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Population dynamics and natural mortality factors of the Oriental armyworm, *Mythimna separata* (Lepidoptera: Noctuidae), in South-Central India

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Abstract

The population dynamics and key mortality factors of the Oriental armyworm, *Mythimna separata* (Walker) (Lepidoptera: Noctuidae), a serious pest of cereal crops in Asia and Australia, were studied in southern India. Adults were generally caught in light traps 15–20 days after the initiation of the monsoon rains in the first week of June, and reached a peak in September, nearly one month after the peak in larval density. Rainfall, and maximum and minimum relative humidity were positively associated moth catches in the light traps, while maximum temperature, open pan evaporation, solar radiation, sunshine hours, and wind velocity showed a negative correlation with moth abundance. Stepwise regression analysis of moth catches with weather conditions over the previous 2 and 4 weeks explained 54–68% of the variation in the number of moths caught in the light traps. Five hymenopteran parasitoids [*Costesia ruficrus* (Haliday), *Metopius rufus* Cameron, *Disophyrys* sp., *Compoletis chlorideae* Uchida, *Enicospilus* sp.], and five dipteran parasitoids [*Carcelia illota* (Curran), *Sturmiopsis inferens* Townsend, *Palexorista solennis* (Walker), *P. laxa* (Curran), and *Megasellia* sp.], mermithid (*Neoplectana* sp.), and nuclear polyhedrosis virus (NPV) regulated its populations under natural conditions. Parasitism levels were much greater in sorghum (34.6%) than in pearl millet (17.6%). *Cotesia ruficrus* was the principle mortality factor, which caused up to 47% parasitism in October. Its activity was greater in sorghum (24.6%) than in pearl millet (14.9%). This parasitoid species could be exploited for the biological control of this pest.

Keywords: Oriental armyworm; *Mythimna separata*; Population dynamics; Sorghum; Pearl millet; Parasitism; *Cotesia ruficrus*; Biological control

1. Introduction

The Oriental armyworm, *Mythimna separata* (Walker) (Lepidoptera: Noctuidae) is a pest of several cereal crops in Asia and Australia between 45°N to 45°S latitude, and 60°E to beyond 170°W longitude (Sharma and Davies, 1983). Prior to 1950, it was a minor pest in India, but has since caused serious damage periodically on sorghum [*Sorghum bicolor* Moench (L.)], pearl millet [(*Pennisetum glaucum* (R.Br.) L.)], rice (*Oryza sativa* L.), maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), and sugarcane (*Saccharum officinarum* L.). Yield losses are influenced largely by the stage at which damage occurs and the gregarious behavior of the larvae. Sometimes, its outbreaks result in complete crop loss. Widespread incidence and losses due to this pest may be because of an increase in area under irrigation, and changes in farming systems due to introduction of high yielding varieties, increased fertilizer use, and continuous cultivation. Heavy crop losses have been experienced in India, Bangladesh, China, Japan, Australia, and New Zealand (Sharma and Youm, 1999). It moves along with the wind currents, and its migratory behavior has been well established in China and Japan (Ma, 1979; Lin, 1963; Quo et al., 1963; Lin et al., 1964; Li et al., 1965; Koyama, 1970; Chen et al., 1965; Oku and Koyama, 1976; Nagano et al., 1972).

Outbreaks of *M. separata* have been recorded in Andhra Pradesh during 1977, 1978, and 1981; and during 1980/1981 at Dharwad, Karnataka (Sharma and

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Davies, 1983); during 1983 at Kullu, Himachal Pradesh (Thakur et al., 1987), and during 1984 at Hissar, Haryana (Singh et al., 1987) in India, and during 1984 in Japan (Hirai et al., 1985). The occurrence of these *M. separata* outbreaks was attributed to drought following rains (which may possibly restrict the activity of parasitoids, predators, and diseases), floods resulting from heavy rainfall, induction of migrant populations into a geographic area, heavy fertilizer use and manuring (leads to better crop growth for insect feeding and development), trash mulching (provides a good site for oviposition and a better place in which the larvae can hide), and temperature and humidity regimes in the periods preceding and during the outbreaks (Butani, 1955; Puttarudriah and Usman, 1957; Chin, 1979; Grist and Lever, 1969; Avasthy and Chaudhary, 1965; Koyama, 1970).

Forty-two parasitoids, 15 predators, 4 bacteria, 5 fungi, and 3 viral strains have been reported as natural control agents of *M. separata* (Sharma and Davies, 1983). High levels of natural mortality have been reported from several places in India (Neelgund and Mathad, 1972; Bindra and Singh, 1973; Butter, 1978; Gopinadhan and Kushwaha, 1978; Dilawari et al., 1981). Some attempts have been made to construct life tables (key mortality factor analysis) for *M. separata* (Huang et al., 1992). *Cotesia ruficrus* and *Pseudogonia rufifrons* (Wied.) have been identified as the key mortality factors at Dharwad, Karnataka (Mallapur and Kulkarni, 1998). In China, temperature, relative humidity, and parasitization by the entomopathogenic nematode, *Ovomermis sinensis* are the key mortality factors.

This paper reports information on the biology, population dynamics, and key mortality factors of *M. separata* in South-Central India.

2. Material and methods

2.1. Biology

The insects were reared in the laboratory in wire mesh-screened cages ($30 \times 30 \times 30\,cm^3$) at $27 \pm 2°C$ and $65 \pm 5\%$ relative humidity (RH). Moths provided with 10% honey solution in a cotton swab, laid eggs on dry sorghum leaves or butter paper placed in the cage. Larvae were reared on fresh pearl millet leaves in 1 litre plastic jars. The food was changed daily. Egg, larval, and pupal developmental periods were recorded. Fecundity of the females was also recorded. There were three replications, and each replicate had 20 insects.

2.2. Population dynamics

2.2.1. Adults

Numbers of *M. separata* moths were monitored daily using a modified Robinson type light trap (Bhatnagar and Davies, 1979) installed at four locations [Manmool Village—trap surrounded by off-season nursery area, irrigated paddy fields, and rainfed Alfisols; Crop Improvement Building (RA-1)—trap near the Hyderabad–Mumbai highway with trees on one side and rainfed Alfisols on the other); and Vertisol watersheds—trap located in the middle of fields with deep black soil and cropped twice a year] at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Research Farm, Patancheru, India.

Daily moth catch data were converted into 4 week moving means (FMM) to minimize any moon phase effects. Female moths were dissected to determine their reproductive status as indicated by the presence or absence of spermatophores. These data were analyzed in relation to weather parameters (open pan evaporation, maximum and minimum temperatures, rainfall, maximum and minimum relative humidity, solar radiation, sunshine hours, and wind velocity). Correlation and regression analysis of the weather conditions during the same week, and two and 4 weeks before the trap catches, and across years was carried out to understand the role of weather conditions on the population dynamics of *M. separata*. Regression analysis of weather conditions two weeks before the trap catch was the most efficient means of predicting the moth populations. These data were therefore, subjected to a stepwise regression analysis to identify the weather factor having greatest effect on population dynamics of *M. separata*.

2.2.2. Activity and abundance of natural enemies

The larval population of *M. separata* was monitored at fortnightly intervals during 1981–1982 at four locations representing different ecological zones at the ICRISAT farm: (1) pesticide-free Alfisols (light red Laterite soils), (2) pesticide-free Vertisols (deep black clay soils), (3) pesticide-treated Alfisols, and (4) pesticide-treated Vertisols. A fifth location was selected on farmer's fields (Vertisols cropped to sorghum), 4 km west of ICRISAT Center. Vertisol and Alfisol sprayed areas comprised of irrigated, high fertility fields, with pesticides used according to recommended crop management practices. These areas are normally cropped twice a year during the rainy (June–October) and the postrainy (November–April) seasons. The unsprayed areas were located in rainfed fields, generally of low fertility, and where pesticides have never been sprayed. These areas are cropped only once a year during the rainy season.

The pesticide-treated Alfisols during the 1980 rainy season received one application of endosulfan ($0.7\,kg\,ai\,ha^{-1}$) on pearl millet against *M. separata* and *Helicoverpa (Heliothis) armigera* (Hub.) on 28 August 1980. During the 1981 rainy season, propazine (@ 2 kg and endosulfan (@ $0.7\,kg\,ai\,ha^{-1}$) were applied on pearl millet in the Alfisols. The former was used to check weeds on 1 July 1981, while the latter was applied on 17 August and 8 September 1981 against *M. separata* and *H. armigera*, respectively. In the pesticide-treated Vertisols, endosulfan (0.7 kg ai ha^{-1}) was applied on sorghum on 12 July and 1 August 1980 against the gray weewil, *Myllocerus* sp., and the sorghum shoot fly, *Atherigona soccata* Rondani, respectively. In pesticide-treated Vertisols planted to sorghum, carbofuran 3G (@ 1 kg ai ha^{-1}) was applied against *A. soccata* on 1 and 9 July 1981, and endosulfan (@ 0.7 kg ai ha^{-1}) against *M. separata* and *H. armigera* on 18 July and 17 September 1981, respectively. At the time of grain-filling stage, carbaryl (@ 1 kg ai ha^{-1}) was applied against the sorghum head bug, *Calocoris angustatus* Lethiery on sorghum.

The larval abundance was recorded per 100 plants in three plots selected diagonally across the field. The larval survey, which began during July, when the crop (sorghum or pearl millet) was 10–15 days old, was continued until crop maturity in October. At each fortnightly survey, samples of 25–100 larvae were collected from each location. The field-collected larvae were reared in the laboratory (27 ± 2°C and 65 ± 5% relative humidity) on natural food (leaves of 20–30 day old pearl millet seedlings), and data were recorded on larval survival and pupation, adult emergence, number of larvae parasitized and the parasitoid species involved, and natural mortality due to fungi, viruses, and bacteria. The parasitoids involved were identified at the British Museum, London, UK. Data on larval abundance, survival, and parasitization were averaged across seasons and/or locations, to have an estimate of the standard error mean for each location or crop.

3. Results

3.1. Biology

The pre-oviposition period lasted for 2–5 days, and a female laid an average of 996 eggs. The egg incubation period was 4–5 days. Larval development period for instars I–VII was 3.9, 3.3, 3.1, 2.7, 3.1, 2.2, 1.8 days, respectively. Pre-pupal and pupal periods lasted for 1–2 and 8–12 days, respectively. The entire post-embryonic development was completed in 29–39 days. A third instar larva weighed 0.10–0.15 g, and a pupa 0.26–0.42 g. Color variation was an important characteristic of *M. separata* larvae under solitary and crowding phases. Larvae reared under crowded conditions assumed darker coloration. Such larvae ate more food and developed more rapidly. However, they gave rise to smaller pupae compared with those reared in isolation. The darkening was also induced by food supply, and was reversed and reduced by subsequent isolation. The larvae damaged pearl millet (*Pennisetum glaucum*), sorghum (*Sorghum bicolor*), maize (*Zea mays*), rice (*Oryza sativa*), and Bermuda grass (*Cynodon dactylon*) at the ICRISAT farm.

3.2. Population dynamics

Light trap catches of *M. separata* moths at ICRISAT Center over the five-year period (1976–1980) are given in Fig. 1. Numbers of moths trapped per night were low during the first 28 weeks (January–July), when there was less than one moth per trap per night. No moths were caught in the light traps between 21 and 25 standard weeks, i.e., during the summer in May. Moths in the light traps were generally caught 15–20 days after the initiation of the monsoon rains, which usually occurred during the first week of June. Moth catches in the light traps were higher during 1977–1978 (more than 50 moths per trap per night), while the moth catches were low during 1976, 1979, and 1980 (<4 moths per trap per night). Moth catches in the light traps during March 1977 were very high, which could be linked to cyclone along the eastern coast of Andhra Pradesh, nearly 250 km east of the ICRISAT farm. Most moths were caught during the rainy season between mid-July and September, but the numbers varied between sites. More moths were caught in light traps located at Manmool village and Vertisol watershed than in the light trap located in RA 1. During 1981 and 1982, more males were caught in the light traps than females, and a large proportion of females were unmated (Fig. 2). During August–September, the proportion of males was greater than the females.

3.3. Relationship between larval abundance in the field and moth catches in the light traps

Peak in larval abundance was observed during August–September (Fig. 3). The larval density declined thereafter, and very few larvae were observed by the end of the rainy season during October–November. The peak in moth catches in the light traps was recorded in September, i.e., nearly one month after the peak in larval density. Larval density was greater in sprayed Alfisols on pearl millet than on sorghum in unsprayed Vertisols.

3.4. Association between weather parameters and the moth catch in the light traps

Open pan evaporation ($r = -0.34$ to -0.51), and maximum temperature ($r = -0.20$ to -0.47) showed a negative association with the moth catches in the light traps (4 week moving means and the weather conditions two weeks earlier) (Table 1). Association between minimum temperature and moth catches was consistent across years. Rainfall in general was positively

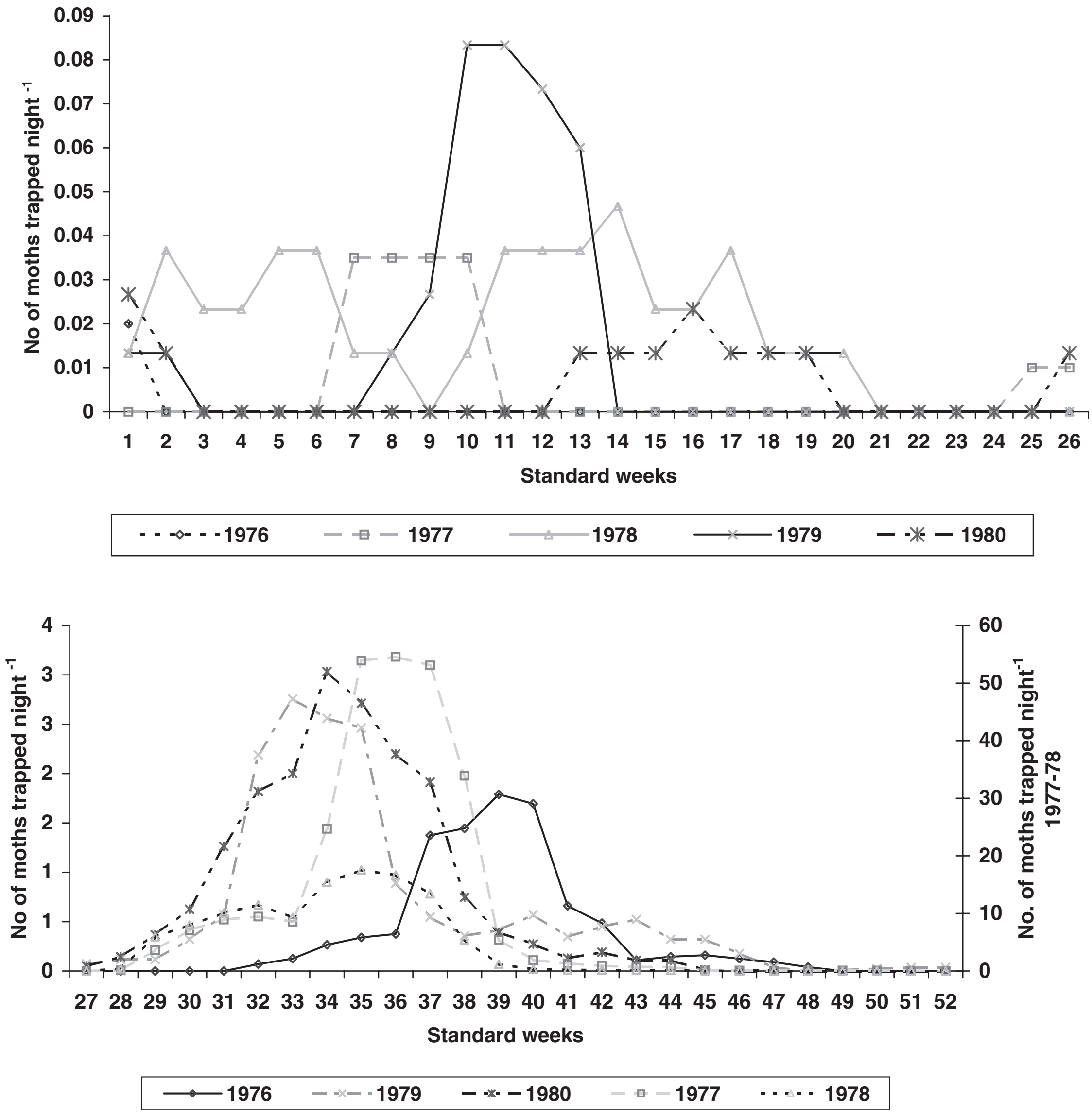

Fig. 1. Light trap catches[a] of *Mythimna separata* moths over 5 years (ICRISAT, Patancheru 1976–1980). a—4 week moving means across four light traps located at different places on the ICRISAT farm. Light trap catches for 1977 and 1978 have been plotted against the right axis.

associated with the moth catches in the light traps ($r = 0.22$–0.78) (except in 1974 and 1975). Maximum ($r = 0.27-0.48$) and minimum ($r = 0.30-0.74$) relative humidity was positively associated with the moth catches in the light traps (except in 1974 and 1975). Solar radiation and sunshine hours were negatively associated with moth catches (except sunshine hours during 1974 and 1975). Wind velocity was negatively associated with the moth catches in the light traps during 1974–1976.

Weather conditions during the same week explained the 17.8–52.7% of the variation in number of moths caught in light traps. However, FMM (which normalized the data for moon phase effect) improved the reliability of predicting *M. separata* populations ($R^2 = 37.3-68.8\%$). Prediction of the *M. separata* population improved when the FMM were regressed against the weather conditions two (FMMTB) ($R^2 = 45.8-76.3\%$) and 4 weeks (FMMFB) earlier ($R^2 = 42.1-70.9\%$).

Multilinear and stepwise regression analysis of moth catches (FMM) in the light traps with the weather conditions during the same week, and two (FMMTB) and 4 weeks (FMMFB) earlier explained 54.5–68.4% of the variation in the number of moths caught in the light traps (Table 2). The correlation and regression coefficients for moth catches (FMM) and weather conditions were significant for rainfall and open pan evaporation, maximum temperature, and sunshine hours. The correlations between moth catches and maximum and

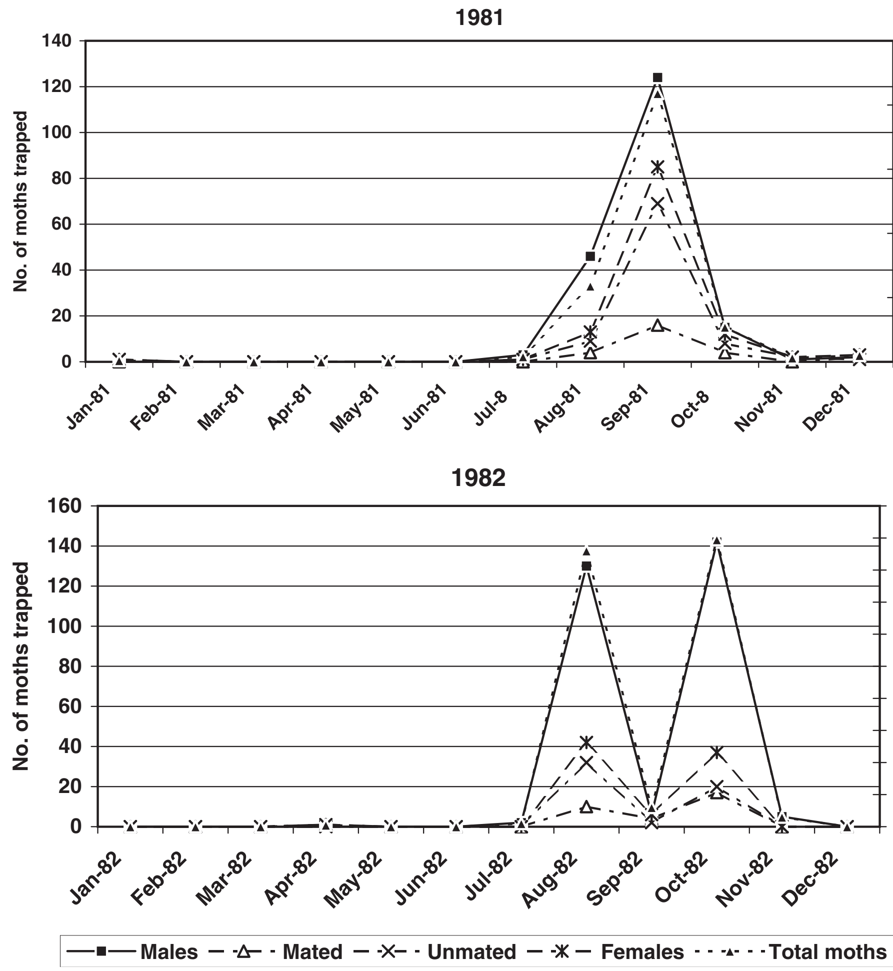

Fig. 2. Mating status of the *Mythimna separata* females caught in the light traps (ICRISAT, Patancheru 1981–1982). Numbers of mated and unmated females have been plotted in relation to the second axis on the right.

minimum relative humidity, and solar radiations were significant, but the regression coefficients were non-significant, while the reverse was true for wind velocity. A similar trend in correlation and regression coefficients was also observed between moth catches and weather conditions two week before (FMMTB) (except for maximum temperature and sunshine hours). Maximum and minimum relative humidity and wind velocity 4 weeks earlier showed significant correlation and regression coefficients with moth catches in light traps (FMMFB).

Stepwise regression analysis indicated that rainfall, open pan evaporation, maximum and minimum temperature, and wind velocity had maximum effect on moth catches in the light traps (FMM). Rainfall, open pan evaporation, maximum relative humidity and wind velocity two weeks (FMMTB) earlier has a maximum effect on the moth catches in the light traps ($R^2 = 68.5\%$), while minimum temperature, maximum relative humidity, solar radiation, and wind velocity over the preceding 4 weeks (FMMFB) showed maximum influence on moth catches in the light traps.

3.5. Key mortality factors under field conditions

Natural mortality during its peak period of activity between July and October (which also included mortality due to nuclear polyhedrosis virus and bacteria) was high at the beginning (39.96% in July) and end (30.66% in October) of the rainy season (Table 3). The hymenopteran parasitoid, *Cotesia* (*Apanteles*) *ruficrus* (Haliday), was the principle mortality factor, and the parasitism levels increased from 1.89% in July to 47.15% in October, and the parasitization increased over the crop-growing season. Mortality due to the dipteran parasitoids *Carcelia illota* (Curran) and *Sturmiopsis inferens* Townsend, was low (<3%). Parasitism levels were low at the beginning of the rainy season (2.89%), but increased considerably during August – September (22.05 and 37.14%, respectively). Maximum

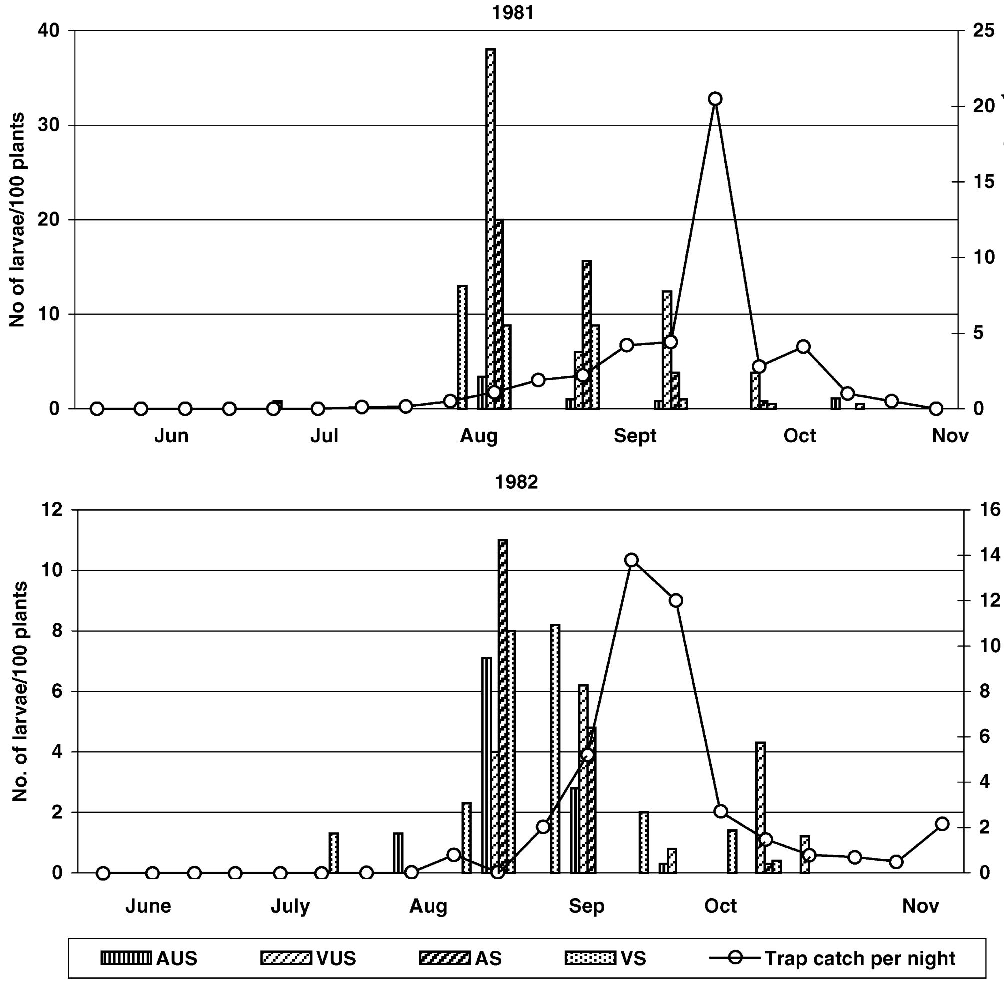

Fig. 3. Larval density of *Mythimna separata* in relation to moth catches in the light traps at ICRISAT farm (ICRISAT, Patancheru 1981–1982). AUS—Alfisols unsprayed, VUS—Vertisols unsprayed, AS—Alfisols sprayed, and VS—Vertisols sprayed.

parasitism of 47.71% was recorded at the end of the rainy season during October. Larval mortality due to factors other than parasitism decreased from June to October.

3.5.1. Activity and abundance of different parasitoids

From over 5000 field-collected larvae, five hymenopteran parasitoid species were recovered [*Cotesia* (*Apanteles*) *ruficrus* (Haliday), *Metopius rufus* Cameron, *Disophrys* sp., *Campoletis chlorideae* Uchida, *Enicospilus* sp.]. Five dipteran parasitoids [*Carcelia illota* (Curran), *Sturmiopsis inferens* Townsend, *Palexorista solennis* (Walker), *P. laxa* (Curran), and *Megasellia* sp.] also parasitized the *M. separata* larvae. Hymenopteran parasitism increased from June to September, while the activity of dipteran parasitoids remained low (Fig. 4), and the greatest parasitism was observed during August–September. The most abundant parasitoid species was *C. ruficrus.* Parasitism by *C. ruficrus,* in general, mirrored the pattern of total parasitism observed. Parasitism levels by *C. ruficrus*, increased from July (12–13%) to September (30–45%) (Fig. 5). During January and March 1982, the levels of parasitism by *C. ruficrus* reached 50–55%. No parasitoids were recorded in the first generation larvae collected during June. Among the dipterans, *C. illota*, was most numerous, followed by *S. inferens*. Mermithid nematodes (*Neoplectana* sp.) were also recorded as one of the important parasite, and *Anedrallus spinidens* Fab. was observed preying on the larvae.

3.5.2. Parasitism levels in sorghum vs. pearl millet

Total parasitism was greater in sorghum (34.6%) than in pearl millet (17.6%), and this was largely because of greater parasitism by hymenopteran parasitoids in sorghum (30.9%) than in pearl millet (15.8%) (Table 4). Although the level of parasitism by the dipterans was low, they were more active in pearl millet (1.2%) than in sorghum (0.6%). The reduced larval parasitism by Hymenoptera in pearl millet may partially explain the

Table 1
Association of light trap catches of *Mythimna separata* moths with weather parameters over NINE years (ICRISAT, Patancheru 1974–1982)

Year	OPE		T_{max}		T_{min}		Rain		RH_{max}		RH_{min}		SR		SH		WV	
	FMM	FMMTB	FMM	FMMTB	FMM	FMMTB	FMM	FMMTB	FMM	FMMTB	FMM	FMMTB	FMM	FMMTB	FMM	FMMTB	FMM	FMMTB
1974	−0.34*	−0.33*	−0.44**	−0.47**	−0.59**	−0.70**	−0.34*	−0.35*	0.28*	0.27	−0.05	−0.14	−0.35**	−0.35**	0.21	0.27*	−0.35**	−0.35*
1975	−0.51**	−0.45**	−0.45**	−0.41**	−0.34*	−0.38**	0.05	−0.15	0.45**	0.37**	0.2	0.06	−0.25*	−0.14	0.02	0.18	−0.48**	−0.4**
1976	−0.37**	−0.35**	−0.22	−0.20	0.14	0.03	0.48**	0.22	0.38**	0.31*	0.47	0.3	−0.19	−0.08	−0.29	−0.13	−0.32*	−0.38**
1977	−0.34*	−0.35**	−0.24	−0.21	0.19	0.18	0.56**	0.56**	0.36**	0.38**	0.55**	0.51**	−0.27*	−0.24	−0.48**	−0.36**	−0.10	−0.24
1978	−0.39**	−0.42**	−0.30*	−0.28*	0.25*	0.23	0.73**	0.72**	0.41**	0.44**	0.69**	0.66**	−0.42**	−0.38**	−0.68**	−0.57**	0.07	−0.12
1979	−0.39**	−0.40**	−0.30*	−0.29*	0.19	0.14	0.61**	0.54**	0.39**	0.39**	0.62**	0.56**	−0.43**	−0.29*	−0.58**	−0.45**	0.03	−0.19
1980	−0.40**	−0.41**	−0.30*	−0.28*	0.24	0.21	0.72**	0.67**	0.41**	0.43**	0.68**	0.63**	−0.43**	−0.33*	−0.65**	−0.52**	0.04	−0.17
1981	−0.36**	−0.36**	−0.27*	−0.25*	0.19	0.16	0.60**	0.53**	0.36**	0.37**	0.58**	0.53**	−0.37**	−0.25*	−0.55**	−0.42**	0.01	−0.19
1982	−0.41**	−0.46**	−0.31*	−0.32*	0.27*	0.24	0.75**	0.78**	0.45**	0.48**	0.74**	0.72**	−0.45**	−0.45**	−0.73**	−0.62**	0.1	−0.09

FMM—Correlations of four week moving means with weather conditions during the same week, FMMTB—Correlations of FMM with weather conditions two weeks before the trap catch, OPE—Open pan evaporation, T_{max}—maximum temperature, T_{min}—minimum temperature, RH_{max}—maximum relative humidity, and RH_{min}—minimum relative humidity, SR—solar radiation, SH—sunshine hours, and WV—wind velocity.
*, **—Correlation coefficients significant at $P = 0.05$ and 0.01, respectively.

heavy leaf defoliation experienced in pearl millet compared to sorghum, in addition to greater number of female moths in pearl millet. Mean natural mortality of the larvae (due to pathogens, bacteria and viruses) was similar in both sorghum (16.5%) and pearl millet (16.2%).

3.5.3. Parasitism levels in alfisols vs. vertisols

There were no statistically significant differences in the overall parasitism in sorghum between Alfisols (35.7%) and Vertisols (33.7%) (Table 4), but in pearl millet, parasitism was much greater in Alfisols (26.7%) than in Vertisols (8.4%). Parasitism by hymenopterans in sorghum in Alfisols (31.3%) was similar to that observed in Vertisols (29.4%), but this was not true in pearl millet where the parasitism by Hymenoptera was lower in Vertisols (7.6%) as compared to Alfisols (23.9%). In sorghum, the dipteran parasitoids were more active in Vertisols (4.2%) than in Alfisols (1.8%), while the reverse was true in pearl millet (1.8% and 0.7%). Natural mortality in sorghum was similar on both Alfisols (16.4%) and Vertisols (17.8%). Similar trends were also recorded for natural mortality in pearl millet on Alfisols (17.8%) and Vertisols (14.7%).

3.5.4. Parasitism levels in sprayed vs. unsprayed fields

There were no noticeable differences in total parasitism levels on sorghum in sprayed (36.7%), unsprayed (33.8%), and farmers' fields (33.4%) (Table 4). However, in pearl millet, there was more parasitism in unsprayed fields (23.1%) compared to the sprayed fields (12.0%). Levels of parasitism by Hymenoptera in sorghum did not vary much between sprayed, unsprayed, and farmers' fields. Parasitism by Hymenoptera was greater in unsprayed than in sprayed pearl millet. No dipteran parasitoids emerged out of the larvae collected from sprayed Vertisols in pearl millet.

There were no significant differences in parasitism levels by *C. ruficrus* in sorghum between Alfisols and Vertisols, and between sprayed and unsprayed fields (Table 5). In pearl millet, however, parasitism by *C. ruficrus* dropped dramatically from 23.2% in the Alfisols to 4.5% in the Vertisols. There was no parasitism by *C. ruficrus* in sprayed Vertisols. The dipteran parasitoids had overall lower levels of parasitism as exemplified by *Carcelia* spp. and *S. inferens.* There were no apparent trends in parasitism levels by dipterans across crops and/or locations.

4. Discussion

At ICRISAT Center, *M. separata* was observed feeding on pearl millet, sorghum, maize, rice, and Bermuda grass. Elsewhere, this polyphagous pest has been reported feeding on 33 plant species and some

Table 2
Correlation/regression coefficients of weather parameters with *Mythimna separata* moth catches in the light traps (means across nine years, and four light traps) (ICRISAT Center, 1974–1982)

Moth catch		a	RF	OPE	T_{max}	T_{min}	RH_{max}	RH_{min}	WV	SR	SH	R^2 (%)
			X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	
FMM	*r*		0.63**	−0.38**	−0.28**	0.21	0.39**	0.63**	−0.06	−0.29**	−0.55**	
	b	113.7*	0.145*	0.721*	−5.12**	1.57	−0.06	−0.04	−1.441**	−1.060	−2.20*	54.5
FMMTB	*r*		0.60**	−0.39**	−0.25	0.19	0.42**	0.57**	−0.24	−0.24*	−0.41**	
	b	−43.9	0.233**	0.968**	−2.80	1.62**	1.012	−0.179	−2.045**	0.329	−0.45	68.4
FMMFB	*r*		0.39**	−0.37**	−0.20	0.12	0.36**	0.42**	−0.37**	−0.09	−0.25*	
	b	−81.8	0.132	0.314	−1.56	2.68*	1.304**	−0.822*	−1.606**	1.516*	−2.40	64.4

Stepwise linear regression equations:
FMM (Y) = 90.5** + 0.162R* + 0.696 OPE**−4.82T_{max}** + 2.173T_{min}**−1.346 W** ($R^2 = 54.9\%$).
TWB (Y) = −99.3** + 0.285R** + 0.749 OPE** + 1.025RHmax**−1.752WV** ($R^2 = 68.5\%$).
FWB (Y) = −85.7** + 1.226** T_{min} + 0.597RH_{max}** + 1.480SR*−0.958WV** ($R^2 = 61.6\%$).
FMM—correlation/regression coefficients of 4 week moving means with weather condition during the same week, FMMTB—correlation/regression coefficients of FMM with weather conditions 2 weeks before the trap catch, and FMMFB—correlation/regression coefficients of FMM with weather conditions 4 weeks before the trap catch.
*, ** = Correlation (*r*) and regression (*b*) coefficients significant at *P* 0.05 and 0.01, respectively.
RF—rain fall, OPE—open pan evaporation, T_{max}—maximum temperature, T_{min}—minimum temperature RH_{max}—maximum relative humidity, and RH_{min}—minimum relative humidity, WV—wind velocity, SR—solar radiation and SH—sunshine hours, R^2 (%)—Coefficient of determination.
r—correlation coefficient, b—regression coefficient, and a—constant.

Table 3
Larval abundance, and principle mortality factors of *Mythimna separata* (ICRISAT, Patancheru, 1981)

Month	No. of larvae per 100 plants	No. of larvae pupated (%)	No. of adults emerged (%)	Natural mortality (%)	*Cotesia ruficrus* (%)	Parasitism by Hymenoptera (total)	*Carcelia illota* (%)	*Sturmiopsis inferens* (%)	Parasitism by Diptera (total)	Total parasitism (%)
July	62.33	82.94	57.15	39.96	0.56	1.89	0.67	0.33	1.00	2.89
August	56.13	73.45	61.57	16.30	18.44	19.46	1.03	0.60	2.58	22.05
September	58.00	57.07	42.80	12.07	33.47	34.14	1.33	1.00	3.00	37.14
October	39.33	34.17	21.64	30.66	23.12	47.15	0.00	0.57	0.56	47.71

unspecified grasses belonging to eight families (Sharma and Davies, 1983). Catindig et al. (1994) reported that 31 plant species supported the development of *M. separata,* but in general, it is primarily a pest of Gramineae. In South-Central India, it causes severe damage to sorghum and pearl millet during August–September. Over a ten year period, no adult moths were trapped during May and the first week of June, but the larvae were observed in sorghum and pearl millet crops 7–10 days after the initiation of monsoon rains, usually in first fortnight of June. The population of *M. separata* can increase rapidly due to the high fecundity of females (nearly 996 eggs per female). A computer-based model has been developed by Wang et al. (1997) to simulate the population dynamics under variable temperatures. This model can be used to predict its populations under field conditions to provide support for decision making for controlling this pest.

The peak in moth catches in light traps in September was recorded one month after the peak in larval abundance due partly to the time required by larvae to complete development. However, adult migration and weather conditions add to the complexity of *M. separata* population dynamics under natural conditions. Heavy rainfall followed by drought often leads to *M. separata* outbreaks. Rainfall promotes the growth of grasses (including cultivated crops), which may lead to an increase in local populations. Weather conditions also result in aggregation of moths, and thus lead to heavy infestations. This is similar to observations in Africa, where *Spodoptera exempta* (Walk.) outbreaks were negatively associated with rainfall of the preceding 6–8 months (Haggis, 1996). The first outbreak of *S. exempta* moths originates in the coastal zone and eastern Africa that can support persistently low population densities (Tucker, 1984). Moths may then be dispersed to the west and north by wind (Tucker et al., 1982). See also Rose et al. (2000). In China, moths from South China are considered to be a source of early spring populations, which follow ascending, trans, and descending movements (Lin, 1963). The appearance of *M. separata* larvae after the initiation of monsoon rains lends credence to the fact that outbreaks can only occur after rain has allowed growth of grasses to enable larvae to develop. The moths are also known to be concentrated by wind convergence. The period before sexual maturity has

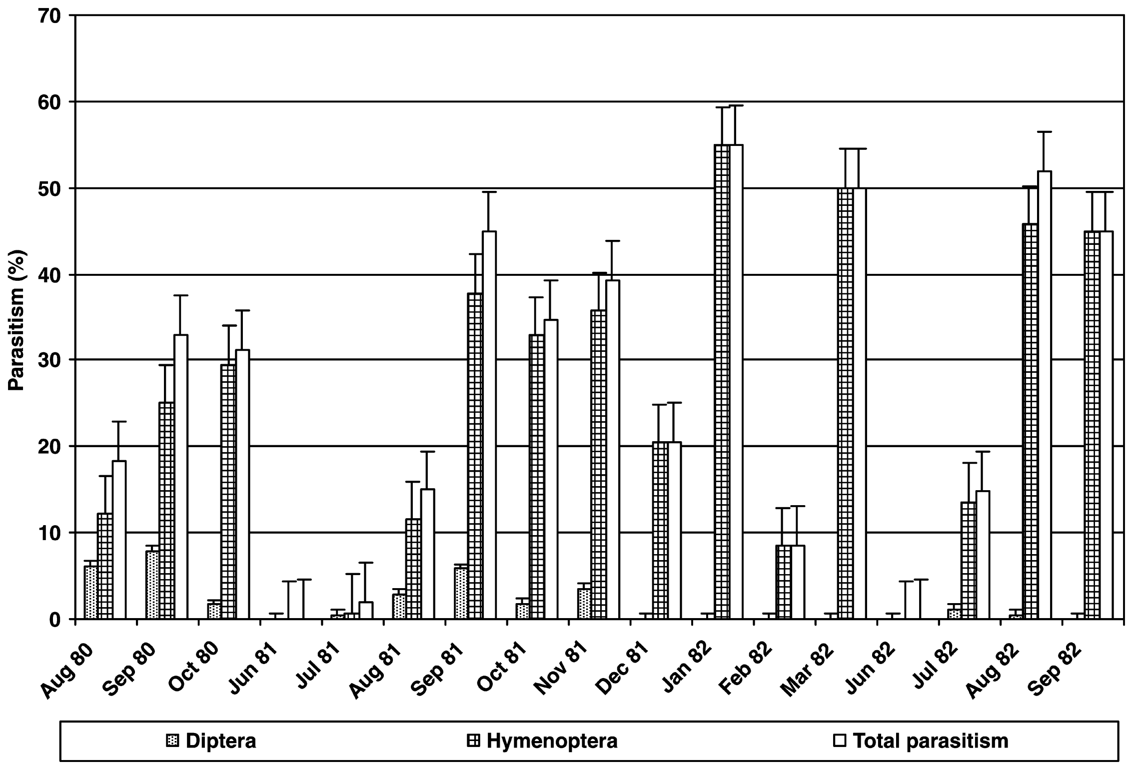

Fig. 4. Percentage of Oriental armyworm, *Mythimna separata*, larvae parasitized by Diptera and Hymenoptera (ICRISAT Center, Patancheru, Andhra Pradesh, India).

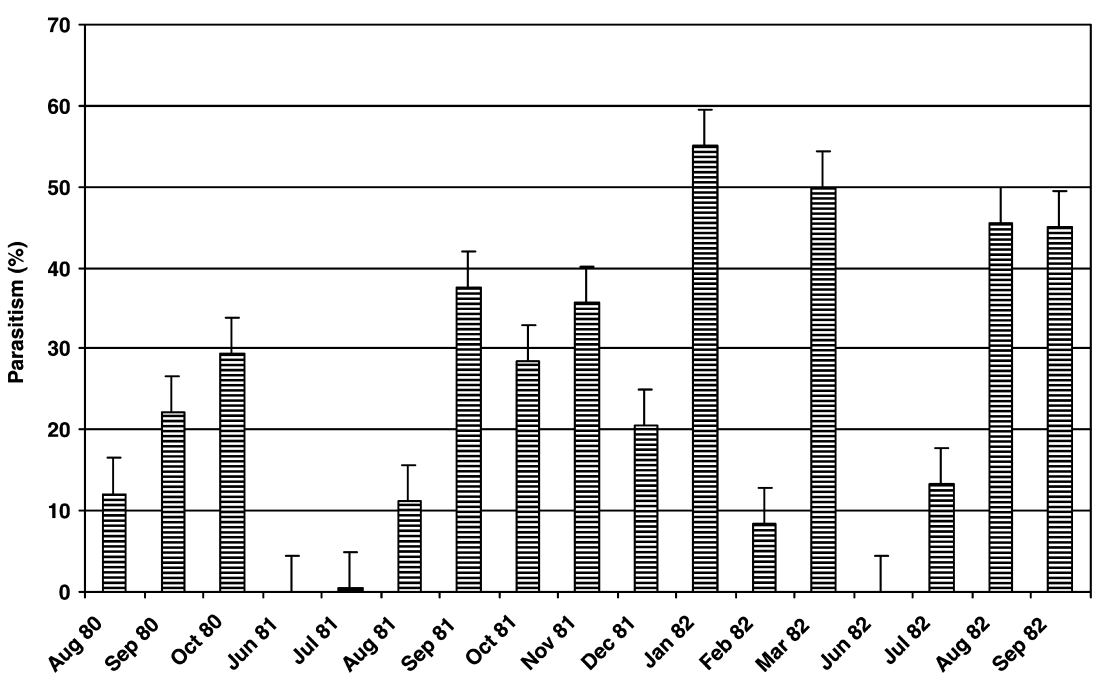

Fig. 5. Percentage of Oriental armyworm, *Mythimna separata*, larvae parasitized by *Cotesia ruficrus* (ICRISAT Center, Patanchęru, Andhra Pradesh, India).

Table 4
Comparative Parasitism levels of the Oriental armyworm, *Mythimna separata*, in sorghum and pearl millet on Alfisols (red soils) and Vertisols (black soils) (ICRISAT Center, Patancheru, Andhra Pradesh, India)

Fields	Sorghum			Pearl millet		
	Alfisols	Vertisols	Mean	Alfisols	Vertisols	Mean
Total parasitism (%)						
Sprayed	38.7±4.9	34.7±3.7	36.7	22.9±3.8	1.2±0.01	12.0
Unsprayed	34.9±11.3	32.6±5.4	33.8	30.6±22.8	15.6±7.5	23.1
Farmer's field	33.4±10.8	—	33.4	—	—	—
Mean	35.7	33.7	34.6	26.7	8.4	17.6
Hymenoptera (%)						
Sprayed	30.8±4.3	31.7±3.6	31.2	18.2±3.5	1.21±0.01	9.7
Unsprayed	30.4±10.5	27.1±4.8	28.8	29.7±24.0	14.1±6.1	21.9
Farmer's field	32.7±11.01	—	32.7	—	—	—
Mean	31.3	29.4	30.9	23.9	7.6	15.8
Diptera (%)						
Sprayed	2.9±1.1	2.9±0.6	2.9	2.9±0.8	0.0±0.01	1.45
Unsprayed	1.9±0.7	5.5±2.1	3.7	0.7±0.7	1.4±1.4	1.0
Farmer's field	0.6±0.6	—	0.6	—	—	—
Mean	1.8	4.2	0.6	1.8	0.7	1.2
Natural mortality						
Sprayed	17.3±2.1	15.5±2.1	16.4	22.1±2.6	9.7±0.01	15.9
Unsprayed	17.7±2.7	20.2±2.6	18.9	13.4±6.8	19.7±2.6	16.6
Farmer's field	14.1±2.5	—	14.1	—	—	—
Mean	16.4	17.8	16.5	17.8	14.7	16.2

Data not recorded: —.

Table 5
Comparative parasitism (%) levels of the Oriental armyworm, *Mythimna separata*, in sorghum and pearl millet by *Cotesia ruficrus*, *Carcelia* sp. and *Sturmiopsis inferens* (ICRISAT Center, Patancheru, Andhra Pradesh, India)

Fields	Sorghum			Pearl millet		
	Alfisols	Vertisols	Mean	Alfisols	Vertisols	Mean
Cotesia ruficrus						
Sprayed	28.8±4.0	27.6±3.4	28.2	17.4±3.5	0.0	8.7
Unsprayed	21.8±10.1	24.9±4.5	23.4	29.0±24.3	13.4±6.3	21.2
Farmer's field	22.1±8.7	—	22.1	—	—	—
Mean	24.2	26.2	24.6	23.2	4.5	14.9
Carcelia sp.						
Sprayed	1.7±0.9	1.6±0.4	1.6	1.16±0.4	0.0	0.6
Unsprayed	0.6±0.3	3.5±1.7	2.0	0.0	0.0	0.0
Farmer's field	0.6±0.6	—	0.6	—	—	—
Mean	1.0	2.6	1.4	0.6	0.0	0.3
Sturmiopsis inferens						
Sprayed	0.4±0.17	0.7±0.2	0.5	0.7±0.3	0.0	0.4
Unsprayed	0.7±0.3	1.2±1.7	0.9	0.0	1.4+1.4	0.7
Farmer's field	0.0±0.0	—	0.0	—	—	—
Mean	0.4	0.9	0.5	0.4	0.7	0.5

Data not recorded: —.

been suggested as the optimum time for long distance migration (Hwang and How, 1966). Unusually heavy moth catches recorded during March 1977 at ICRISAT Center may be associated with cyclonic storm along the east coast of India along the Bay of Bengal. Similar positive spatial and temporal association has also been observed between rainstorms and *S. exempta* outbreaks (Tucker and Pedgley, 1983; Rose et al., 2000).

The moths can fly 600–1400 km (Grist and Lever, 1969), and have been intercepted even over the sea (Hsia et al., 1963). During unfavorable conditions, moths resort to migration. The low population levels during the post-rainy season, in spite of the substantial area planted to pearl millet and sorghum at the ICRISAT farm, indicates the possible movement of moths away from the source of infestation. In addition, decreased egg hatching and reduced larval survival because of lower humidity and lower or higher temperatures (than the optimum) may be a possible cause of low population densities during the post-rainy season.

Although *M. separata* is a voracious and polyphagous pest of a number of plant species, there is considerable variation in genotypic susceptibility to this pest (Sharma and Sullivan, 2001), both under multi-choice field, and no-choice conditions in the greenhouse. Weeding and lower planting density reduce the leaf feeding by *M. separata* larvae. Plant products from neem are also effective for controlling this pest (Sharma and Davies, 1983), and may form an important component in integrated pest management (IPM).

The hymenopteran parasitoid, *C. ruficrus*, was by far the major biological control agent, resulting in up to 47.15% parasitism in October. It has also been reported to be the most important mortality factor in Gujarat (Patel and Patel, 1991), Uttar Pradesh (Charyulu et al., 1994) and Maharashtra (Mallapur, 1997) in India. However, In Orissa, India, tachinids have been found to cause maximum mortality during April–May (Pati et al., 1986). Mortality of *M. separata* larvae increases towards the end of the rainy season, of which NPV is an important factor. Overcast and rainy conditions also promote the NPV infection in *S. exempta* (Persson, 1981; Odindo, 1983). Complete biological control of *M. separata* has been achieved in New Zealand by using a strain of *C. ruficrus* imported from Pakistan (Simmonds, 1976; Mohyuddin and Shah, 1977). The extent of larval parasitism was higher in sorghum than in pearl millet, and the impact of parasitoids increased from June to October. The sex ratio tended to be more in favour of females in pearl millet than in sorghum, and this coupled with low levels of parasitism possibly resulted in large-scale defoliation in pearl millet as compared to sorghum. A number of hymenopteran and dipteran parasitoids, as well as mermithids and NPV regulated its populations under natural conditions, of which *C. ruficrus* can be used for the biological control of *M. separata*.

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