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Natural Enemies of Sorghum Shoot Fly, *Atherigona soccata* Rondani (Diptera: Muscidae)

B. U. SINGH AND H. C. SHARMA

Germplasm Resources and Enhancement Program, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India

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The sorghum shoot fly, Atherigona soccata *is one of the most important pests of grain sorghum in Asia, Africa and the Mediterranean Europe. This paper reviews the current state of information on diversity, ecobiology, parasitism levels, and mass rearing of the parasitoids, predators and pathogens attacking different stages of* A. soccata. *Among the parasitoids,* Trichogramma chilonis *Ishii and* Trichogrammatoidea simmondsi *Nagaraja on the eggs, and* Neotrichoporoides nyemitawus *Rohwer on the larvae are most important. Although 15 species of predators have been recorded, their predation potential has not been assessed under field conditions. Several species of spiders are important predators on eggs. The ecobiology of* T. chilonis, T. simmondsi, N. nyemitawus, Spalangia endius *Walker and* Trichopria *sp. has been studied in considerable detail. The parasitism levels are quite high during the post-rainy season by* Aprostocetus *sp.,* N. nyemitawus, Opius *sp. and* S. endius. *Augmenting populations of* T. chilonis *does not reduce the shoot fly infestation under field conditions. Parasitism by* N. nyemitawus *is greater in sorghum-cowpea intercrop than where sorghum is the sole crop. Mass rearing techniques are available only for* T. chilonis *and* T. bactrae. *The constraints and challenges for utilizing the natural enemies in integrated pest management have been discussed.*

Keywords: *shoot fly,* Atherigona soccata, *natural enemies, biological control, sorghum,* Trichogramma, Trichogrammatoidea, Neotrichoporoides nyemitawus

INTRODUCTION

Sorghum (*Sorghum bicolor* (L.) Moench) is a major food crop for millions of people in the semi-arid tropics. It is primarily grown under subsistence farming conditions, and the average grain yield is 0.5–0.9 t ha^{-1} (FAO, 1999). However, many of the high yielding cultivars have the potential to yield $>$ 10 t ha^{-1}. It is cultivated under diverse agroecosystems, and grain yields are influenced by various biotic and abiotic factors. Among the biotic factors, arthropods constitute a major constraint to the increase of sorghum production.

Correspondence to: H.C. Sharma. E-mail: h.sharma@cgiar.org

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Over 150 insect species have been reported to damage sorghum in different agroecosystems (Reddy & Davies, 1979; Jotwani *et al.*, 1980). Among them, the shoot fly (*Atherigona soccata* Rondani) (Diptera: Muscidae) is one of the most important and destructive pests at the seedling stage. It is widely distributed in tropical and subtropical areas of southeast Asia, Africa, Mediterranean Europe, and the middle East (CIE, 1973). It has not yet been recorded from Australia and the Americas, although a shoot fly species has been found to infest the sorghum crop in Australia (Sharma, H.C., 1997, unpublished).

The eco-biology of *A. soccata* has been reviewed extensively (Jotwani & Young, 1972; Odhiambo, 1981; Delobel, 1984). Adults oviposit at early dawn, and each female lays up to 75 eggs. The eggs are cigar-shaped, laid singly on the abaxial leaf surface between the first and fourth week after seedling emergence. The eggs hatch in 1–2 days. After eclosion, the larva moves to the growing point through the leaf sheath, and cuts the growing point, resulting in wilting and drying of the central leaf, known as a 'deadheart'. The larva feeds on the decaying plant tissue in the shoot. There are 4–5 instars, and the larval development is completed in 8–10 days. Pupation occurs either at the base of the damaged seedling or in the soil. The pupal period lasts for 5–7 days. Adults survive for 12 days on sorghum seedlings (Barry, 1972a,b). The life-cycle from egg-to-adult is completed in 17–21 days, but can be as long as 45 days, with up to 10 generations per year. Early crop infestation may result in loss of plant stand. Shoot fly infestations generally promote the development of side-tillers after the main shoot is killed. Some of the side-tillers produce productive panicles, which often are subjected to the ravages of panicle feeding insects and birds.

Nearly 32% of the sorghum crop is lost due to insect pests in India (Borad & Mittal, 1983), of which 5% of the loss has been attributed to sorghum shoot fly (Jotwani, 1982, 1983). Total plant stand loss is not uncommon in delayed sorghum plantings in India (Sharma, 1968). Annual losses have been estimated to exceed US$100 million (ICRISAT, 1992). The economic threshold levels (ETLs) vary over cultivars, locations, and seasons, and are influenced by variation in input costs, value of produce, productivity potential of the crop, as well as other socioeconomic factors. The ETLs have been estimated to be 4–10%, 3–9% and 6–15% deadheart incidence in sorghum cultivars CSH 1, CSH 5 and *Swarna* (CSV 1), respectively, in India (Rai *et al.*, 1978). However, there can be a considerable compensation in grain yield by productive tillers in the damaged plants under high input conditions. Increase in deadhearts by 1% leads to 89.1 and 30.5 kg ha^{-1} reduction in grain yield in CSH 5 and M 35–1, respectively (Mote, 1986).

In India, the shoot fly has attained the status of a principal pest because of the introduction of improved sorghum varieties and hybrids susceptible to this insect, continuous cropping, ratooning, and reduced genetic variability (Singh & Rana, 1986). Further, its high fecundity and shorter generation span result in rapid population buildup. It is also able to feed on several other plant species including other cereal crops and weeds (Davies & Seshu Reddy, 1980). In view of its effects on plant stand and loss in grain yield, considerable research efforts have been made to develop strategies for the management of this pest.

Methods currently used to manage sorghum shoot fly during the rainy season include early planting, increased seed rate, thinning and destroying the seedlings with deadhearts, seed treatment or soil application of carbofuran, intercropping sorghum with leguminous crops, crop rotations, and fallowing. Although chemical control with systemic insecticides provides good control, it is not accessible to majority of the small-scale farmers. Thus, host plant resistance can play a vital role in containing shoot fly infestations. However, agronomically acceptable sorghum cultivars with adequate levels of resistance to shoot fly are not available. In such circumstances, natural enemies can play a significant role to suppress *A. soccata* populations below the economic threshold levels.

There is a considerable diversity of natural enemy fauna on shoot fly eggs (Deeming, 1971; Pont, 1972; Taley & Thakare, 1979; Delobel & Lubega, 1984; Zongo, 1992, 1995), larvae (Kundu *et al.*, 1971a–c; Kishore *et al.*, 1977a,b; Pont, 1972; Taley & Thakare, 1979; Delobel & Lubega, 1984; Zongo, 1992, 1995) and pupae (Deeming, 1971; Taley & Thakare,

TABLE 1. Natural enemies of sorghum shoot fly, *Atherigona soccata* reported from different countries

	Parasites			Predators			Pathogens	
Country	Egg	Larva	Pupa	Egg	Larva	Pupa	Egg	Total
Burkina Faso	2	3	1	5	—	—	2	13
India	7	21	2	—	1	—	—	31
Italy	1	—	1	—	—	—	—	2
Kenya	1	1	—	4	—	—	—	6
Morocco	—	4	—	—	—	—	—	4
Nigeria	1	3	2	—	—	—	—	6
Pakistan	—	—	—	5	—	—	—	5
Thailand	—	3	—	—	—	—	—	3
Uganda	—	—	—	—	—	1	—	1

1979), including spiders (Reddy & Davies, 1979; Delobel & Lubega, 1984). The diversity of natural enemies varies widely across the geographic regions (Table 1). Most of the literature reports have only listed the natural enemies recorded on this insect (Gilstrap, 1980; Young, 1981; Zongo, 1995). The primary objective of this review is to summarize the information on the diversity, ecobiology, parasitism levels, and mass rearing techniques of the natural enemies of *A. soccata*, and to assess the potential for strengthening research on promising natural enemies.

EGG PARASITOIDS

Diversity

Egg parasitoids of sorghum shoot fly belong to the genera *Trichogramma* and *Trichogrammatoidea*. Five species (*Trichogramma* sp., *T. bactrae* Nagaraja from India and Burkina Faso; *Trichogramma chilonis* Ishii and *T. japonicum* Ashmead from India) (Taley & Thakare, 1979); *T. evanescens* Westwood from Nigeria (Deeming, 1971), Burkina Faso (Breniere, 1972) and Italy (Del Bene, 1986), and *T. kalkae* Sch. & Feij. from Kenya (ICIPE, 1982; Delobel & Lubega, 1984) are known to parasitize the eggs of sorghum shoot fly. *Trichogramma chilonis* was earlier described as *T. australicum* Girault or *T. confusum* Viggiani, which are synonyms to *T. chilonis* (Nagarkatti & Nagaraja, 1977, 1979). Of the two species of *Trichogrammatoidea*; *T. bactrae* Nagaraja (Jai Rao *et al.*, 1987), and *T. simmondsi* Nagaraja from India (Taley & Thakare, 1979), and Burkina Faso (Zongo, 1992; Zongo *et al.*, 1993b) have been recorded on the eggs of shoot fly (Table 2). Some of these species have also been reported from eggs of other insect hosts. However, the most important and well studied egg-parasitoids, *T. chilonis* and *T. simmondsi* are considered as important mortality factors for *A. soccata*.

Ecobiology

Both *T. chilonis* and *T. simmondsi* are endo-parasitoids of shoot fly eggs. The life cycle of *T. chilonis* has not been studied fully due to short incubation period. The larvae are immobile in the host egg fluid and pupate *in situ*. On emergence, the parasitoid stays for 3–5 min on the host egg shell. The total life-cycle is completed in 7–10 days. The male-to-female ratio is 1: 3 (Table 3).

In a sample of 305 eggs, Zongo *et al.* (1993b) observed one exit hole in 44.9% eggs, two in 53.5%, and three in 1.6%, which indicates super-parasitism by *T. simmondsi*. Similarly, fewer eggs with two exit holes and high rate of parasitism (73%) have been recorded in $<$ 24 h old eggs of *A. soccata* compared with parasitism in $>$ 24 h old eggs by *T. simmondsi*. Two days after parasitism, the shoot fly eggs become opaque because of *T. simmondsi* larval development. The duration of development from egg-to-adult emergence is 7–12 days.

The life cycle from the egg-to-adult emergence of *T. simmondsi* usually takes an average

TABLE 2. Parasitoids of the sorghum shoot fly, *Atherigona soccata* recorded in different countries

Order/Family	Parasitoid	Host stage	Country	Reference
Diptera				
Muscidae	*Acritochaeta orientalis* Schiner	Larva	Nigeria	Adesiyun, 1981
Phoridae	*Megaselia scalaris* Loew.	Larva	Nigeria	Adesiyun, 1981
Hymenoptera				
Braconidae	*Alysia* sp.	Pupa	Burkina Faso	Zongo *et al*., 1993a
			India	Taley & Thakare, 1979
			Nigeria	Deeming, 1971
	Bracon sp.	Larva	Burkina Faso	Zongo *et al*., 1993d
	Bracon greeni (Ashmead)	Larva	India	AICSIP, 1979
	Opius sp.	Larva-pupa	India	Taley & Thakare, 1979
	Trichosteresis Gen. near *Alysia*	Pupa	Nigeria	Deeming, 1971
	Trichosteresis sp. nr. *Foersteri* Kieffer	Larva	India	Pont, 1972; Kundu *et al*., 1971a,b; Taley, 1978; Taley & Thakare, 1979
Chalcididae	*Hockeria* sp.	Larva	Burkina Faso	Zongo *et al*., 1993a
Chloropidae	*Scoliopthalmus micantipennis* Duda	Larva	Burkina Faso	Zongo *et al*., 1993a
	Scoliopthalmus nicans Lamb.	Larva	India	Chopde, 1978
Diapriidae	*Monelta* sp.	Larva	India	Taley & Thakare, 1977, 1979; Taley, 1978
	Odonteucoila sp.	Larva	India	AICSIP, 1976; Shivpuje, 1977; Chopde, 1978
	Psilus sp.	Larva	India	Kishore *et al*., 1977a,b
			Thailand	Thongsanga, 1985
	Trichopria sp.	Larva	India	Taley & Thakare, 1977, 1979; Taley, 1978, 1979
			Morocco	Bleton & Fieuzet, 1939, 1943
			Thailand	Thongsanga, 1985
Encyrtidae	*Exoristobia deemingi* Subbarao	Pupa	Nigeria	Deeming, 1971
Eucoilidae	*Eucoila haywardi* L. (*Ganaspis haywardi*)	Larva	India	AICSIP, 1976, 1979; Shivpuje, 1977; Kishore *et al*., 1977a,b; Jotwani, 1978; Chopde, 1978
	Rhoptromeris sp.	Larva	India	Taley & Thakare, 1977, 1979; Taley, 1978, 1979
	Trichoplasta Benoit sp.	Pupa	Italy	Del Bene, 1986
Eulophidae	*Aprostocetus* sp.	Larva	India	Kundu *et al*., 1971a,b; Kishore *et al*., 1977a,b; Jotwani, 1978; AICSIP, 1979, 1980; Taley & Thakare, 1979
	Crataepiella sp.	Larva-Pupa	India	Kishore *et al*., 1977a,b; Jotwani, 1978
	Diaulinopsis sp.	Larva	India	AICSIP, 1976; Kishore *et al*., 1977a,b; Jotwani, 1978
	Eupelmus australiensis Girault	Larva	India	AICSIP, 1976, 1979
	Gronotoma sp.	Larva	India	AICSIP, 1979
	Hemiptarsenus semialbiclavus (Gir.)	Larva	India	AICSIP, 1976; Kishore *et al*., 1977a,b; Jotwani, 1978
	Neotrichoporoides sp. (*Tetrastichus* sp.)	Larva-Pupa	India	Rohwer, 1921; Raodeo *et al*., 1972; AICSIP, 1976, 1979, 1980, 1987; Kishore *et al*., 1977a,b; Taley & Thakare, 1979; Reddy & Davies, 1979

TABLE 2. *Continued*

Order/Family	Parasitoid	Host stage	Country	Reference
	Neotrichoporoides nyemitawus Rohwer	Larva-Pupa	Burkina Faso	Zongo, 1992; Zongo *et al*., 1993c
	(*Tetrastichus nyemitawus* Rohwer)		India	Rohwer, 1921; Rawat & Sahu, 1968; Raodeo *et al*., 1972; AICSIP, 1979, 1980, 1987; Reddy & Davies, 1979
			Kenya	ICIPE, 1982; Delobel & Lubega, 1984
			Thailand	Meksongsee *et al*., 1981; Thongsanga, 1985
Ichneumonidae	*Diplazon bizonarius* Gravenhorst	Larva	India	Kundu *et al*., 1971a,b
	(*Homocidus bizonarius* Gravenhorst)		Morocco	Bleton & Fieuzet, 1939, 1943
	Phygadeuon sp.	Larva	Morocco	Bleton & Fieuzet, 1939, 1943
	Pimplomorpha sp.	Larva	Nigeria	Adesiyun, 1981
	Syrphophilus bizonarius Gravenhorst	Larva	Morocco	Bleton & Fieuzet, 1939, 1943
Pteromalidae	*Callitula* spp.	Larva	India	Kundu *et al*., 1971b; Kishore *et al*., 1977a; Jotwani, 1978
	Callitula bipartitus Farooqui	Larva	India	Kundu *et al*., 1971c
	Spalangia endius Walker	Larva	India	Taley & Thakare, 1977, 1979; Taley, 1978, 1979
Trichogrammatidae	*Trichogramma* spp.	Egg	India	Pont, 1972; Taley & Thakare, 1979
			Nigeria	Deeming, 1971
	T. bactrae Nagaraja	Egg	Burkina Faso	Zongo, 1992, 1995; Zongo *et al*., 1993b
	T. chilonis Ishii. (*T. australicum* Girault) (*T. confusum* Viggiani)	Egg	India	Taley, 1978, 1979; Jotwani, 1978; Taley & Thakare, 1979; AICSIP, 1986, 1987
	T. evanescens Westwood	Egg	Italy	Venturi, 1940
			Nigeria	Deeming, 1982
			Upper Volta	Breniere, 1972
	T. japonicum Ashmead	Egg	India	ICRISAT, 1980, 1982
	T. kalkae Sch. & Feij.	Egg	Kenya	ICIPE, 1982; Delobel, 1984
	Trichogrammatoidea sp.	Egg	India	ICRISAT, 1982
	T. bactrae	Egg	Burkina Faso	Zongo, 1992; Zongo *et al*., 1993a,d
	T. simmondsi Nagaraja	Egg	India	AICSIP, 1986, 1987, 1989

of 9.8 days on the eggs of *A. soccata* at 26°C (Zongo *et al*., 1993b), and 11 days on the eggs of rice stalk-eyed fly, *Diopsis* (*Macrophthalma* Dalm.) *thoracica* Westwood at 25°C (Feijen & Schulten, 1981) (Table 3). The longevity of adult male and female parasitoids on *A. soccata* is 25.0 and 35.2 h, respectively, with a sex ratio of 1:1.5 (Zongo *et al*., 1993c), while the female parasitoid survive for 57.6 h on *D. thoracica* (Feijen & Schulten, 1981).

Parasitism Levels

The levels of egg parasitism vary widely across seasons and locations. In Burkina Faso, *T. simmondsi* was recorded on the sorghum crop between 17 and 38 days after planting.

TABLE 3. Life-cycle duration, longevity, and sex ratio of parasitoids recorded on sorghum shoot fly, *Atherigona soccata*

Parasitoid	Duration (days) Egg incubation	Larva	Pupa	Total life-cycle Mean	Total life-cycle Range	Adult longevity (days) Male	Female	Sex ratio Male: Female	Reference
Monelta sp.	—	—	—	—	20–30	—	—	—	Taley & Thakare, 1979
N. nyemitawus	2–3	15–20	8–12	21.7	25–35	—	—	1:1.47	Zongo *et al*., 1993c
						21.7	51.0	1:3	Taley & Thakare, 1979
Rhoptromeris sp.	—	—	—	—	20–30	—	—	—	Taley & Thakare, 1979
S. endius	2–3	9–12	15–90	—	26–106	—	—	1:1	Taley & Thakare, 1979
Trichopria sp	—	—	—	—	24–44	—	—	1:3	Taley & Thakare, 1979
T. chilonis	—	—	—	—	7–10	—	—	3:1	Taley & Thakare, 1979
T. simmondsi	—	—	—	9.8	7–12 (22–26)	25.0 (25–50)	35.2	1:1.28	Zongo *et al*., 1993c

Although 8.8 and 12.3% egg parasitism was recorded in two consecutive years in sorghum-cowpea intercrop, no significant differences were observed between sorghum and sorghum-cowpea intercrop (Zongo *et al*., 1993a).

Inundative releases of *T. chilonis* at weekly intervals, over a period of 3 weeks, starting with first appearance of eggs of *A. soccata* did not give consistent results on parasitism of shoot fly eggs (AICSIP, 1997). The parasitoids *T. chilonis* and *T. simmondsi* also have several alternate hosts such as spotted stem borer, *Chilo partellus* Swinhoe, *Helicoverpa armigera* Hub., and *Mythimna separata* Walk. in sorghum; and *C. partellus*, *Sepedon* sp. (Diptera: Sciomyzidae), and the rice stalk-eyed fly, *D. thoracica* in rice for *T. chilonis* in India (Nagaraja, 1978), and *D. thoracica* in rice for *T. simmondsi* in Malawi (Feijen & Schulten, 1981) and India (Nagaraja, 1978). Numbers of exit holes (1, 2, and 3) by *T. simmonds*; on each shoot fly egg have been observed in the proportion of 44.9%, 53.5% and 1.6%, respectively, indicating super-parasitism (Zongo *et al*., 1993a).

Mass Rearing

Techniques for mass rearing of *Trichogramma* spp. and *Trichogrammatoidea* spp. have been developed. In many countries, they are usually reared on eggs of the factitious host, *Corcyra cephalonica* Stainton (Lepidoptera: Pyralidae). Before exposure to the parasitoids, *C. cephalonica* eggs are killed by either UV irradiation (Maninder & Varma, 1980; Singh *et al*., 1994), or chilling at −5°C for 48 h, but the chilled eggs are significantly less acceptable to *T. chilonis* than the untreated eggs (Hugar *et al*., 1990). Parasitized eggs can be stored at 10°C for as long as 49 days without affecting the parasitoid survival (Jalali & Singh, 1992). Several constraints to mass rearing of *T. chilonis* have been reported. Laboratory-reared females have shown a significantly higher degree of sterility than those collected from the field (Nagarkatti & Nagaraja, 1978), and laboratory–reared populations are more sensitive to both high and low temperatures than the wild-types (Nagarkatti, 1979). In searching for better field-adapted strains, *T. chilonis* populations collected from different habitats and locations were compared by Mandal and Somchoudhury (1991) and Jalali and Singh (1993). They found variability in morphometrics and biological attributes such as the number of host eggs parasitized per female and adult longevity. Abraham and Pradhan (1976) attempted to select a *T. chilonis* strain adapted to high temperatures and low humidity, but without much success.

Another egg parasitoid, *T. bactrae*, has been successfully reared on *C. cephalonica* eggs (Jai Rao *et al*., 1980).

LARVAL PARASITOIDS

Diversity

The larval stadia of shoot fly are attacked by a diverse group of parasitoids, but their impact is usually too little to influence shoot fly population dynamics since the larvae feed inside the shoot in a protected environment. The larval parasitoids belong to Muscidae and Phoridae in Diptera; and Braconidae, Ceraphrontidae, Chalcididae, Chloropidae, Diapriidae, Eucoilidae, Eulophidae, Ichneumonidae and Pteromalidae in Hymenoptera (Table 2). The endo-larval parasites, *Neotrichoporoides* sp. and *N. nyemitawus* Rohwer have been studied extensively in India (Raodeo *et al*., 1972), and Burkina Faso (Zongo, 1992; Zongo *et al*., 1993c).

Ecobiology

Neotrichoporoides nyemitawus was first recorded on sorghum shoot fly at Coimbatore, Tamil Nadu, India and described as *Tetrastichus nyemitawus* (Rohwer, 1921). Subsequently, it was reported from Maharashtra (Raodeo *et al*., 1972), Delhi (Kishore *et al*., 1977a,b), and Andhra Pradesh in India (Reddy & Davies, 1979), Thailand (Meksongsee *et al*., 1981; Thongsanga, 1985), Kenya (ICIPE, 1982; Delobel & Lubega, 1984), and Burkina Faso (Zongo, 1992). In a revision of the European Tetrastichinae (Hymenoptera: Eulophidae), Graham (1987) replaced the genus *Tetrastichus* by *Neotrichoporoides* Girault. The searching behavior of *N. nyemitawus* has been studied by Zongo *et al*. (1993c), and categorized into four phases: exploration, ovipositor insertion, oviposition, and resting. The female parasitoid uses its antennae to explore the sorghum seedlings, and inspects the leaves adjacent to the point of leaf whorl and sometimes enters the central whorl to detect the presence of shoot fly larvae. After locating the shoot fly larvae inside the seedling, the parasitoid moves the ovipositor around the sorghum seedling several times (8–123 times) till it finds a suitable penetration site, and then inserts the ovipositor into the plant tissues. The exploration and oviposition after seedling penetration usually take about 10 min. During the oviposition process, the female holds the seedling with its legs, and upper leaves are used for resting. Usually a single egg is laid in each shoot fly larvae between the VII and VIII abdominal segment, but two eggs per larva have also been observed (1 in 30 samples). The lack of attraction to the first instar, and high and low per cent parasitism of second and third instars, respectively, suggests that the size of shoot fly larva is used as physical cue by the females for oviposition. After parasitism, the *A. soccata* larva dies in 5.1 days. The deadheart is caused mainly by the first instar larval feeding within 1–3 days after reaching the growing point (Raina, 1981). Therefore, the deadheart formation cannot be avoided before or after shoot fly larvae are parasitized. Maximum longevity of the adult female parasitoid is 51 days. *Neotrichoporoides nyemitawus* is an internal larval parasite, and the egg incubation period is 2–3 days. The larva passes through four instars, and takes about 15–20 days to complete the development. When the parasitoid larva reaches the third-instar, it makes the host larva inactive, and completely diseased (Taley & Thakare, 1979). The pupal period lasts for 8–12 days. The total life-cycle takes 24–35 days, and the sex ratio is 1:3. The average life span of *N. nyemitwus* adult males and females is 21.7 and 51.0 days, respectively (Taley & Thakare, 1979).

Parasitism Levels

Shivpuje and Chopde (1976) recorded *Ganaspis* sp. and *Odonteucoila* sp. on shoot fly eggs. Eleven new hymenopterous parasites including *N. nyemitawus*, *T. chilonis* and *Spalangia* sp. were studied between 1968 and 1971 by Taley and Thakare (1979). In Udaipur, larval parasitism was found to be 24, 16 and 6% in September, October and November, respectively, and the predominant parasite was *Aprostocetus* sp., while only a few specimens of *Callitula* sp. were collected (Kundu *et al*., 1971b). *Neotrichoporoides* sp. and *N. nyemitawus* emergence was observed in September, December, and January at Parbhani, India (Raodeo *et al*., 1972) (Table 6).

An endo-parasite, *Trichoplasta* Benoit sp. (Hymenoptera: Eucoilidae), has been recorded from shoot fly pupae in Italy (Del Bene, 1986). In India, *Aprostocetus* sp., *Callitula bipartitus* Farooqui, *Neotrichoporoides* sp., and *N. nyemitawus* have been recorded from a number of locations. The maximum parasitism was found to be 35.3% during the first week of August (Jotwani, 1981). A few other parasites recorded from shoot fly include *Psilus* sp. (Diapriidae), *Hemiptarsenus* sp., and *Diaulinopsis* sp. (Eulophidae), and the extent of parasitism ranged between 1 and 4% (Kishore *et al*., 1977a,b).

Although *N. nyemitawus* cannot prevent deadheart formation, it may be of potential use in reducing population buildup of shoot fly in the first generation, which is quite low in early plantings. Parasitism levels increase by the second generation, coinciding with delayed plantings during the rainy season (Zongo *et al*., 1993a,d). Intercropping of sorghum with cowpea has a beneficial effect in increasing the levels of parasitism by *N. nyemitawus*. There was a nearly 2-fold and 1.4-fold increase in larval parasitism (11.8 and 17.5%) in sorghum-cowpea intercrop over monocrop sorghum. Parasitism ranged from 6.0–17.5% in Burkina Faso (Zongo *et al*., 1993a); 1.6–8.3% in Maharashtra (Taley & Thakare, 1979), 22–30% in Madhya Pradesh in India (Rawat & Sahu, 1968) and 37.4% in Thailand (Thongsanga, 1985). Parasitism by *N. nyemitawus* during October to March has been reported to be 1.6–8.3%.

Other larval parasitoids such as *Bracon* sp. and *Hockeria* sp. have also been recorded from shoot fly larvae, but are present in small numbers (Zongo *et al*., 1993a,d). *Hockeria* sp. is distributed worldwide and contains 30 described species (Halstead, 1990). The results suggested that *T. simmondsi* was more effective than *N. nyemitawus* in reducing shoot fly populations.

Investigations carried out in India have shown that *Aprostocetus* sp. may be one of the major parasites of shoot fly (AICSIP, 1977; Jotwani, 1978). At Udaipur, Kundu *et al.* (1971b) observed up to 60% parasitism. Subsequently, other parasites such as *Callitula* sp. (Eucoilidae), *Psilus* sp. (Diapriidae), *Hemiptarsenus* sp. and *Diaulinopsis* sp. (Eulophidae) from Delhi, India (Jotwani, 1978), *Scoliopthalmus nicans* Lamb. (Chloropidae) from Parbhani, India (Chopde, 1978), and *S. micantinpennis* Duda from Burkina Faso (Zongo *et al*., 1993a) have been recorded. Parasitism by *Ganaspis* sp. and *Odonteucoila* sp. in October was 2 and 5%, respectively (Chopde, 1978) (Table 4). More information is needed on the biology and parasitism levels to exploit the full potential of natural enemies for shoot fly control.

TABLE 4. Parasitism levels of sorghum shoot fly, *Atherigona soccata* recorded in different countries

Parasitoid	Parasitism levels (%) Mean	Range	Country	Reference
Aprostocetus sp.	—	6.0–24.0	India	Kundu *et al*., 1971a
Ganaspis sp.	2.0		India	Shivpuje & Chopde, 1976; Chopde, 1978
Monelta sp.		0.9–3.3	India	Taley & Thakare, 1979
N. nyemitawus	—	6.0–17.5	Burkina Faso	Zongo *et al*., 1993c
		1.6–8.3	India	Taley & Thakare, 1979
		22.0–30.0	India	Rawat & Sahu, 1968
	37.4		Thailand	Thongsanga, 1985
Odonteucoila sp.	4.0		India	Chopde, 1978
Opius sp.		0.3–4.5	India	Taley & Thakare, 1979
Rhoptromeris sp.		0.5–4.2	India	Taley & Thakare, 1979
S. endius	—	8.0–10.6	India	Taley & Thakare, 1979
T. chilonis	—	20.0–60.0	India	Taley & Thakare, 1979
T. simmondsi		7.0–12.3	Burkina Faso	Zongo *et al*., 1993b
Trichopria sp.	—	1.2–5.8	India	Taley & Thakare, 1979

Mass Rearing

The development of techniques to rear larval parasitoids has largely been focussed on *N. nyemitawus* because of its better parasitism potential as compared to the other parasitoids. The egg-to-adult development was completed in 25 days. The females lay an average of 168 eggs at 27°C and 17 eggs at 31°C (Taley & Thakare, 1979). Adults survived on 10% honey solution for 8 days (Zongo *et al*., 1993c). The techniques for mass production of *N. nyemitawus* are still unavailable (Taley & Thakare, 1979; Zongo *et al*., 1993c).

PUPAL PARASITOIDS

Diversity

Six pupal parasitoids have been recorded on *A. soccata* from India and Burkina Faso, which include two braconids, an encyrtid, an eucoilid and two eulophids (Table 2). The larval–pupal parasitoids include *Spalangia endius* Walker, *Trichopria* sp. and *Opius* sp. Pupal parasitoids such as *Monelta* sp., and *Rhoptromeris* sp. have been reported from Maharashtra, India (Taley & Thakare, 1979); *Alysia* sp. from Nigeria (Deeming, 1971), India (Taley & Thakare, 1979), and Burkina Faso (Zongo *et al*., 1993a,d), and *Crataepiella* sp. from Delhi, India (Kishore *et al*., 1977a,b; Jotwani, 1978), and *Trichoplasta* Benoit sp. from Tuscany and Lazio, Italy (Del Bene, 1986). Since *A. soccata* pupates inside the seedlings and occasionally in the soil, pupae are rarely sampled. Therefore, the pupal mortality reported in *A. soccata* is caused by larval–pupal parasitoids and does not reflect the impact of true pupal parasitoids. However, the pupal parasitoids may also play an important role in population dynamics of sorghum shoot fly.

Ecobiology

The life cycle of the pupal parasitoid, *Trichopria* sp. (Hymenoptera: Diapriidae) is completed in 24–44 days. Morphometrics of the egg and larva have been described by Taley and Thakare (1979). *Spalangia endius* (Hymenoptera: Pteromalidae) inserts the eggs into the body of shoot fly larva or pupa, and the egg incubation period lasts for 2–3 days. There are three larval stadia, which complete development in 9–12 days, and the pupal stage lasts for 15–90 days. The total life cycle from egg-to-adult is completed in 25–106 days, and the sex ratio is 2:1. The emergence of *S. endius* in June–July from the pupae collected in February and March indicates hibernation during the pupal stage. Although the life cycle of *Opius* sp. has not been studied, the emergence of adults from the pupae collected in March and October during June–July and November, respectively, suggests possible aestivation during the pupal stage. *Monelta* sp. and *Rhoptromeris* sp. takes 20–30 days for adult emergence (Taley & Thakare, 1979) (Table 3).

Parasitism

Parasitism during March by *Monelta* sp. and *Rhoptromeris* sp. was 3.3 and 4.2%, respectively. Higher levels of parasitism by *Trichopria* sp. have been recorded from February (1.3%) to March (1.8–5.8%). The parasitism levels by *S. endius* range between 8.0 and 10.6% in June and October, respectively (Taley & Thakare, 1979) (Table 3).

PREDATORS

Diversity

More than 15 species of arthropods such as coccinellids, formicids, thrips, and spiders have been recorded as predators in sorghum fields on one or more stages of *A. soccata* (Table 5).

Ecobiology

Shoot fly eggs are among the most vulnerable to predation. In Burkina Faso, Zongo *et al.* (1993a) studied the feeding potential of *Tapinoma* sp. Forster (Formicidae) as a voracious

TABLE 5. Arthropod predators of sorghum shoot fly, *Atherigona soccata* recorded in different countries

Order/Family	Predator	Host	Country	Reference
Coleoptera				
Coccinellidae	*Brumoides suturalis* F.	Egg	Pakistan	Rahim, 1990
	Cheilomenes sexmaculata F. (*Menochilus sexmaculatus* Fabricius)	Egg	Pakistan	Rahim, 1990
	Coccinella septempunctata L.	Egg	Pakistan	Rahim, 1990
	Coccinella undecimpunctata L.	Egg	Pakistan	Rahim, 1990
	Scymnus trepidulus Weise	Egg	Kenya	ICIPE, 1982; Delobel & Lubega, 1984
Diptera				
Cecidomyiidae	*Dicrodiplosis* sp.	Egg	Burkina Faso	Zongo *et al.*, 1993d
Hymenoptera				
Formicidae	*Tapinoma* sp.	Egg	Burkina Faso	Zongo *et al.*, 1993d
Sphecidae	*Dasyproctus bipunctatus* Lepeletier and Brulle	Adult	Uganda	Deeming, 1983
Thysanoptera				
Haplothripinae	*Thrips* sp.	Egg	Burkina Faso	Zongo *et al.*, 1993d
Phlaethripidae	*Thrips* sp.	Egg	Burkina Faso	Zongo *et al.*, 1993d
Acari				
Erythraeidae	*Abrolophus* sp.	Larva	India	Reddy & Davies, 1978
Astigmata				
Araneidae	*Araneus* sp.	Egg	Burkina Faso	Zongo *et al.*, 1993a,d
	Spider (unidentified)	Egg	Kenya	Delobel & Lubega, 1984
Histiotomtidae	Spider (unidentified)	Egg	Burkina Faso	Zongo *et al.*, 1993b
Linyphiidae	*Meioneta prosectes* Locket	Egg	Burkina Faso	Zongo *et al.*, 1993d
Lycosidae	*Misumenops* sp.	Egg	Burkina Faso	Zongo *et al.*, 1993a,d
	Neoscona sp.	Egg	Burkina Faso	Zongo *et al.*, 1993a,d
	Pardosa injuncta P.P.Cbr.	Egg	Burkina Faso	Zongo *et al.*, 1993d
Salticidae	Spider (unidentified)	Egg	Kenya	Delobel & Lubega, 1984
Saproglyphidae	*Suidisia pontifica* Oudemans	Egg	Burkina Faso	Zongo *et al.*, 1993d
Theridiidae	*Latrodectus geometricus* C.L. Koch	Egg	Burkina Faso	Zongo *et al.*, 1993d
	Steatoda badia Rohwer	Egg	Burkina Faso	Zongo *et al.*, 1993d
Thomisidae	Spider (unidentified)	Egg	Kenya	Delobel & Lubega, 1984

predator of the shoot fly eggs. It consumes up to 18 eggs/day in the laboratory. In addition, the thysanopteran species (Phlaethripidae and Haplothripinae), a cecidomyiid species, *Dicrodiplosis* sp. and a few mite species of the family Histiotomtidae and *Suidasia pontifica* Oudemans (Astigmata: Saproglyphidae) were found in association with shoot fly eggs (7.1 per sample) (Zongo *et al.*, 1993a,d). Reddy and Davies (1979) observed *Abrolophus* spp. (Acari: Erythraeidae) feeding on eggs and larvae of *A. soccata* in India. Larvae of *Dicrodiplosis* spp. have also been reported as predators on mealy bugs. More research is needed to draw valid conclusions on the status and predatory potential of these predators for controlling shoot fly populations.

Several unidentified species of spiders from Kenya have been reported as predators on shoot fly eggs (Delobel & Lubega, 1984). In Uganda, Deeming (1983) reported predation of shoot fly adults by *Dasyproctus bipunctatus* Lepeletier and Burlle (Hymenoptera: Sphecidae). Forel (1920) mentioned that the genus *Tapinoma* sp. is widely distributed, but many species are opportunistic nestlers (Holldobler & Wilson, 1990). Zongo *et al.* (1993a,d) observed that saltids, thomisids, and aranaeids were predominant in a monocrop of sorghum, but the number of spider species such as *Araneus* sp., *Latrodectus geometricus* C.L. Koch (Theridiidae), *Meioneta prosectes* Locket (Linyphiidae), *Misumenops* sp., *Neoscona* sp., *Pardosa injuncta* P.P.Cbr. (Lycosidae) and *Steatoda badia* Rohwer (Theridiidae) increased in sorghum-cowpea intercrop. Bailey and Chada (1968) reported that the species belonging to Lycosidae, Thomisidae and Salticidae are common in sorghum crop, and spider populations in sorghum fields play a significant role in containing the sorghum insect pests. In view of the increase in spider population fauna by 31 days after crop planting, the period coinciding with the susceptible stage of sorghum to shoot fly, it may be concluded that spider populations play an important role in reducing the shoot fly populations. Zongo *et al.* (1993a,d) also opined that information on the bionomics of spider species may help to understand the real impact of spiders on shoot fly abundance in sorghum-based cropping systems.

PATHOGENS

Diversity

Information on the diversity of pathogens on shoot fly populations is limited. A fungus, *Fusarium* sp. Link ex Fr. and a bacterium, *Corynebacterium* sp. Lehmann and Neumann have been isolated from shoot fly eggs (Zongo *et al.*, 1993a,d). However, it may be that inoculum of these pathogens, which usually infects sorghum may persist in the field and contaminate the eggs of shoot fly. Further, the genus *Fusarium* infects a wide range of insect hosts. Some species such *as F. avenaceum* Fries Saccardo, and *F. merismoides* Corola have been recorded on the eggs of *Lymantria dispar* L. (Humber & Soper, 1986). Similarly, *Corynebacterium* species are widely distributed in nature, and some species are associated with insects and birds (Buchanan and Gibbons, 1974).

CHALLENGES AND CONSTRAINTS

Atherigona soccata continues to be an economically important pest on sorghum in the semi-arid tropics. For sustainable sorghum crop production, there is a need to consider the role of natural enemies as a component in integrated management of this species. The seasonal appearance of sorghum shoot fly depends mostly on the rainfall pattern, latitude, cultivar and time of planting. Sorghum is grown as a single season crop in most of the countries, except in India, where shoot fly infestation starts in early June, and during July and August in the north coinciding with the onset of monsoon rains. Although the crop harvest usually destroys the habitat, a small residual population of the natural enemies may survive on low populations of shoot fly on wild grasses, and on tillers from harvested stubble and ratoon sorghums during the off-season. Moreover, the coevolved guilds of natural enemies in some cases have been unable to exploit their host(s) in the ecosystem due to changes in cultivation of commercial cultivars vis-à-vis local landraces during the rainy and postrainy seasons, the canopy architecture or phenology, spread of the crop/cultivars into new areas, adoption of monoculture rather than polyculture production methods, and/or asynchrony between the parasitoid and the host. Thus, the parasitoids may simply be slow to follow the host.

Although parasitoids and predators are known to attack *A. soccata* at different stages, some of these associations may be incidental, whereby some species may be merely associated with other hosts. Among the egg parasitoids, the genus *Trichogramma* is most widely distributed in India, Burkina Faso, Kenya, and Thailand. In India, attempts to suppress *A. soccata* populations by augmenting *T. chilonis* populations have been inconsistent, and economic feasibility has not been demonstrated. Hymenopteran larval parasitoids have been reported on *A. soccata*, but reports on parasitoids that attack the pupal stage are relatively fewer. Although many of the parasitoids have evolved adaptations to access and exploit concealed larvae and pupae of shoot fly, generally these life-stages have not been sufficiently exploited by the parasitoids to reduce the pest density to below economic threshold levels (ETLs).

Natural enemy abundance and parasitism is highly dependent on location and season. Some parasitoids appear to be restricted to certain geographic areas and may be suitable for redistribution in other areas. Sorghum-based cropping systems are being practiced by the farming community in the semi-arid tropics. The influence of these cropping systems in promoting enhanced natural enemy activity needs to be assessed. Of greater importance is the paucity of information concerning the impact of known natural enemies on shoot fly populations in the field, and possible reasons for their failure to maintain *A. soccata* populations below ETLs. Researchers have carried out life-history studies on a few natural enemies to predict their ecological adaptability to aid in developing mass-rearing methods. There still is a need for identification and introduction of potential natural enemies, and also examine the possibilities for manipulating the sorghum-based cropping systems to enhance the impact of natural enemies, conserve the natural enemy fauna by synchronizing their seasonal abundance with that of the pest, establish the natural enemy population required per unit area, and study the economic impact of the natural enemies under subsistence farming. Life table studies have not been carried out on the population dynamics and survival rates of *A. soccata*. Gilstrap (1985) indicated the lack of intensive studies on the role of natural enemies on wild host plants of shoot fly. It has been suggested that the natural enemy diversity and enhancement of their efficacy through suitable sorghum-based cropping systems are the prerequisites without which their prospects cannot be assessed accurately for development and implementation of appropriate management strategies (Bellows *et al.*, 1992). Climatically comparable locations and those with similar habitats may harbor natural enemies with best ability for successful control of sorghum shoot fly.

Existence of a parasite in a natural habitat is most important, and success of associations follow a sequence of events by which the natural enemies utilize the host for development and survival. These events include: habitat selection, host-finding, and the behavioral aspects of the host, including the physiological aspects of host acceptance, host suitability, and host regulation. However, little attention has been paid to behavioral aspects. Cues associated with these processes are mainly derived from the sorghum seedlings, the microhabitat, and the host plant reaction to insect attack. There is a need to conduct studies on tritrophic interactions involving the host genotypes, natural enemy, and the environment, to understand the factors affecting the ecobiology and performance of natural enemies. The biology of most of the predators is unknown and their role in regulating *A. soccata* populations, individually or as a group, has not been quantified. There has been relatively little research effort on shoot fly predators due to the enormous amount of samples required, and the sampling time to produce quantitative data.

Among the natural enemies recorded, 11 species of insects, and several species of spiders predate on the eggs, larvae, and pupae of *A. soccata*. Deeming (1971) observed that the solitary larvae of *Scoliopthalmus micantipennis* Duda destroy young sorghum seedlings. But, Zongo (1992) reported that a dozen of *S. micantipennis* larvae are associated with *A. soccata* larvae in the same infested seedling. Similarly, the larvae of certain chloropids, *Anatrichus erinaceum* Loew., *Elachipterus abessynicus* Becker; a diopsid, *Diopsis* sp.; a phorid, *Megaselia scalaris* F. and a muscid, *Acritochaeta orientalis* Schiner have also been found in the infested seedlings along with sorghum shoot fly larvae, and it may be that the *A. soccata* damaged sorghum seedlings are more attractive to these insects (Gahukar, 1985; Doumbia & Gahukar, 1986). From a two-year study, Zongo *et al.* (1993a) reported highest percentages of larval parasitism by *N. nyemitawus* at 31 and 38 days after planting in monocrop sorghum and sorghum-cowpea intercrops, respectively.

Aprostocetus spp. have been recorded parasitizing eggs, larvae, and pupae of several species of Diptera, Hemiptera, and Coleoptera (e.g., eggs of *Tragocephala* sp. by *A.* near *diplosidis* Crwf. in West Africa) (Smith, 1961), *Conchyloctenia* (*Aspidomorpha*) *punctata parumaculata* (Boh.) by *A. aspidomorpha* Ferriere in Kenya (Maitai, 1958), and larvae of sorghum midge, *Stenodiplosis sorghicola* Coq. in East Africa (Geering, 1953); larvae and pupae of rice stem borer, *Pachylophus* sp. by *A. dioprisi* Risbec in Cameroon (Descamps, 1957), and grubs of amaranthus weevil, *Lixus truncatulus* Fab. by *A. krishnieri* Mani in India (Mani, 1941). Therefore, *Aprostocetus* sp. might play an important role in biological control of insects in sorghum. Similarly, *Callitula bicolor* Spin. has been recorded parasitizing the pupae of different species of frit fly viz., *Oscinella frit* Linn., *O. minor* L., and *O. carbonaria* L. in North America, and larvae of *O. frit* in Westphalis (Hemer, 1960). The spider, *Suidisia pontifica* Oudemans is associated with shoot fly eggs (Zongo *et al.*, 1993d), but earlier reports suggested that it is mycophagous (due to variable degrees of selectivity in choosing fungi) (Sinha, 1966). Thus, there may be misconception about their predatory nature on shoot fly eggs.

Recovery of parasitoids from immature stages presents different challenges. Rearing of immature stages of the parasitoids requires suitable growth stages of *A. soccata* in sorghum seedlings or a suitable artificial diet. Thus, there is a need to standardize artificial diet for shoot fly to enable the testing of these parasitoids across different growth stages, as well as mass multiplication and inundative releases on a large scale for biological control of the insect. With the advent of novel biotechnological tools, as well as the availability of new and potent Bt endotoxins (Cry II and Cry IV), which are effective for dipterans, future research efforts may have exciting potential in the development of transgenic sorghum plants resistant to shoot fly, but compatible with the natural enemy complex.

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