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Review

The panicle rice mite, *Steneotarsonemus spinki* Smiley, a re-discovered pest of rice in the United States

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ABSTRACT

The panicle rice mite (PRM), *Steneotarsonemus spinki* Smiley, was reported in 2007 in the United States in greenhouses and/or field cultures of rice (*Oryza sativa* L.) in the states of Arkansas, Louisiana, New York, and Texas. PRM had not been reported in rice culture in the United States since the original type specimen was collected in Louisiana in association with a delphacid insect in the 1960s. PRM is the most important and destructive mite pest attacking the rice crop worldwide. It has been recognized as a pest of rice throughout the rice-growing regions of Asia since the 1970s. Historical reports of rice crop damage dating back to the 1930s also have been speculatively attributed to the PRM in India. In the late 1990s PRM was reported in Cuba, and quickly spread throughout the Caribbean and Central America. Rice crop losses of up to 90% in the Caribbean have been attributed to the PRM since first reported. The PRM attacks rice plants by feeding on the inside of the leaf sheath and developing grains. Damage associated with PRM infestations in rice includes plant sterility, partial panicle infertility, and grain malformation. However, it is difficult to characterize the damage caused solely by the PRM because the mite is commonly reported interacting with several rice plant pathogens including *Sarocladium oryzae* (Sawada) and *Burkholderia glumae* (Kurita and Tabei). The purpose of this article is to review the literature regarding the PRM in response to its re-discovery in the United States. We also summarize findings from countries where the PRM has historically been a significant pest of the rice crop. This article re-examines the taxonomic ranking of the PRM and includes a key to the USA species of *Steneotarsonemus*, its current distribution, damage to rice plants, its association with plant pathogens, host plant records, life history, survival under extreme temperature conditions, and current management strategies. Our hope is that this article will stimulate research on the biology and management of the PRM in the United States.

1. Introduction

The panicle rice mite (PRM), *Steneotarsonemus spinki* Smiley, is the most important and destructive mite pest attacking rice crops worldwide (Tseng, 1984). *S. spinki* has been recognized as a pest of rice throughout rice-growing regions of Asia since the 1970s. Reports from India in the 1930s attribute damage to a rice crop as caused by *S. spinki* (Ramaiah, 1931). *S. spinki* was reported in Cuba in 1997 and since that time, it has quickly spread throughout rice producing areas in the Caribbean where it was initially reported to cause from 30 to 90% rice crop loss (Almaguel et al., 2000). The damage and effects associated with *S. spinki* infestations include rice plant sterility, partial panicle infertility, and deformity of rice grains. It is difficult to characterize and isolate the precise damage attributed to *S. spinki* because it is commonly reported in conjunction with a number of plant pathogens. Most recently, *S. spinki* was collected on the continental United States in Texas in July 2007 (Texas Department of Agriculture, 2007) and subsequently in the states of Arkansas, California, Louisiana, and New York (Hummel et al., 2007; NAPPO, 2007; UCDavis, 2009).

S. spinki is known in rice producing areas of the world by a variety of common names including the panicle rice mite, rice tarsonemid mite, rice white mite, rice mite, spinki mite, and ácaro del vanéo del arroz. The original description of *S. spinki* was provided by R.L. Smiley (1967) from specimens collected in 1960 by Dr. Will Spink for whom the species was named. Smiley's article (1967) indicated that *S. spinki* was collected on a planthopper *Togasodes orizicolus* (Muir) (Hemiptera: Fulgoroidea: Delphacidae)

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(formerly *Sogata orizicola* Muir) in Baton Rouge, Louisiana, United States. However, a recent review of Dr. Spink's notes revealed that the female and male *S. spinki* specimens were actually collected on the eggs of the delphacid insect, not adults. This discovery complicates our understanding of this mite–insect association. No further details are offered in Smiley's article as to where the delphacid insects were collected, or the association of the collected *S. spinki* and insect specimens with rice plants, much less with any association with damage on a plant. *S. spinki* was not reported as a rice pest in Louisiana in Smiley's article and was only referred to as a new species discovery. No other reference to *S. spinki* was reported in Louisiana until August 2007 when large *S. spinki* populations where observed associated with rice plant damage in isolated locations in southwest Louisiana, following an earlier discovery of *S. spinki* in southeast Texas in July 2007 (Hummel et al., 2007; Texas Department of Agriculture, 2007).

2. Louisiana Rice Survey — 2005

Prior to the confirmed re-discovery of *S. spinki* in 2007, an intense field survey in commercial rice fields at six phenological stages of plant growth was conducted in 15 parishes across southwest, central, and northeast Louisiana in 2005 (Castro et al., 2006). Rice fields were monitored every two weeks starting from four weeks after planting until harvest and included fields at the green ring, early boot, late boot, milk, soft dough and hard-dough stages. Samples were taken from ten random sites per field including field margins. If fields showed signs of grain discoloration and panicle/sheath blight symptoms, those plants were included in the sample. At each sampling site, ten sweep net passes were conducted to collect fulgoroid leafhoppers present. Insects collected were placed in 70% ethyl alcohol and labeled per site. Plant material was bagged in sealed plastic bags and labeled separately per site per field, and then transported in ice chests to the laboratory. Different clean sweep nets were used at each inspected rice field. Plants and insects were inspected in the laboratory on the day of collection under 400× magnification using a compound microscope. All plant tissue was observed under magnification including the inside and outside surface of each leaf sheath, plant stems and leaf blades as well as the outer surface of developing panicles and florets. In addition, when panicles were present, developing grains were cut in half with scissors and the pieces were placed and shaken in 10 ml of 70% ethyl alcohol inside one-qt zip-lock bags. The rinsate was then poured into 10 ml Petri dishes and observed under 400× magnification. The rinsate procedure was repeated three times per each of the ten samples per field. The legs of cicadellid and delphacid insects collected during the sampling were also examined under 400× magnification including the alcohol in which they were transported. *S. spinki* was not detected during this survey in Louisiana (Castro et al., 2006). Castro et al. (2006) concluded that *S. spinki* was either absent from inspected fields or, if present, the populations were below detectable levels. Thus, large populations of *S. spinki* were not detected or collected in Louisiana between the time of the initial collection by Dr. Spink and the survey by Castro et al. (2006). During our redescription of the species, the specimens mentioned above, the type specimens designated by Smiley and other specimens deposited in collections in North America were examined, compared and measured.

3. Systematics

Species: *S. spinki* Smiley (1967: 129), Yang et al. (1983: 131), Smiley et al. (1993: 91); Cosmopolitan (Acari: Tarsonemidae) (Fig. 1A and B).

4. Morphology and description of adults

4.1. *Steneotarsonemus* Beer

Female mites in the genus *Steneotarsonemus* are characterized by having stigmata close to setae v1; an elongate-slender body with reduced sejugal and poststernal apodemes; males often with round to membranous lobes on femorogenu IV; both genders with small pharynx and broadly subquadrate to broadly ovoid gnathosoma (Fig. 3A and B) (Beer, 1954; Lindquist, 1986). All measurements are given in micrometers (μm).

Key to *Steneotarsonemus* species collected on *Oryza sativa* in the United States.

1. Adult female and male: gnathosoma subquadrate; female: atrium of main tracheal trunk large, each side divided into two elongate portions; male: seta $v'F$ on femorogenu leg IV setose 2
   - Adult female and male: gnathosoma subcircular; female (Fig. 2A): atrium of main tracheal trunk conspicuously encapsulated, strongly ovoid; male (Fig. 2B): seta $v'F$ on femorogenu leg IV modified, bifurcate – *Steneotarsonemus furcatus*
2. Female (Fig. 2C and 3A): apodeme II strong, seam-ripperlike; hysterosomal setae *c*1 and *d* barbed; male (Figs. 2D and 3B): ventral hysterosoma with fine punctuations; leg IV with setae $v'G$ (femorogenu) and $v'Ti$ (tibia) slender, as long as femorogenu; femorogenual flange large, elongated, smooth – *S. spinki*
   - Female (Fig. 2E): apodeme II slender, slightly curved distally, hysterosomal setae *c*1 and *d* smooth; male (Fig. 2F): ventral hysterosoma with reticulations, leg IV with setae $v'G$ and $v'Ti$ small; flange rounded with conspicuous fine linear striations – *Steneotarsonemus konoi*

4.2. *S. spinki* Smiley (1967)

4.2.1. Diagnosis

Adult females of *S. spinki* (Fig. 2C) resemble those of *S. konoi* Smiley & Emmanouel (Fig. 2E) and *Steneotarsonemus madecassus* Gutierrez in having gnathosoma subquadrate, strong small pharynx, large conspicuous banana-like atria, spiculate bothridial setae and elongate body. Adult males of *S. spinki* (Fig. 2D) resemble those of *S. konoi* (Fig. 2F) and *S. madecassus* in having round elongate flanges on leg IV (Guitierrez, 1967; Smiley and Emmanouel, 1980). The female of *S. spinki* (Fig. 2C) is distinguished by having hysterosomal setae *c1* and *d* barbed, and by the presence of strong, wide, seam-ripperlike apodeme 2 ventrally. The male of *S. spinki* (Fig. 2D) is distinguished from *S. madecassus* male by having sc_1 longer than sc_2, apodemes 3 and 4 united distally and from *S. konoi* (Fig. 2F) male by no ventral ornamentation, leg IV with a strong, long smooth flange, and ventral trochanter setae longer than $v'G$.

4.2.2. Female (Figs. 2C and 3A)

Idiosoma elongate, ornamented, tegument finely punctate, length 222–350 μm and width 84–108 μm (range of paratype and 40 specimens). Gnathosoma subquadrate, as long (24–30 μm) as wide (25–32 μm). Dorsal gnathosomal setae (11–15 μm) finely pilose, longer than ventral setae (8–10 μm). Palpcoxal setae absent. Palpi small, directed anteriorly, each with two short setae and three wide, rounded, conspicuous processes distally. Cheliceral stylets short, strongly curved, with basal levers conspicuous. Pharynx short, with muscular, thinly sclerotized walls, and with freely exposed paired gland-like structures posteriorly.

Prodorsal shield truncated anteriorly, not projected beyond basal part of gnathosoma. Stigmata on margins of prodorsal shield,

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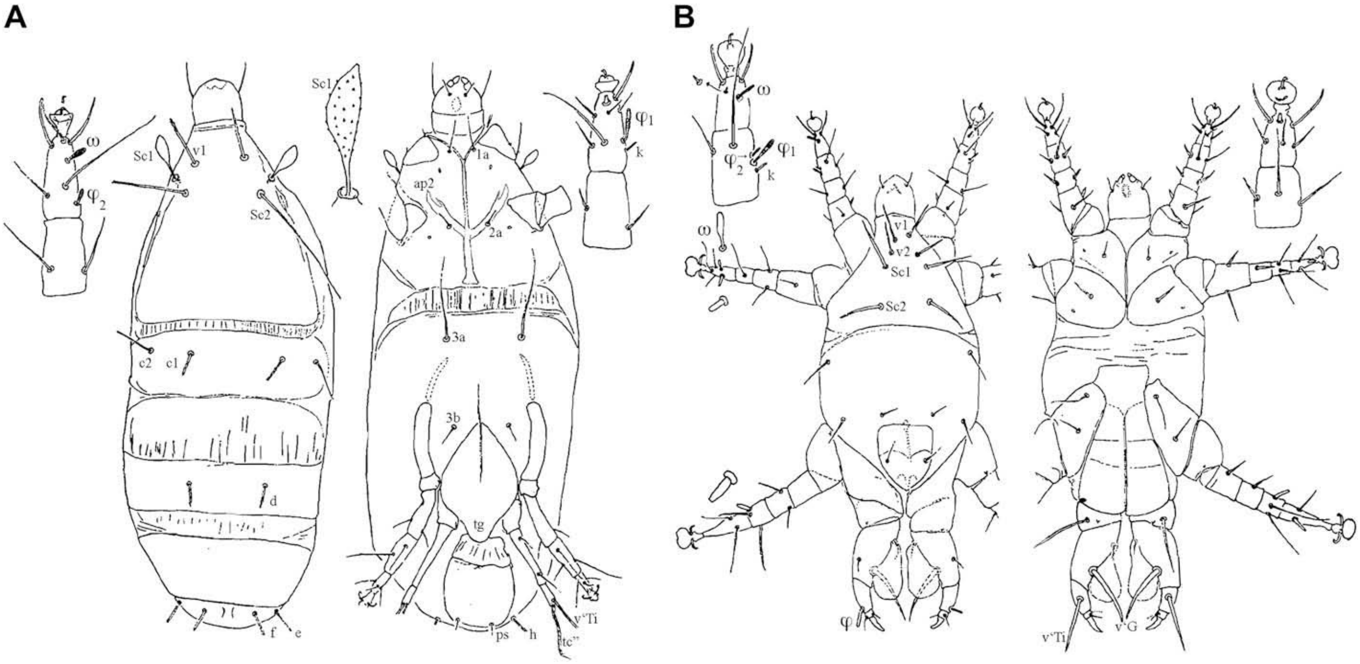

Fig. 1. (A) *Steneotarsonemus spinki* female and (B) male. Line drawing, modified from Smiley (1967) by Ochoa & Kane.

situated posterolateral of setae v_1; main tracheal trunks with large sclerotized atria, each side divided into two banana-like elongate halves (length 10–20 μm, width 3–6 μm). Setae v_1 (16–20 μm) stout, finely pilose; setae sc_2 (48–58 μm) long, filiform. Base of sc_2 posterolateral of sc_1. Bothridial setae sc_1 (18–21 μm) leaflike, finely pilose with rounded bases (Fig. 3B and D), not covered by prodorsal shield. Setae c_1 (9–12 μm) barbed, shorter than setae c_2 (17–24 μm), filiform. Base of c_2 and c_1 transversely aligned. Setae *d* (9–10 μm), setiform, stout, barbed. Cupules "ia" anterolateral of setae *d*. Setae *e* (8–10 μm) as long as setae *f* (8–10 μm), setiform, stout, barbed. Cupules "im" located anterolateral of setae *e*. Tergite EF with setae *e* and *f* transversely aligned. Setae *h* (10–12 μm) elongate, stout, barbed. Cupules *ih* anteromedial of setae *h*.

4.2.2.1. Venter. Apodemes I short, united with prosternal apodeme; apodemes II conspicuous and curved, seam-ripperlike, united with prosternal apodeme (Fig. 2C). Prosternal apodeme with a strong triangular ending, sejugal apodeme inconspicuous. Apodemes III shorter than apodemes II, conspicuous, not uniting with poststernal apodeme and not extending posteriad trochanters III. Apodemes IV bladelike distally, not uniting with poststernal apodeme, but extending posteromediad of setae 3b. Poststernal apodeme not present or inconspicuous. Setae 1a (15–17 μm) two times longer than 2a (7–9 μm), 3a (39–44 μm) long, filiform, 6× longer than 3b (6–8 μm). Tegula moderately wider (13–15 μm) than long (9–11 μm), rounded apically. Pseudanal setae present (6–7 μm).

4.2.2.2. Legs. Legs I (47–74 μm) and II (44–77 μm) subequal in length; leg III (99–116 μm) longer than legs I, II and IV (50–63 μm). Number of setae and solenidia on femur, genu, tibia and tarsus, respectively: leg I: 4-4-6 (2φ) + 8 (1ω); leg II: 3-3-4-6 (1ω); leg III: 1 + 3-4-5. Solenidion (ω) of tibiotarsus I (4–6 μm) about same length as solenidion (ω) of tarsus II (4–6 μm), both clavate, rounded distally. Tarsus I with subunguinal seta spinelike and bifid distally. Tibia I with sensory cluster complete, solenidion φ_1 capitate (6–8 μm), φ_2 clavate (4–6 μm), and seta k cylindrical, pointed distally (2–4 μm). Leg IV short and cylindrical 49 (49–60 μm); terminal seta (tc″ 86–126 μm), filiform, three times longer than subterminal seta (v′Ti 26–34 μm); subterminal setae stout, finely pilose; femorogenu with genual seta v′ (16–20 μm) about same length as seta v′ (14–16 μm).

4.2.3. Male (Figs. 2D and 3B)

Idiosoma smooth, tegument finely punctate, length 217 (217–244) μm, width 121 (109–122) μm (holotype, and range of 11 specimens). Gnathosoma subquadrate (Figs. 2D and 3B), as long 30 (24–30) μm as wide 32 (25–32) μm. Dorsal gnathosomal setae pilose basally, ventral gnathosomal setae smooth, palpcoxal setae absent. Palpi stout, short, directed anteriorly, each with two small setae and three processes distally (Fig. 4A). Cheliceral stylets moderately short, straight, attached to basal levers. Pharynx teardrop, small as female, with muscular, thinly sclerotized walls, and with freely exposed paired gland-like structures posteriorly.

Dorsal shielding unornamented (Fig. 3B). Prodorsal shield weakly sclerotized, subtriangular. Vertical setae v_1 26 (24–35) μm stout, slightly pilose, longer than v_2 20 (17–31) μm. Scapular setae stout, slightly pilose, sc_1 40 (33–49) μm about same length as sc_2 30 (30–45) μm. Base of sc_2 longitudinally aligned with sc_1. Metapodosomal plate CD with setae c_2 33 (33–53) μm, filiform, ten times longer than c_1 18 (13–19) μm. Setae c_1 and *d* 10 (10–13) μm stout, pilose. Base of c_2 anterolateral to c_1. Cupules "*ia*" inconspicuous. Subterminal plate EF with setae *f* 15 (12–17) μm, stout, pilose. Genital capsule subcircular in dorsal view, as long as wide, with caudal setae *h* setiform; accessory copulatory structures ps_1 spinelike, pointed apically.

4.2.3.1. Venter. Apodeme I short, united with prosternal apodeme; prosternal apodeme interrupted closely to apodeme II; apodeme II conspicuous and slightly curved, weakly uniting with prosternal apodeme (Fig. 2D). Prosternal apodeme weakly uniting with sejugal apodeme. Sejugal apodeme inconspicuous. Apodeme III united anteriorly with apodeme IV, which in turn are indistinctly united anteriorly with each other. Poststernal apodeme fragmented, not united with apodemes III and IV. Coxal setae *1a* 7 (7–11) μm filiform; coxal setae *2a* 12 (12–25) μm setiform. Coxal alveoli *1b* and *2b* located lateral of setae *1a* and *2a*, respectively. Coxal setae *3b* 30 (30–49) μm filiform longer than *3a* 13 (13–25) μm, setiform.

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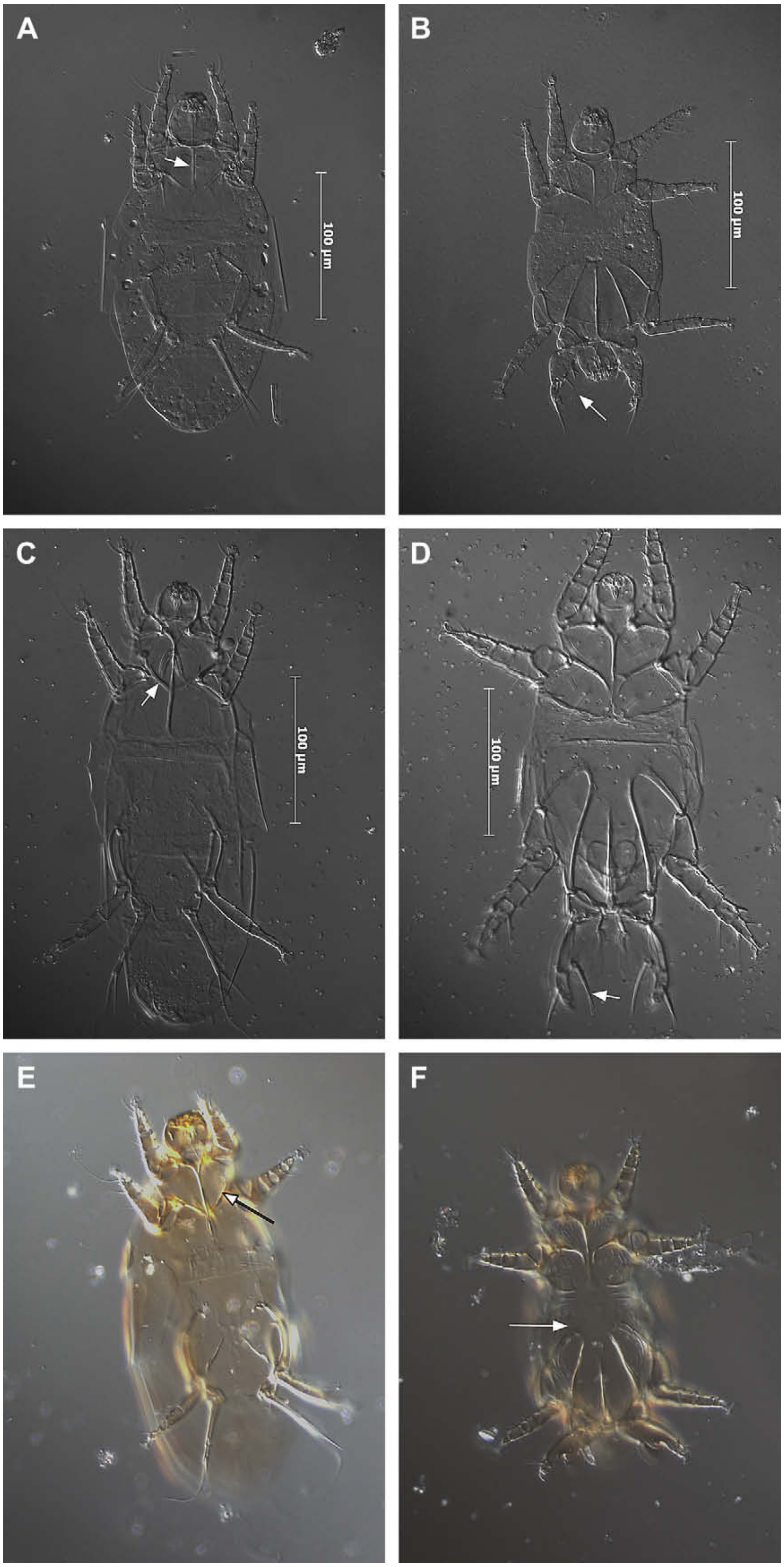

Fig. 2. *Steneotarsonemus furcatus* female (A) atrium of main tracheal trunk conspicuously encapsulated, strongly ovoid and, male (B) seta v′F on femorogenu leg IV modified, bifurcate. Scale bar = 100 µm. *Steneotarsonemus spinki* female (C) apodeme II strong, seam-ripperlike, and male (D) leg IV with setae v′G (femorogenu) and v′Ti (tibia) slender, long, as long as femorogenu. Scale bar = 100 µm. *Steneotarsonemus konoi* female (E) apodeme 2 slender, slightly curved distally and male (F) ventral hysterosoma with reticulations, flange rounded with conspicuous fine linear striations.

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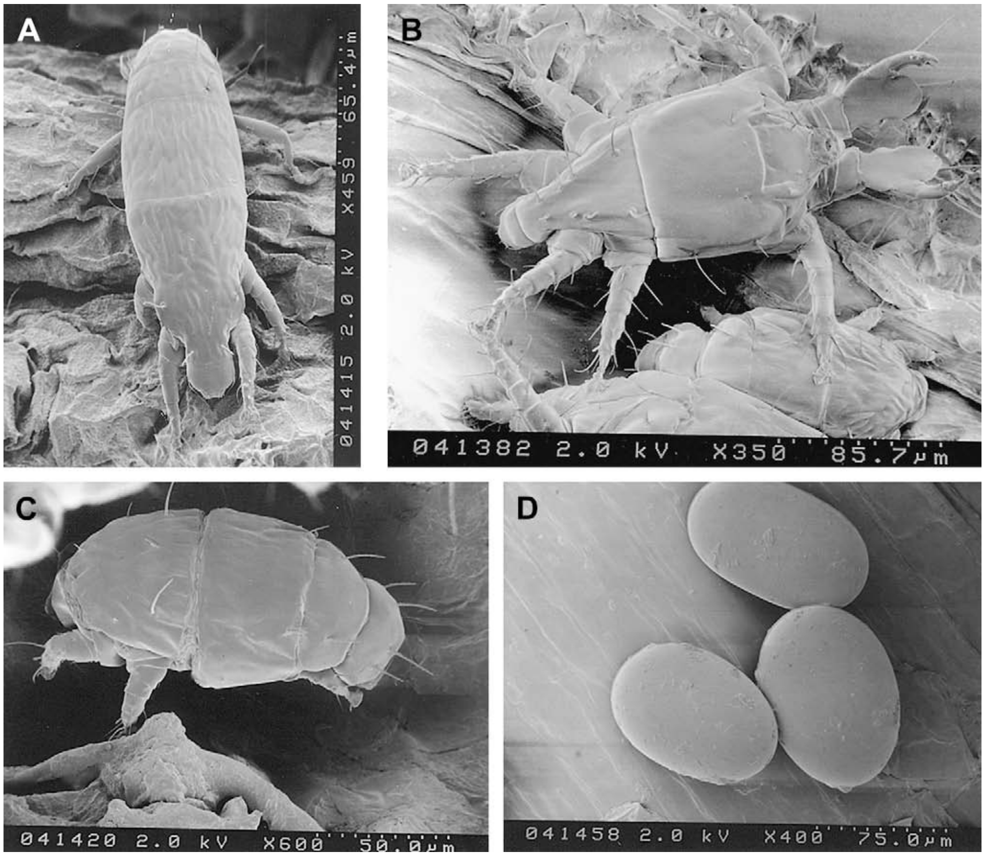

Fig. 3. LT SEM of *Steneotarsonemus spinki* (A) female, (B) male, (C) larva, (D) eggs. Pictures by E. Erbe, USDA-ARS-EMU.

4.2.3.2. Legs. Legs I 96 (89–105) µm and II 107 (89–109) µm subequal in length; leg III 122 (119–143) µm longer than legs I, II and IV 87 (85–112) µm. Number of setae and solenidia on femur, genu, tibia and tarsus, respectively: leg I: 4-4-6 (2φ)-10 (1ω); leg II: 3-3-4-6 (1ω); leg III: 1-3-4-4; leg IV: 1+2-1 (1φ)+3. Solenidion (ω) of tarsus I narrowly capitate 7 (5–7.5) µm. Solenidion (ω) of tibia II 6 (6–7.5) µm narrowly capitate, about same length of solenidion (ω) of tarsus I. Tibia I sensory cluster complete, solenidion φ_1 narrowly capitate 8 (7–8) µm and φ_2 clavate 5 (4–6) µm, seta *k* 4 (3–4) µm bluntly pointed. Leg IV (Figs. 2D and 3B) with trochanter setae elongate 40 (40–69) µm, filiform, similar in length to *v′G* 45 (40–63) µm, stout, daggerlike, slightly pilose. Setae *v′Ti* 41 (30–57) µm stout, daggerlike. Solenidion (φ) of tibia IV 8 (7–9) µm rodlike.

4.2.4. *Material examined*

Holotype and paratypes of *S. spinki*, National Insect and Mite Collection, NMNH, Smithsonian located at the USDA-ARS-SEL, Beltsville, Maryland 20507. Female and male specimens collected from rice from China, Colombia, Costa Rica, Cuba, Dominican Republic, India, Kenya, Philippines, Puerto Rico, Taiwan, and the United States (Arkansas, Louisiana, New York, Ohio, Texas) and deposited at National Insect and Mite Collection, NMNH, Smithsonian located at the USDA-ARS-SEL, Beltsville, Maryland 20507.

4.2.5. *Remarks*

S. konoi is associated with Bermuda grass (*Cynodon dactylon* L.), and its presence on rice is considered accidental, no reproductive populations have been observed or collected on rice. *S. furcatus* had been reported causing direct damage to rice in Brazil (Navia et al., 2006). It also was reported in association with *S. spinki* affecting rice in Colombia, Costa Rica, Cuba, and India (Sanabria and Aguilar, 2005; Navia et al., 2006; Karmakar, 2007). The low numbers of *S. furcatus* collected during the rice survey conducted by USDA-APHIS-PPQ in the United States in 2007 could be an indication of low populations or associations with another host plant in close proximity to the rice fields (E. McDonald, Pers. Obs.). Additional details on the morphology and biology of *S. spinki* can also be found in Lo and Ho (1980) and Zhang (1984).

5. Geographical distribution

S. spinki is distributed in all the major rice producing countries of the world (Table 1). Rao and Prakash (2003) indicate that the probable first mention in the literature of *S. spinki* is in reference to a "tiny moving arthropod" that was attacking rice plants in India (Ramaiah, 1931). The first published reference to *S. spinki* as a pest of a rice crop was from southern China in 1968 (Ou et al., 1977). This was followed by reports in India in November 1975 (Rao and Das, 1977), Taiwan, Kenya and Philippines in 1977 (Lo and Hor, 1977; Rao and Das, 1977; Sogawa, 1977; Smiley et al., 1993), and in Japan infesting greenhouse-grown rice seedlings in 1984 (Shikata et al., 1984). In 1999, *S. spinki* was found in Korea, Thailand, and Sri Lanka (Cheng and Chiu, 1999; Cho et al., 1999; Cabrera et al., 2002b).

The first report of *S. spinki* as a pest of rice in the America was in Cuba in 1997 (Ramos and Rodríguez, 1998). *S. spinki* rapidly spread throughout the Caribbean and Central American region. It was reported in the Dominican Republic in 1999 (Ramos et al., 2001); and Panama (Almaguel and Botta, 2005), Haiti (Herrera, 2005) and Costa Rica (Sanabria and Aguilar, 2005) in 2004. *S. spinki* was intercepted and subsequentially eradicated from a greenhouse in

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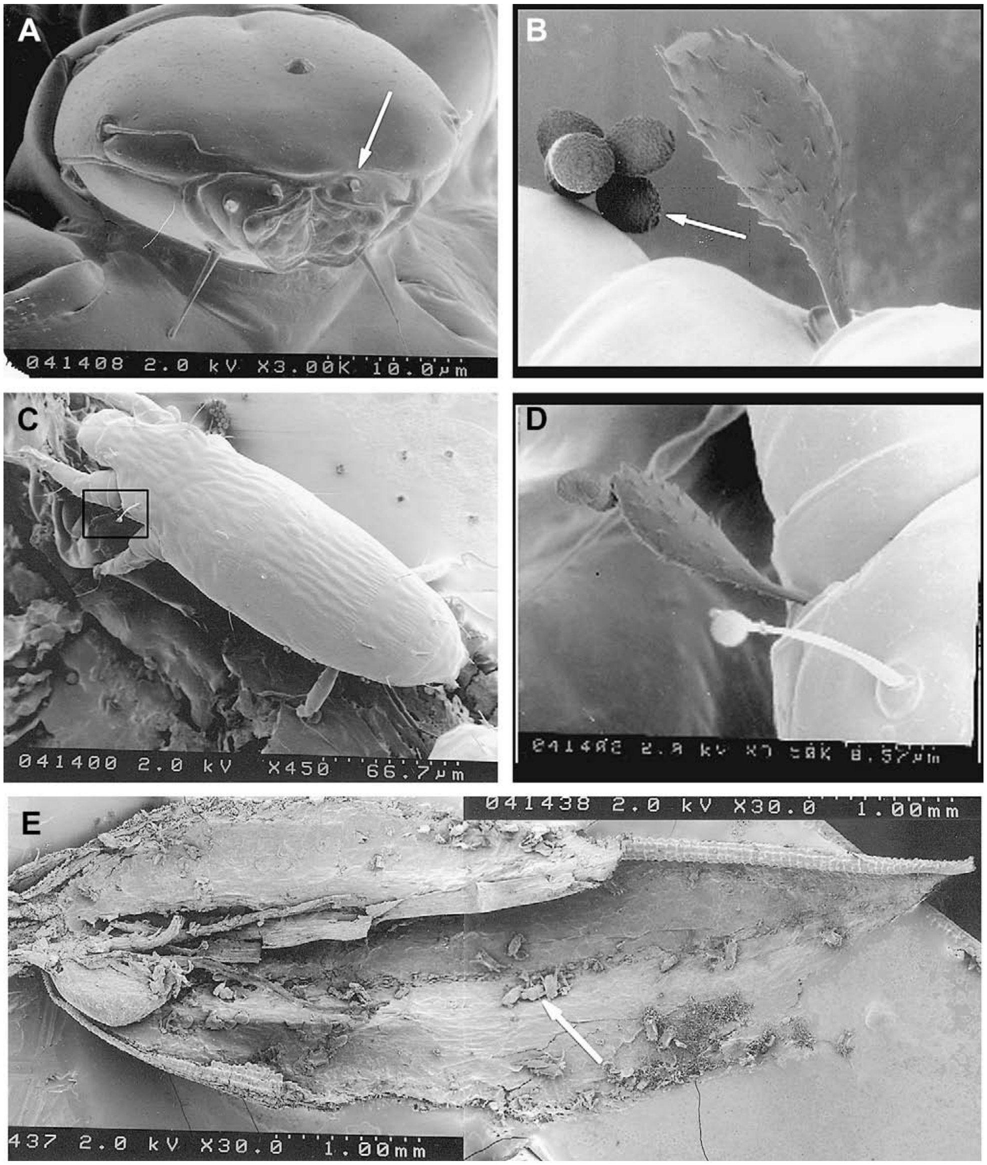

Fig. 4. (A) LT SEM of *Steneotarsonemus spinki* male palps (white arrow). (B) Spores attached to the body of a *S. spinki*. (C) Female *S. spinki* with spores (white box) attached to her body, (D) Close-up of black box. (E) *S. spinki* mites inside of empty hull of rice grain. Pictures by E. Erbe, USDA-ARS-EMU.

2004 in Ohio, United States (R. Ochoa, Pers. Comm.). In 2005, *S. spinki* was reported in Colombia (Instituto Colombiano Agropecuario, 2005), Guatemala, Honduras (Castro et al., 2006), Nicaragua, and Venezuela (Aguilar and Murillo, 2008). In 2006, *S. spinki* was reported from Palizada town, in Campeche, Mexico (Arriaga, 2007). During 2007, a re-examination of specimens mounted in 1993 from a rice greenhouse facility in Beaumont, Texas revealed that *S. spinki* had been collected but misidentified as *S. madecassus* (F. Beaulieu, Pers. Comm.). However, no further reports of *S. spinki* in the USA had been issued until July 2007 (Texas Department of Agriculture, 2007). This report indicates that *S. spinki* was positively identified from greenhouse and research plots at a rice breeding facility in Alvin, Texas (Brazoria County). This became the first report indicating the presence of *S. spinki* in research rice fields in the United States (Texas Department of Agriculture, 2007). This was quickly followed by interceptions during the 2007 rice season in more greenhouses and research fields in Beaumont (Jefferson County), Texas; Crowley (Acadia Parish) and one commercial field in Kaplan (Vermillion Parish), Louisiana; and research greenhouses at Stuttgart (Arkansas County), Arkansas; Ithaca (Tompkins County), New York (Hummel et al., 2007; NAPPO, 2007) and, most recently, in Davis, California in 2009 (UCDavis, 2009).

6. Host range

The host range of *S. spinki* is currently being investigated. It appears that the preferred host of *S. spinki* is rice, *O. sativa* L. (Ho and Lo, 1979; Jiang et al., 1994). Ho and Lo (1979) surveyed over 70 species of plants including weed species growing in or near rice paddies in Taiwan for the presence of *S. spinki*. These included 44 species of Poaceae with one species in the Oryzae tribe. *S. spinki* was found on rice, but not on any other examined plants. Jiang et al. (1994) conducted a similar study examining samples from nine plant families and also concluded that the preferred host for *S. spinki* was rice. However, Sanabria and Aguilar (2005) reported American wild rice, *Oryza latifolia* Desv., as an alternate host for *S. spinki* in Costa Rica and Panama. In addition, *C. dactylon* (L.) Pers.

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Table 1
Countries reported infested with *Steneotarsonemus spinki* as of March, 2009.

Country infested	Year	Reference
Louisiana (USA)	1960	Smiley (1967)
China	1968	Ou et al. (1977)
India	1975	Rao and Das (1977)
Taiwan	1977	Lo and Hor (1977)
Kenya	1977	Rao and Das (1977)
Philippines	1977	Sogawa (1977)
Japan	1984	Shikata et al. (1984)
Korea	1999	Cho et al. (1999)
Thailand	1999	Cheng and Chiu (1999)
Sri Lanka	1999	Cabrera et al. (2002b)
Cuba	1997	Ramos and Rodríguez (1998)
Dominican Republic	1998	Pellerano, Pers. Commun.
Panama	2004	Almaguel and Botta (2005)
Haiti	2004	Herrera (2005)
Costa Rica	2004	Sanabria and Aguilar (2005)
Ohio (USA)	2004	Interception in greenhouses (R. Ochoa, Pers. Comm.)
Colombia	2005	ICA (2005)
Nicaragua	2005	Aguilar and Murillo (2008)
Venezuela	2005	Aguilar and Murillo (2008)
Guatemala	2006	Castro et al. (2006)
Honduras	2006	Castro et al. (2006)
Mexico	2006	Arriaga (2007)
Texas (USA)	2007[a]	Texas Department of Agriculture (2007)
Puerto Rico	2007	Texas Department of Agriculture (2007)
Crowley, Louisiana (USA)	2007	Hummel et al. (2007)
Stuttgart, Arkansas (USA)	2007	NAPPO (2007)
Ithaca, New York (USA)	2007	NAPPO (2007)
Davis, California (USA)	2009	UCDavis (2009)

[a] 1993 first occurrence, unpublished record.

(Poaceae) (Rao and Prakash, 1996), *Cyperus iria* L. (Cyperaceae) (Central Rice Research Institute, 2006), and *Schoenoplectus articulatus* (L.) Palla (Cyperaceae) have been reported as alternate hosts for *S. spinki* in India (Rao and Prakash, 2002). Table 2 provides a list of plant species from which egg, larva or adult *S. spinki* has been reported in various countries. It is important to note that it has not been confirmed experimentally that these are 'true' hosts in the sense that they can support a reproducing population of *S. spinki*, and they may be accidental hosts. Research is needed to determine the range of hosts on which *S. spinki* can survive and or reproduce in order to develop an effective management plan in cultivated rice.

7. Biology of feeding – damage to plant

S. spinki feed by perforating the epidermal cells of the host plant using stylets (5 μm in length) (Fig. 4A). In a rice host, this feeding damage results in brown necrotic regions on the upper surface of leaf sheath and on the hull of grain (Chow et al., 1980) (Fig. 5A–D). The damage is similar in appearance to that caused by the pathogen *Sarocladium oryzae* (Sawada, 1922). *S. spinki* infestation of rice has been associated with black lesions in the leaf sheath, discolored grains, partial to complete chaffy grains, and various malformations in grains (Chein, 1980; Reissig et al., 1986; Rao and Prakash, 1992; Rao et al., 1993).

8. Impact on yield

S. spinki has been reported to cause significant crop loss in Taiwan (Cheng and Chiu, 1999), China (Jiang et al., 1994), India (Ou et al., 1977), Cuba (Ramos and Rodríguez, 2000), Dominican Republic (Ramos et al., 2001), Panama (García, 2005), and Costa Rica (Barquero, 2004). In the Tainan (southern) region of Taiwan, 60% crop damage was reported in 1974 (Cheng and Chiu, 1999). Researchers concluded that variety Tainan #5 was extremely susceptible to *S. spinki* damage and in response to extensive crop losses, the acreage of Tainan #5 was reduced from 400,000 ha in 1975 to 80,000 ha in 1981 (Cheng and Chiu, 1999). Another report from the 1976 outbreak in southern Taiwan reported that approximately 20–60% of harvested grains were empty, a loss equivalent to 20,000 metric tons and valued at $9.2 million US (Chen et al., 1979). The damage was especially pronounced in the second crop of rice. In the Guandong Province of southern China, a 5–20% yield reduction in both early and late season rice crops was attributed to *S. spinki* (Jiang et al., 1994), while Japonica varieties in India were reported to be more susceptible to *S. spinki* than Indica varieties with a 20% yield loss (Ou et al., 1977). A detailed survey in India revealed that *S. spinki* accounted for 80% of the total mite population in rice crops and that sterility may be correlated with the size of the *S. spinki* population present in the crop (Rao and Prakash, 2003). For example, in the Orissa Province, sterility of 4–90% was associated with 7–600 *S. spinki* per tiller, in the Ghandari District of Andhra Pradesh Province 15–50% sterility was associated with *S. spinki* densities of 150–900 mites per tiller, and in Jharkhand Province 19–28% sterility was associated with a density of only 3–7 *S. spinki* per tiller (Rao and Prakash, 2003). This survey was

Table 2
Plant species from which eggs, larvae and/or adult *Steneotarsonemus spinki* have been reported.

Plant family	Plant species[a]	Adult	Larvae	Eggs	Author	Country
Caryophyllaceae	*Stellaria* spp.	*			Jiang et al. (1994)	China
Cyperaceae	*Cyperus iria*	*	*		CRRI (2006)	India
Cyperaceae	*Schoenoplectus articulatus*	*	*		Rao and Prakash (2002)	India
Poaceae	*Alopecurus aequalis*	*			Jiang et al. (1994)	China
Poaceae	Bamboo	*	*	*	Jiang et al. (1994)	China
Poaceae	*Zizania caduciflora*	*	*	*	Jiang et al. (1994)	China
Poaceae	*Coix lacryma-jobi*	*			Jiang et al. (1994)	China
Poaceae	*Cynodon dactylon*	*	*	*	Rao and Prakash (1996)	India
Poaceae	*Digitaria sanguinalis* L.	*+	*	*	Jiang et al. (1994); M. Pellarano (Pers. Obs.)	China, Dominican Republic
Poaceae	*Echinochloa colona* L.	*			M. Pellarano (Pers. Obs.)	Dominican Republic
Poaceae	*Echinochloa crusgalli*	*			Jiang et al. (1994)	China
Poaceae	*Eleusine indica*	*+	*	*	Ou and Fang (1978), Jiang et al. (1994), M. Pellarano (Pers. Obs.)	Taipei, China, Dominican Republic
Poaceae	*Ischaemum rugosum* L.	*			M. Pellarano (Pers. Obs.)	Dominican Republic
Poaceae	*Leptochloa filiformis* L.	*			M. Pellarano (Pers. Obs.)	Dominican Republic
Poaceae	*Oryza latifolia*	*	*	*	Navia et al. (2005)	Costa Rica
Poaceae	*Panicum repens*	*	*	*	Jiang et al. (1994)	China
Poaceae	*Phragmites australis*	*	*	*	Jiang et al. (1994)	China
Polygonaceae	*Polygonum hydropipar*	*			Jiang et al. (1994)	China

[*] Indicates that one of the above life stages has been collected from the species listed: adult, larvae and/or eggs.

[a] Many of the plants listed in this Table need to be further examined as possible hosts of *S. spinki*. Voucher specimens need to be collected and compared.

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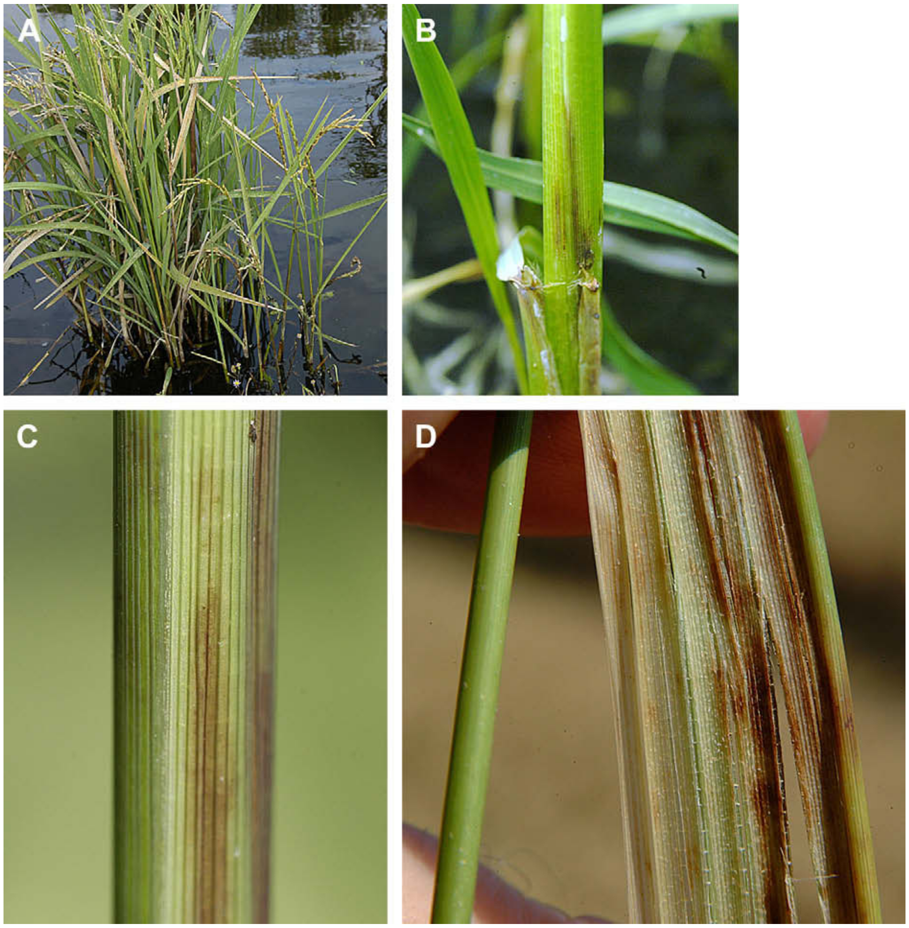

Fig. 5. *Steneotarsonemus spinki* damage to rice plants. (A) Entire plant with discolored hulls and stems. (B), (C) Feeding lesions on leaf sheaths. (D) Discoloration on the inside of the leaf sheath.

conducted in both rain-fed upland and irrigated rice ecosystems, and hence moisture stress due to drought could have contributed to the high levels of damage observed at such low *S. spinki* densities. Karmakar (2007) conducted a study in West Bengal during the rainy season in which the relationship between *S. spinki* density and resulting crop damage was examined. Karmakar (2007) found a significant negative correlation between *S. spinki* density and grain yield and a significant positive correlation between *S. spinki* density and percent chaffy grains. These studies indicate that there is a relationship between *S. spinki* density and resulting crop yield loss in India.

S. spinki was first reported in America in Cuba in 1997 where crop losses ranged from 30 to 70% in the first year of infestation (Ramos and Rodríguez, 1998, 2000). In Cuba, the *S. spinki*/fungus complex is now considered to be the greatest economic threat to rice production (Perez, 2002). Following the introduction of *S. spinki* into the Dominican Republic in 1998, more than 40% of grains were reported empty or stained in some rice producing regions (Díaz et al., 1999; Ramos et al., 2001). In Haiti, 60% yield losses were attributed to *S. spinki* (Almaguel and Botta, 2005), and similarly 40–60% yield losses were reported in Panama (García, 2005). During the first year of *S. spinki* infestation (2004) in Costa Rica, yield losses of up to 45% were observed, which translated to $10.96 million USA in loss (Barquero, 2004). There is a great concern that *S. spinki* will soon enter Brazil, where rice is a main food source for the country's population (Mendonça et al., 2004). The average harvest of rice in Brazil is c. 12.7 million tons/year, and losses are predicted to be similar to those reported in the Caribbean region, i.e. 30–70% or 3.8–8.9 million tons/year, which would seriously impair the country's rice industry (Navia et al., 2005).

9. *S. spinki* damage to plants and association with plant diseases

Although millions of dollars of crop loss have been attributed to *S. spinki* infestations around the world, it is possible that this damage is primarily caused by pathogens that are found in association with *S. spinki*. Plant pathogens that have been found in conjunction with *S. spinki* include bacterial, fungal, spiroplasm, and virus-like particles (Hsieh et al., 1977; Chow et al., 1980; Shikata et al., 1984; Rao et al., 1993; Almaguel et al., 2003; Rao and Prakash, 2003; Sanabria and Aguilar, 2005) (Table 3). Symptoms associated with *S. spinki* infestation of rice plants include the "Sterile Grain Syndrome" described by Chen et al. (1979) as "loose and brownish flag leaf sheath, a twisted panicle neck, impaired grain development resulting in empty or partially filled grains with diseased brown spots and the panicles standing erect". In India, grains infested with *S. spinki* were described as being discolored, and pathogenic fungi and bacteria were isolated from *S. spinki* infested plants (Rao and Prakash, 2003). These fungi and bacteria included *Alternaria padwickii* (Ganguly), *Burkholderia (Pseudomonas) glumae* (Kurita & Tabei), *Curvularia lunata* [*Cochliobolus lunatus* R.R. Nelson & Haasis], *Fusarium graminearum* [*Gibberella zeae* (Schwein)], and *Fusarium moniliforme* J. Sheld (Rao and Prakash, 2003). Rao and

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Table 3
Rice plant diseases that have been associated with *Steneotarsonemus spinki* infestations around the world.

Pathogens	Disease	Country	Reference
Alternaria padwickii (Ganguly)	Stackburn disease	India	Rao and Prakash (2003)
Burkholderia (Pseudomonas) glumae (Kurita & Tabei)	Bacterial Panicle Blight	India	Rao and Prakash (2003)
Curvularia lunata [*Cochliobolus lunatus* R.R. Nelson & Haasis]	General fungus – black kernel, pecky rice	India	Rao and Prakash (2003)
Fusarium graminearum [*Gibberella zeae (Schwein)*]	Pecky rice, kernel spotting	India	Rao and Prakash (2003)
Fusarium moniliforme J. Sheld.	Pecky rice, kernel spotting	India	Rao and Prakash (2003)
Pseudomonas fuscovaginae	Sheath brown rot	India, Costa Rica	
Pyricularia oryzae Cavara	Blast	Cuba	Almaguel et al. (2003)
Rhizoctonia (spp.)	Sheath blight	Cuba	Almaguel et al. (2003)
Rhynchosporium	Leaf scald	Cuba	Almaguel et al. (2003)
Sarocladium (Acrocyilindrium) oryzae	Sheath rot, also causes pecky rice	China, Cuba, India, Costa Rica, Caribbean region	Rao et al., 1993, Hsieh et al. (1977), Sanabria (2005)
Spiroplasma citri	Rice yellow dwarf	Taiwan	Chow et al. (1980)
Small virus-like particles	Rice dwarf	Japan	Shikata et al. (1984)

Prakash (2003) also found *S. spinki* on plants from which no pathogens were isolated, they concluded that the grain discoloration could be caused by a chemical reaction to toxic saliva of *S. spinki*. Chen et al. (1979) found that *S. spinki* carried spores of *Acrocylindrium oryzae* Sawada (now *S. oryzae*) on their body and attributed the plant symptoms to a combination of *S. spinki* damage and disease. In Cuba, *S. oryzae* was isolated from 70% of *S. spinki* transferred to Sabouraud Glucose Agar, further supporting the hypothesis that *S. spinki* is an important vector of this phytoparasitic fungus. Tarsonemid mites have been reported to carry spores of pathogenic fungi in sporotheca on their body (Moser, 1985; Blackwell et al., 1986; Blackwell et al., 1989; Bridges and Moser, 1983; Levieux et al., 1989; Ochoa et al., 1991, 1994; Moser et al., 1995). In addition to typical mite damage symptoms, rice plants that were infested with *S. spinki* in Louisiana also showed symptoms of bacterial panicle blight damage which included empty hulls and panicles standing erect (Fig. 5A). Discolored regions on the flag leaf sheaths of rice plants (Fig. 5B and C) were associated with *S. spinki* feeding inside the leaf sheath (Fig. 5D). *S. spinki* was collected and found to have spores attached to their body (Fig. 4B–D). The type of spore is unknown at this time.

Fields that were infested with *S. spinki* in Honduras were found to contain grains that had parrot-beaking symptoms (Castro et al., 2006). In Dominican Republic (M. Pellerano, Pers. Obs.), field-collected discolored rice grains, stems and closed panicles were examined for the presence of *S. spinki* and plant pathogenic fungi. *S. spinki* was present in all the discolored rice grains and was found in association with *Fusarium* spp., *Helminthosporium* spp., and *Sclerophthora* spp. *Fusarium* spp. and *Rhizoctonia* spp. were most commonly associated with *S. spinki* in rice stems. In closed panicles, *S. spinki* was most commonly associated with *Sarocladium* spp. and *Sclerophthora* spp. (M. Pellerano, Pers. Obs.). An unidentified virus was isolated from *S. spinki* on greenhouse-grown rice in Japan, and in rice tissues infested with *S. spinki* (Shikata et al., 1984). Shikata et al. (1984) isolated spherical, virus-like particles (~35 nm diameter) from rice plants that were infected with rice black-streaked dwarf, rice dwarf, rice grassy stunt, rice ragged stunt viruses, and also from "healthy" rice plants. These particles were also isolated from the body of *S. spinki* and eggs and in areas where *S. spinki* was present on the plant including rice leaf sheaths and the hulls of rice kernels, but were not isolated from leaves and roots of rice plants. Shikata et al. (1984) suggested that *S. spinki* may be injecting the virus-like particles into plant tissue during feeding. Further research is needed to determine if *S. spinki* is a viral vector. Fig. 5 shows rice plants infested with *S. spinki* in the United States. Damage symptoms included empty panicles, discolored hulls, orange discoloration of the leaf sheath (Fig. 5B and C). *S. spinki* is relatively easily found feeding inside the leaf sheath using a 30× hand microscope in the field (Fig. 5D).

S. spinki causes the most significant crop damage when feeding on developing panicles at the boot stage of development. This feeding can result in sterility and partial infertility of plants. The exact mechanism by which *S. spinki* feeding causes sterility is not yet understood. Recently, Nandakumar et al. (2007) described an association of the proteobacteria *B. glumae* (Kurita & Tabei) and *Burkholderia gladioli* (Severini) with panicle blight symptoms on rice in Panama. Producers initially attributed the rice crop symptoms to a severe infestation by *S. spinki*. Based on these observations and photographs from other fields worldwide, some scientists believe that the majority of damage attributed to *S. spinki* is actually caused by the bacteria (CIAT, 2005). According to Nandakumar et al. (2007), "similar symptoms reported in Cuba, Haiti, and the Dominican Republic were attributed to damage from the spinki mite [*S. spinki*] in association with *S. oryzae* (Sawada) W. Gams & D. Hawksw. (Bernal et al., 2002)". In Andhra Pradesh, India (Rao et al., 2000) 24 villages in two districts were examined following reports of spikelet sterility and grain discoloration in up to 50% of rice in the area. Researchers observed four visual symptoms on affected plants: 1) mite damage alone; 2) mite and saprophytic fungus; 3) mite and saprophytic fungus and sheath rot fungus; and 4) mite and white-tip nematode and other saprophytic fungal damage. Rao et al. (2000) concluded that *S. spinki* was the dominant problem. Another possible explanation for this common co-occurrence of *S. spinki* and disease is that feeding by *S. spinki* causes increased incidence of panicle blight and sheath rot infection because the seed and sheath have been damaged by *S. spinki* feeding making it easier for bacteria to enter the seed and cause sterility.

The fact that *S. spinki* has been associated with a large number of diseases of rice plants (Table 3) is of particular interest to Louisiana researchers because of the twelve plant diseases associated with *S. spinki*, eight already occur in Louisiana rice fields (Hummel et al., 2007). These diseases include bacterial panicle blight, blast, curvilaria, leaf scald, pecky rice (caused by *Fusarium* spp.), sheath blight, sheath rot, and stackburn disease. It is important to develop an understanding of the potential of *S. spinki*/disease complex which may occur in Louisiana and other rice producing regions of the United States.

9.1. Biology and ecology

9.1.1. Life history of S. spinki

S. spinki has fast and efficient reproduction with females (Fig. 3A) producing 50 (Lo and Ho, 1979; Xu et al., 2001) to 70 eggs (Fig. 3D) in their lifetimes (Castro et al., 2006). *S. spinki* is also

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arrhenotokous parthenogenetic, whereby virgin females produce male offspring (Fig. 3B). In a laboratory study by Xu et al. (2001), virgin females produced an average of 79.4 adult mites at 24.1–35.3 °C in 17 d. The male offspring mate with their mother who will then be capable of producing both female and male offspring (Xu et al., 2001). Zhang (1984) reported the sex ratio of female:male *S. spinki* to be 22:1, 32:1, and 8:1 at 32 °C, 28 °C, and under field temperature conditions, respectively. Mated females produced 55.5 eggs on average at 24.5–35.4 °C under laboratory conditions (Xu et al., 2001). M. Pellerano (Pers. Obs.) reports that females will lay their eggs in clusters. *S. spinki* has a short generation time ranging from 8.5–13.6 d at 25–30 °C in China (Xu et al., 2001) to 8–17 d at 25 °C in Cuba (Ramos and Rodríguez, 2000). Increasing the temperatures results in shorter generation times: 11.3 d at 20 °C, 7.8 d at 23.9 °C, and 4.9 d at 33.9 °C and *S. spinki* is able to produce 48–55 generations per year under ideal climatic conditions (Castro et al., 2006). Thus, a large population of *S. spinki* can develop very quickly in a rice crop during a single growing season.

9.1.2. Population dynamics

Tseng (1984) studied population dynamics of *S. spinki* in the southern regions of Tainan and Pingtung in Taiwan, and documented an outbreak of *S. spinki* that occurred during 1977–1978. In the first crop which was grown from January to May, the population of *S. spinki* peaked in the month of May with populations of 10–100 *S. spinki* per tiller. While in the second crop which was grown from mid-May to October, the *S. spinki* population peaked between August and October at 600–1100 *S. spinki* per tiller, after which the *S. spinki* population crashed. Tseng (1984) speculated that this population boom and crash may be related to the warm temperature and high humidity requirements of *S. spinki*.

In China, Lo and Hor (1977) reported that *S. spinki* was found on rice during flowering, milk, soft dough, medium dough and hard dough grain maturity stages, and that the density of *S. spinki* differed with the phenological stage of the plant. A three year study conducted by Jiang et al. (1994) sampled rice on a regular basis throughout the season and found that during the early stage of rice growth *S. spinki* was present on lower leaves, and the density of *S. spinki* gradually increased as the season progressed. Densities were greater in late-planted rice than in early season rice. Very little damage was observed for most varieties of rice in the seedling bed of late season rice, and damage was restricted to brown discoloration of the leaves of susceptible varieties located on the edges of the plots. By mid-June, when the rice was at the milk stage, damage was visible for some varieties even though the population density was very low [1.8 *S. spinki*/100 heads (panicles)] (Jiang et al., 1994). In late-planted rice, when rice began to mature and grains were maturing from medium to hard-dough stages, the population density increased to 30 *S. spinki*/100 heads, and when the rice was fully mature, the density dramatically decreased again. Adults and eggs of *S. spinki* were observed in numbers higher than in early season planted rice, but there was no *S. spinki* damage apparent prior to the tillering stage. The population density was highest at the boot and soft dough grain maturity stages (7775–13,000 *S. spinki*/100 heads). Following medium to hard dough grain maturity, the number of *S. spinki* started to decrease. After the rice was harvested, *S. spinki* moved to alternative sources of moisture and sustenance including rice stubble, regenerated rice, seedlings from fallen seeds, and other Poaceae hosts, where *S. spinki* could continue to grow and reproduce.

Ou and Fang (1978) also observed population dynamics in a commercial rice production field in the Guantian District. They reported that in the middle-tillering stage the ratio of male:immature:female:eggs was 1:2:6:12. The number of *S. spinki* was greatest on the outer one or two leaf sheaths, and less on the most interior leaf sheaths. In the early tillering stage, *S. spinki* density was low, but in mature rice, *S. spinki* density (1992.5 *S. spinki* per plant) and natural mortality were quite high. Many *S. spinki* were found inside and outside the grain, and furthermore, a large number of *S. spinki* were found in leaves and husks of rice on the second crop. In the ratoon crop, *S. spinki* was found on regenerating (re-grown) plant tissue (75 *S. spinki* per plant with few eggs). The proportion of mite:egg was 3:1, and the sex ratio male:female was 1:2. The number of *S. spinki* in the flag leaf and the second leaf from the top was much higher than that on other leaves of the plant. *S. spinki* was also observed in rice hulls in the United States (Fig. 4E) (E. McDonald & R. Ochoa, Pers. Obs.).

Studies of population dynamics of *S. spinki* have also been conducted in the America. In Cuba, Ramos and Rodríguez (2001) examined changes in the density of *S. spinki* during the season. They reported that *S. spinki* populations were low during the tillering stage, the population multiplied by 24× at the green ring stage and then another 3× during the bloom. The population reached a maximum at grain filling and then decreased as the grain progressed from milk to soft dough stages of maturation. Leyva et al. (2003) found that in Cuba, rice planted during December to May escaped higher infestations while rice planted from August through October experienced much greater levels of *S. spinki* infestation and damage.

9.1.3. Biotic factors

9.1.3.1. Influence of natural enemies. Predators and fungi have been used as components of integrated pest management programs to manage *S. spinki*. In Asia, four predaceous mites of importance were identified during the 1977–1978 outbreak of *S. spinki*, including *Amblyseius taiwanicus* Ehara (Acari: Phytoseiidae) and *Lasioseius parberlesei* Bhattacharyya (Acari: Ascidae) (Lo and Ho, 1979). Other predatory mite species that have been found in association with *S. spinki* include *Cheiroseius serratus* (Halbert) and *Cheiroseius napalensis* (Evans & Hyatt) (Acari: Ascidae) (Tseng, 1984). Mites in the family Phytoseiidae and predatory thrips (Thysanoptera) have been observed preying on *S. spinki* in Dominican Republic (M. Pellerano, Pers. Obs.). In Cuba, *Hypoaspis* sp. (Family: Laelapidae), several species of Ascidae (*Aceodromus asternalis* Lindquist & Chant, *Asca pineta* De Leon, *Lasioseius* (≈*tridentis*), *Lasioseius* sp., *Proctolaelaps bickleyi* Bram) and Phytoseiidae (*Galendromus alveolaris* (De Leon), *Galendromus longipilus* (Nesbitt), *Galendromus* sp., *Neoseiulus paraibensis* (Moraes & Mc Murtry), *Neoseiulus baraki* Athias-Henriot, *Neoseiulus paspalivorus* De Leon, *Proprioseiopsis asetus* (Chant)), and *Typhlodromus* sp. have been reported to prey on *S. spinki* (Ramos and Rodríguez, 1998; Cabrera et al., 2003; Ramos et al., 2005).

Fungi that attack *S. spinki* include *Hirsutella nodulosa* Petch, which has been reported to cause 71% mortality in treated mites (Cabrera et al., 2005a). According to Cabrera et al. (2005a), other entomopathogenic fungi that attack *S. spinki* include *Penicillium* spp. Link, *Cladosporium* spp. Link, and *Cephalosporium* spp. Corda.

9.1.4. Abiotic factors

9.1.4.1. Climate and environment. Food (flooded environment) – Xu et al. (2002) conducted a laboratory experiment to examine the ability of *S. spinki* to survive in a flooded rice field, with no plant material. In this experiment, 30 adult male, 30 adult female, 30 larvae (Fig. 3C), or 30 eggs of *S. spinki* were placed in plastic cups filled with water and held at room temperature with no food provided. Xu et al. (2002) observed that *S. spinki* survived for a long period of time (adults and immatures survived 23 and 25 d respectively) and continued their development with 94.3% of eggs hatching successfully and larvae molting to either the stationary phase (most) or the adult stage. It was reported that adult females

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had a greater tolerance to submergence than did adult males, and furthermore, immatures had a stronger flood tolerance than did adults. This flooding study also demonstrated the ability of *S. spinki* to tolerate extended periods of starvation as *S. spinki* was able to survive up to 25 d in the absence of food. *S. spinki* has been observed floating and mating on the surface of water (M. Pellerano, Pers. Obs.). M. Pellerano (Pers. Obs.) has also observed flood tolerance in *S. spinki* in the Dominican Republic. These data and observations indicate that *S. spinki* is well adapted to the flooded environments of rice fields.

Temperature (greenhouse and lab experiments) – *S. spinki* is able to survive exposure to high temperatures. Xu et al. (2002) conducted a greenhouse study on the effect of high temperatures on *S. spinki* survival. In this experiment, four replicates of 2 cm sections of leaf sheaths were infested with thirty adult *S. spinki* and placed in incubators held at constant temperatures of 37, 39, and 41 °C. Mortality was first assessed at 24 h and at every 12 h thereafter. At 37 °C, no mortality was recorded until 48 h when 21.1% mortality had occurred, and by 96 h the recorded mortality was 97.7%. At 39 °C, the mortality at 24 h was 15.57%, mortality increased at 36 h, and by 72 h 100% of mites were dead. At 41 °C, 50% of mites were dead after 36 h of exposure, while 100% mortality was observed at 60 h. As in the study of flood tolerance, female *S. spinki* showed greater tolerance for high temperatures than did the male *S. spinki*. The first female mortality began after the last male had died. Additionally, *S. spinki* females were also reported to have greater cold tolerance than males, as female mortality did not commence until after most males had died (Xu et al., 2002).

Relative humidity – *S. spinki* thrive in environments with high humidity, such as that found in most of the rice producing regions of the world, including the southeastern USA The percent of eggs hatching in a population appears to be strongly influenced by relative humidity and temperature exposure during development. The percent hatch of eggs maintained in a growth chamber at a constant temperature of 25 °C at 70, 95 and 100% relative humidity for seven days was 0, 65, and 96%, respectively (Liang, 1980). Similarly, when eggs were maintained for 7 d at constant relative humidity, the percent egg hatch at 18, 25, and 36 °C was 19.2, 92, and 50, respectively (Liang, 1980). A similar relationship between relative humidity and percent egg hatch was reported by Chen et al. (1979). The ability of *S. spinki* to survive exposure to extreme environmental conditions will significantly impact our ability to manage *S. spinki* and must be seriously considered when developing a management plan.

10. Prevention and control

S. spinki is spread via wind (Jiang et al., 1994), water (Xu et al., 2002), on insects (Tseng, 1984), green rice seed (Rao et al., 2000), and possibly by contaminated rice harvesting equipment. Ou and Fang (1978) used a simple sticky trap method to demonstrate that *S. spinki* uses wind for dispersal, and showed that no soil-borne or water-borne transfer occurred, nor were *S. spinki* found on the bees foraging in the crop at the time. They also speculated that an important mode of dispersal was on clothes of people. Similarly, Tseng (1984) investigated birds, insects, rats, frogs, millipedes, snakes, and water as possible means of dispersal by *S. spinki*, and concluded that none of these were utilized by *S. spinki* for dispersal. Tseng (1984) recovered *S. spinki* from 6 of 239 planthopper specimens examined. As the average number present was 2.5 *S. spinki* per planthopper, Tseng (1984) concluded that planthoppers appear to be an incidental method of dispersal (Tseng, 1984). After an outbreak of *S. spinki* in Taiwan in 1977–1978, Ou and Fang (1978) speculated that the outbreak of *S. spinki* was attributable to the current and more "sophisticated" rice culturing methods which included increased reliance on chemicals to control insects.

The question of whether or not *S. spinki* can disperse on or in harvested rice seed is a contentious issue that needs resolution. The only published report of dispersal via seed is Rao et al. (2000) in which seeds that were harvested from an infested field were planted and the resulting seedlings showed visible evidence of mite damage. Unfortunately, Rao et al. (2000) do not report the number of mites observed on plants, but stop at reporting symptoms of mite damage. Because mite damage is similar to damage caused by many plant pathogens, we cannot be certain that mites were present on plants. Other than this report, and observations of harvested seed from panicles containing *S. spinki* populations feeding on the endosperm (E. McDonald and R. Ochoa, Pers. Obs.; Fig. 4E), there is no other evidence that *S. spinki* is seed-borne. Furthermore, there is no evidence that *S. spinki* can survive the normal drying and processing of rice seed in the U.S. However, dead colonies of *S. spinki* were located on seed imported from China (E. McDonald, Pers. Obs.). Research is needed to resolve this issue. Rice is moved between rice producing countries to extend the growing season and for the purpose of developing superior rice varieties. At the time of rice harvest in the USA, rice is being planted in tropical countries, such as Puerto Rico, as part of a USA rice-breeding program. Thus, there is a steady, regulated flow of rice seed from the Caribbean to the USA.

10.1. Rice varietal resistance to S. spinki

Leyva et al. (2003) studied the population dynamics of *S. spinki* in Cuba and reported that there was a significant difference in density of populations over time depending on the variety of rice. Densities of up to 141 *S. spinki* per stem were present on variety J-104 compared to 58 *S. spinki* per stem in iaCuba28. This observation indicated the potential for varietal resistance. The time of peak infestations differed by variety. For example, peak infestation in variety iaCuba28 occurred from August to September, while the peak for variety J-104 occurred in September and December. Ramos et al. (2001) surveyed 60 farms throughout the Dominican Republic. In every location, they sampled four varieties and at each location collected at least one sample for each of five phenological stages. They used a square sampling design in each field with the squares separated from each other by 5 m. At the tillering and panicle initiation stages, variety ISA-40 was more susceptible to *S. spinki* infestation when compared to the varieties JUMA-57, Prosedoca, Prosequisa, with 100% infestation occurring in ISA-40. As plants reached the blooming stage, the differences between varieties diminished. As previously discussed, in the Tainan (southern) region of Taiwan, researchers concluded that variety Tainan #5 was highly susceptible to *S. spinki* and, in response to extensive crop losses, the acreage of Tainan #5 was reduced from 400,000 ha in 1975 to 80,000 ha in 1981 (Cheng and Chiu, 1999). After this shift in acreage, *S. spinki* was not reported as a pest in the region in subsequent years. This indicates that varietal resistance may decrease the impact of *S. spinki* infestation on yield.

10.2. Chemical control

Because *S. spinki* colonizes a protected area of the plant – behind the leaf sheath or inside the hulls of developing grains (Figs. 4E and 5D) – it will be necessary to develop a systemic miticide to control this pest. There are many limitations on pesticide use in the rice culture of the United States because of the close association with water and nearby wetlands. Irregardless of this challenge, the use of systemic products has not effectively controlled *S. spinki* infestations (Chow et al., 1980; Almaguel et al., 2000). Chemically

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intensive rice pest management was implicated as the primary cause of *S. spinki* outbreaks in Taiwan (Ou and Fang, 1978). It has also been reported in Cuba that reliance on miticides is not an effective way to manage *S. spinki* (Cabrera et al., 1998) and should only be considered in emergency outbreak type situations (Ramos and Rodríguez, 1998, 2000; Cheng and Chiu, 1999; Almaguel et al., 2000). To further complicate matters, many classes of miticides do not have activity against *S. spinki*. Most of the miticides that have been used effectively in *S. spinki* infested countries are classified as organophosphates. The pesticide Triazophos (Hostathion 40 CE) has been reported to effectively control *S. spinki* in Cuba (Cabrera et al., 1999, 2002a). Other products that have been tested under laboratory conditions and reported to cause more than 95% mortality of adult *S. spinki* include Bromopropilato, Diafentiuron, Dicofol, and Edifenphos (Cabrera et al., 2005b). Field trials conducted in India reported up to 90% mortality following treatments with Dicofol 18.5 EC (Bhanu et al., 2006). An evaluation of seven pesticides reported that Dimethoate 30 EC caused 88.49% mortality in India (Ghosh et al., 1998). This efficacy was correlated with a reduction in the percent of damaged grains (Ghosh et al., 1998). The miticides recommended in the integrated management of *S. spinki* in the Caribbean and other Central American countries include Abamectin, Biomite, Dicofol, Endodsulfan, Ethoprophos, and Triazophos (Almaguel et al., 2005). García et al. (2002) also recommend treatment of seeds with Benomyl 5 PM plus TMTD (Thiran) 200 ppm because it has significantly decreased the percentage of sterile and spotted grains and increased yield in rice producing regions infested with *S. spinki*.

10.3. Cultural control

Lo and Ho (1980) reported that high densities of *S. spinki* were associated with high rice planting density and high relative humidity. According to Navia et al. (in press) a set of cultural procedures have been established in infested countries to reduce populations of *S. spinki*, delay its arrival into the crop and reduce yield losses and production costs (Ho and Lo, 1979; Cabrera et al., 1998; Ramos et al., 2001; Hernández et al., 2003, 2005; Romero et al., 2003; Sanabria and Aguilar, 2005). The primary methods that are utilized to manage *S. spinki* in infested countries include the following:

1) rice crop residue destruction and removal of invasive plant species that can act as a source of infestation. These measures should be adopted in the production area as well as in neighboring areas (Ho and Lo, 1979);
2) clean the new crop areas to remove any remaining mites before planting a field;
3) clean machinery and other equipment when used by different farmers or in different areas, to avoid the dissemination of the mite from an infested area to an uninfested area;
4) leave the fields fallow for at least two weeks between crop cycles;
5) use clean, certified seed to plant fields;
6) plant rice varieties with demonstrated resistance to *S. spinki* damage;
7) use the lowest seeding rate possible for the variety planted;
8) plant continuous rice production areas simultaneously (avoid staggered plantings in infested areas);
9) avoid planting rice in adjacent areas during harvest time or areas that have recently been harvested and always consider the wind direction to avoid planting rice downwind from an infested field;
10) divide the doses of nitrogen fertilizers into different treatments;
11) use a shallow depth of permanent flood water;
12) monitor the crop 15 days after planting, especially in fields downwind of infested areas, to ensure early detection of *S. spinki* presence in the crop and implement control measures using acaricides (modified from Navia et al., in press).

11. Summary

Based on the reports in Asia, India, Central America, and the Caribbean, we hypothesize that the panicle rice mite, *S. spinki*, has the potential to cause substantial rice crop losses in the southeastern United States. In 2008, a delimited survey of *S. spinki* did not detect *S. spinki* in the Louisiana rice fields that were infested in 2007. Populations of *S. spinki* were once again reported in some greenhouses in 2008 and 2009. We are uncertain why *S. spinki* was not reported in large densities in any research rice fields, but this may have been due to a combination of factors including weather conditions during the overwintering period, field preparation, varietal selection and other unknown factors. In spite of low densities reported in 2008, it will be wise to begin a program of research on the biology of *S. spinki* in the United States in order to develop an integrated pest management plan. To begin, we will need to determine the extent of the infestation in the USA by continuing to survey for *S. spinki* in the rice producing regions of the USA It will also be essential to determine if there are other significant hosts, such as weeds commonly found on levees that border rice fields. This information will determine if we can concentrate our efforts solely on the rice crop, or if we must consider overwintering behavior on weed hosts. It will also be essential to carefully examine the interaction between *S. spinki* infestations and the occurrence of rice diseases. Furthermore, evaluation of miticides and biological control methods will be necessary to determine their possible use to manage *S. spinki* in commercial rice production. It is our hope that this review of the literature will assist in framing questions for future study of *S. spinki* biology in the USA and stimulate important research efforts to minimize the impact of this pest on the USA rice industry.

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