

An Updated Review of Research on *Heliocheilus albipunctella* (Lepidoptera: Noctuidae), in Sahelian West Africa

Ruparao T. Gahukar¹ and Malick N. Ba^{2,3,*}

¹Arag Biotech Pvt. Ltd., Plot 220, Reshimbag, Nagpur 440009, Maharashtra, India, ²International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Sahelian Centre, B.P. 12404, Niamey, and ³Corresponding author, e-mail: b.malick@cgiar.org

Subject Editor: Donald Weber

Received 26 September 2018; Editorial decision 23 January 2019

Abstract

In the Sahelian region of West Africa, pearl millet, which is a major subsistence food crop supporting families' livelihoods, is regularly attacked by the millet head miner/spike worm, *Heliocheilus* (= *Raghuva*) *albipunctella* de Joannis (Lepidoptera: Noctuidae). The pest infestation levels, damage ratings, and yield losses vary within and among countries because of differences in millet cultivars, the planting period, the onset time and seasonal distribution of rains, synchronization of moth flight with head development stages, and pest control practices. Egg laying by moths and the distribution of larval populations are governed by the development stages of millet head and the soil type. Rainfall patterns affect the distribution of diapaused pupae. The implications of this information for future pest control strategies are discussed in this review. Control measures including the planting of pest tolerant/resistant cultivars, the application of chemical pesticides, and the abundance of natural enemies have had significant impacts on larval mortality but have limited application. In recent years, augmentative releases of the larval ectoparasitoid, *Habrobracon hebetor* Say (Hymenoptera: Braconidae), have been tested in a pilot project in Burkina Faso, Mali, Niger, and Senegal. Because of the success of the program and the increasing demand for parasitoids farmers cooperatives are being engaged in producing parasitoids for the large-scale distribution of 'ready-to-use' bags containing braconids. This would sustain continuous availability and generate profitable businesses. To achieve this goal, farmers' economic problems and technical challenges need to be resolved at the village level, and marketing avenues need to be established.

Key words: biological control, head miner, pearl millet, pest ecology, pest management

In the Sahelian region of West Africa, pearl millet, *Pennisetum glaucum* (L.) R. Br., is a major staple food crop cultivated in poor sandy and loamy soils. Although monocropping is common, millet is often intercropped with cowpea, sorghum, or groundnut. Pearl millet is still the best choice for indigenous communities, because it is compatible with their food habits/preferences; it has good nutritional value; the crop has low input requirements; and it tolerates drought, heat, and erratic rainfall. Grain production is affected by the amount and seasonal distribution of rains and is negatively affected by weeds, pests, and plant pathogens.

During millet cultivation, plants are attacked by >100 insect species over all growth stages (Ndoye and Gahukar 1987, Nwanze and Harris 1992). Among them, the millet head miner/spike worm (MHM), *Heliocheilus* (= *Raghuva*) *albipunctella* de Joannis, is the most devastating pest. The millet head miner is a monophagous species that feeds only on millet. This insect species was first detected in the Sahel on wild millet *Pennisetum violaceum* (Lam.) and its hybrids in 1925. During the drought period in the 1970s, the

insect switched from wild species to cultivated millet varieties. The first outbreak was recorded in Senegal in the late 1970s (Vercambre 1978). It has a geographical distribution between the latitudes of 11° N and 15° N within the Southern Sahel and Sudan bioclimatic zones (Nwanze and Shivakumar 1990). Pest damage occurs every year, and the infestation levels have shown an increasing trend in Sahelian countries, notably Burkina Faso, Chad, Gambia, Mali, Mauritania, Niger, Nigeria, Senegal, and Sudan (Nwanze and Shivakumar 1990). Infestations of MHM are more severe in the drier zones of the Sahel (Gahukar et al. 1986). Almost every year, MHM outbreaks occur in the Sahel, especially in early planted or early maturing crops, causing yield losses of up to 85% (Gahukar et al. 1986, Nwanze and Shivakumar 1990, Krall et al. 1995, Youm and Owusu 1998a).

Damage to the millet crop is due to larvae that feed on the panicle and prevent grain formation (Gahukar et al. 1986). Young larvae perforate the glumes and eat away the flowers. The characteristic damage caused by later larval instars is spiral mines

produced by cutting floral peduncles as the larvae move (Fig. 1) (Gahukar et al. 1986).

The yield losses resulting from MHM have affected farmers' livelihoods and have motivated farmers, researchers, and government organizations to investigate control measures. This situation has led to the planning and execution of field projects funded by international donors from developed countries, including various French institutions, USAID, U.S. universities, the Natural Resources Institute of the United Kingdom, and the McKnight Foundation (USA). A research and development project on pest management (Projet de lutte intégrée= Integrated pest management) initiated by the Food and Agriculture Organization (FAO) in 1981 ended in 1987, and its activities and scientific collaborations were discontinued.

As pointed out by Payne et al. (2011), progress in implementing pest management programs has been sporadic during the last 35 yr, because of various constraints (deficiencies of laboratory equipment, infrastructure, trained personnel, and funds, and administrative barriers). In last decade (2006 to 2017), a project entitled 'Gestion intégrée de la mineuse de l'épi de mil' = Integrated Management of Millet Head Miner (Baoua et al. 2009), funded by the McKnight Foundation, has funded the establishment of laboratory and field research facilities and operational resources at national institutes in Burkina Faso, Mali, and Niger. In addition, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has established the Sahelian Center for Millets in Niger to continue research on MHM. Some French institutes are supporting projects in Senegal. These joint efforts have resulted in many publications (journal articles, country reports, conference proceedings). Gahukar et al. (1986) reviewed relevant research and highlighted gaps in the knowledge that should be addressed by local researchers and foreign collaborators. This review continues from that work and summarizes the results of more recent studies and progress in the assessment of yield loss, pest life history, and management practices. The ultimate aim of MHM research was

to develop efficient, cost-effective, practical, and environmentally friendly MHM control strategies for resource-poor farmers in the fragile agroecosystems prevailing in the Sahelian region.

Assessment of Pest Infestation and Yield Loss

Pest Infestation

The level of pest infestation varies considerably depending on the climate, soil type, crop cultivar, plant density, plant growth stage, dispersal of pest populations, and abundance of natural enemies (Gahukar et al. 1986). Head damage is affected by the level of pest infestation (percentage of infested heads), the size of the larval population (number of larvae/head), and the number and length of larval mines in the head. These parameters can be affected by the physical characteristics of the cultivar (head length and diameter, length and number of floral peduncles, length of involucre bristles, and head compactness) (Gahukar et al. 1986), planting date, period of panicle exertion, and the occurrence of a critical number of moths (Nwanze and Shivakumar 1990). In general, early planted or early maturing pearl millet becomes heavily infested with MHM (Gahukar et al. 1986, Nwanze and Shivakumar 1990, Eisa et al. 2007).

Pest infestation is expressed as the number of heads with eggs or larvae, irrespective of their stage of development. The severity of damage was initially rated on the basis of the number of mines per head using a 1–5 scale (Guevremont 1983), and was adjusted by (Gahukar 1984) to include only mines longer than 1 cm. After a decade, Youm and Owusu (1998a) proposed a 1–9 scale (1–2 = no damage, 3–5 = very little to moderate damage, 6–8 = moderate to severe damage, 9 = very severe damage) that is now used for rapid assessment. The reliability of the damage rating scale was confirmed by comparing observed and predicted yield losses in Niger (Youm and Owusu 1998a). Farmers tend to prefer visual assessments because they are faster and easier than more scientific methods to assess insect counts and damage (Youm and Owusu 1998b). Farmers are very knowledgeable about MHM and the damage it causes to millet (Youm and Owusu 1998b, Ba et al. 2013), but they tend to attribute crop loss primarily to visual head damage rather than the number of insects (Youm and Owusu 1998b).

Grain Yield Loss

On-farm losses have been estimated by measuring head damage and comparing grain yields (Nwanze 1988). Yield loss (%) is computed using the following simple formula: (grain weight in severely damaged head/grain weight in healthy head) × 100. This is a practical and easy method that can be used by technical staff with little technical background. The losses can vary depending on the crop season, millet cultivar (cv.), and geographical location in each country, as explained in Table 1.

Krall et al. (1995) reported variable yield losses due to MHM across West Africa, with losses of up to 85%. They established the following relationship between the number of MHM larvae per head and grain loss: 1–2 larvae = 3.5% loss, 3–4 larvae = 20.7% loss, 5 larvae = 34.5% loss, and >5 larvae/head = 46.8% loss. A recent study of the local cv. Souna in Senegal reported average mine length of 9.37 cm (range of 1–44 cm), and two mines/head (range of 1–11 mines), with grain loss of 10.6% (range of 3.8–17.2%) (Thiaw et al. 2017a). Likewise, Sow et al. (2017) reported 2–20% grain losses in 2013–2014 in Senegal. The ratings of millet crops assigned by farmers and researchers showed that the rating system can be used for quick on-farm assessments of yield losses. Surveys indicated that the farmers were aware of the benefits of crop loss assessment



Fig. 1. Pearl millet head infested by head miner (left) and miner larvae inside head (right).

Table 1. Yield losses reported from three countries during different crop seasons

Country	Region	Crop season	Cultivar	Yield loss (%)	Reference
Senegal	Central region	1974–1977	Souna-3	13.0–85.0	Gahukar (1982)
		1981–1982	Souna-3	3.0–82.0	Gahukar (1982)
		1982–1983	Souna-3	17.0–100	Gahukar (1983)
Niger	Central region	1980–1983	Sadore	1.0–41.0	Nwanze and Shivakumar (1990)
		1981–1982	IVSP-78	6.0	Guevremont (1982)
		2015–2016	Sadore	60.0	Amadou et al. (2017)
	Southern region	1985–1986	Sadore	82.6	Youm and Owusu (1998b)
		1995–1996	Sadore	11.7–41.9	Youm and Owusu (1998a)
Burkina Faso	Southern region	1987–1988	Local	16.0–85.0	Anonymous (1990)

studies (Youm and Owusu 1998b). Most farmers (85.3%) were able to assess qualitative losses, but only 14.7% of farmers could perceive losses in grain yield. These findings are rather unexpected because farmers can directly observe grain losses in fields.

Pest Life History

Vercambre (1978) and Guevremont (1982, 1983) studied the life cycle of MHM in detail. It completes only one generation per year. In Niger, the flight period spans some 6–8 wk, but the moth population usually peaks at the end of August, coinciding with the main period of emergence and flowering of millet panicles (Guevremont 1982, 1983). For 2–3 h after dusk, males generate a buzzing sound by the percussive vibration of their forewings, while simultaneously exposing their genitalia. This display is performed either singly or by groups of males perched low down on millet stems or vegetation at the side of the fields. Females approach buzzing males directly from downwind, and mating occurs immediately on arrival, lasting for ~1 h (Green et al. 2000a,b). In the field, more females invade millet fields on nights with wind than on nights without wind (especially after rain) or nights very strong wind (Owusu et al. 2004). The females can be seen flying through millet fields from dusk onward (Green et al. 2000a), actively moving between millet panicles. The females prefer to oviposit on millet panicles at 30% exertion development stage compared with flowering panicles and panicles at grain-filling stages (Owusu et al. 2004, Karimoune et al. 2018).

After landing on millet panicles, females can spend 15–20 min walking slowly upward toward the apex of the panicle, probing with the ovipositor before ovipositing (Owusu et al. 2004). Typically, eggs are laid singly or in small clusters on the panicle and are attached loosely to the rachis or the base of the florets or their peduncles (Vercambre 1978). Majority of eggs (80–90%) are laid within 3–5 cm of the tip/head (Vercambre 1978). Females lay about 300–400 eggs in total, in batches of 20–50 eggs (Bernardi et al. 1989 Nwanze and Harris 1992) but can lay as many as 93 eggs per head during head development (Bhatnagar 1983). On fully developed heads, 52.0% of the eggs are laid on involucre bristles of the flower, 36.5% on the stamens, and 11.5% on the rachis (Gahukar 1990a). Eggs normally hatch in 3–5 d and the developing larvae feed on floral glumes and flower stems. Larval development passes through five instars and takes ~25 d under laboratory conditions (27–31°C and 14:10 [L:D] h; Green et al. 2004). Thiaw et al. (2017a) recorded on average of 1.60 larvae per head (maximum of 42 larvae per head) in Senegal. Thus, a mean population of 230,000–350,00 larvae/ha can be present in millet fields in heavily infested areas. Final instar

larvae turn green and then pink prior to pupation. In the field, the prepupal larva emerges from the panicle, drops to the ground, and then burrows to a depth of about 25 cm before pupation occurs (Nwanze and Shivakumar 1990, Green et al. 2004). Pupae remain in diapause for about 10 mo. Pupal mortality occurs if loamy soil becomes compact once the rains are over or in sandy soil lacking moisture if rains stop early. For example, 15,000–140,000 pupae/ha were recovered by digging the soil in a central region of Senegal where the local cv. Souna-3 was planted (Vercambre 1978, Gahukar 1990a). This nearly 10-fold variation in larval abundance could be attributed to crop season, rainfall distribution, soil type, and larval survival. Approximately half of pupae in diapause (51.0%) were found within 25 cm of the plant at 10- to 20-cm soil depth in Niger (Nwanze and Shivakumar 1990), whereas diapaused larvae were found to be distributed at a depth of 10–15 cm in loamy soil and 20–30 cm in sandy soil in Senegal (Gahukar 1990a).

Normally, diapause ends when the soil moisture content increases to an adequate level after the onset of the rainy season. Moth emergence is facilitated by loose soil. The moths emerge nearly 1 mo after first rains of the season, and live for 2–7 d (Kad-Kadi et al. 1998). Hughes and Rhind (1988) studied adult emergence in Sudan and reported that the peak flight period occurred 7 wk after a rainfall of >300 mm, which coincided with peak of head emergence and flowering. Analyses of insects caught in light traps indicated a higher number of female moths than that of male, affecting sex-ratio in moth populations (Bhatnagar 1983, Guevremont 1983, Bayoun et al. 1995). These findings may be used for mass trapping of females and reducing their populations in the field.

Natural Enemies of MHM

An exhaustive list of MHM natural enemies was provided by Bhatnagar (1987) and completed by Ndoye (1991). In summary, Gahukar et al. (1986) reported 11 insect predators, 12 insect parasitoids, 1 nematode parasitoid, and 3 pathogens. Recently, Sow et al. (2018) updated the list of natural enemies of MHM in Senegal. By using DNA sequencing, they identified 13 species of primary parasitoid, including 10 Hymenoptera belonging to the Braconidae (7), Ichneumonidae (1), Encyrtidae (1), and Trichogrammatidae (1), and 3 tachinid flies (Diptera). Other predators include ants (28% of population), earwigs (26%), mirid bugs (20%), spiders (12%), carabid beetles (7%), anthorid bug (6%), and coccinellid beetles (1%) (Sow et al. 2018). The occurrence and distribution of predators was noted from head emergence to grain maturity, but their role in the mortality of eggs and larvae was not investigated (Sow et al. 2018).

The parasitoids include egg parasitoids, *Trichogrammatoidea* spp., which were found to parasitize 2.0–60.0% of MHM eggs (Bal 1993, Thiaw et al. 2017a). The parasitoid *Trichogrammatoidea armigera* Nagaraja (Hymenoptera: Trichogrammatidae) was found to parasitize 12.4% of MHM eggs in Senegal (Sow et al. 2018). In Niger, unidentified *Trichogrammatoidea* spp. were found parasitizing up to 10.0% of MHM eggs (Garba and Gaoh 2008). The species was confirmed as *T. armigera*, and a recent study found that it parasitized 17.0% of MHM eggs in Niger (Karimoune et al. 2018). Another egg parasitoid, *Telenomus* sp. (Hymenoptera: Scelionidae) was also detected in Niger (Nwanze and Harris 1992).

In addition to egg parasitoids, there is an ovo-larval parasitoid, *Copidosoma* (= *Litomatix*) sp. (Hymenoptera: Encyrtidae) (Bayoun et al. 1995, Boire 1998, Sow et al. 2018). *Copidosoma* lays its eggs in MHM eggs, and the eggs continue to develop in the MHM larvae. Its parasitism level ranged from 14.1 to 31.0% in Senegal (Bhatnagar 1984, Ndoye 1991) but could reach 80–90% under favorable conditions (Vercambre 1978). This species has recently been identified as *Copidosoma primulum* Mercet and was found to account for 45.8% of MHM larval parasitism in Senegal (Sow et al. 2018).

Another larval parasitoid, *Cardiochiles* sp., has also been reported from Niger and Senegal (Bhatnagar 1984, Ndoye 1991, Boire et al. 1998). Recently, Sow et al. (2018) confirmed the identity of *Cardiochiles* sp. as *Schoelandella sahelensis* Huddleston & Walker (Hymenoptera: Braconidae). Another larval parasitoid, *Pristomerus pallidus* Kriechbaumer (Hymenoptera: Ichneumonidae) has been detected in Senegal (Bhatnagar 1987, Ndoye 1991, Sow et al. 2018). According to Sow et al. (2018), *S. sahelensis* and *P. pallidus* caused 32.4 and 10.2% parasitism of MHM larvae, respectively. Earlier studies in Senegal reported 59.0–94.0% larval parasitism due to *Habrobracon* (= *Bracon*) *hebetor* Say (Hymenoptera: Braconidae) (Bhatnagar 1984). However, the recent study by Sow et al. (2018), who used DNA tools to identify parasites, indicated that *H. hebetor* no longer parasitizes MHM in Senegal. However, *H. hebetor* remains the major larval parasitoid of MHM in other Sahelian countries and causes as much as 95.0% larval parasitism (Guevremont 1983, Bayoun et al. 1995, Ba et al. 2010). This parasitoid is active during the latter part of the crop season after crop damage has occurred (Ba et al. 2010).

Among the pathogens, *Aspergillus* sp. infects ~4% of pupae (Bhatnagar 1984). Sow et al. (2018) reported on the infection of MHM by an unidentified entomophagous nematode species (Sow et al. 2018). The impact of diseases as natural agents on pest mortality needs to be studied more.

Management Measures

Cultural Practices

Various cultivation practices such as the planting of trap crops, changing the planting period, deep ploughing, and fertilization have been tested against MHM. The cvs. MBH-110, ICMV-IS-89305, and Chalakha have been suggested as trap crops for planting around the main field to attract moths for egg laying (Owusu et al. 2004). This approach has never been field-tested.

Likewise, ploughing millet fields up to 15- to 25-cm deep in the off-season in April–June exposed the pupae to heat, resulting in desiccation, and to predators and parasitoids (Gahukar 1990a). This resulted in a 20% increase in pupae mortality (Gahukar 1990a). However, this practice has not been scientifically tested and replicated. Recommending this practice may, therefore, be precarious. In many Sahelian countries, most farmers do not plough sandy soil. Also, ploughing could be harmful in causing soil erosion, as pointed out

by Ratnadass et al. (2014). For ploughing to be effective, all farmers in the area would have to plough their land, otherwise MHM moths could fly in from neighboring uncultivated areas.

The late planting of pearl millet was recommended to avoid the moth flight period coinciding with vulnerable stages of head development (Nwanze and Harris 1992). The MHM population densities were significantly reduced by delaying planting of short-cycle cvs. by 2 wk in Senegal (Vercambre 1978), Sudan (Hughes and Rhind 1988), and Niger (Youm and Giltrap 2011). Delayed plantings, however, are vulnerable to a lack of soil moisture if the rains stop early and are prone to attack by stem borer, *Coniesta ignefusalis* Hampson (Lepidoptera: Crambidae), and gall midge, *Geromyia penniseti* Felt (Diptera: Cecidomyiidae) (Gahukar et al. 1986). For these reasons, and because of unpredictable rainfall, most farmers in the Sahel plant just after the first heavy rains or sometimes in dry soil before rain. Most of the time, farmers sow millet two to three times for successful crop establishment. Thus, there is no fixed temporal pattern of resowing.

Crop fertilization as a method to control MHM has had mixed results. In Sudan, application of triple superphosphate at 20 kg/ha enhanced plant growth and reduced MHM attack by 27–36%, because the period from planting to heading was considerably reduced (Hughes and Rhind 1998). Thus, the reduction in MHM attack could not be directly attributed to soil fertilization and could vary with the type of cultivar because the emergence of the heads prior to the emergence of the pest is crucial. A dose of 30 kg N/ha or 30 kg P/ha applied separately or in combination did not result in significant differences in head infestation compared with that in nonfertilized fields in Gambia (Zethner and Olivier 1984). In Senegal, soil application of urea at 50–200 g/ha or NPK (10:20:20) fertilizer at 50–300 g/ha significantly reduced head infestation and the number of larvae in cvs. Souna and IBV-8001, but application of superphosphate at 50–200 kg/ha did not have these effects (Gahukar 1992). These recommendations have never been implemented, as the application of mineral fertilizer to pearl millet is not common in the Sahel due to the market price.

Mechanical Measures

Light traps and/or pheromone traps are a practical and effective method for monitoring adult MHM populations. So far, pheromone-mediated mating behavior has not been demonstrated for *H. albipunctella* (Green et al. 2000a,b). Traps with 25-W mercury vapor battery-operated lamps caught 1,300 moths per night in millet fields in Niger (Guevremont 1983) and traps with 125-W mercury vapor lamps caught 7,143 moths per night in Senegal (Bhatnagar 1983). In Niger, as many as 700 individuals were caught in one night in a light trap operated with a 250-W mercury vapor white incandescent bulb in 2015 (Ba et al. 2017). Further studies are required to determine the optimal number of traps required per acre of pearl millet, the optimum installation height, and their cost effectiveness in terms of photovoltaic energy. This could be implemented as an integrated approach to control MHM and other insect pests of pearl millet in association with poultry production, where insects are used as feed.

Use of Pest Tolerant/Resistant Cultivars

Resistance and/or tolerance to MHM has been reported for three cvs.: 3/4 HK, Souna, and ICMV-7819 in Mali, Burkina Faso, Senegal, and Niger (Gahukar et al. 1986). However, an earlier study did not find this difference (Vercambre 1978). In a 2-yr field screening trial of 20 cvs. in Senegal, Gahukar (1990c) noted significantly smaller proportions of infested heads in the improved cv. IBV-8004 (21.9–40.0%) than in the local cv. Souna (56.7–60.0%). Interestingly, the

local cv. was more tolerant to MHM than the improved cv. IBV-8004. Recently, Goudiaby et al. (2018) identified MHM resistance in the variety ISM-19705 and MHM tolerance in Thiameck-2. However, because their observations were based on natural infestation, one could not rule out natural low infestation rates. Using the egg infestation technique developed by Youm et al. (2001), researchers at ICRIAT found consistent resistance in the genotypes Moro, Souna 3, and PE08043 after 3 yr of screening (Ba et al. 2017). Resistance to MHM has been attributed to various characters; varieties with compact heads; varieties with small involucre bristles and small floral peduncles experienced less damage (Guevremont 1982, Gahukar 1984), antibiosis, and antixenosis (Ba et al. 2017). Further research is needed to identify the genetic basis of resistance to MHM.

Plant-Derived Products and Synthetic Pesticides

In Sudan, pyrethroids (including cypermethrin) significantly reduced pest incidence but did not significantly increase grain yield (Hughes and Rhind 1998). A single spray at 75% flowering or two sprays, the first at beginning of flowering and the second at 5–7 d later, of synthetic pesticides (endosulfan, trichlorfon, acephate, chlordimeform, trichlorfon, and chlorpyrifos) and insect growth regulators (diflubenzuron and lufenuron) were tested in Senegal and Niger. These treatments had limited effectiveness because the larvae hide in spikelets, thereby avoiding contact with the insecticide (Gahukar et al. 1986). Another factor is the proper stage of head development for treatment. In the local cv. Souna, the most susceptible stage for insecticide spraying was found to be the head emergence stage (10–15 cm from flag leaf). Spraying at this stage resulted in lower rates of head infestation (21.2–24.4%) and smaller larval populations (7–24 larvae/10 heads) than those in plants sprayed at the 50% female flowering stage (34.2–73.2% infestation and 12–84 larvae/10 heads) or the milky grain stage (45.0–51.5% infested heads and 17–176 larvae/10 heads). It is, therefore, advisable to treat crops at the head emergence stage, the preferred stage for ovipositing (Gahukar 1990b).

Given the types of sprayers available (knapsack/backpack sprayers), the application of pesticides to pearl millet head in the Sahel could be somewhat challenging. Moreover, the economic benefits to smallholder farmers of applying synthetic pesticides to pearl millet are still to be demonstrated. The chemical pesticides used to control insect pests are toxic to the major parasitoid, *H. hebetor* (Dastijerdi et al. 2009). Therefore, their use cannot be recommended. Instead, alternative ecofriendly or less toxic pesticides such as plant products (Anaso et al. 1998) or biopesticides (Dastijerdi et al. 2009) should be tested. The neem tree in the Sahel is not used to produce plant protection products, although it is abundant in and around villages. In Mali, Passerini (1991) found that 0.5–1.0% aqueous extracts of neem seed kernels were effective against MHM in caged plants, with residual effects of up to 7 d. A reduction in MHM infestation after on-farm spraying of neem was also observed (Passerini 1991). However, as reported in other settings, the effectiveness of neem is variable from year to year (Bottenberg and Singh 1996). This should not be surprising because the concentration of active chemicals may vary from plant to plant, among seasons, and with the maturity of the source material. This would result in variations in the effectiveness of neem products depending on the neem harvest time and location.

Biological Control

Current research is focussed on the use of natural antagonists against MHM, and encouraging significant results have been obtained in Burkina Faso, Mali, Niger, and Senegal.

Conservation Biological Control

Thiaw et al. (2017b) found that landscape was an important factor in controlling MHM because of the diversity of the millet agroecosystem. They found that the biocontrol service index values increased with landscape diversity. Landscape diversity and composition around millet fields at 1,750-m distance was responsible for variations in the effectiveness of biological controls. In fact, according to Soti et al. (2019), landscape diversity, and tree density, especially the ratio of seminatural vegetation within landscapes enhances biological control of millet head miner. Sow et al. (2017) and Lale and Igwebukew 2002 found that, particularly the common tree, *Faidherbia albida* (Dell) A. Chev. enhanced the survival of *H. hebetor*, which feeds on its flowers. Recently, Brevault and Clouvel (2019) discussed the role and potential of landscape including cultivated and uncultivated habitats of pests and agroecological management (farming practices, life system of pest populations, impact of natural enemies, etc.). They found that biological control was enhanced, at a local scale, in close-to-village fields compared with distant and usually less organically fertilized bush fields (Brevault and Clouvel 2019). To target pest control in pearl millet, Soti (2018) suggested the use of remote sensing and geographical information system to map areas of pest infestation with vegetation in regularly damaged cultivars in 'hot-spot' areas.

Augmentative Release of *H. hebetor*

The use of native *H. hebetor* in augmentative biological control against MHM started in the 1980s in Senegal (Bhatnagar 1989). Bhatnagar found that the parasitoid survived the dry season on *Ephestia* sp. on stored grains. He, thus, began rearing *H. hebetor* using *Ephestia* larvae as the host in simple jute bags and/or bamboo sticks placed in baskets or clay jars. Over the next few years, Bhatnagar (1989) further refined the method of rearing *H. hebetor*, with a view toward a rearing and release system that could be adapted to on-farm conditions. In 1985 and 1986, initial release trials were carried out. The rate of parasitism was 50–78% in fields where releases had occurred, compared with only 19% in control fields (Bhatnagar 1989). Augmentative releases of *H. hebetor* were attempted in Niger from the late 1990s to early 2000s (Garba and Gaoh 2008). More recently, augmentative releases of *H. hebetor* have been successfully carried out in Burkina Faso, Mali, and Niger (Payne et al. 2011; Ba et al. 2013, 2014; Baoua et al. 2014).

Rearing of Parasitoids

The development of a mass culture method was required to obtain sufficient *H. hebetor* for augmentative releases. Since the parasitoid could not be reared on MHM (Green et al. 2004), there was a need to identify an alternate host for parasitoid rearing. Based on the polyphagous behavior of *H. hebetor* to attack many lepidopterous species in stored grain, the parasitoid was first reared on *Ephestia* sp. (Lepidoptera: Pyralidae) (Bhatnagar 1989). Later, in Niger, a method for the mass culture of the parasitoid reared on the larvae of rice moth *Corcyra cephalonica* (Stainton) was developed (Bal et al. 2002). In that method, *C. cephalonica* was reared in wooden cages (20-cm long × 20-cm wide × 13-cm deep) with muslin cloth on three sides. A mixture of 1.2-kg millet flour and 1.8-kg millet grains was added to each cage, and then inoculated with ~3,000 eggs of *C. cephalonica*. Subsequent generations were regularly obtained after 30 d at room temperature (average 26°C), and third- and fourth-instar larvae were used for mass rearing of *H. hebetor*. For this purpose, *C. cephalonica* larvae were confined within a Petri dish for 48 h with two mated *H. hebetor* females. A subsequent generation of *H. hebetor* emerged 7–14 d after confinement (Ba et al. 2013). The mass rearing of *H. hebetor* was further refined

by Kabore et al. (2018). They found that *H. hebetor* females fed with 30% honey solution and supplied daily with one late-larval-stage *C. cephalonica* produced the most progeny and that optimal times for mating and egg fertilization were achieved when a male and female pair was confined for 24 h in a 30-cc vial. The suggested rearing method resulted in 14 times greater parasitoid production than a method in which females are given 25 larvae of *C. cephalonica* all at once (Kabore et al. 2018). Further studies showed that parasitoid females could be stored for up to 3 wk at fluctuating temperature (23–32°C) and 25–80% relative humidity to increase their numbers before on-farm augmentative release without altering their fitness (Kabore et al. 2018). In addition, the quality of the host larvae, *C. cephalonica*, and the emerging numbers of *H. hebetor* were found to be significantly increased by feeding *C. cephalonica* on a mixed diet of pearl millet and cowpea (Amadou et al. 2018).

Technique for Field Release of Parasitoids

Ba et al. (2014) developed a simple and effective technique for on-farm delivery of parasitoids for augmentative release. In this method, a jute bag (10-cm long × 7-cm wide) was filled with 50-g millet grains, 30-g millet grain flour, and 25 larvae of *C. cephalonica*, and then two mated *H. hebetor* females were added. The parasitoid adults started emerging from the bag 8 d after confinement, and 57–71 adults without deformation emerged from the bag. This technique has proved to be the most effective, practical, and cheap method for rearing host larvae and parasitoids. In a practical test of the method, 15 parasitoid bags were distributed to the farmers in villages in an area with 1-km diameter (Ba et al. 2014). Bags were suspended from the ceilings of nearby straw granaries or hung from trees in millet fields. Parasitoids multiplied within the bag, exited through the jute mesh, and dispersed in the field. Approximately 1,000 parasitoids were released in 12 d (average adult life span) with 15 bags per village. This technique for the mass release of parasitoids is currently used in Burkina Faso, Mali, and Niger.

Impact of Released Parasitoid on Larval Mortality

Ba et al. (2013) reported up to 97.0% pest mortality in fields covering over 3 million ha in 500 villages in Mali, Burkina Faso, and Niger. In Burkina Faso, releases of parasitoids in two successive years did not necessarily increase the level of parasitism in the second year, but slightly reduced the number and length of mines caused by MHM (Kabore et al. 2017). Parasitism decreased in subsequent years if no additional parasitoids were released (Kabore et al. 2017). In Niger, augmentative releases using the jute bag technique resulted in 90–95% parasitism of MHM (Ba et al. 2014, Baoua et al. 2014). Further augmentative releases of *H. hebetor* in Niger in 2015 and 2016 resulted in more than eightfold increase in parasitism and resulted in fewer mines per head (Amadou et al. 2017). Overall, the releases of *H. hebetor* led to a 34% grain yield increase, on average (Baoua et al. 2014). Farmers perceived a significant gain in grain yield due to the biological control (Ba et al. 2013, Amadou et al. 2017).

In a study on the field dispersal of *H. hebetor* in millet in Burkina Faso and Niger, Baoua et al. (2018) recorded weekly parasitism levels at 3 and 5 km away from release points and at a control site (a village 15 km away from the dispersal point). At each site, 900–1,000 braconids were released over a period of 3 wk. At first, parasitism levels were higher at the dissemination site than at sites 3–5 km away. Later, successive generations dispersed up to 3 km from the dissemination site and caused 90% MHM mortality in 5 wk, which was equal to that recorded at the release points.

Therefore, Baoua et al. (2018) recommended that parasitoids should be released at field sites with 3-km spacing to achieve timely and effective pest control.

Commercialization of the Technique

Guerci et al. (2018) recently recommended the jute bag technique to multiply and spread *H. hebetor* in Niger. Small local industries can sell bags containing *H. hebetor*. Generally, 15 bags are needed for each village, and the business can be profitable when 195 bags are sold to 13 villages. For distribution of bags containing braconids, bags can be prepared by each enterprise by hiring three local workers from late May to late August. This pilot project launched in Niger in 2015 showed that parasitoids could be transported up to 500 km away without losing their efficacy for pest control. It is expected that the current price of US\$3–4 per bag could be reduced depending upon the number of villages and farmers who would be willing to purchase these ‘ready to use’ bags.

Guerci et al. (2018) calculated the value of yield gain at US\$2.08–460.00/yr. Nevertheless, net financial benefits to each enterprise in each country will depend upon variations in the market price of millet grain and fees paid to market agencies or cooperative societies when purchasing grain. This technique and the business model were found to be successful and sustainable in a trial in Niger, where 12,000 bags in 500 villages were sold in 2015 and 2016. Therefore, it may have bright prospects for use in other Sahelian countries.

Recommendations

It is feasible to rear *H. albipunctella* in the laboratory on an artificial diet, as demonstrated by Green et al. (2004). The multiplication of larvae will facilitate infestation of millet heads artificially using the Youm et al. (2001) technique, so that genotypes bred for high grain yield can be screened for their susceptibility to MHM. Another alternative is to run a set of two to three light traps to collect MHM moths, allow them to lay eggs on millet heads in the laboratory, and then use the eggs to infest millet heads in the field (Ba et al. 2017). Laboratory rearing had been tested in Senegal, where MHM were fed on a diet of corn meal and millet flour (Vercambre 1978). Research to optimize the diet and rearing conditions for MHM as described by Kadi-Kadi (1999) should be re-established so that insects are available for the screening of millet genotypes.

For biological control, the augmentative release of efficient parasitoids like *H. hebetor* is a welcome step. However, the braconid was reported to be attacked by two hyperparasitoids, *Eurytoma* sp. (Pteromalidae) and *Pediobius* sp. (Eulophidae), the latter achieving up to 56% hyperparasitism in millet fields in Niger (Guevremont 1983). This issue has not been addressed in projects implemented in the Sahel. The current impact of these hyperparasitoids is still unknown, but it may be necessary to maintain a high population of braconids during the peak pest infestation period. This can be achieved with augmentative releases and management practices (agroforestry, manure fertilization) that enhance antagonist survival and multiplication. Moreover, biological control programs could be reinforced by adding the egg parasitoid *Trichogrammatoidea armigera* Nagaraja. This could complement the current program and may result in better control of MHM.

The *H. hebetor* jute bag technique seems practically feasible and cost-efficient and can be implemented in Sahelian countries (particularly, Mali, Burkina Faso, Niger, and Senegal). However, the success of this technique depends upon how many farmers are willing to pay for the parasitoid bags. As revealed by Guerci

et al. (2018), commercialization of *H. hebetor* may encounter a 'free rider' problem because all farmers within a 3- to 5-km radius of release could benefit from the parasitoids' activity. Therefore, farmers could have an incentive to wait for their neighbors to buy parasitoids so that they can receive the benefits without incurring the cost. This could potentially make it difficult for businesses producing the beneficial insects to sell requisite quantities to cover costs. As suggested by Guerci et al. (2018), establishing cooperatives to purchase parasitoids could limit the free-riding problem. Further trials are needed to test the effectiveness of such an approach.

The developmental stages of millet head (emergence, flowering, and grain dough stage) and local weather conditions are important for rapid pest multiplication. A forecasting and warning system can be implemented by the Regional Center of Agriculture, Hydrology, Meteorology (AGRHYMET) based at Niamey (Niger), at least in 'hot-spot' areas. Such forecasting has a role to play in the context of climate change and may help farmers to modify cultivation practices according to the conditions in each country. Broadcasting announcements of the peak infestation period, availability of parasitoid stock, and planned release periods through radio programs, group meetings, and other possible means would increase farmers' awareness and confidence.

Although much research has been carried out on individual control measures, efforts to integrate them in an effective integrated pest management module are lacking. Currently, the emphasis is on biological control, but integration with pest-resistant cultivars could give better protection. The ICRISAT Sahelian Center can probably develop cultivars that are resistant/tolerant to MHM (using the Moro, Souma 3, and PE08043 cvs as donor parents), and augmentative releases of parasitoids of MHM would further reduce the incidence of the pest.

Disseminating biological technologies in farming communities needs strong extension, which is currently not the case in Sahelian countries (Gahukar 1990d). Training of local government staff and personnel from co-operative societies associated with grain marketing is essential. There is also a need to educate farmers by holding classes and field demonstrations, and to increase local empowerment and understanding of the potential of biological control. The extension activities should cover surveys in areas where braconids are released, to learn about farmers' difficulties in adopting the technique, and the impacts of parasitoid releases in different cropping systems and geographical locations. Participation of farmers (individuals and groups), NGO extension workers, researchers, cooperative societies/federations, and local government staff can achieve the goal of mass releases on a wide scale in millet-growing zones in each country.

Conclusions

For more than 20 yr, MHM has regularly devastated crops of pearl millet, a major subsistence food crop in the Sahelian region of West Africa. Recent research on this pest has significantly complemented earlier findings on bioecology and control. A high level of pest infestation and plant damage results in considerable losses in grain yields. The losses greatly vary with cultivation practices, particularly the cultivar planted, geographical location, and rainfall pattern in each area. Few moths may be able to produce a second generation in the same field. This is an alarming fact that needs urgent attention because the larvae may damage late-planted cultivars or plants with late tillers which otherwise escape pest attack. Further research is needed to identify pheromone components that can be used to trap male moths.

To control the pest efficiently, it is important to develop practical, simple, and cost-effective control measures for easy adoption by farmers. Natural enemies causing egg and larval mortality have not received much attention from researchers. Pest-tolerant/resistant millet cultivars are not available to farmers in every country, and local cultivars vary in their pest tolerance. An integrated pest management strategy has not yet been planned or implemented. Currently, the development of biological control has been given priority and augmentative releases of a larval ectoparasitoid (*H. hebetor*) have been tested in Burkina Faso, Mali, and Niger. Recent trials have confirmed that the release of *H. hebetor* can be practically applied at the village level. Commercialization of the technique has been proposed and may prove to be a profitable business for local entrepreneurs. This should be tested in practice, because farmers may not be willing to pay US\$3–4 per bag. Because millet is a subsistence crop that supports the family livelihood of poor farmers, initiating and encouraging biocontrol as a business concept in the Sahel with its fragile ecosystem, poor crop yields, and weak economy is a significant challenge.

Acknowledgments

We are greatly thankful to our colleagues currently working on millet head miner, for their suggestive criticism of the manuscript. The second author is grateful to the Collaborative Crop Research Program (CCRP) of the McKnight Foundation, Minneapolis, MN, for funding most of the recent research on biological control of the millet head miner reported in the paper. This work is part of the CGIAR Research Program on Grain Legumes and Dryland Cereals (GLDC-CRP).

References Cited

- Amadou, L., I. B. Baoua, M. N. Ba, B. Haussman, and M. Altine. 2017. Gestion de la chenille mineuse de l'épi du mil par des lachers du parasitoïde, *Habrobracon hebetor* Say au Niger. Cah. Agric. 26: 55003.
- Amadou, L., I. B. Baoua, M. N. Ba, and R. Muniappam. 2019. Developing an optimum diet for mass rearing of the rice meal moth *Corcyra cephalonica* (Stainton) (Lepidoptera: Pyralidae) for production of the parasitoid *Habrobracon hebetor* Say (Hymenoptera: Braconidae). Accepted in J. Insect Sci.
- Anaso, C. E., N. E. S. Lale, M. A. Kano, and A. B. Anaso. 1998. Use of pesticidal plant extracts for pest control in millet based cropping systems, pp. 154–170. In A. B. Emechebe, C. Ikwelle, O. Ajayi, M. Aminu-Kano, and A. B. Anaso (eds.), Pearl millet in Nigerian agriculture. Ramadan Press, Maidugiri, Nigeria.
- Anonymous. 1990. Rapport des groupes de travail mil. Sahel PV Info. 19: 4–6.
- Ba, M. N. 2017. Sustainable large-scale biological control of the millet head worm in the Sahel. ICRISAT Technical annual report for Mcknight foundation. ICRISAT, Niamey, Niger.
- Ba, M. N., C. L. Dabire-Binso, A. Sanon, B. Diallo, A. Kabore, and T. Ouedraogo. 2010. Integrated management of the millet head miner for enhancement of millet productivity in the Sahel. Internal report, INERA, Kamboïse, Burkina Faso.
- Ba, M. N., I. B. Baoua, M. N'Diaye, C. Dabire-Binso, A. Sanon, and M. Tamo. 2013. Biological control of the millet head borer, *Heliocheilus albipunctata* in the Sahelian region by augmentative releases of the parasitoid wasp, *Habrobracon hebetor* effectiveness and farmers' perceptions. Phytoparasitica. 41: 569–576.
- Ba, M. N., I. B. Baoua, A. Kabore, L. Amadou, N. Oumarou, C. Dabire-Binso, and A. Sanon. 2014. Augmentative on-farm delivery methods for the parasitoid, *Habrobracon hebetor* Say (Hymenoptera: Braconidae) to control the millet head miner, *Heliocheilus albipunctata* (Lepidoptera: Noctuidae) in Burkina Faso and Niger. Biocontrol. 59: 689–696.
- Bal, A. B. 1993. Etude du parasitisme naturel d'*Heliocheilus albipunctata* de Joannis (Lepidoptera: Noctuidae) par *Trichogrammatoides* sp. (Hymenoptera: Trichogrammatidae) a Bamby. Int. J. Trop. Insect Sci. 14: 221–223.

- Bal, A. B., S. Kogo, A. Dankoulou, and S. Gagare. 2002. Guide d'élevage et de lachers de *Habrobracon hebetor* (Say) (Hymenoptera: Braconidae), parasitoïde de la chenille mineuse de l'épi de mil et son hôte de substitution, *Corcyra cephalonica* (Stainton) (Lepidoptera: Pyralidae). Technical document, AGRHYMET Centre, Niamey, Niger.
- Baoua, I. B., M. N. Ba, M. N'Diaye, C. Dabire-Binso, and M. Tamo. 2009. Annual report of the project on the Integrated management of the millet head miner in the Sahel. McKnight Foundation collaborative crop research program, McKnight Foundation, Minneapolis, MN.
- Baoua, I. B., M. N. Ba, L. Amadou, N. Oumarou, W. Payne, J. D. Roberts, K. Stefanova, and C. Nansen. 2014. Estimating effect of augmentative biological control on grain yields from individual pearl millet fields. *J. Appl. Entomol.* 138: 281–288.
- Baoua, I. B., M. N. Ba, L. Amadou, A. Kabore, and C. Dabire-Binso. 2018. Field dispersal of the parasitoid wasp, *Habrobracon hebetor* (Hymenoptera: Braconidae) following augmentative release against the millet head miner, *Heliocheilus albipunctella* (Lepidoptera: Noctuidae) in the Sahel. *Biocontrol Sci. Technol.* 28: 404–415.
- Bayoun, I. M., F. E. Gilstrap, and O. Youm. 1995. Assessment of the effectiveness of natural enemies of the millet head miner. *Int. Sorghum Millets Newsl.* 36: 55–56.
- Bernardi, M., J. W. Mishoe, and J. W. Jones. 1989. Raghava: A computer simulation of *Raghava albipunctella* population dynamics and *Pennisetum americanum* and *P. typhoides* phenology. *Ecol. Model.* 44: 275–298.
- Bhatnagar, V. S. 1983. Programme de lutte biologique, Projet CILSS de Lutte Intégrée Nioro du Rip, Senegal. Project Technical Report for the period June-October 1982. CILSS, Bambey, Senegal.
- Bhatnagar, V. S. 1984. Synthèse des résultats du programme de lutte biologique pour 1983 et programme proposé pour 1984. IPM CILSS Project Technical Report, CILSS, Bamako, Mali.
- Bhatnagar, V. S. 1987. Conservation and encouragement of natural enemies of insect pests in dryland subsistence farming: problems, progress and prospects in the Sahelian zone. *Int. J. Trop. Insect Sci.* 8: 791–795.
- Bhatnagar, V. S. 1989. Lutte biologique contre la chenille mineuse de l'épi de mil. *Sahel PV Info.* 12: 5–17.
- Boire, S., F. E. Gilstrap, and G. L. Teetes. 1998. Impact of natural enemies on abundance of millet head miner (Lepidoptera: Noctuidae) in Niger. *Int. Sorghum Millet Newsl.* 39: 144–145.
- Bottenberg, H., and B. B. Singh. 1996. Effect of neem leaf extract applied using the « broom » method on cowpea pest and yield. *Int. J. Pest Manage.* 42: 207–209.
- Brevault, T., and P. Clouvel. 2019. Pest management: reconciling farming practices and natural regulations. *Crop Prot.* 115: 1–6.
- Dastijerdi, H. R., M. J. Hejazi, G. N. Ganbalani, and M. Saber. 2009. Sublethal effects of some conventional and biorational insecticides on ectoparasitoid, *Habrobracon hebetor* Say (Hymenoptera: Braconidae). *J. Entomol.* 6: 82–89.
- Eisa, M. A., E. M. Elamin, A. Elbadawi, A. E. B. El-Hassan, M. K. Rudwan, U. M. Ratschker, and M. Roth. 2007. Ecological characteristics of the millet head miner, *Heliocheilus albipunctella* (Lepidoptera: Noctuidae): a pest on pearl millet in Sudan, pp 1–7. *In Proceedings, Tropentag 2007 Conference on international agricultural research for development, 9–11 October 2007, University of Kassel-Witzenhausen and University of Göttingen, Göttingen, Germany.*
- Gahukar, R. T. 1982. Rapport d'activité de l'année 1981, Programme d'entomologie. IPM CILSS Project Technical Report, Nioro du Rip, Senegal.
- Gahukar, R. T. 1983. Rapport d'activité de l'hivernage 1982. Programme d'entomologie, Projet CILSS de lutte intégrée, Nioro du Rip, Senegal.
- Gahukar, R. T. 1984. Rapport d'activité de l'année 1983. Programme d'entomologie, Projet CILSS de lutte intégrée, Nioro du Rip, Senegal.
- Gahukar, R. T. 1990a. Sampling techniques, spatial distribution and cultural control of millet spike worm, *Raghava albipunctella* (Noctuidae: Lepidoptera). *Ann. Appl. Biol.* 117: 45–50.
- Gahukar, R. T. 1990b. Preliminary comparison of spike development stages for insecticide application against *Heliocheilus albipunctella* de Joannis in pearl millet. *Int. J. Trop. Insect Sci.* 11: 205–208.
- Gahukar, R. T. 1990c. Field screening of pearl millet cultivars in relation to insects and diseases. *Int. J. Trop. Insect Sci.* 11: 13–19.
- Gahukar, R. T. 1990d. Role of extension in protecting food crops in sub-Saharan Africa. *Outlook Agric.* 19: 119–123.
- Gahukar, R. T. 1992. Effect of various fertilizers and rates on insect pest/pearl millet relationship in Senegal. *Trop. Agric.* 69: 149–152.
- Gahukar, R. T., Guevremont H., Bhatnagar, V.S., Doumbia, Y.O., Ndoye, M., and Pierrard, G. 1986. A review of the pest status of the millet spike worm, *Raghava albipunctella* de Joannis (Noctuidae: Lepidoptera) and its management in the Sahel. *Int. J. Trop. Insect Sci.* 7: 457–463.
- Garba, M., and N. B. Gaoh. 2008. Use of *Habrobracon hebetor* in biological control of *Heliocheilus albipunctella*, pearl millet head miner, pp. 436–444. *In Proceedings, 8th international conference on pests in agriculture, 22–23 October 2008, Montpellier, France. Association Francaise de Protection des Plantes and Institut National de la Recherche Agronomique, Montpellier, France.*
- Goudiaby, M. F., I. Sarr, and M. Sembene. 2018. Source of resistance in pearl millet varieties against the stem borers and the earhead miner. *J. Entomol. Zool. Stud.* 6: 1702–1708.
- Green, S. V., E. O. Owusu, O. Youm, and D. R. Hall. 2000a. Mating behaviour of the millet head miner moth, *Heliocheilus albipunctella*, de Joannis (Lepidoptera: Noctuidae: Heliethinae), Appendix 3. *In D. R. Hall (ed.), Chemical ecology and mating behaviour of the millet pests Coniesta ignefusalis and Heliocheilus albipunctella.* Natural Resources Institute, University of Greenwich, Chatham Maritime, United Kingdom.
- Green, S. V., E. O. Owusu, O. Youm, T. J. Bruce, and D. R. Hall. 2000b. Investigation on a long range sex pheromone of the millet head miner moth, *Heliocheilus albipunctella*, De Joannis (Lepidoptera: Noctuidae: Heliethinae). Appendix 5. *In D. R. Hall (ed.), Chemical ecology and mating behaviour of the millet pests Coniesta ignefusalis and Heliocheilus albipunctella.* Natural Resources Institute, University of Greenwich, Chatham Maritime, United Kingdom.
- Green, S. V., O. Youm, D. R. Hall, M. Yacouba, and D. I. Farman. 2004. Methods for rearing *Heliocheilus albipunctella*, in the laboratory and eliminating the pupal diapause. *Int. Sorghum Millets Newsl.* 45: 69–72.
- Guerci, M. J., G. M. Norton, M. N. Ba, I. Baoua, J. Alwang, L. Amadou, O. Moumouni, L. Karimoune, and R. Muniappan. 2018. Economic feasibility of an augmentative biological control industry in Niger. *Crop Prot.* 110: 34–40.
- Guevremont, H. 1982. Etude sur la mineuse de l'épi et autres insectes du mil. Rapport Annuel de Recherches pour l'année 1981. Centre National de Recherches Agronomiques de Tarna, Maradi, Niger.
- Guevremont, H. 1983. Recherches sur l'entomofaune du mil. Rapport Annuel de Recherches pour l'année 1982. Centre National de Recherches Agronomiques de Tarna, Maradi, Niger.
- Hughes, D., and D. Rhind. 1988. Control of the millet head worm in northern Sudan. *Int. J. Pest Manage.* 34: 346–348.
- Kad-Kadi, H. A., F. E. Gilstrap, G. L. Teetes, O. Youm, and B. Pendleton. 1998. Field evaluation of fecundity, longevity and oviposition period of millet head miner (Lepidoptera: Noctuidae) in Niger. *Int. Sorghum Millet Newsl.* 39: 143–144.
- Kadi-Kadi, H. A., F. E. Gilstrap, G. L. Teetes, O. Youm, and B. B. Pendleton. 1999. Population reproductive statistics of millet head miner (Lepidoptera: Noctuidae) reared in a laboratory in Niger. *Int. Sorghum Millet Newsl.* 40: 60–61.
- Kabore, A., M. N. Ba, C. Dabire-Binso, and A. Sanon. 2017. Field persistence of *Habrobracon hebetor* Say (Hymenoptera: Braconidae) following augmentative releases against the millet head miner, *Heliocheilus albipunctella* (de Joannis) (Lepidoptera: Noctuidae), in the Sahel. *Biol. Control.* 108: 64–69.
- Kabore, A., M. N. Ba, C. Dabire-Binso, A. Sanon. 2019. Towards development of a parasitoid cottage industry of *Habrobracon hebetor* (Say): optimum rearing and releases conditions for successful biological control of the millet head miner *Heliocheilus albipunctella* (De Joannis) in the Sahel. *Int. J. Trop. Insect Sci.* doi: 10.1007/s42690-019-00005-w
- Karimoune, L., N. M. Ba, I. B. Baoua, and R. Muniappan. 2018. The parasitoid *Trichogrammatoidea armigera* Nagaraja (Hymenoptera: Trichogrammatidae) is a potential candidate for biological control of the millet head miner *Heliocheilus albipunctella* (de Joannis) (Lepidoptera: Noctuidae) in the Sahel. *Biol. Control* 127: 9–16.

- Krall, S., O. Youm, and S. A. Kogo. 1995. Panicle insect pest damage and yield loss in pearl millet, pp. 135–145. In K. F. Nwanze and O. Youm (eds.), Proceedings, International Consultative Workshop on Panicle Insect Pests of Sorghum and Millet, 4–7 October 1993, Niamey, Niger. International Crops Research Institute for the Semi-Arid Tropics, Patancheru, Andhra Pradesh, India.
- Lale, N. E. S., and J. U. Igwebukew. 2002. Field infestation of *Faidherbia* (*Acacia*) *albida* (Del.) A. Chew. pods by stored product Coleoptera in the Nigerian savanna and effect of infestation on nutrient quality. *J. Arid Environ.* 51: 103–112.
- Ndoye, M. 1991. Biologie et dynamique des populations de *Heliocheilus albipunctella* (de Joannis), ravageur de la chandelle de mil dans le Sahel. *Sahel PV Info* 39: 11–20.
- Ndoye, M., and R. T. Gahukar. 1987. Insect pests of pearl millet in West Africa and their control, pp. 195–205. In Proceedings, International Pearl Millet Workshop, 7–11 April 1986, Patancheru, Andhra Pradesh, India. International Crops Research Institute for the Semi-Arid Tropics, Patancheru, India.
- Nwanze, K. F. 1988. Assessment of on-farm losses in millets due to insect pests. *Int. J. Trop. Insect Sci.* 9: 673–678.
- Nwanze, K. F., and K. M. Harris. 1992. Insect pests of pearl millet in West Africa. *Rev. Agric. Entomol.* 80: 1132–1185.
- Nwanze, K. F., and M. V. K. Shivakumar. 1990. Insect pests of pearl millet in Sahelian West Africa. II. *Raghuva albipunctata* (de Joannis) (Noctuidae: Lepidoptera): distribution, population dynamics and assessment of crop damage. *Int. J. Pest Manage.* 36: 59–65.
- Owusu, O. E., O. Youm, D. R. Hall, and S. V. Green. 2004. Observations on factors affecting attraction and oviposition preferences of the millet head miner, *Heliocheilus albipunctata* to pearl millet panicles. *Int. Sorghum Millets Newsl.* 45: 72–74.
- Passerini, J. 1991. Field and lab trials in Mali to determine the effects of neem extracts on the millet pests: *Heliocheilus albipunctata* (de Joannis) (Lepidoptera: Noctuidae), *Coniesta ignifusalis* Hampson (Lepidoptera: Pyralidae) and *Kraussaria angulifera* Krauss (Orthoptera: Acrididae). Ph.D dissertation, McGill University, Montreal, Canada.
- Payne, W., H. Tapsoba, I. B. Baoua, M. N. Ba, M. N'Diaye, and C. Dabire-Binso. 2011. On-farm biological control of the pearl millet head miner: realization of 35 years of unsteady progress in Mali, Burkina Faso and Niger. *Int. J. Agric. Sustainability* 9: 186–193.
- Ratnadass, A., H. Kadi-Kadi, A. Mato, A. Idrissa, S. Hamidine, I. Oumarou, and D. Fatondji. 2014. Are pest regulation and erosion alleviation services conflicting or synergistic? lessons from Sahel pearl millet. *Agric. Ecosyst. Environ.* 186: 144–147.
- Soti, V. 2018. A spatial sampling design based on landscape metrics for pest management: the millet head miner case study in the Bambey area, Senegal, pp. 215–244. In N. Baghdadi, C. Mallet, and M. Zribi (eds.), QGIS and applications in water and risks, vol. 4. John Wiley & Sons, Hoboken, NJ.
- Soti, V., I. Thiaw, Z. M. Debaly, A. Sow, M. Diaw, S. Fofana, M. Diakhate, C. Thiaw, and T. Brévault. 2019. Effect of landscape diversity and crop management on the control of the millet head miner, *Heliocheilus albipunctella* (Lepidoptera: Noctuidae) by natural enemies. *Biol. Control* 129: 115–122.
- Sow, A., T. Brévault, G. Delvare, J. Haran and M. Sembene. 2017. Natural regulation of field populations of the millet head miner, *Heliocheilus albipunctella* (Lepidoptera, Noctuidae), in Senegal, pp. 382–389. In Proceedings, 11th international conference on pests and antagonist in agriculture, 24–26 October 2017, Montpellier, France. Association Française de Protection des Plantes and Institut National de la Recherche Agronomique, Montpellier, France.
- Sow, A., T. Brévault, G. Delvare, J. Haran, L. Benoit, A. C. d'Acier, M. Galan, C. Thiaw, V. Soti, and M. Sembene. 2018. DNA sequencing to help identify crop pests and their natural enemies in agro-ecosystems: the case of the millet head, miner, *Heliocheilus albipunctata* (Lepidoptera: Noctuidae) in sub-Saharan Africa. *Biol. Control* 121: 199–207.
- Thiaw, C., T. Brévault, N. F. Diallo, A. Sow, D. Ngom, V. Soti, I. Sarr, G. S. Dorego, M. Diop, N. Cisse, et al. 2017a. Incidence et regulation naturelle de la chenille mineuse de l'épi de mil, *Heliocheilus albipunctata* de Joannis (Lepidoptera: Noctuidae) a Bambey dans le basin arachidier au Senegal. *Agron. Afric.* 29: 83–95.
- Thiaw, I., V. Soti, F. R. Goebel, A. Sow, T. Brévault, and M. Diakhate. 2017b. Effect of landscape diversity on biocontrol of the millet head miner, *Heliocheilus albipunctata* (Lepidoptera: Noctuidae) in Senegal. *IOBC/WPRS Bull.* 122: 38–42.
- Vercambre, B. 1978. *Raghuva* spp., *Masalia* spp., chenilles des chandelles du mil en zone sahelienne. *Agron. Trop.* 33: 62–79.
- Youm, O., and F. E. Giltrap. 2011. Population dynamics and parasitism of *Coniesta* (*Haimbachia*) *ignifusalis*, *Sesamia calamistis* and *Heliocheilus albipunctella* in millet monoculture. *Int. J. Trop. Insect Sci.* 14: 419–426.
- Youm, O., and E. O. Owusu. 1998a. Assessment of yield loss due to the millet head miner, *Heliocheilus albipunctata* (Lepidoptera: Noctuidae) using a damage rating scale and regression analysis in Niger. *Int. J. Pest Manage.* 44: 119–121.
- Youm, O., and E. O. Owusu. 1998b. Farmers' perception of yield loss due to insect pests and methods for assessment in pearl millet. *Int. J. Pest Manage.* 44: 123–125.
- Youm, O., M. Yacouba, and A. K. Kumar. 2001. An improved infestation technique using eggs of the millet head miner (*Heliocheilus albipunctella*) (Lepidoptera: Noctuidae) in millet resistance screening. *Int. J. Pest Manage.* 47: 289–292.
- Zethner, O., and S. Olivier. 1984. Annual report. CILSS/IPM Project, Yundum, Gambia.