple rates of lambda-cyhalothrin for observations made at 8 and 24 h after exposure for collections made throughout the growing season in Arkansas from 2021 and 2022.

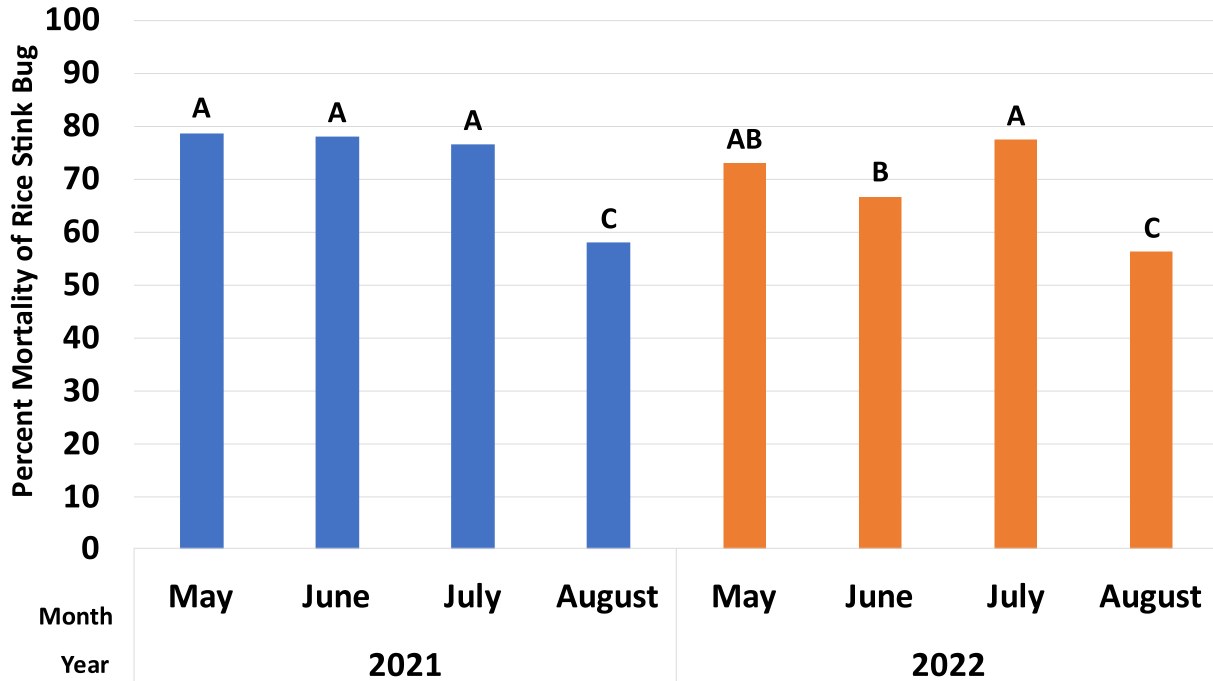

Figure 2.4. Percent mortality of rice stink bug exposed to multiple rates of lambda-cyhalothrin by collection month and year for collections made in 2021 to 2022 throughout the growing season in Arkansas.

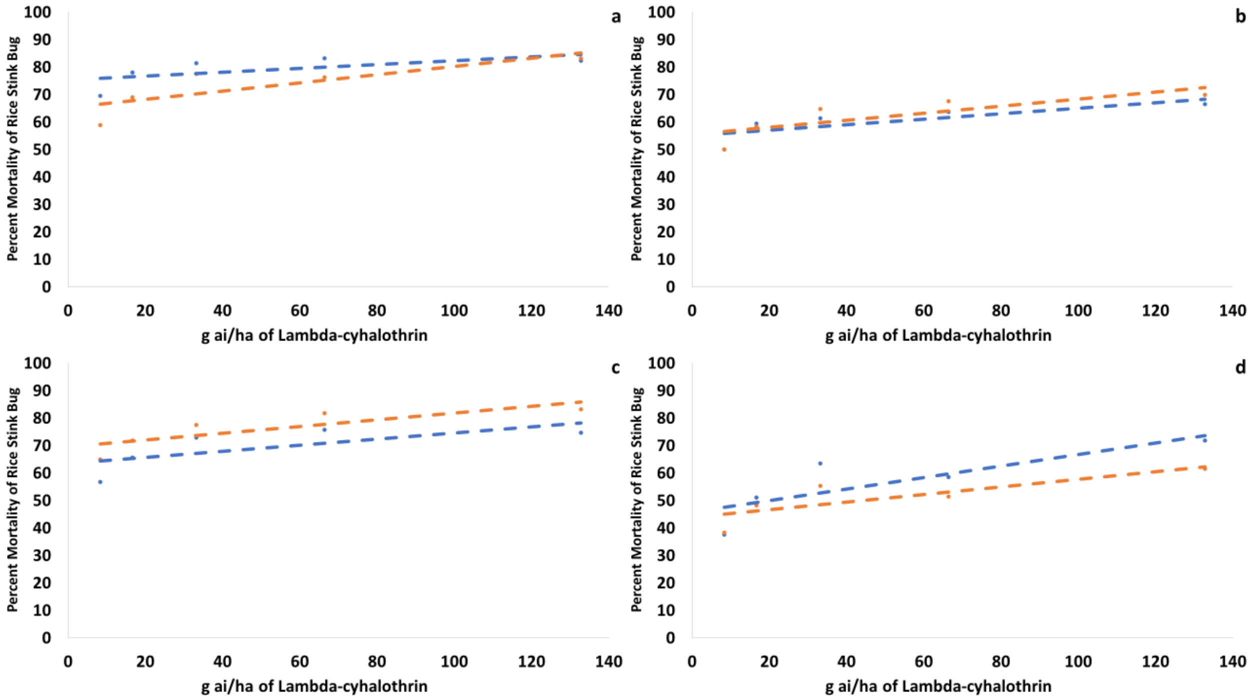

Figure 2.5. Regression analysis for rice stink bug mortality for multiple rates of lambda-cyhalothrin by month and year for collections made throughout the growing season across Arkansas in 2021 and 2022. Blue represents 2021 and orange represents 2022.

A. May 2021 y=64.6x+0.33 ($p<0.01$); May 2022 y=57.02x+0.37 ($p<0.01$).
B. Jun 2021 y=65.16x+0.30 ($p<0.01$); Jun 2022 y= 52.94x+0.32 ($p<0.01$).
C. Jul 2021 y=61.74x+0.35 ($p<0.01$); Jul 2022 y=61.94x+0.36 ($p<0.01$).
D. Aug 2021 y=41.98x+0.44 ($p<0.01$); Aug 2022 y=43.7x+0.29 ($p<0.01$).

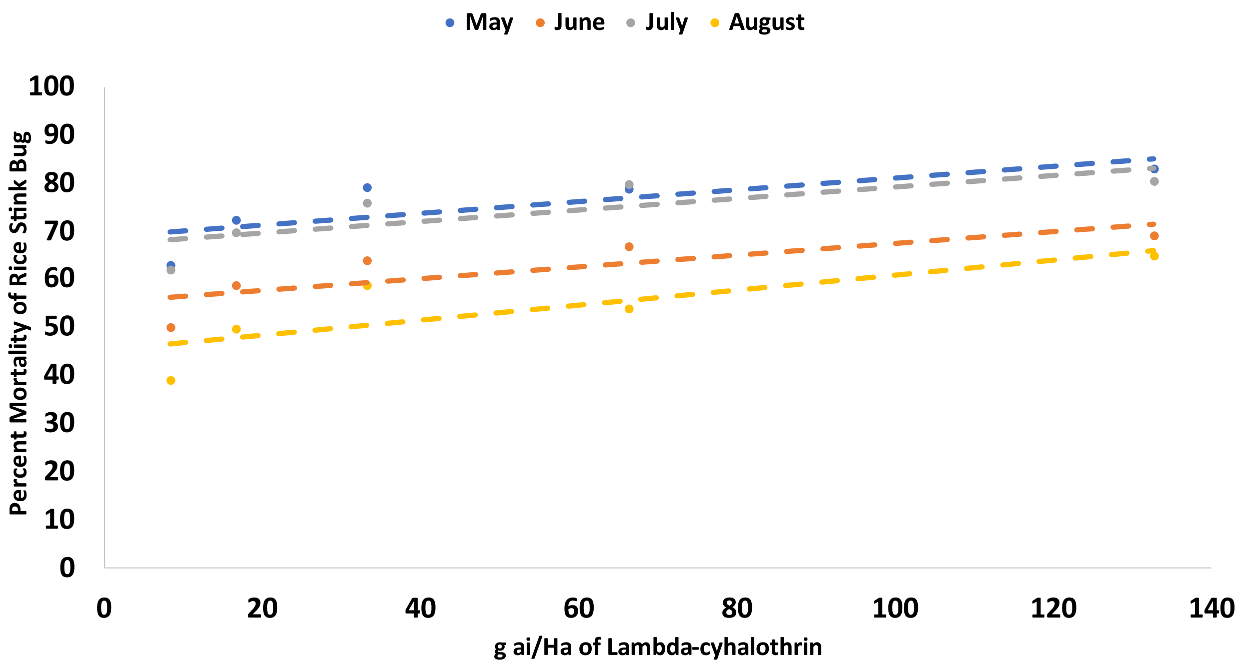

Figure 2.6. Regression analysis for rice stink bug mortality to multiple rates of lambda-cyhalothrin by month for collections made throughout the growing season across Arkansas in 2021 and 2022.

Blue line represents the month of May $y=59.78x+0.36$ ($p<0.01$).

Orange line represents the month of Jun $y=56.01x+0.32$ ($p<0.01$).

Grey line represents the month of Jul $y=61.83x+0.36$ ($p<0.01$).

Yellow line represents the month of Aug $y=42.94x + 0.33$ ($p<0.01$).

Chapter III – Management of Rice Stink Bug, Oebalus pugnax F., in Arkansas Rice Production and Quantification of Rice Quality Impacts

Abstract

The rice stink bug (RSB, *Oebalus pugnax* F., Hemiptera: Pentatomidae), is an important economic late-season pest of rice *Oryza sativa* L., in the southern United States. RSB can be very damaging to rice kernels by reducing yields, lowering crop quality, and injuring developing fruits allowing for pathogens to enter. Historically, adequate control of adults and nymphs has been provided by pyrethroid insecticidal applications. Foliar efficacy trials were performed in 2021 and 2022 across seven locations, to compare efficacy and residual control of multiple insecticides and to determine the most economical control solution for Arkansas, RSB management. Insecticides tested were lambda-cyhalothrin (32 g ai/ha), zeta-cypermethrin (28 g ai/ha), malathion (1,404 g ai/ha), carbaryl (1,123 g ai/ha), dinotefuran (112 g ai/ha), and two rates of thimathoxam + lambda-cyhalothrin (79 g ai/ha + 40 g ai/ha, 95 g ai/ha + 47 g ai/ha). Higher efficacy was observed for both rates of thiamethoxam + lambda-cyhalothrin and dinotefuran across all sample dates compared to zeta-cypermethrin and lambda-cyhalothrin. Additionally, reduced quality losses, increased milling yields, and overall increases for economic returns were observed for both rates of thiamethoxam + lambda-cyhalothrin and dinotefuran compared to lambda-cyahalothrin, zeta-cypermethrin, and malathion. Furthermore, an economic application timing test was conducted in 2022 at three field locations. Lambda-cyhalothrin (32 g ai/ha), dinotefuran (112 g ai/ha), and thimathoxam + lambda-cyhalothrin (95 g ai/ha + 47 g ai/ha) were applied at either the flowering, soft dough, or at both timings. Increases in quality, milling yields, and economic returns were observed for dinotefuran and thiamethoxam + lambda-cyhalothrin compared to lambda-cyhalothrin. No difference was observed between timings for either dinotefuran or thiamethoxam + lambda-cyhalothrin for any variable tested, however soft

dough applications and two applications of lambda-cyhalothrin performed better than a single application occurring at flowering.

Introduction

The rice stink bug (RSB), *Oebalus pugnax* F. (Fabricius 1775), is a major pest of rice in the southern rice growing states (Swanson and Newsom 1962, Awuni et al. 2015a). RSB is the major pest of rice during the reproductive stage and should be carefully monitored throughout the heading and grain filling phases of rice development. Damage magnitudes vary based on the stage of grain development when feeding occurs (Swanson and Newsom 1962, Awuni et al. 2015a). The heading stage of rice last approximately thirty days in most rice cultivars (Fageria 2007) and begins when panicles start to appear from the end of the rice stem (Awuni et al. 2015a). During the heading stage, rice maturity can be further separated as either flowering stage or grain filling stages. Grain filling stages are separated into milk, soft dough, hard dough, and physiological maturity (Fageria 2007).

RSB have been documented to reduce rough rice yield and decrease both quality and milling yields (Bowling 1963, Harper et al. 1993, Espino et al. 2007, Wilson and Stout 2020). Both adult and nymph RSB cause damage to rice grain, with adults being the most damaging (Espino et al. 2007). Depending on rice development stage, either quality loss or yield loss is observed from RSB feeding (Swanson and Newsom 1962). Direct yield loss due to blanked kernels and reduced kernel weights is associated with RSB feeding during the flowering and milk stages (Swanson and Newsom 1962, Espino et al. 2007). Quality reductions and reduced milling yields are observed when excessive RSB feeding occurs during the late milk, soft dough, and hard dough growth stages (Swanson and Newsom 1962, Cato et al. 2019). Due to rice being a food crop, quality reductions or “pecky” rice need to be kept to a minimum to make the grain

maintain value (Wang et al. 2002). Damaged rice referred to as "peck", appears smaller in size, has brown to black discoloration, and typically has a bullseye shaped lesion on the rice kernel. This damage is caused by RSB feeding on rice kernels during the later stages of heading, where feeding allows a pathway for fungi to enter into the kernel (Harper et al. 1993). Injured kernels are more vulnerable to breakage, during the milling process, leading to broken kernels and reducing the amount of whole grains (Harper et al. 1993). During the milling process, milling companies try to eliminate any discolored or broken kernels (Brorsen et al. 1988). Deductions in grain price for rice occur as grain grade is decreased due to "peck" and as the amount of broken kernels increase (Espino et al. 2007). To achieve US grade No. 1 or 2, no more than 1 to 2 percent of a sample can contain damaged kernels, respectively (Wang et al. 2002).

Evaluating RSB populations is vital to estimate the possible losses in rice yield and grain quality (Rashid et al. 2006), and in Arkansas it is recommended to start monitoring fields for RSB when 75% heading is achieved, and continue until grain maturity (Lorenz et al. 2018). Monitoring is done using a 38.1 cm sweep net, conducting random sets of 10 sweeps across the field should be performed, to provide proper evaluation of RSB densities (Rashid et al. 2006). In Arkansas, there are two separate action thresholds for monitoring RSB density. For the first two weeks after 75% heading, treatment is recommended if sampling averages five RSB per 10 sweeps to protect yield losses. During the third and fourth weeks after 75% heading, the action threshold is doubled to ten RSB per 10 sweeps, to prevent quality loss (Lorenz et al. 2018). When rice reaches 60% hard dough in grain maturity, insecticide applications are not recommended if RSB populations are below threshold (Cato 2018).

Chemical control strategies are the primary control tactic used to manage RSB infestation in rice (Awuni et al. 2015a, Blackman et al. 2015). Chemical applications should not be applied

on a regular, preventive basis, but only when control is necessary (Brück et al. 2009). Insecticidal applications target both nymphs and adults (Blackman et al. 2015). However, the amount of available products with different chemical classes for RSB control is minimal and resistance is a concern (Brück et al. 2009). Lambda-cyhalothrin (Warrior II, Syngenta Crop Protection) is applied on approximately half of Arkansas' rice acres, due to being relatively cheap compared to other insecticides (Lorenz 2020). For the last 15 years, lambda-cyhalothrin, has been the most utilized insecticide for controlling RSBs. Alternatives, like dinotefuran (Tenchu 20SG, Belchim Crop Protection) have become more accessible to Arkansas rice producers but has a much higher price point (Lorenz 2020). Bateman et al. (2019) showed lambda-cyhalothrin and dinotefuran, both provided sufficient contact kill but lacked residual control, in high field populations, with no differences between treatments. Newkirk et al. (2021a) found that lambda-cyhalothrin and dinotefuran applications, maintained RSB populations below threshold up to 10 DAT. The introduction of new insecticides with alternative modes of action are vital for RSB control (Bhavanam et al. 2021). In 2020 and 2021, bioassay experiments were conducted to determine RSB susceptibility to lambda-cyhalothrin, across Arkansas RSB populations (Newkirk et al. 2021, Newkirk et al. 2022). Assay experiments showed even with a 4X rate 100% mortality was unachievable, for both experimental years. Endigo® ZC (thiamethoxam + lambda-cyhalothrin, Syngenta Corporation) is an un-labeled insecticide but has been granted a Section 18 exemption the past two growing seasons in Arkansas. Field foliar efficacy trials were performed in 2021, across three locations in Arkansas, to evaluate insecticides for RSB control. Previous field experiments have observed greater control of RSB nymphs at 3 and 7 DAT, with dinotefuran and thiamethoxam + lambda-cyhalothrin of RSB, compared to all other treatments. Field experiments also documented dinotefuran and

thiamethoxam + lambda-cyhalothrin maintained RSB populations below threshold levels up to 13 DAT. The objective of this study was to determine the economic impact multiple foliar insecticides have on rice with respect to management of RSB.

Materials and Methods

Foliar Insecticide Comparison Study

Foliar insecticide studies were conducted in 2021 and 2022 to compare multiple insecticides for efficacy and residual control of RSB, as well as the economic impacts based on quality assessments. Studies were conducted in grower fields near Stuttgart, AR at a total of seven sites between 2021 (three sites) and 2022 (four sites). Field selection was based on heading percentage (75% headed) and RSB densities (a minimum of 5 RSB/10 sweeps). Insecticides evaluated and rates are listed below (Table 3.1). Applications of insecticides were made with a CO_2 backpack sprayer equipped with a 3.7 m hand boom using TXVS-6 (TeeJet®) hollowcone nozzles calibrated to 94.6 L/ha at 275.8 kPa. Plots were arranged in a randomized complete block design and replicated four times with a plot size of 5 m by 12.5 m. Plots were sampled using a 38.1 cm diameter sweep net, with sampling occurring at 3, 7, 10, and 14 days after treatment (DAT) to monitor RSB density. Sweep net samples were performed in the early morning hours, to determine an accurate population level and the number of RSB adults and nymphs were recorded separately. RSB populations were converted to percent control based on the difference between the given product and untreated control (UTC) within a replication.

Foliar Spray Timing

A foliar insecticide spray timing test was conducted in 2022 on three grower fields near Stuttgart, AR, to determine at which time in grain maturity is insecticidal application for RSB most critical. Three insecticides were applied at their recommended rate for this experiment:

lambda-cyhalothrin (Warrior II, Syngenta Crop Protection) 33.2 g ai/Ha, dinotefuran (Tenchu 20SG, Belchim Crop Protection) 112 g ai/Ha, and thiamethoxan + lambda-cyhalothrin (Endigo ZCX, Syngenta Crop Protection) 119 g ai/Ha. All products were applied at multiple timings with grain maturity dictating timings. Applications either occurred at the flowering, soft-dough, or at both stages. Field selection, application methods, randomization, replication, plot size, and sampling technique were the same as the foliar insecticide comparison study.

Both studies harvested with a Wintersteiger® classic plot combine (Wintersteiger Inc., 4705 W. Amelia Earhart Drive, Salt Lake City, UT). Harvested rice grain from each plot was collected and stored in straw bags, then transported to the University of Arkansas System Division of Agriculture Rice Research and Extension Center, near Stuttgart, Arkansas. A 100 g rough rice sample was dehulled and brown rice was placed into envelopes with their respected plot number and location. Peck sampling was performed on each sample, to determine the amount of injury caused by RSB feeding, and to determine which insecticide provided the best protection to rice kernels. Peck samples were separated out into three categories: Undamaged, RSB peck, and other, where other represented kernels that were damaged, but damage did not meet the classical signs of RSB injury. Weights for each category was recorded and converted to a percentage of the overall brown rice sample.

To determine milling yields, a 162 g rough rice sample for each plot was obtained. Rough rice then went through the milling process, milled with a laboratory-scale mill (McGill #2, Rapsco, Brookshire, Texas, USA) to provide white rice samples. White rice was weighed to record the total rice weight, before further processing. Kernels less than three-fourths typical grain length were divided out from whole-kernels, by using a shaker with a No. 11 grate (Model

61, Grain Machinery Manufacturing Corp., Miami, Florida, USA), to determine head rice weight.

All data was analyzed in PROC GLIMMIX (SAS Institute, Cary NC) with an alpha level of 0.05. Site-year (site by year variable), replication, and replication nested in site-year were considered random variables. Yield data was not analyzed due to variability plot to plot in the field and due to the damage occurred in each plot due to sampling. Furthermore, an economic assessment was made based on the cost of treatment, grain grade, and milling yields to determine the best return on investment for growers. The cost of treatment was determined by informal surveys with multiple chemical retailers and aerial application fees were derived from the UADA Enterprise Budgets (UADA 2022). Grain grade was determined by the peck samples for each plot (USDA 2020). Grain discounts, as well as whole kernel and broken kernel premiums and discounts were derived from FSA Rice Loans (USDA 2022).

Results

Foliar Insecticide Comparison Study

No interaction was observed between site-year and insecticide treatment for control of RSB nymphs (F=1.14, df= 36, 383, p=0.27), adults (F=0.66, df=36, 447, p=0.94), or total RSB (F=0.78, df=36, 483, p=0.82). An interaction was observed between insecticide treatment and days after treatment (DAT) for control of RSB nymphs (F=10.41, df 18, 516, p<0.01), adults (F=16.11, df=18,588, p<0.01) and total RSB (F=19.88, df=18, 624, p=0.02). At 3 DAT, carbaryl, dinotefuran, and both rates of thiamethoxam + lambda-cyhalothrin provided better control of RSB nymphs than lambda-cyhalothrin (Table 3.2). At 7 DAT, dinotefuran and the high rate of thiamethoxam + lambda-cyhalothrin had increased control of RSB nymphs than lambda-cyhalothrin or zeta-cypermethrin. At 10 and 14 DAT both rates of thiamethoxam + lambda-

cyhalothrin and dinotefuran performed better than lambda-cyhalothrin and malathion with respect to RSB nymph control.

Only at 3 DAT was a difference observed among insecticide treatments for control of RSB adults (Table 3.2). Lambda-cyhalothrin and zeta-cypermethrin provided less control of RSB adults at 3 DAT than either rate of thiamethoxam + lambda-cyhalothrin or dinotefuran. Similar results were observed for total RSB (Table 3.2). At 3 and 7 DAT dinotefuran and both rates of thiamethoxam + lambda-cyhalothrin provided more control of total RSB than lambda-cyhalothrin or zeta-cypermethrin. No differences were observed among insecticide treatments for total RSB at 10 DAT. At 14 DAT, dinotefuran provided better control of total RSB than malathion, lambda-cyhalothrin, and zeta-cypermethrin.

An interaction was observed between insecticide treatment and site-year for RSB peck ($F=2.04$, $df=42, 165$, $p<0.01$). Higher RSB peck was observed for lambda-cyhalothrin and zeta-cypermethrin compared to dinotefuran and both rates of thiamethoxam + lambda-cyhalothrin plots at five of the seven locations (Table 3.3). At few locations were differences observed for RSB peck between malathion, lambda-cyhalothrin, or zeta-cypermethrin. Across all locations, dinotefuran and both rates of thiamethoxam + lambda-cyhalothrin had less RSB peck than all other treatments except carbaryl.

An interaction was observed between insecticide treatment and site-year for total peck ($F=1.72$, $df=42, 165$, $p=0.01$). Higher total peck was observed for lambda-cyhalothrin and zeta-cypermethrin plots compared to dinotefuran and thiamethoxam + lambda-cyhalothrin (both rates) at the Arkansas1 and Jefferson1 locations (Table 3.3). At six of the seven, no differences were observed for total peck between malathion, lambda-cyhalothrin, or zeta-cypermethrin. Across all locations, reduced total peck was observed for dinotefuran and both rates of thiamethoxam +

lambda-cyhalothrin compared to malathion, lambda-cyhalothrin, or zeta-cypermethrin. The highest rate of thiamethoxam + lambda-cyhalothrin tested lowered the percent of RSB peck within total peck compared to all other treatments. No difference was observed for the percent of RSB peck within total peck between the low rate of thiamethoxam + lambda-cyhalothrin, dinotefuran, or carbaryl, however only thiamethoxam + lambda-cyhalothrin (either rate) and dinotefuran lowered the percent of RSB peck within total peck compared to lambda-cyhalothrin and zeta-cypermethrin.

Higher rice grades (lower quality) and larger grade discounts were observed for lambda-cyhalothrin, zeta-cypermethrin, and malathion compared to dinotefuran and either rate of thiamethoxam + lambda-cyhalothrin (Table 3.4). The high rate of thiamethoxam + lambda-cyhalothrin, dinotefuran, and carbaryl had higher head rice yields than lambda-cyhalothrin and malathion. Only dinotefuran and carbaryl had higher head rice yields than zeta-cypermethrin. Lower total rice yields were observed for lambda-cyhalothrin, zeta-cypermethrin, and malathion compared to carbaryl, dinotefuran, and the high rate of thiamethoxam + lambda-cyhalothrin. Lambda-cyhalothrin, zeta-cypermethrin, and malathion were no different from the untreated control with respect to net returns. Higher net returns were observed for dinotefuran and both rates of thiamethoxam + lambda-cyhalothrin compared to all other treatments except carbaryl. Only dinotefuran provided higher net returns than carbaryl. When comparing insecticide treatments for return on investment, dinotefuran, both rates of thiamethoxam + lambda-cyhalothrin, and carbaryl provided greater returns on investment than lambda-cyhalothrin, zeta-cypermethrin, or malathion. Only dinotefuran and the low rate of thiamethoxam + lambda-cyhalothrin provided greater return on investment than carbaryl. Lambda-cyhalothrin, zeta-cypermethrin, and malathion provided a negative return on investment.

Foliar Spray Timing

In general, RSB numbers on average were at or above threshold across all locations (Figure 3.1). At the Arkansas location, population increased throughout the sampling period. At the Jefferson location RSB numbers stayed relatively flat throughout the season, however numbers stayed above threshold. At the Monroe location, field densities increased between 3 and 10 DAT before declining between 10 and 14 days.

An interaction was observed between insecticide treatment, application timing, and location for RSB peck ($F=2.03$, $df=22, 105$, $p=0.01$) but not for total peck ($F=1.24$, $df=22, 105$, $p=0.23$). Furthermore, an interaction was observed between insecticide treatment and application timing for both RSB peck ($F=23.73$, $df=11, 105$, $p<0.01$) and total peck ($F=16.60$, $df=11, 105$, $p<0.01$). A general trend was observed at each location, that RSB peck was decreased when either dinotefuran or thiamethoxam + lambda-cyhalothrin were used compared to the UTC or lambda-cyhalothrin (Table 3.5). At all three locations, two applications of dinotefuran or thiamethoxam + lambda-cyhalothrin reduced RSB peck compared to two applications of lambda-cyhalothrin. Across all locations, lambda-cyhalothrin was only able to reduce RSB peck when applications were made late or twice compared to the UTC, whereas any application timing for dinotefuran and thiamethoxam + lambda-cyhalothrin where able to reduce RSB peck compared to the UTC. Within each timing both thiamethoxam + lambda-cyhalothrin and dinotefuran reduced RSB peck lower than lambda-cyhalothrin. Similar results were observed for total peck. Additionally, when two applications of dinotefuran or thiamethoxam + lambda-cyhalothrin were made, the percent of RSB peck within total peck was reduced compared to all other treatments. Lambda-cyhalothrin at any application timing was not able to reduce the percent of RSB peck within total peck compared to the UTC.

An interaction was observed between insecticide treatment, application timing, and location for total rice ($F=1.81$, $df=22, 105$, $p=0.02$) but not for head rice ($F=1.18$, $df=22, 105$, $p=0.23$). At each location, thiamethoxam + lambda-cyhalothrin applied twice had increased total rice yields compared to the UTC or lambda-cyhalothrin applied at either the early, late, or combined timings (Table 3.6). Regardless of application timing, no difference was observed between dinotefuran or thiamethoxam + lambda-cyhalothrin.

All insecticides and application timings reduced rice grades (increased quality) compared to the UTC, except for lambda-cyhalothrin applied early (Table 3.7). No difference was observed within spray timings for rice grades between dinotefuran and thiamethoxam + lambda-cyhalothrin, however when either product was applied at both timings the increased quality compared to either spraying just early or just late. At all timings, both thiamethoxam + lambda-cyhalothrin and dinotefuran performed better than lambda-cyhalothrin. Similar results were observed for grade discounts. Higher head rice milling yields were observed for thiamethoxam + lambda-cyhalothrin applied twice compared to any application timing of lambda-cyhalothrin or the UTC. Higher total rice milling yields were observed for dinotefuran and thiamethoxam + lambda-cyhalothrin when applied twice compared to any application timing of lambda-cyhalothrin or the UTC. No difference was observed between dinotefuran and thiamethoxam + lambda-cyhalothrin within or across application timing. Higher net returns were observed for dinotefuran and thiamethoxam + lambda-cyhalothrin at all application timings than the UTC or lambda-cyhalothrin at any application timing. Similar results were observed for return on investment. Lambda-cyhalothrin applied just at the early timing had a negative return on investment.

Discussion

Injury from RSB feeding appears on rice kernels as a circular lesion and discolored, and often referred to as pecky rice (Swanson and Newsom 1962, Bowling 1963). High field populations enhance the risk of higher amounts of pecky rice and lower milling yields. The current studies suggest that traditional insecticides used for RSB management are not providing adequate control of RSBs, compared to dinotefuran and thiamethoxam + lambda-cyhalothrin. Bowling et al. (1962), observed that carbaryl and malathion provided efficient knockdown kill of RSB adults and nymphs in field trials, however only carbaryl provided adequate control of both adults and nymphs two week after application (Bowling 1962). Modern products such as dinotefuran and thiamethoxam + lambda-cyhalothrin both provided nearly 100% control of RSB nymphs at 3 DAT and above 70% control of nymphs two weeks after treatment. Previous research utilizing net cages, determined that lambda-cyhalothrin, carbaryl, malathion, and zeta-cypermethrin provided above 90% control of RSB adults (Cherry et al. 2018). Cage trials prohibit migrating adults from inserting themselves onto treated plants, providing better analysis on treatment performance. In the current studies, RSB adult populations were sporadic past the three-day field assessment. This was most likely due to adults migrating into the treated plot area, after application. In the current studies, plots were established within a large grower field, where the additional portion of field was not treated. Blackman et al. (2015) observed that dinotefuran maintained RSB populations below threshold over a 7 d sampling period and reduced the percent of pecky rice, compared to lambda-cyhalothrin. Results provided by this research is consistent with previous research by Blackman et al. (2015), in determining that dinotefuran outperformed synthetic pyrethroids. Furthermore, dinotefuran and thiamethoxam +

lambda-cyhalothrin provided substantial control of RSB nymphs. Adult RSB amount did not correspond with control based on quality analysis.

The current studies focused on natural field populations to determine which insecticide would provide the greatest efficacy, residual control, and return on investment. A large amount of research has been focused on quality losses from RSB feeding in rice. A large portion of this work has been done by performing cage trials and mechanically infesting RSBs (Swanson and Newsom 1962, Bowling 1963, Patel et al. 2006, Awuni et al. 2015a). Patel et al. (2006) found that RSB feeding during late milk and soft dough stages, commonly lead to high proportions of pecky rice, due to RSBs removing grain contents. Assessments on rice kernels determined insufficient control of RSBs with insecticides, promoted a higher volume of RSB peck. Espino et al. (2007) observed that RSB adults and nymphs feeding reduces the quality of grain, and the milk and soft dough stages are the most vulnerable to peck. In our experiments, the highest number of damaged kernels were in lambda-cyhalothrin, zeta-cypermethrin, and malathion treated plots, which provided the least amount control of RSB nymphs. Pecky rice was less in plots treated with dinotefuran and thiamethoxam + lambda-cyhalothrin, due to higher percent control provided by both products. Milling yields also decreased for lambda-cyhalothrin, zeta-cypermethrin, and malathion treated plots due to a lack of RSB control. Awuni et al. (2015a), found that infestations of RSB at the milk stage reduced kernel weight significantly more than infestations made at soft dough, however this more represents rough rice yields instead of milling yields. The increase in broken kernels led to a higher rice grade for lambda-cyhalothrin, zeta-cypermethrin, and malathion. Higher quality rice with larger net returns were achieved with dinotefuran and thiamethoxam + lambda-cyhalothrin. Espino et al. (2007) failed to correlate a

relationship with peck and amount of whole kernels. In the current study, head rice yields were lower as the amount of peck increased.

In general, insecticide applications are recommended if RSB levels are above threshold after 75% heading. Economic analyses were carried out to determine the most appropriate timing for an insecticide application for different rice growth stages, 'early' treatment was applied at anthesis or flowering and 'late' applications were made at soft dough. The economic timing experiment was designed to determine if an early application or late application, or both would provide a greater ROI. Harper et al. (1993) suggest earlier applications of insecticides for RSB management perform better than later insecticide applications. While maybe true for previous research, in the economic timing test RSB populations increased throughout the sampling period. Harper et al. (1993) found that higher adult populations decreased head rice yields due to the increase of peck present (Harper et al. 1993). Results from the experiment showed that lambda-cyhalothrin had the highest level of RSB peck and lowest total rice weight and rice grade, at all three timings compared to dinotefuran and thiamethoxam + lambda-cyhalothrin. Both dinotefuran and thiamethoxam + lambda-cyhalothrin had better rice grades leading to better returns for the grower. The test also determined that an application of either dinotefuran or thiamethoxam + lambda-cyhalothrin at both timings is not economical since a single application at either timing provided similar returns. Moving forward, growers should consider the use of products like dinotefuran, as well as thiamethoxam + lambda-cyhalothrin if a label is granted, for RSB management. Pyrethroids nor malathion are providing adequate control of RSB, and rarely pay for themselves. If lambda-cyhalothrin is used for RSB management, then an application during the soft dough growth stage is suggested. Based on this study, regardless of product,

applications occurring during the soft dough growth stage trended towards higher returns than other timings.

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Table 3.1. Site description and application date for foliar rice stink bug studies conducted near Stuttgart, AR in 2021 and 2022.

		Coordinates				
Year	Location	Latitude	Longitude	Cultivar	Planting Date	Application Date
2021	Prairie	34°40’19”	91°29’28”	RT753	27 Mar	16-Jul
	Jefferson1	34°23’42”	91°50’49”	RT7521 FP	6 Apr	31-Jul
	Monroe1	34°34’30”	91°28’28”	CLL16	11 May	16-Aug
2022	Arkansas2	34°21’30”	91°23’46”	RTv7231 MA	24 Mar	19-Jul
	Monroe2	34°34’30”	91°28’28”	CLL17	14 Apr	1-Aug
	Jefferson2	34°20’19”	91°45’12”	RT7321 FP	28 Apr	15-Aug
	Arkansas1	34°35’21”	91°32’55”	RT7331 MA	5 May	15-Aug

Table 3.2. Site description and application date for application timing studies for rice stink bug control conducted near Stuttgart, AR in 2022.

	Coordinates				Application Date	
Location	Latitude	Longitude	Cultivar	Planting Date	Early	Late
Monroe	34°34’30”	91°28’28”	CLL17	14 Apr	1-Aug	11-Aug
Jefferson	34°20’19”	91°45’12”	RT7321 FP	28 Apr	15-Aug	25-Aug
Arkansas	34°35’21”	91°32’55”	RT7331 MA	5 May	15-Aug	25-Aug

Table 3.3. Insecticide trade names, common names, class, and rates for insecticides tested in °multiple foliar rice stink bug studies conducted near Stuttgart, AR during 2021 and 2022.

Common Name	Trade Name	Manufacturer	IRAC	Rate g ai/ha
lambda-cyhalothrin	Warrior II	Syngenta Crop Protection, Greensboro, N.C.	3A	32
zeta-cypermethrin	Mustang Maxx	FMC Corporation, Philadelphia, PA	3A	28
malathion	Malathion 57	FMC Corporation, Philadelphia, PA	1B	1,404
carbaryl	Carbaryl 4L	Drexel Chemical Company, Memphis, TN	1A	1,123
dinotefuran	Tenchu 20SG	Belchim Crop Protection, Wilmington, DE	4A	112
thiamethoxam + lambda-cyhalothrin	Endigo ZCX	Syngenta Crop Protection, Greensboro, N.C.	3A / 4A	79+40
thiamethoxam + lambda-cyhalothrin	Endigo ZCX	Syngenta Crop Protection, Greensboro, N.C.	3A / 4A	95+47

*Insecticide Resistance Action Committee **(IRAC)**

Table 3.4. Percent control compared to the untreated control of rice stink bug nymphs, adults, and total rice stink bugs for multiple insecticides at 3, 7, 10, and 14 days after treatment for foliar insecticide comparison studies conducted near Stuttgart, AR in 2021 and 2022.

	3 days after treatment			7 days after treatment			10 days after treatment			14 days after treatment		
	%											
Insecticide Treatment	Nymph	Adult	Total	Nymph	Adult	Total	Nymph	Adult	Total	Nymph	Adult	Total
lambda-cyhalothin 32 g ai/ha	60.2 c	22.3 c	43.1 c	77.8 b	-44.0 b	21.1 c	25.1 cd	-20.1	-2.0 a	-8.0 bc	-8.0	-7.0 bc
zeta-cypermethrin 28 g ai/ha	76.3 abc	33.1 c	42.8 c	55.7 c	-5.4 ab	22.7 c	40.5 bcd	16.8	20.5 a	-1.0 bc	30.2	5.3 bc
malathion 1404 g ai/ha	71.8 bc	46.2 bc	59.8 bc	84.0 ab	7.4 ab	42.6 bc	18.8 d	4.4	11.2 a	-26.0 c	-5.1	-29.0 c
carbaryl 1123 g ai/ha	93.4 ab	72.3 ab	70.7 ab	94.3 ab	13.4 ab	53.1 ab	71.0 abc	21.3	45.5 a	45.5 ab	9.4	16.6 abc
dinotefuran 112 g ai/ha	99.2 a	85.4 a	87.7 a	99.8 a	46.0 a	71.8 a	95.8 a	-26.1	57.3 a	80.0 a	47.0	60.0 a
thiamethoxam + lambda-cyhalothrin 79 g ai/ha + 40 g ai/ha	98.8 a	81.1 ab	85 a	95.8 ab	24.5 a	59.7 ab	90.2 a	-25.0	46.0 a	72.5 a	16.7	33.3 ab
thiamethoxam + lambda-cyhalothrin 95 g ai/ha + 45 g ai/ha	99.4 a	79.1 ab	86.1 a	99.4 a	52.4 a	68.8 a	86.2 ab	18.5	55.0 a	73.6 a	3.6	18.6 abc
DF	6, 95	6, 130	6, 137	6, 116	6, 137	6, 144	6, 123	6, 119	6, 130	6, 60	6, 77	6, 84
F	3.0	9.2	5.0	5.9	1.9	5.5	3.5	1	1.02	7.7	0.8	2.3
P	0.01	0.02	0.01	<0.01	0.09	<0.01	0.03	0.43	0.41	0.01	0.61	0.04

*Negative numbers represent treatments providing less control of RSBs compared to the UTC.
Means with the same letters are not significantly different at an alpha level of 0.05.

Table 3.5. Analysis rice stink bug (RSB) peck and total peck (TOT) for multiple foliar insecticides used for rice stink bug control in rice for insecticide comparison studies conducted near Stuttgart, AR in 2021 and 2022.

	Location																
	Prairie		Arkansas1		Arkansas2		Jefferson1		Jefferson2		Monroe1		Monroe2		All		
	%														%		
Insecticide Treatment	RSB	TOT	RSB	TOT	RSB	TOT	RSB	TOT	RSB	TOT	RSB	TOT	RSB	TOT	RSB	TOT	RSB of TOT†
UTC	2.7 a	2.7 a	5.9 a	7.6 a	1.5 a	1.6 a	4.7 a	5.0 a	5.0 a	6.5 a	2.4 a	2.4 a	3.3 a	5.1 a	3.7 a	4.4 a	87.3 a
lambda-cyhalothrin 32 g ai/ha	1.5 bc	1.5 bc	5.0 ab	6.1 b	1.0 b	1.0 b	3.3 ab	3.5 b	2.6 bc	4.8 abc	1.9 ab	1.9 ab	2.5 b	4.0 bc	2.5 b	3.3 bc	84.0 ab
zeta-cypermethrin 28 g ai/ha	1.6 b	1.6 b	5.0 ab	6.3 b	0.8 cd	0.8 bc	3.7 ab	3.9 b	3.8 ab	5.5 ab	1.8 ab	1.8 abc	2.4 b	4.3 ab	2.7 b	3.5 b	84.6 ab
malathion 1,404 g ai/ha	1.5 bc	1.5 bc	4.3 bc	5.6 bc	1.0 bc	1.0 bc	3.4 a	3.5 b	2.2 c	4.4 bc	2.2 a	2.2 a	2.2 bc	3.4 cd	2.4 b	3.1 bc	83.6 ab
carbaryl 1,123 g ai/ha	1.3 bc	1.3 bc	3.5 cd	4.8 c	0.7 cd	0.7 cd	2 bc	2.1 c	1.6 cd	3.3 cd	1.3 bc	1.3 bcd	2 bc	3.2 cd	1.8 c	2.4 cd	82.4 bc
dinotefuran 112 g ai/ha	0.8 cd	0.8 cd	1.6 e	2.7 d	0.5 d	0.6 d	2 c	2.2 c	0.6 d	2.4 d	0.7 c	0.7 d	1.7 cd	3.4 cd	1.1 d	1.8 d	79.0 c
thiamethoxam + lambda-cyhalothrin 79 g ai/ha + 40 g ai/ha	0.64 c	0.64 d	2.6 de	3.6 d	0.6 d	0.7 cd	1.5 c	1.7 c	1.6 cd	3.2 cd	0.7 c	0.7 d	1.7 cd	3.0 d	1.3 d	2.0 d	78.4 c
thiamethoxam + lambda-cyhalothrin 95 g ai/ha + 47 g ai/ha	0.8 cd	0.8 cd	2.2 e	3.3 d	0.5 d	0.5 d	1.7 c	1.8 c	1.4 cd	3.4 cd	0.9 c	0.9 cd	1.5 d	2.8 d	1.3 d	2.0 d	73.2 d
DF	7, 21	7, 21	7, 21	7, 21	7, 21	7, 21	7, 21	7, 21	7, 21	7, 21	7, 21	7, 21	7, 21	7, 21	7, 207	7, 213	7, 189
F	7.6	7.6	14.2	18.4	9.1	8.5	15.9	14.7	9.1	5.1	5.4	5.2	7.5	7.5	32.1	7.8	8.19
P	0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	0.01	0.01	0.01	0.02	<0.01	<0.01	<0.01

†The percentage of peck identified as rice stink bug peck out of the total amount of peck observed
Means with the same letters are not significantly different at an alpha level 0.05.

Table 3.6. Economic analysis based on rice grade and milling yields for multiple foliar insecticide studies targeting rice stink bug in rice conducted in Arkansas during 2021 and 2022.

Insecticide Treatment	TOT Cost of App†	AVG Grade‡	AVG Grade Discount‡‡	Head Rice§	Total Rice§§	Net Returns⁎	ROI⁑
	USD/ha		USD/per 20KG	%		USD/ha	USD/ha
UTC	$0.00	3.46 a	$0.22 a	57.8 de	67.5 d	$2908.65 cd	
lambda-cyhalothrin 32 g ai/ha	$33.75	2.93 b	$0.16 b	58 de	67.8 cd	$2904.74 cd	-$3.91 c
zeta-cypermethrin 28 g ai/ha	$25.38	2.89 bc	$0.16 b	58.2 cde	67.6 d	$2901.67 d	-$6.81 c
malathion 1,404 g ai/ha	$48.13	2.64 c	$0.13 b	57.1 e	67.7 d	$2893.88 d	-$14.77 c
carbaryl 1,123 g ai/ha	$61.88	2.29 d	$0.09 c	59.0 ab	68.6 ab	$2928.11 bc	$19.46 b
dinotefuran 112 g ai/ha	$46.25	1.89 e	$0.04 d	59.8 a	68.9 a	$2968.52 a	$59.87 a
thiamethoxam + lambda-cyhalothrin 79 g ai/ha + 40 g ai/ha	$44.50	1.89 e	$0.05 cd	58.4 bcd	68.3 bc	$2957.46 ab	$42.81 a
thiamethoxam + lambda-cyhalothrin 95 g ai/ha + 47 g ai/ha	$49.40	1.96 e	$0.06 cd	59.0 abc	68.6 ab	$2949.18 ab	$40.53 ab
DF		7, 189	7, 189	7, 206	7, 206	7, 188	6, 161
F		32.21	21.35	5.41	7.66	10.63	12.21
P		<0.01	<0.01	<0.01	<.01	<0.01	<0.01

†Cost of insecticide plus the cost of aerial application ($20/ha) in USD/ha. Cost based on UADA 2022 and chemical retailer surveys.
‡Rice grain grade based on peck analysis (USDA 2020). ‡‡Discount for damaged kernels based on 2022 FSA loan rates (USDA 2022)
§White rice with brokens kernels removed. §§White rice with broken kernels and whole kernels combined.
⁎Price in USD/ha based on grade deductions and milling rates minus insecticide and application cost. Grain price is set at $0.36 USD/kg, yield was 372.4 kg/ha, with a whole kernel value of $0.25 usd/kg, and a $0.14 broken kernel value with a base milling yield of 55/70.
⁑ROI=Return on investment figured as the return above or below the untreated control.
Means with the same letters are not significantly different at an alpha level of 0.05.

Table 3.7. Analysis of rice stink bug peck (RSB) by location and RSB and total peck (TOT) across locations for foliar insecticide application timing studies conducted near Stuttgart, AR in 2022 to determine control of rice stink bug in rice.

		Location			All Locations		
		% RSB Peck					
Insecticide Treatment	Application Timing§	Jefferson	Monroe	Arkansas	% RSB Peck	% TOT Peck	% RSB of TOT†
UTC		4.2 a	2.3 ab	5.4 a	4.0 a	5.2 a	75.0 a
lambda-cyhalothrin 32 g ai/ha	Early	3.4 ab	2.4 a	4.6 ab	3.5 ab	4.6 ab	74.5 a
dinotefuran 112 g ai/ha	Early	0.9 de	1.1 cde	1.3 fg	1.1 def	2.0 de	53.2 d
thiamethoxam + lambda-cyhalothrin 95 g ai/ha + 47 g ai/ha	Early	1.4 cde	1.4 cd	2.5 de	1.8 cd	2.8 cd	65.5 abc
lambda-cyhalothrin 32 g ai/ha	Late	2.0 cd	1.7 abc	4.1 bc	2.6 bc	3.6 bc	73.9 a
dinotefuran 112 g ai/ha	Late	1.1 de	1.0 cde	2.0 def	1.4 d	2.3 de	59.8 cd
thiamethoxam + lambda-cyhalothrin 95 g ai/ha + 47 g ai/ha	Late	0.9 de	1.6 bc	1.5 efg	1.3 de	2.3 de	61.8 bcd
lambda-cyhalothrin 32 g ai/ha	Early / Late	2.5 bc	2.4 a	3.0 cd	2.6 c	3.6 bc	72.3 ab
dinotefuran 112 g ai/ha	Early / Late	0.2 e	0.4 e	0.5 g	0.4 f	1.3 e	30.3 e
thiamethoxam + lambda-cyhalothrin 95 g ai/ha + 47 g ai/ha	Early / Late	0.2 e	0.7 de	0.6 g	0.5 ef	1.5 e	32.2 e
DF	11, 105	11, 33	11,33	11, 33	11, 127	11, 129	11, 120
F	23.7	12.2	6.8	21.2	20.2	12.5	17.5
P	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

§Early applications were made during the flowering stage, late applications occurred during the soft dough stage, and at the early / late timing, applications were made at both timings

†The percentage of peck identified as rice stink bug peck out of the total amount of peck observed

Means with the same letters are not significantly different at an alpha level of 0.05.

Table 3.8. Analysis of total rice milling yields by location for foliar insecticide application timing studies conducted near Stuttgart, AR in 2022 to determine control of rice stink bug in rice.

		Location		
		Jefferson	Monroe	Arkansas
Treatment	Timing	% Total Rice		
UTC		65.7 d	71.2 c	69.7 e
lambda-cyhalothrin 32 g ai/ha	Early	65.8 d	71.0 c	70.5 de
dinotefuran 112 g ai/ha	Early	69.4 a	71.8 abc	72.0 ab
thiamethoxam + lambda-cyhalothrin 95 g ai/ha + 47 g ai/ha	Early	69 ab	71.8 abc	71.5 bc
lambda-cyhalothrin 32 g ai/ha	Late	67.0 bcd	71.2 c	70.7 cd
dinotefuran 112 g ai/ha	Late	69.0 abc	72.2 ab	71.7 b
thiamethoxam + lambda-cyhalothrin 95 g ai/ha + 47 g ai/ha	Late	68.8 abc	71.3 c	72.3 ab
lambda-cyhalothrin 32 g ai/ha	Early / Late	66.8 cd	71.7 bc	71.7 b
dinotefuran 112 g ai/ha	Early / Late	68.0 abc	72.3 ab	72.7 a
thiamethoxam + lambda-cyhalothrin 95 g ai/ha + 47 g ai/ha	Early / Late	69.0 a	72.5 a	73.0 a
DF		11, 33	11, 33	11, 33
F		4.2	2.9	13.9
P		0.03	0.01	<0.01

Means with the same letters are not significantly different at an alpha level of 0.05.
*Total Rice – the amount of rice (whole and broken kernels) obtained after milling.

Table 3.9. Economic analysis for multiple insecticides and spray timings for rice stink bug in rice based on rice grade and milling yields for studies conducted in Arkansas during 2021 and 2022.

Insecticide Treatment	Application Timing	TOT Cost of App††	AVG Grade‡	AVG Grade Discount‡‡	Head Rice	Total Rice	Net§§	ROI⁎
		USD/ha		USD/per 20KG	%		USD/ha	USD/ha
UTC		$0.00	3.92 a	$0.28 a	54.8 e	68.9 d	$2880.94 cd	
lambda-cyhalothrin 32 g ai/ha	Early	$33.03	3.83 a	$0.26 a	55.4 de	69.1 d	$2864.85 d	-$16.09 c
dinotefuran 112 g ai/ha	Early	$46.25	2.17 c	$0.05 cd	57.6 abc	71.1 a	$2973.90 a	$92.96 a
thiamethoxam + lambda-cyhalothrin 79 g ai/ha + 40 g ai/ha	Early	$44.50	2.5 c	$0.10 bc	57.7 abc	70.8 ab	$2951.92 ab	$71.33 a
lambda-cyhalothrin 32 g ai/ha	Late	$33.03	3.17 b	$0.17 b	56.0 cde	69.6 cd	$2909.47 bc	$28.54 b
dinotefuran 112 g ai/ha	Late	$46.25	2.25 c	$0.07 cd	57.0 abcd	70.9 ab	$2963.50 a	$82.56 a
thiamethoxam + lambda-cyhalothrin 79 g ai/ha + 40 g ai/ha	Late	$44.50	2.25 c	$0.07 cd	57.9 ab	70.8 ab	$2969.16 a	$88.23 a
lambda-cyhalothrin 32 g ai/ha	Both	$66.05	3.17 b	$0.17 b	56.5 bcde	70.1 bc	$2889.48 cd	$8.54 bc
dinotefuran 112 g ai/ha	Both	$92.50	1.42 d	$0.00 d	57.8 abc	71.0 a	$2949.36 ab	$68.42 a
thiamethoxam + lambda-cyhalothrin 79 g ai/ha + 40 g ai/ha	Both	$89.00	1.58 d	$0.01 d	58.6 a	71.6 a	$2958.86 a	$77.93 a
DF			9, 99	9, 99	11, 105	11, 121	9, 99	8, 88
F			20.08	14.40	4.53	10.37	7.26	8.27
P			<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

†Cost of insecticide plus the cost of aerial application ($20/ha) in USD/ha. Cost based on UADA 2022 and chemical retailer surveys.
‡Rice grain grade based on peck analysis (USDA 2020). ‡‡Discount for damaged kernels based on 2022 FSA loan rates (USDA 2022)
§White rice with brokens kernels removed. §§White rice with broken kernels and whole kernels combined.
⁎Price in USD/ha based on grade deductions and milling rates minus insecticide and application cost. Grain price is set at $.36 USD/kg, yield was 372.42 kg/ha, with a whole kernel value of $0.25 usd/kg, and a $0.14 broken kernel value with a base milling yield of 55/70.
⁑ROI=Return on investment figured as the return above or below the untreated control.
Means with the same letters are not significantly different at an alpha level of 0.05.

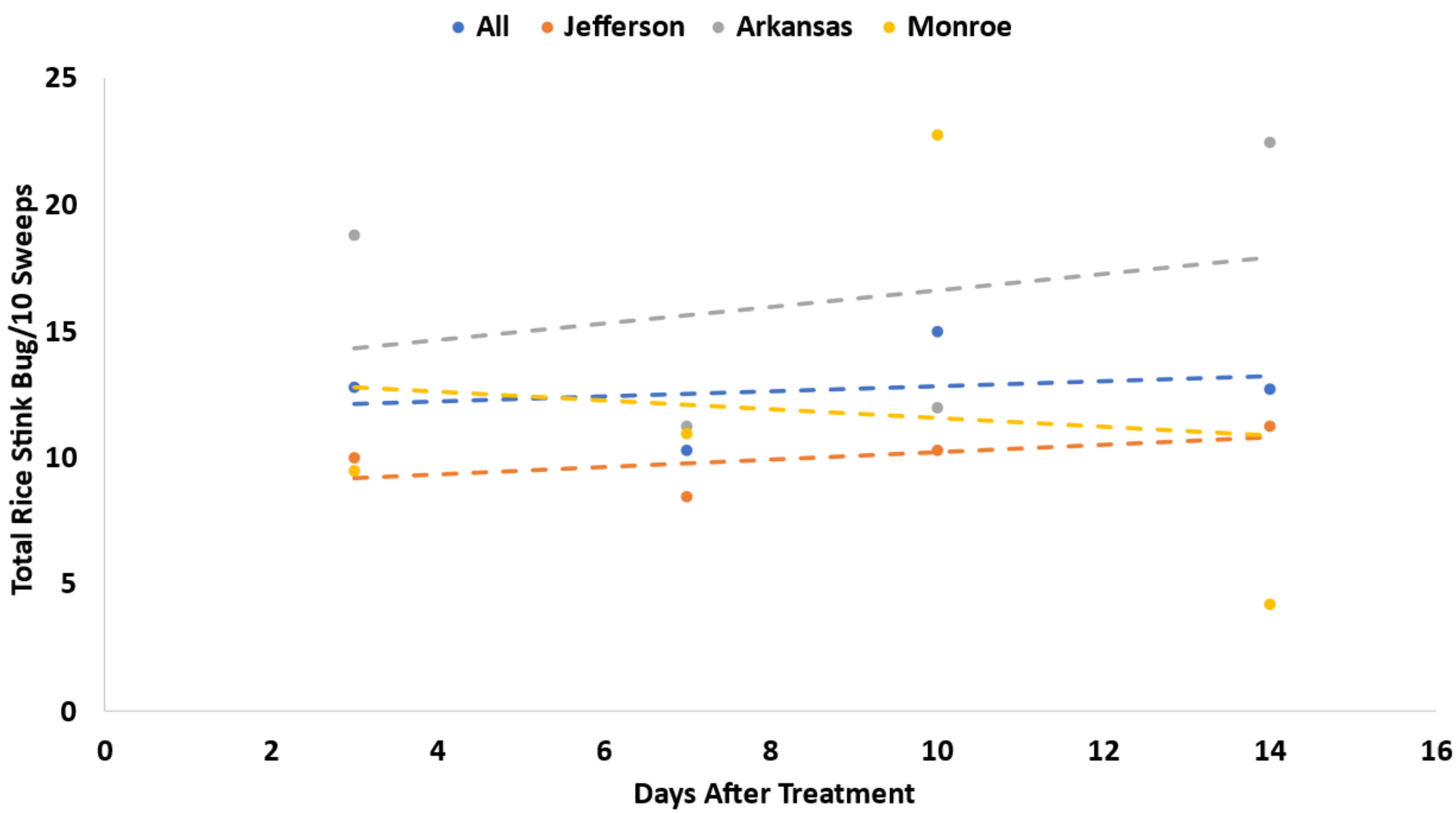

Figure 3.1. Mean total rice stink bug densities at days after treatment for the untreated control for multiple insecticide application studies conducted in 2022 near Stuttgart, AR.

Conclusion

There is a long history of studies on rice stink bug (RSB), *Oebalus pugnax* F., control, and damage, with most research using cage techniques to evaluate damage and control. Our research was carried out in real world field experiments, to better assess RSB control and damages to rice quality that occur due to RSB feeding.

Higher RSB tolerance was present throughout Arkansas in resistance assays with lambda-cyhalothrin compared to previous work. Higher susceptibility was observed for overwintering populations (collections made in May), but RSB susceptibility lessened as the growing season progressed. Overall lambda-cyhalothrin was unable to achieve 80% control at any tested rate or within any month. Mortality increased with increasing rates of lambda-cyhalothrin. Surrounding states such as Texas and Louisiana, have also reported lambda-cyhalothrin control problems. Control failures in late season populations of RSB have been recorded in Arkansas since 2019. The limited availability of alternative control options and the reduced vulnerability to lambda-cyhalothrin, is problematic for the Arkansas rice production. Since pyrethroid resistance is growing, preparing rice growers and consultants on the importance of sustainable insecticide resistance management, is important. Furthermore, future research should continue to examine the ongoing resistance mechanism in RSB populations across the state.

In experiments assessing multiple control options for RSB, dinotefuran and thiamethoxam + lambda-cyhalothrin provided superior control and protected grain quality from RSB injury. Over all locations, dinotefuran and thiamethoxam + lambda-cyhalothrin had a reduction in RSB and total peck compared to all other treatments excluding carbaryl. The plots treated with lambda-cyhalothrin, zeta-cypermethrin, and malathion had marginal residual for RSB nymph control. Only at a few sites were there differences observed for total and RSB peck between lambda-cyhalothrin, zeta-cypermethrin, and malathion. Rice grades (lower quality) and

discounts were higher for lambda-cyhalothrin, zeta-cypermethrin, and malathion compared to dinotefuran or thiamethoxam + lambda-cyhalothrin. Compared to the UTC, lambda-cyhalothrin, zeta-cypermethrin, and malathion provided no net returns, with negative return on investment. Higher net returns were documented for thiamethoxam + lambda-cyhalothrin and dinotefuran, as well as greater return on investment.

For studies determining the most economically import timing of insecticidal applications targeting RSB, lambda-cyhalothrin only performed better than the UTC when applied at soft dough with respect to peck. Less peck was documented for dinotefuran and thiamethoxam + lambda-cyhalothrin compared to lambda-cyhalothrin at any timing. At each location plots receiving two applications of lambda-cyhalothrin had higher amounts of RSB peck compared to two applications of thiamethoxam + lambda-cyhalothrin and dinotefuran. No difference was observed within application timing regarding rice grade between dinotefuran and thiamethoxam + lambda-cyhalothrin, although if either treatment was applied at both, flowering and soft dough, an increase in quality was observed in comparison to a single application. Throughout, all treatment timings, dinotefuran and thiamethoxam + lambda-cyhalothrin performed greater compared to lambda-cyhalothrin. Lower total rice milling yields were observed at all lambda-cyhalothrin timings compared to thiamethoxam + lambda-cyhalothrin or dinotefuran. Higher net returns and return on investment were observed for dinotefuran and thiamethoxam + lambda-cyhalothrin at each treatment timing, compared to the UTC and lambda-cyhalothrin. If a single application of lambda-cyhalothrin was made early a negative return on investment was observed.

Insecticide treatments are the primary control tactic for RSB management, throughout, the Mid-South rice growing states. Overuse of applications, such as treating fields prior to populations exceeding threshold levels or reapplying the same insecticide, has reduced RSB

susceptibility to pyrethroids. This research provides sufficient evidence that dinotefuran is a reliable labeled insecticide for Arkansas rice growers and consultants to use in managing RSB. The establishment of new products like thiamethoxam + lambda-cyhalothrin could be a major asset in RSB management practices. Providing growers and consultants with another insecticide option such as thiamethoxam + lambda-cyhalothrin would help with resistance management. The ability to rotate insecticides with different modes of action would help sustain the longevity of insecticides. During the 2021 and 2022 growing seasons a section 18 was granted in Arkansas for the use of thiamethoxam + lambda-cyhalothrin, to help manage RSB.

Appendix

Materials and Methods

Studies were conducted in 2021 and 2022 to determine the impact rice stink bug (RSB) has on rice grain quality as well as the economic impacts based on quality assessments. Studies were conducted in grower fields near Stuttgart, AR at a total of seven sites between 2021 (three sites) and 2022 (four sites). Field selection was based on heading percentage (75% headed) and RSB densities (a minimum of 5 RSB/10 sweeps). Plot size was 5 m by 12.5 m and sampling was repeated four times at each sample date at each site-year. Plots were sampled using a 38.1 cm diameter sweep net, with sampling occurring at 3, 7, 10, and 14 after 75% heading to monitor RSB density. Sweep net samples were performed in the early morning hours, to determine an accurate population level and the number of RSB adults and nymphs were recorded separately.

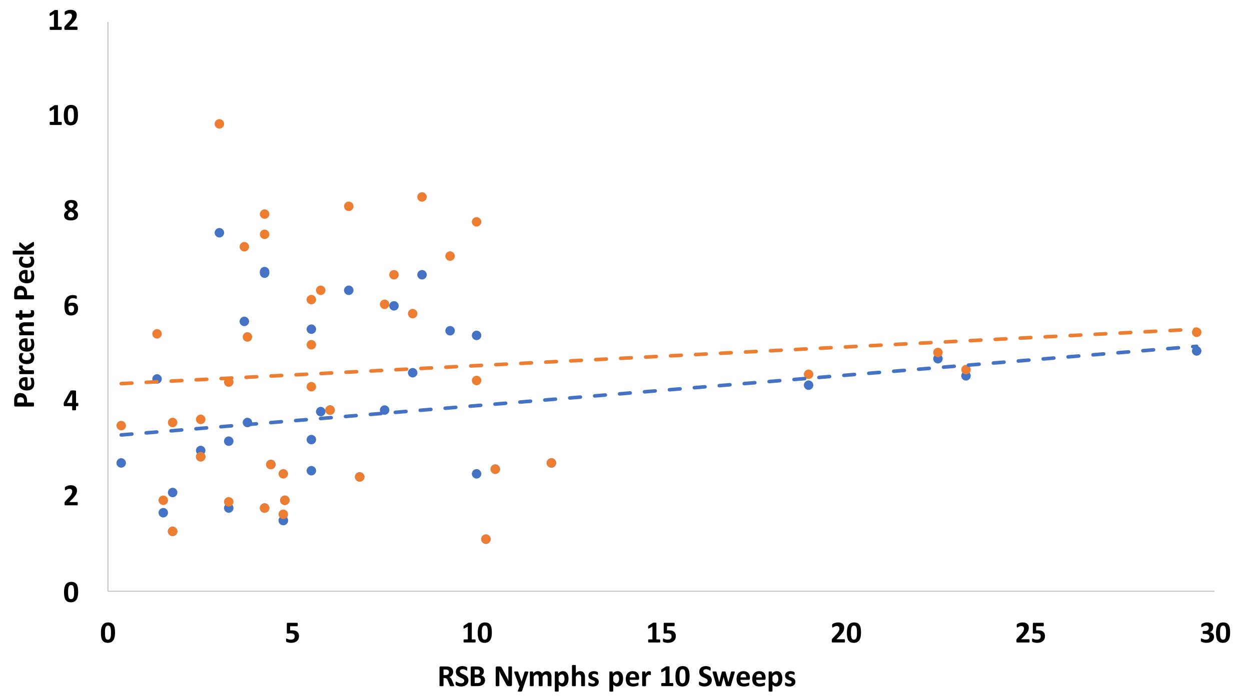

Figure 1. Regression analysis for percent peck from foliar tests for RSB nymphs over all tested locations throughout the growing season in Arkansas from 2021 and 2022.

Blue line represents RSB peck; y=3.28x+0.06 (p<0.01)

Orange line represents Total peck; y=4.35x+0.39 (p<0.01)

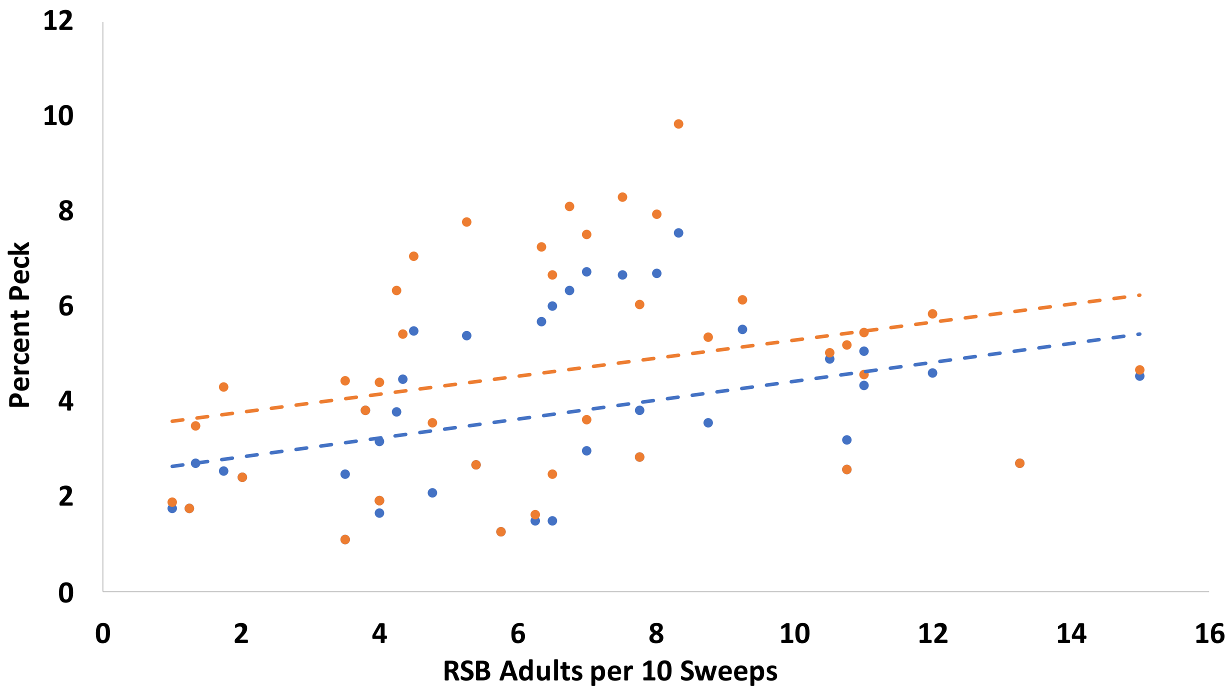

Figure 2. Regression analysis for percent peck from foliar tests for RSB adults over all tested locations throughout the growing season in Arkansas from 2021 and 2022.

Blue line represents RSB peck; 2.45x+0.2 ($p<0.01$)

Orange line represents Total peck; 3.4x+0.2 ($p<0.01$)

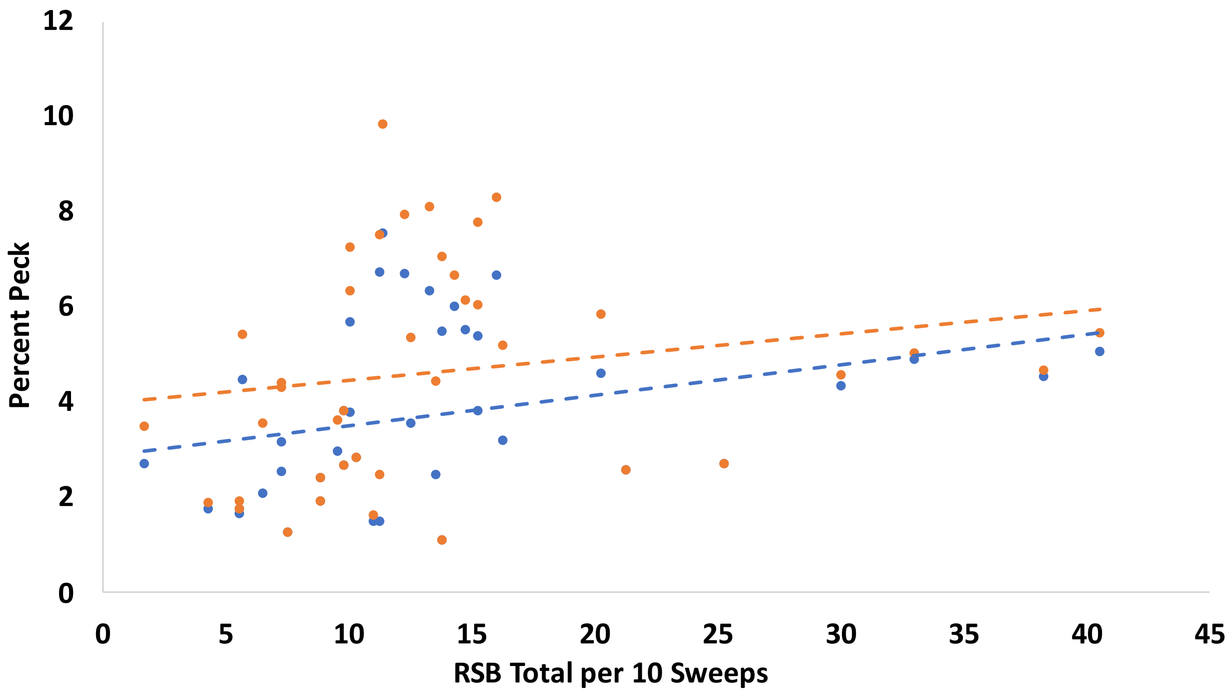

Figure 3. Regression analysis for percent peck from foliar tests for total RSBs over all tested locations throughout the growing season in Arkansas from 2021 and 2022.

Blue line represents RSB peck; 2.87x+0.06 ($p<0.01$)

Orange line represents Total peck; 3.96x+0.05 ($p<0.01$)

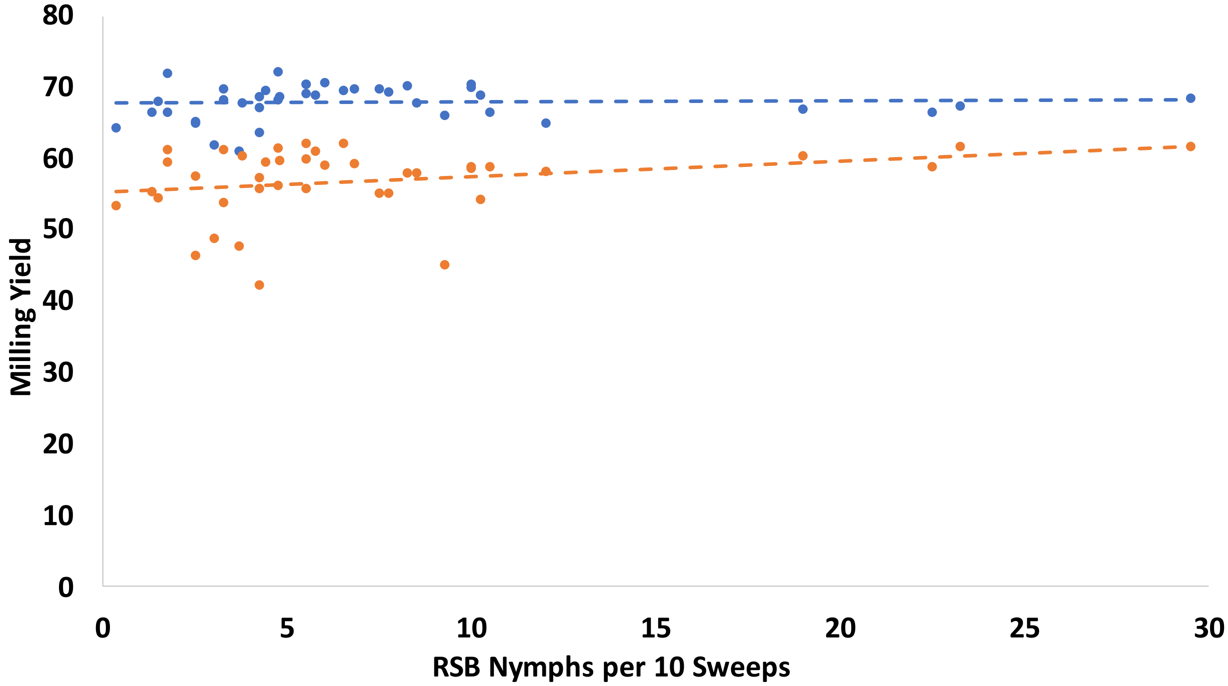

Figure 4. Regression analysis for milling yield from foliar tests for RSB nymphs over all tested locations throughout the growing season in Arkansas from 2021 and 2022.

Blue line represents total rice; y=67.78x+0.02 ($p<0.01$)

Orange line represents head rice; y=55.29x+0.22 ($p<0.01$)

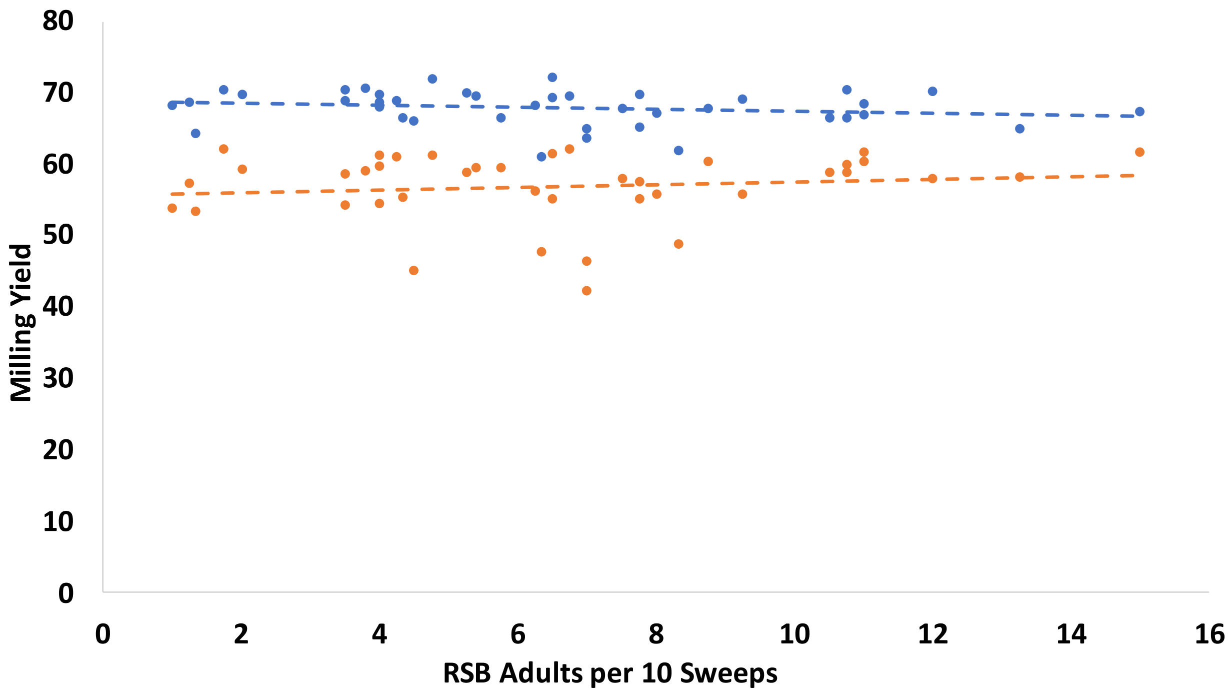

Figure 5. Regression analysis for milling yield from foliar tests for RSB adults over all tested locations throughout the growing season in Arkansas from 2021 and 2022.

Blue line represents total rice; y=68.87x+-0.15 ($p<0.01$)

Orange line represents head rice; y=55.69x+0.18 ($p<0.01$)

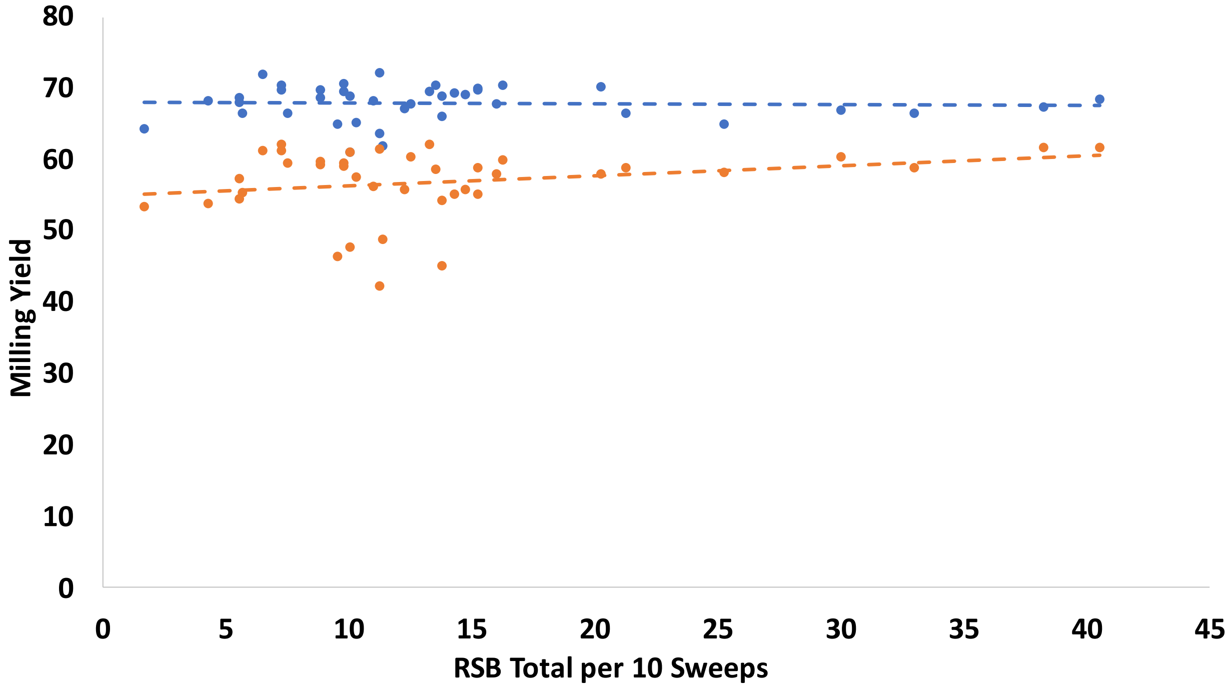

Figure 6. Regression analysis for milling yield from foliar tests for total RSBs over all tested locations throughout the growing season in Arkansas from 2021 and 2022.

Blue line represents total rice; y=68.09x+-0.01 ($p<0.01$)

Orange line represents head rice; y=54.92x+0.14 ($p<0.01$)

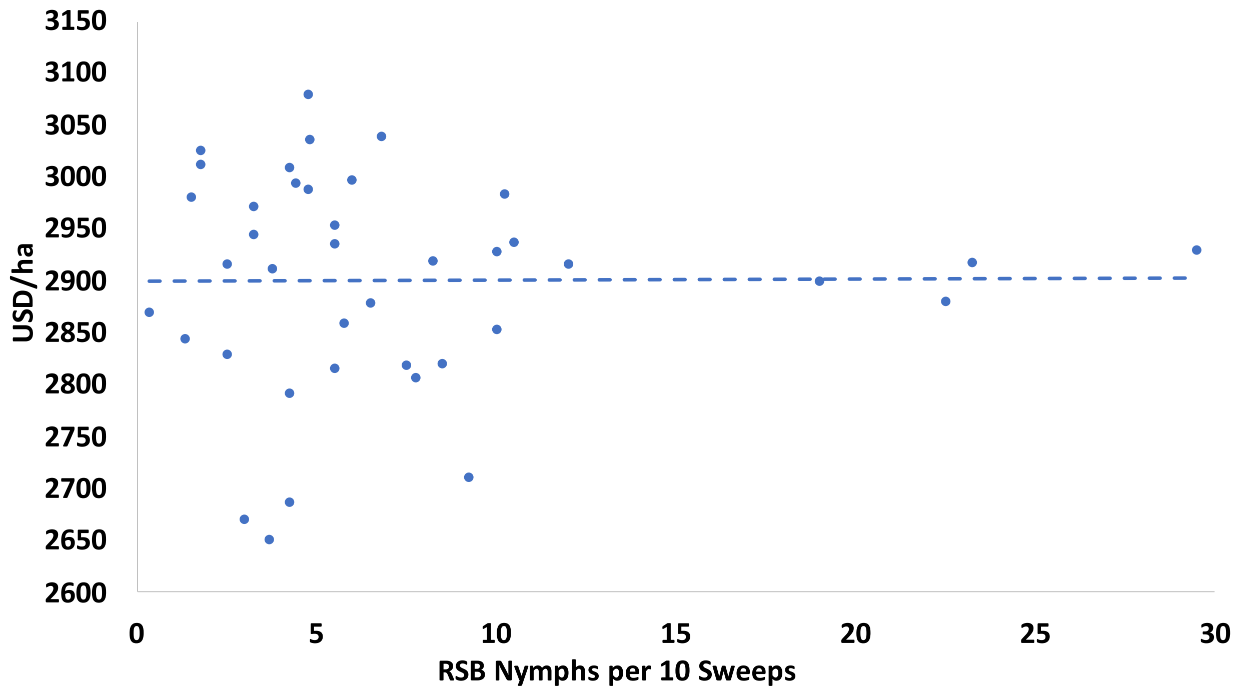

Figure 7. Regression analysis for losses per/ha from RSB nymphs for foliar tests over all tested locations throughout the growing season in Arkansas from 2021 and 2022.

Gross income; $y=2899.74x+0.08$ ($p<0.01$)

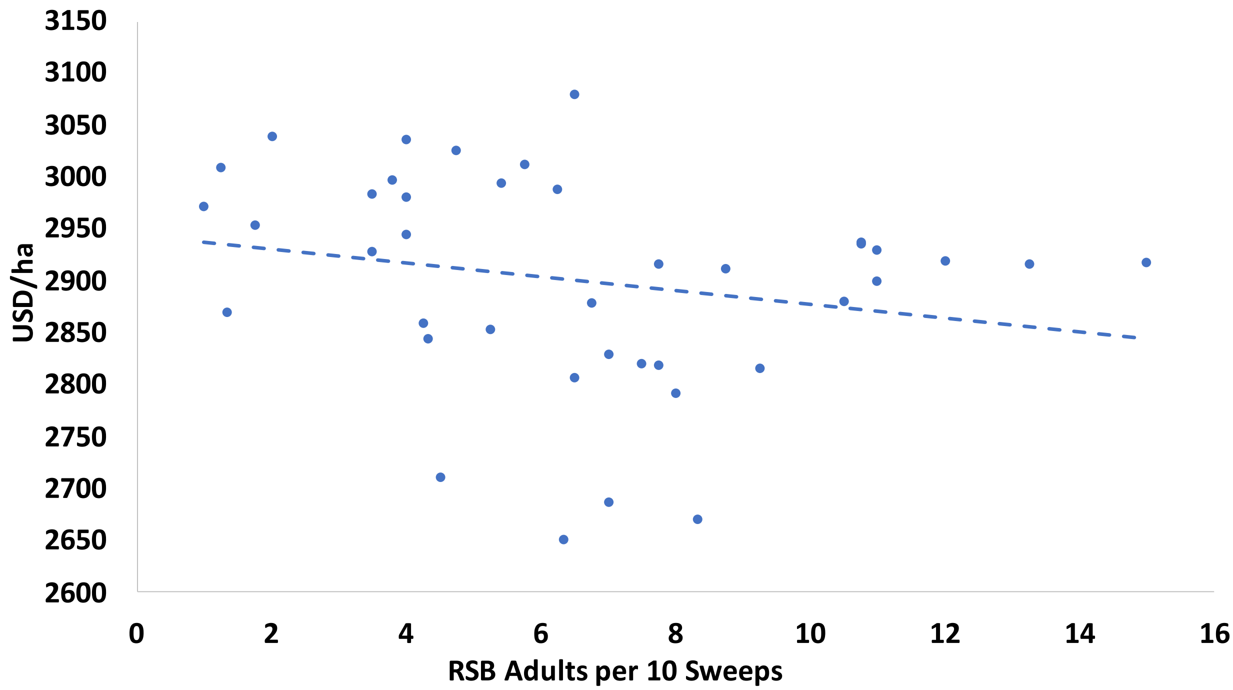

Figure 8. Regression analysis for losses per/ha from RSB adults for foliar tests over all tested locations throughout the growing season in Arkansas from 2021 and 2022.

Gross income; $y=2944.28x+-6.7$ ($p<0.01$)

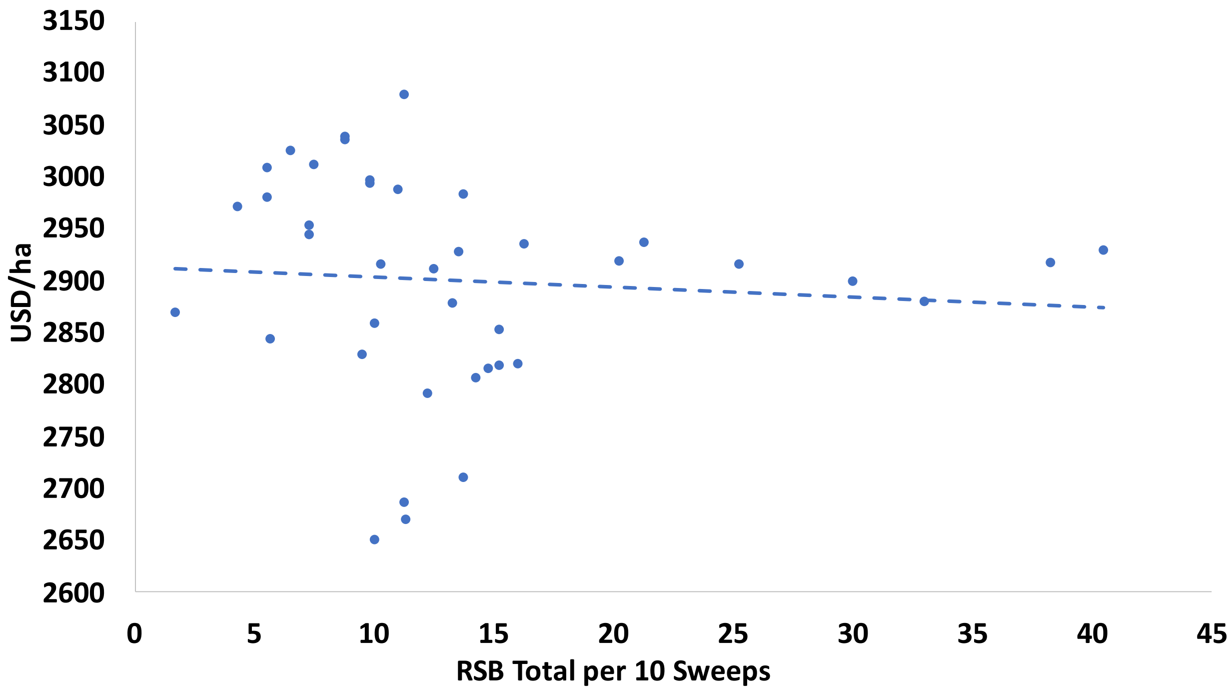

Figure 9. Regression analysis for losses per/ha from total RSBs for foliar tests over all tested locations throughout the growing season in Arkansas from 2021 and 2022.

Gross income; y=2913.87x+-0.98 ($p<0.01$)