Management of Sweet Potato Weevil, *Cylas formicarius*: A World Review

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ABSTRACT

Sweet potato is infested by many insect pests. Sweet potato weevil (SPW) *Cylas formicarius* (Fab.) is the important insect pest throughout the world, wherever it is grown. The weevil is managed by a package of practices together called integrated pest management (IPM). In India, a few genotypes of sweet potato have shown durable resistance throughout 2006 to 2011. A new screening method of germplasm, volatile-assisted selection (VAS), was developed to identify resistance/susceptibility in sweet potato genotypes based on the volatile chemicals that are released. Transgenic sweet potato was not successful at the field level. Farmers in Asia practice intercropping of sweet potato with ginger, *bhendi*, taro and yams to reduce the incidence of pests as well as to conserve soil moisture. Entomopathogenic fungi and nematodes are used successfully to control *C. formicarius* in the West and Latin America. Female sex pheromone (Z)-3-dodecen-1-ol (E)-2-butenolate has changed the pest dynamics in the field and has become an important tool in *C. formicarius* IPM. It was used to monitor and trap male weevils, thus reducing the reproductive success of female weevils. A number of botanical pesticides are available and their use is limited in developed countries. A few insecticides that were used to control *C. formicarius* were banned in recent years in many countries and it is essential to identify new molecules with low or no persistence in tubers and soil with toxic effects on weevils. We reviewed the research done on SPW during the last five decades to assess the management practices of SPW and to identify new strategies required to control the pest effectively and economically.

Keywords: biological control, botanicals, cultural methods, host plant resistance, insecticides, integrated pest management, pheromones, sweet potato

Abbreviations: AVRDC, Asian Vegetable Research Centre; Bt, *Bacillus thuringiensis*; Cry, crystalline; CTCRI, Central Tuber Crops Research Institute; EPF, entomopathogenic fungi; EPN, entomopathogenic nematode; GC-MS, Gas Chromatography-Mass Spectrometry; IAA, indole-3-acetic acid; IIE, International Institute of Entomology; kPa, kilo Pascal; NAA, α-naphthaleneacetic acid; NMR, Nuclear Magnetic Resonance; SPW, sweet potato weevil; USDA-TARS, United States Department of Agriculture-Tropical Agricultural Research Station

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INTRODUCTION

Sweet potato is an important crop in many countries and east and south Asia, and its production is limited by insect pests. Sweet potato weevil (SPW) *Cylas formicarius* (Fab.), which is supposed to have originated from India about 80–100 million years ago (Wolfe 1991), has become widely dispersed mainly in tropical and subtropical regions of the world, and recently has been found in higher latitude areas as well (Nilakhe 1991; IIE 1993). The establishment of *C. formicarius* in Muroto (Japan) shows that it can tolerate low temperature in winter to some extent, though it is a tropical and subtropical insect (Kandori et al. 2006). The weevil continues to infest sweet potato at higher altitudes of 1600 m above mean sea level in Meghalaya, India (Korada et al. 2010a). In an observatory trial, a change in dynamics of population of *C. formicarius* was noticed. Our experiments suggested that the number of *C. formicarius* were increased in relation to female population over a period of time in between 2005 to 2010. These changes in sex ratio would...
have a tremendous impact on its damage potential and its management methods. Though several eradication programmes for this pest were taken in some countries, still *C. formicarius* continue to be one of the major insect pests in the sweet potato producing countries worldwide. An overview of research in sweet potato weevil management during the last twenty years was reviewed by Korada et al. (2010b). In the present chapter, the status of research done in SPW management worldwide during the last five decades is discussed to evolve suitable and viable management strategies.

**PLANT RESISTANCE**

The shape of the tuber, tuber length, neck length and thickness plays in important role in preference by *C. formicarius* and from the inherent nutritional quality of the sweet potato plant and tuber. Round tubers are preferred more than elongate and spindle shaped ones. Teli and Salunkhe (1996) reported that round and oval tubers of sweet potato were more infested in the field by *C. formicarius* than long stalked, spindle and elongate ones. Tuber damage in the field was negatively correlated with stalk length and positively with girth of tuber. Rind thickness and length of tuber measured in relation with weevil damage. Pink and red coloured cultivars were generally less susceptible than white and brown coloured ones. Cultivars with thin foliage and lobed leaves with purple coloration at emergence were less susceptible. They also reported that the sweet potato variety CO3 was the most resistant to SPW feeding (Teli and Salunkhe 1995). Low yielding varieties with small roots were less infested than higher yielding entries (AVRDC 1990). Tuber damage by SPW in many varieties or cultivars differ only in relative terms. β-Carotene-rich accessions were found to be susceptible to SPW (AVRDC 1987a).

The interaction between drought stress and genotype was significant for adult feeding indicating a different response between the two genotypes ‘Beauregard’ and ‘Excel’ (Mao et al. 2004). Drought stress seemed to favour the feeding and oviposition of *C. formicarius* but it reduced larval survival rate. The magnitude of response of the two genotypes appeared to differ (Mao et al. 2004). Drought stress may increase the activity of oviposition stimulant present in the genotypes because weevils deposited more eggs on drought stressed plants (Mao et al. 2004). Some of the plant metabolites are produced and influenced by environmental stress which would have a bearing on resistance or tolerance. Jackson and Peterson (2000) reported sub-lethal effects of sweet potato resin glycosides on *Plutella xylostella*. Caffeic acid showed adverse effects on a genovar of herbivore, *Helicoverpa zea* (Summers and Felton 1994) and sweet potato pathogenic fungi (Harrison et al. 2003a). Recent analyses showed that the levels of resin glycosides and caffeic acid vary between sweet potato genotypes and within genotypes among years or areas of production (Harrison et al. 2003a, 2003b) and showed insecticidal activities (Peterson and Harrison 1992; Jackson and Peterson 2000). This relationship suggests these two compounds and the antibiosis of sweet potato. It also may indicate that the production of these compounds is subject to environmental influence.

The search for sweet potato cultivars resistant to SPW has been conducted for decades, but little success has been achieved, partly because of the inconsistent expression of the resistance (Collins et al. 1991). Identification of environmental factors that affect the expression of resistance and knowledge of the magnitude of these variations would assist in the development of cultivars with stable SPW resistance. In addition, secondary plant compounds are often associated with host plant resistance. Sweet potato resin glycosides and caffeic acid are two such compounds found in the sweet potato storage roots that have shown insecticidal activities (Peterson and Harrison 1992; Jackson and Peterson 2000). Any effect of environmental factors on the level of these two compounds may provide insights on SPW resistance.

The sweet potato varieties ‘H85-168’ had the least SPW damage, while ‘H85-70’ and ‘H85-16’ were also better than the local check in Puri, Balasore, Mayurbhanj and Keonjhar districts, Orissa, India during 1988-1990 (Bhat and Naskar 1994). Cabrera et al. (1990) conducted two field experiments, one carried out in Isabela and one in Mayaguez, Puerto Rico and observed that the total yield of sweet potato was not significantly affected by drought stress caused by *C. formicarius elegantulus*. In Isabela, cv. ‘WRAS-3’, ‘WRAS-7’, ‘WRAS-31’, ‘WRAS-36’, ‘Mojave’ and ‘Gemi’ were highly susceptible to attacks by *C. f. formicarius* whereas cv. ‘Regal’, ‘Sumor’ and ‘WRAS-27’ were moderately susceptible. In Mayaguez, cv. ‘WRAS-36’, ‘Mojave’, ‘Miguela’ and ‘Gemi’ were highly susceptible and cv. ‘WRAS-3’, ‘WRAS-7’, ‘Resisto’, ‘Sumor’, ‘WRAS-25’ and ‘WRAS-35’ were moderately susceptible. ‘Regal’, ‘WRAS-37’ and ‘WRAS-40’ were the most resistant varieties in Mayaguez. Three sweet potato breeding lines, ‘MS-501’, ‘MS-503’, and ‘MS-510’ are released by the Mississippi Agricultural and Forestry Experiment Station. They have moderate levels of resistance to the *C. f. elegantulus* and to the wire worm (*Conoderus* sp.), *Diabrotica* sp. (cucumber beetle), *Systena* sp. (flea beetle) complex (Thompson et al. 2001).

In Bihar, India, among 13 short duration sweet potato cultivars evaluated, one cv ‘X24’ had the fewest SPW damage (0.42 t/ha) but produced the lowest marketable tuber yield (4.35 t/ha) (Sarkar et al. 1992). Studies carried out in Kerala, India with 40 sweet potato hybrids showed that the cv. Selopia is the most resistant to SPW (Collins et al. 1991). Identification of environmental factors on the level of these two compounds and the antibiosis of sweet potato. It also may indicate that the production of these compounds is subject to environmental influence.

Wilson et al. (1989) demonstrated that a methylene chloride surface extract of the periderm of storage roots of the susceptible line *C. f. elegantulus* infestation of sweet potato in the United States Virgin Islands (USVI). The germplasm evaluation trials were conducted using cultivars obtained from the USA, Puerto Rico (USDA-TARS), St. Kitts, and the USVI. Results indicated a high % SPW infestation on storage roots of high yielding cultivars, but local cultivars produced lower yields than introduced cultivars. Most cultivars from Puerto Rico were very well adapted for production in the USVI. Mulching increased yield of medium sized roots while grass mulch reduced SPW infestation of storage roots. Irrigation significantly increased marketable yields of storage roots compared to the rainfed treatment. Additionally, irrigation maintained at 40 kPa produced the highest yield of medium sized storage roots which was significantly higher than the 20 kPa and rainfed treatments. Among 100 US sweet potato plant introductions (PIs) SPW injury was less severe in ‘P1508523’, ‘P1531116’, and ‘P1564107’ which have potential use for increasing insect resistance improvement programme (Thompson et al. 1999).

Sweet potato varieties differ in infestation based on kaurenoic compounds present in the plants and tubers. A triterpenol acetate was identified in the root surface of a SPW susceptible cultivar “Centennial”, but not in more resistant cultivars (Nottingham et al. 1989). Wilson et al. (1988) demonstrated that a methylene chloride surface extract of the periderm of storage roots of the susceptible line Centennial stimulated oviposition of *C. f. elegantulus*. It has been established that the major component (compound I) of the surface extract was an oviposition stimulant of female weevils (Wilson et al. 1989). The mass spectrum of compound I displayed a molecular ion at *m/z* 468 with a molecular formula of C₂₉H₄₄O₁₂. The fragmentation pattern was
indicate of a pentacyclic triterpene with isopropyl and acetate. Based on $^1$C-NMR and GC-MS data and physical evidence, the structure of compound I was established and tentatively named boehmeryl acetate (Son et al. 1990a). Bohemeryl acetate extracted from the surface of sweet potato storage roots appears to act as an ovipositional stimulant for the SPW (Son et al. 1990b). Later, in India, Palaniswami et al. (2000) reported the presence of four sweet potato root surface chemical families of sweet potato weevils: \textit{C. formicarius}, \textit{RS-III-2}, \textit{RS-IV-2} and \textit{56-2}, weevils attracted more to periderm extracts of variety RS-III-2. The ratio of male to female weevils attracted ranged from 2 to 7:1. Duration of biological activity of the crude extract and pure compound was in the range of 18-22 days. For the first time, the two triterpenoids, boehmeryl and boehmeryl acetate isolated from the bark of \textit{Boehmeria excelsa} (Bert. ex Steud) Wedd (Oyarzun 1987) commonly known as ‘manzano’ is an endemic shrub growing on Robinson Crusoe Island, Juan Fernandez Archipelago, Chile.

Host plant nutritional parameters have an influence on the infestation of SPW. The relationship between potash and silica in sweet potato stems is negatively correlated with the infestation of SPW. The relationship between potash and pelago, Chile.

The expression of foreign genes in plants to confer pest resistance is an appropriate alternative to reduce crop losses. Most of the references focus on the efficacy of \textit{Bacillus thuringiensis} (Bt) against different pest insects (Keller and Lagenburch 1993). Moran et al. (1999) evaluated clones of sweet potato (\textit{Ipomoea batatas cv. 'Jewel'}) transgenic for the cryIIIA gene from \textit{Bacillus thuringiensis} subsp. \textit{tenebrionis} to SPW. The cryIIIA delta-endotoxin gene was cloned under the regulation of the 35S CaMV promoter and the TMV Omega fragment. Biological activity experiments to evaluate the insecticidal capacity of transgenic plants were performed against SPW under both controlled and field conditions. Garcia et al. (2000) carried out transformation of leaves and stems of sweet potato with \textit{Agrobacterium tumefaciens} C58C1-pGV2200 carrying the Bt endotoxin gene and nptII. Transformants were cultured on media containing various combinations of IAA, NAA, zeatin riboside, kinetin, benzyladenine and paclobutrazol. Resistance trials under controlled conditions indicated that weevil damage on tubers was up to 5 times lower in transgenic compared with control plants. Isakova et al. (2007) identified, cry1A, cry1B and cry1C genes encoding the toxic proteins in 13 Bt strains isolated in Ukraine and then determined the toxicity of these strains against lepidopteran and coleopteran pests from the south eastern United States. The cry1 toxins from three Bt strains were solubilized and trypsinized for bioassay against the boll weevil (\textit{Anthonomus grandis Boheman}) and \textit{C. formicarius}. The toxicity of all three strains was higher than that of the commercial Bt product FoilReg. (ECOGEN Inc., Langhorne, PA) containing cry3 toxin specific for coleopteran. Two of the Ukrainian Bt strains containing cry1B toxins were toxic to both lepidopteran and coleopteran pests. This study thus revealed new Bt strains toxic to lepidopteran and coleopteran pests from the southeastern U.S. indicating specific target pests for a broad spectrum of cry1 toxins, including natural and trypsin activated forms of cry1B proteins.

Thompson et al. (1994) studied genetic variance component and heritability estimates of freedom from \textit{C. f. elegantulus} injury to sweet potato and yield of sweet potato by parent offspring regression and variance component analysis. Heritability estimates by variance component analysis based on half-sib families for percent and number of injured roots were 0.25 and 0.83, respectively. Individual plant heritability estimates for uninjured root percent and number were 0.03 and 0.13, respectively. Heritability estimates by parent offspring regression for uninjured root percent and number were 0.35 and 0.52, respectively. Genetic variance was mostly additive for all the traits except the stem diameter. Genetic correlations between total root number, uninjured root number and percent uninjured roots ranged from 0.66 to 0.87, indicating that selection for uninjured root number should most effectively increase un-
injured root number and percent, as well as total root numbers. Predicted gains in uninfected root percent and number were 8.8 and 0.87%, respectively, in the progeny derived from inter-mating the highest four out of 19 families for uninfected root number. The 0.87 gain in uninfected root number equals a 24% increase in one breeding cycle.

CULTURAL PRACTICES

Cultural practices include those methods which prevent the build up or survival of the insect pests by including advancing planting time, mulching, trap crops, crop rotations, mixed or intercropping, sanitation, birth perches etc. Central Tuber Crops Research Institute (CTCRI), Kerala, India reported on the use of different cultural practices effectively for suppression of SPW. Several sweet potato mixed cropping systems are practiced by farmers in North Eastern Region of India. The component crops include ginger, bhendi, maize, taro and yam. Low incidence of *C. formicarius* was noticed in these systems and a detailed description of interaction of intercrops and multifunctional cropping systems are described by Rajasekhara Rao (2005), Rajasekhara Rao et al (2006) and Korada et al (2010a).

Removal of alternate host plants (*Calystegia soldanella*, *S. peruviana* and *R. indica*) reduced the SPW infestation in Japan (Komi 2000). Teli and Salunkhe (1994a) reported that sweet potato planted during June-August yielded higher yields (9.41 to 10.32 t ha⁻¹) and with least tuber damage (41%) than the crops planted in January-April (above 52%). The orientation of planting of cuttings also influences the tuber yield and the damage by *C. formicarius* (Levett 1993). In a study conducted in dry lowlands of Papua New Guinea, planting of 4 nodes vertically in the soil produced the lowest percentage of non marketable tubers in cv "L22", while 6 nodes placed horizontally was the most effective for "L44". Increasing cutting number at a planting site from 1 (36700 cuttings/ha) to 2 decreased tuber size in cv. "L44" but not in cv. "L22", and increased the proportion of marketable tubers which had internal damage from the *C. formicarius*. In another experiment by Levett (1993), in which *C. formicarius* weevil damage was generally severe, vertical planting of 2 cuttings with 2 nodes, or vertical or horizontal planting of 1 cutting with 4 nodes resulted in minimum damage. Delaying harvest date from 108 to 133 days after planting increased total yield in both trials by 7-8% but increased internal damage of marketable tubers and the percentage of small and non marketable tubers. In both trials, "L44" produced higher yield, with fewer but larger tubers and a lower percentage of non marketable tubers than "L22". Planting sweet potato into the hill and planting into the furrow and earthing up over 6 weeks, offers protection against weevils (Macfarlane 1987). Re-ridging the crop during tuber initiation and formation stage prevent the weevil from laying the eggs as well as its entry into the tuber. The efficacy of re-ridging sweet potato crop, as a cultural practice for reducing *C. formicarius* incidence was investigated over two seasons at Vellayani, Kerala, India (Palaniswami and Molendas 1994). Treatments consisted of up to seven re-ridgings at 10 day intervals between 30 and 90 days after planting (DAP). Re-ridging significantly reduced the weevil damage to the tubers; the damage was lowest with 7 re-ridgings, which was not significantly different from 5 re-ridgings between 50 and 90 DAP.

Mulching with rice straw or black plastic reduced the infestation by SPW in the root zone (AVRDC 1987b). The availability of water from rainfall is a problem especially in dry land areas coupled with higher temperatures. A ten time reduction in SPW is noticed in sweet potato intercropped with rice, cowpea or *Colocasia* (24.0-57.7 weevils/5 kg tubers) as compared with 105.3 weevils for sweet potato followed by flooding and 217.5 weevils for sweet potatoes as a monocrop sequence (Pillai et al. 1987). In low land rice fields in India, the cropping sequences such as rice-sweet potato-cowpea; rice-rice-sweet potato and rice-sweet potato-rice were effective in controlling the weevil infestation (Pillai et al. 1996). Tuber damage in the effective crop rotations ranged from 7-9%, compared with 52% in the sole crop of sweet potato. Sweet potato intercropped with maize plots had a lower percentage of weevil, *C. formicarius* and a chrysomelid *Typhophorus nigritos* damage, with 14.37 and 18.89% less tubers being affected in 1992 and 1993, respectively than in plots with sweet potato alone in Cuba (Suris et al. 1995).

BIOLOGICAL CONTROL

Biological control is encouraging or using beneficial organisms for controlling insects and is most suitable for all types of cropping systems. Castineiras et al. (1985) calculated the economic indices for the biological and chemical control of the principal sweet potato pest in Cuba, the *C. formicarius elegansitus*. Biological control of the pest was calculated to reduce production costs to 13.93% as compared to chemical control. Net profit and yield were also higher in the case of biological control.

Parasites

A solitary, idobiiont, ectoparasitoid *Braccon yasunai* Maeto et Usato sp. nov. from the south west islands of Japan was reported on the larva of the West Indian sweet potato weevil (*WISPW*), *Eusecipes postfasciatus*, and the SPW, *C. formicarius*, both feeding on *I. batatas* (Maeto and Usato 2007). The percentage parasitism of the braconid on *E. postfasciatus* in the vines of *I. batatas* was 19.9-40.7% in the field. Another larval parasitoid *Braccon clyasoveros* (Rohwer) was also reared from *C. formicarius* in the Philippines. In India, Palaniswami and Rajamma (1986) described natural enemies of the SPW. The braconids, *Rhaconotus sp.* and *Braccon sp.* and another unidentified hymenopterous parasitoid were found in larvae. The empycid fly *Drapetes sp.* and an unidentified mite preyed on larvae and adults respectively. The parasitism occurred in July-December, reaching a peak of 32.5% in October. The duration of the egg, larval, prepupal and pupal stages of *Rhaconotus sp.* averaged 2, 9.6, 1 and 72 days, respectively; the adult lifespan averaged 12.8 days in males and 22.5 days in females. Application of insecticides like endosulfan, fenithion or fenitrothion at 0.05% a.i. each as soil drenching at 50 and 80 DAP was effective against *C. formicarius* and did not have significant effects on actinomycetes, bacteria and fungi in sweet potato fields (Palaniswami et al. 2002). Jansson and Lectone (1991) reported that *Euderus purpureus*, an eulophid, was found parasitizing *C. formicarius* in the southern Florida. The success of these parasitoids at field level is doubtful since they were always found in very few numbers.

Entomo-pathogenic nematodes

The entomo-pathogenic nematodes (EPNs) seem to be promising for the control of SPW. Among different species, *Heterorhabditis* is found to be most effective, infective and pathogenic than *Steinernematidae*. Janson et al. (1989) evaluated *Heterorhabditis bacteriophora* (*HP88’ strain) and *Steinernema carpocapsae* (All and G-13 strains) against *C. formicarius elegansitus*. The LD₉₀ to *C. f. elegansitus* larvae were 2.6, 2.9 and 3.4 infective juveniles/ insect for ‘All’, ‘G-13’ and ‘HP88’, respectively. The LD₉₀ to pupae of these nematodes were 4.9, 5.9 and 4.8 infective juveniles/pupa respectively. The ‘G-13’ strain was the most effective in killing the larvae within infested sweet potato roots, followed in decreasing order by ‘HP88’ and ‘All’ nematodes. Efficacy in killing pupae within roots did not differ among the three nematodes or between life stages for each nematode. Field applications of ‘HP88’ and ‘All’ nematodes were more effective than chemical insecticides in reducing weevil densities on plants. ‘HP88’ nematodes were more effective than ‘All’ nematodes and chemical insecticides in reducing weevil damage to fleshy roots. Figueroa et al.
than that rate had no effect on densities of distance of 15 cm within the soil. Among the 5 species of treated and untreated plants. Damage to plants treated with insecticides was intermediate to that on nematode growing season was adequate. Damage to plants treated caused; suggesting that a single application early in the strain FL2122 (isolated in Florida) causing more mortality. Mannion and Jansson (1992, 1993a, 1993b) also reported that S. carpocapsae ('All' strain), was more infective juveniles per cadaver than did Steinernematids. Heterorhabditis favoured the sand arena while S. carpocapsae preferred the loam soil. Jansson et al. (1991) reported that the number of applications of H. bacteriophora did not significantly reduce number of C. formicarius but did consistently reduce damage to sweet potato storage roots. Nematode application rate had no effect on densities of C. formicarius or damage caused; suggesting that a single application early in the growing season was adequate. Damage to plants treated with insecticides was intermediate to that on nematode treated and untreated plants.

Mannion and Jansson (1992b) described the distribution and dispersal of EPNs within the soil rhizosphere. They reported that EPNs could locate and infect the SPW up to a distance of 15 cm within the soil. Among the 5 species of EPNs, H. bacteriophora strain HP88 and Heterorhabditis sp. strain FL2122 (isolated in Florida) causing more mortality of bait insects (Galleria mellonella) than S. carpocapsae, S. feltiae strain N-27 and S. glaseri within the storage roots of sweet potato. All the nematode species were able to move at least 15 cm horizontally from the C. formicarius cadavers within the roots in soil in the laboratory. The heterorhabditids and, to a lesser extent, S. feltiae and S. glaseri (but not S. carpocapsae), were able to locate and infect apionids in roots 15 cm from their original source roots. All these species and S. carpocapsae Mexican strain were recovered 60 cm horizontally from the point of application (as inoculum) in the field, with the heterorhabditids and S. glaseri causing most mortality in the bait insects.

Regarding the dose of the EPNs required, Jansson and Recorne (1994) mentioned that single application of aqueous suspension of H. bacteriophora HP88 nematodes (4.9 billion infective juveniles/ha) was as effective as application of G. mellonella cadavers (83,700/ha) infected with HP88 nematodes in reducing the damage caused by C. formicarius. Jansson and Recorne (1997) observed beneficial interactions between sweet potato varieties and entomopathogenic nematode population within the roots. Studies were conducted on two cultivars, 'Jewel' and 'Picadito' differing in susceptibility to the larvae of C. formicarius. The pathogenicity of S. carpocapsae 'All' strain and H. bacteriophora 'HP88' strain, was compared with that of two chemical insecticides. Ekanayake et al. (2001) that H. megidis caused significantly higher mortality in larvae, pupae and adults of C. formicarius (80-90%) compared to S. feltiae or carbofuran in Sri Lanka. Although carbofuran application resulted in considerable reduction in crop damage by the weevil, the degree of control was significantly lower than those of the two nematode species. Banu and Rajendran (2002) reported that C. formicarius was infected by EPN H. indica. Subramanian (2003) mentioned that C. formicarius larva was also an effective source for multiplication of EPNs in vivo. The larvae of C. formicarius inoculated with 10 infective juveniles per larva yielded higher number of infective juveniles of H. indica and S. glaseri similar to other hosts Corcyra cephalonica, Dichocrocis punctiferalis and Chilo sacchariphagus indicus. Yamaguchi et al. (2006) suggested that S. carpocapsae ('All' strain) would be an appropriate and effective control agent for suppressing C. formicarius population. The pathogenicity of S. carpocapsae ('All' strain), S. feltiae, S. riobrave and S. glaseri ('326', '328', 'Mungyeong' and 'Dongrae' strains) was tested against the SPW under laboratory conditions. S. carpocapsae induced highest mortality in both sexes of the adult SPW (>90%). About 30-60% of pupae and larvae in the root of sweet potatoes were killed by S. riobrave, S. glaseri ('Mungyeong' strain) and S. glaseri ('Dongrae' strain). The efficacy of S. carpocapsae ('All' strain) on the suppression of the weevil population was then tested in a sweet potato field. Application of S. carpocapsae ('All' strain) successfully reduced the root damage rate and root damage index by approximately 60 and 40% respectively, as compared to root damage in the control fields.

Entomopathogenic fungi

Most entomopathogenic fungi (EPF) belonging to Hypocreaceae, Zygomyceetes, order Entomophthorales and Ascomycetes attract to a wide variety of insect pests of different crops. These pathogens enter the body of the insect (both larvae and adults) through natural body openings or by direct penetration through the cuticle. Most promising entomopathogen infecting SPW is Beauveria bassiana (Bals.) Vuill which is used in the form of sprays or in combination with pheromone traps for its successful infection and dispersal of weevils. Su (1989) described the infection process of B. bassiana and disease development in SPW. The time taken to form mycelia bodies of B. bassiana grown on potato dextrose agar (PDA) media decreased with increasing temperature. The mortality of C. formicarius was 85% when treated with 106 × 10° conidia ml-1, and 100% at 1.59 × 10⁷ conidia ml-1 or higher concentration. Fungal examination of dead C. formicarius after varying inoculation periods showed that the muscle, fat body, tracheal matrix cells and digestive tract were infected. The fat body cells showed disruption 24-48 h after inoculation and were filled with hypheae, 72 h or more after inoculation; 120 h after inoculation, the body cavity was filled with hypheae and conidia. The pathological changes to muscle, tracheal and digestive tract. The fat body cells infected in the fat body cells. B. bassiana found in some of the soil samples in Mt. Seven Stars, Taiwan was found infective to SPW (Su et al. 1988).

Burdeos and Villacarlos (1989) evaluated several isolates of other EPF, Metarhizium anisopliae, Paecilomyces lilacinus including B. bassiana. The BPI Tiaong isolate of M. anisopliae gave the lowest LC30 (8.42 × 10⁵ spores ml⁻¹). B. bassiana was found to be virulent (1.54 × 10⁷) while S. carpocapsae ('All' strain) was moderately virulent (1.54 × 10⁷) and Paecilomyces lilacinus caused very low weevil mortality even at high spore concentration (LC₃₀ 3.0 × 10⁷ spores ml⁻¹). M. anisopliae and B. bassiana caused 50% mortality at 3 and 4 days, respectively. A positive correlation was obtained between soil moisture and mortality of Metarhizium treated adults. Soil pH, unlike soil sterilization, showed no significant effect on the pathogenicity of the fungus. Villacarlos and Granados Polo (1989) quantified the efficiency of M. anisopliae for the control of SPW in screen house and field trials.
in 1986-88 in Leyte, Philippines. Screen house tests showed that potted plants treated with the fungus produced a higher percentage of uninfested tuberous roots compared with untreated plants, which was comparable with potted plants growing in soil treated with carbosulfan. The highest percentage of infected weevils was recorded 3 weeks after application of the fungus. Field application of *M. anisopliae* either as coindal suspension at 4 weeks after planting or as conidial spray at any time after planting substantially reduced infested roots by 9%. The number of adult weevils was reduced by 48% in treated plots compared with untreated plots. Though *B. bassiana* was the most pathogenic to SPW in the laboratory, other pathogens were also found to be pathogenic viz. *M. anisopliae var. anisopliae*, *M. flavovorid var. minus*, *Verticillium lecanii*, *P. lilacinus* and *P. fimmosorosus* (Khan et al. 1990).

Spraying *B. bassiana* (isolated from *C. formicarius*) at 1.6 × 10^8 conidia ml\(^{-1}\) at planting and rootstock formation, and broadcasting soybeans containing *B. bassiana* into the rows at planting controlled *C. formicarius* effectively (Su 1991a). Application of *B. bassiana* isolated from honey bees at 1 × 10^8 conidia ml\(^{-1}\) at planting and rootstock formation gave the best results. The type of soil also influences the success of infection of *B. bassiana* on SPW (Su 1991b). The type of soil from different soils collected from central and southern Taiwan were pnenicous to SPW when they were added at planting and the mortality caused to the SPW by *B. bassiana* was over 80%. Spraying of the fungal pathogen at 1.6 × 10^6 conidia/ml before planting and at the time of storage root formation, broadcasting soybean seeds containing the pathogen and broadcasting of Norwich seeds collected in Guan-Miau into the narrow of the row at planting were effective in controlling the weevil in the field. Hou (1997) and Lagnaoui et al. (2000) also reported that *B. bassiana* was lethal to *C. formicarius*. Environmental factors also govern the successful infection of SPW by entomopathogens. Yasuda et al. (1997) reported that less than 43% relative humidity and temperature below 15°C are not conducive for *B. bassiana* infection to adults of SPW.

Yasuda (1999) developed an auto infection system consisting of a modified sex pheromone trap and a bottle with a sifting agent at low doses, but is also capable of inflicting high mortality on adult *C. formicarius* at slightly higher concentrations (Mansingh and Steele 1975; Mansingh and Rawlins 1977).

### PHEROMONES

The SPW infest mainly the tubers below the ground level and identification offoliar damage by the insect is difficult since many other pests of the potato and other crops also cause similar type of punctures on the leaves. The cryptic feeding habits of the SPW larvae and the nocturnal activity of the adults limit the effectiveness of chemical insecticides used for its control. Though different parts of sweet potato attract weevils, the rate of emission of volatiles from them is very small and hence could not be used for monitoring. Soon after the identification of female sex pheromone (Heath et al. 1986), the course of weevil management changed in different parts of sweet potato growing countries around the world. The sex pheromone alone contributed to significant reduction in SPW population and tuber damage and resulted in increase in marketable tubers. When the number of weevils is too large in traps, they are often measured in weight or volume per unit measurement (Villacarlos et al. 1972). The potential of the sex pheromone (Z)-3-dodecen-1-ol (E)-2,6-dimethoxy-3,7-dodecadien-1-ol was also reported, and the mating rate of females is reduced (Yasuda 1995). Sureda et al. (2006) found sex pheromone of feral SPW, *C. formicarius elegantulus* from Cuba, via solid phase microextraction analysis, to be identical to (Z)-3-dodecenyl (E)-2-butene-
noto, a previously reported compound. Females emitted 20 pg pheromone d\(^{-1}\). Palaniswami et al. (2000) reported that dichloromethane extract of sweet potato periderm contained a pentacyclic triterpenoid compound boehemeryl acetate which attracts both the sexes of SPW. They showed that with 100 mg of pure compound, the attraction was 60.88%. The number of weevils attracted towards the extracts from four sweet potato varieties was also different and it was maximum in variety ‘RS-III-2’. The activity of the pure compound as well as the crude extracted lasted up to 18-22 days. The ratio of male and female weevils attracted ranged from 2 to 7:1.

Scanning electron microscopy (SEM) studies carried out on the male antenna of C. f. elegantulus (Sureda et al. 2006) showed several types of sensilla: sensilla trichodea of type 1 (ST1) as long hairs (100-150 μm), sensilla trichodiode of type 2 as short hairs (50-60 μm), sensilla basiconica of type 1 as thick pegs (20-25 μm), sensilla basiconica of type 2 as curved pegs (10-15 μm), and sensilla basiconica of type 3 as thin and straight short pegs (15-20 μm). The same types were observed in female antennae but ST1 were far less abundant than in males. Sensilla chaetica were also found on the flagellum sub-segments in both sexes. In electrophysiological tests, the crotonate function in the pheromone structure was proved to be critical for activity since regular depolarizations (0.6-0.8 mV) were obtained with puffs on 1 μg of the attractant.

Weevils caught in the traps differ significantly during different parts of the day. Maximum weevil catch was recorded in the evening (Islam et al. 1991a; Yasuda et al. 1992; Chiranjeevi et al. 2002). Trap catches were greatest in the active tuber development stage of sweet potato, during February-March that coincides with the harvesting time. The high catch of weevil was reported during the late seasons of late February-March, when the potential for weevil damage of tubers was greatest (Mondal et al. 2006). Yasuda et al. (1992) reported that pheromone traps installed on the ground captured more males than those set above the ground. Most of the males were seen to approach the traps by walking. More males were captured when they were released downwind of the trap than when released from the upwind or other directions. The number of trapped males decreased gradually, thereafter and decreased rapidly after sunrise. Chiranjeevi et al. (2002) found that traps installed at canopy level were more effective than those erected at four feet above ground level.

Different types of traps are used for monitoring and mass trapping studies. When the sex pheromone is discovered and synthesized, various designs and types of traps are developed to improve the efficiency management of the pest. Single funnel, double funnel and plastic funnel live traps, etc. (Lingren et al. 1980). Hwang et al. (1989) determined the efficacy of different formulations of sex pheromone and lure types in the field to determine the efficacy of 3 trap designs for catching the C. f. elegantulus. Single funnel, double funnel and netting funnel PET (polyethylene tetrathalate) bottle traps baited with 1 mg synthetic sex pheromone were more effective in capturing the male adults of C. f. elegantulus males from a distance of 15 m, while 5 traps positioned 20 m away captured 86% of the males. Plastic funnel trap and the universal moth trap (Uni-trap) were more effective in collecting C. formicarius males than a screen-cone boll weevil trap in southern USA (Janson et al. 1992b). The plastic funnel trap was more efficient (72.8%) than the Uni-trap (58.0%) in capturing marked male weevils released at the base of the traps. These traps, however, were equally effective in preventing adults from escaping (2% escape) and were superior to the screen cone boll weevil trap (45% escape). The distance up to which the sex pheromone acts depends mainly on the concentration and the number of traps used in unit area. Trap counts increased (although not consistently significantly) with an increase in pheromone dose between 1 μg and 1 mg (Janson et al. 1992a). In a mark release recapture studies in Florida, Mason et al. (1990) reported that number of males recaptured decreased with an increase in release distance and decreased with a decrease in dosage of sex pheromone baited traps. The number of males captured from a trap baited with the sex pheromone concentration of 0.001-1 mg/trap and the number of weevils captured in a period of 4 weeks. A water trough with openings on all sides proved to be suitable and economical. A 1 mg sex pheromone sample could capture more than 94.7% of marked males from 10 m and 11.4% from 100 m in 24 h. A 10 μg sample was uniformly active for at least 1 month in the field. Basic aspects such as the optimal concentration to be used in pheromone traps and the effective attraction range of sex pheromone in the field and the temporal activity rhythm of males of C. formicarius were studied in sweet potato fields in Thrivananthapuram, Kerala, India. Of three concentrations of pheromone tested (0.25, 0.5 and 1.0 mg), 1.0 mg attracted maximum number of weevils and the efficacy of the pheromone declined after 3 months. Mark/recapture studies revealed that all C. formicarius males were active during 18.00 and 06.00 h in both May and October (Pillai et al. 1994). The SPW sex pheromone used in China at 2 traps/667 m\(^2\) (30 traps ha\(^{-1}\)) with an interval of 15 m between traps reduced tuber damage by 8.5-10.1% whereas control in China was only 53.1-58.2% (Li, Zheng 1998). In Indonesia, marketable yield of sweet potato and damage from weevils were higher during the dry season than in the rainy season (Braun and Fliert 1999). Pillai et al. (1996) reported that trap containing synthetic sex pheromone ([Z]-3-dodecen-1-ol (E=2-butenolate)) at 1 mg concentration installed in sweet potato field at 1 trap 100 m\(^{-1}\) (100 traps ha\(^{-1}\)) area was able to be highly effective for mass trapping the male SPW leading to significant reduction in the number of weevils in the field up and consequent yield increase. The tuber damage in the pheromone treatment was only 7% against 45.7% damage in the control. The marketable tuber yield was 9.0 t ha\(^{-1}\) in the treatment while in the control the yield was only 4.7 t ha\(^{-1}\).

Integration of sex pheromone traps with insecticides or entomopathogenic fungi were successfully used in recent times. Yasuda et al. (2002) developed sex pheromone formulation to increase exposure time to insecticide for control of the SPW. The formulation was a combination of sex pheromone, ([Z]-3-dodecen-1-ol (E=2-butenolate), and an insecticide (MEP) impregnated into a blue ball (2 mm in diameter) made of the diatomaceous soil. The male weevils were attracted to the visual stimulation in addition to the sex pheromone. The attracted males located and tried to mate with the ball, thereby effectively exposed to the insecticide for a longer time. The concentration of the new formulation was extremely low compared to the conventional formulations and, therefore, lowers the cost of application. Hwang (2001) reported that use of pheromone baited traps in the integrated management of SPW is estimated to save 1 to 3 applications of insecticide. In Taiwan, use of pheromone baited traps placed at a density of 4 traps 0.1 ha\(^{-1}\) reduced damage caused by SPW by 57-65%. Use of such traps in combination with the pre-planting application
of chlorpyrifos (Dursban) granules at 2.25 kg a.i. ha⁻¹ reduced SPW damage by 62-75%. The effect was comparable to that of two applications of chlorpyrifos (80-85%), one applied just before planting and the other at the time of earthing up. Insecticide efficacy tests on SPW revealed that chlorpyrifos was more effective, persistent, and was most effective when it was applied before planting than at the time of earthing up.

Insecticides in water pan traps with synthetic pheromone, (Z)-3-dodecen-1-ol (E)-2-butenoate was used. Dipping the sweet potato vines in 0.01% a.i. phenthoate (Elsan 50EC) before planting combined with mass trapping recorded the lowest number of sweet potato roots (7.08%) compared to mass trapping only (9.18%) and highest in the control plots (17.38%) (Islam et al. 1992). Pheromones combined with one application of carbofuran on 45 days after planting is more effective in controlling the weevils than the insecticide treated 3 times (Kawasoe et al. 1993). Pheromone traps (40/ha) reduced sweet potato root damage by 65% and use of chlorpyrifos at 2.25 kg a.i. ha⁻¹ in addition to the pheromone reduced the damage by an additional 10% over the pheromone treatment (Hwang and Hung 1991).

Stereochemically pure pheromone is always not essential to trap the insects (Sureeda et al. 2006). In a dual-choice olfactometer, males showed maximum activity between 4th and 8th h of scotophase at a dose of 50-10000 ng of pheromone. In field tests, a correlation between the contents of the Z, E isomer in the pheromone formulation and activity was noticed, and baits containing this isomer of stereomeric purity above 94% showed highest attraction. The presence of 5% of the Z, Z isomer in the lure did not induce any synergistic or inhibitory effect and the alcohol precursor of the pheromone was inactive. The results showed that use of a stereochemically pure pheromone may not be necessary in pest control strategies. Yasuda et al. (1992) reported addition of up to 10% of the (E, E)-isomer of synthetic sex pheromone (Z)-3-dodecenyl (E)-2-butenenate (1 mg/dispenser) did not inhibit the activity of the pheromone and was attractive to males of C. formicarius in a sweet potato field in Japan for more than one month. As the pheromone is used to monitor weevils both in weevil free and infested regions, the role of sex pheromone (Z)-3-dodecenyl (E)-2-butenenate) with a purity level above 99% is most appropriate (Jansson et al. 1992a).

Yen and Hwang (1990) found improved synthesis of sex pheromone wherein the carcinogenic solvent HMPT is replaced with DMPU. Lo et al. (1992) reported an alternative synthesis of (Z)-3-dodecen-1-yl (E)-2-butenenate without using carcinogenic ethylene oxide and hexamethyl phosphortriamide (HMPT). By coupling the tetrahydropyranyl ether of 3-butylnol with 1-bromoocotenyl with sodium amide in liquid ammonia, 12-(2-tetrahydropyranyloxy)-9-dodecencyne was obtained; subsequent hydrolysis and semi hydrogenation afforded (Z)-3-dodecen-1-ol. The alcohol was then reacted with crotonyl chloride to give the desired crotonate with a total yield of 29.8%. Males of C. f. elegantulus were strongly attracted to the synthetic sex pheromone and attraction to polyethylene tube dispensed with crotonate to a rubber septum dispenser. Another sex pheromone trans-2-butenolic acid-cis-3-laurylene ester was also used to trap C. formicarius (Chen et al. 2001) and its effect lasted for 110 days and up to 15 m. After trapping for one year, the number of male weevils was reduced by 62-75%. The effect was comparable to that of two applications of chlorpyrifos (80-85%), one applied just before planting and the other at the time of earthing up. Tobacco pan traps with synthetic pheromone wherein the carcinogenic solvent HMPT is replaced with DMPU. Lo et al. (1992) reported an alternative synthesis of (Z)-3-dodecen-1-ol (E)-2-butenoate was used. Dipping the sweet potato vines in 0.01% a.i. phenthoate (Elsan 50EC) before planting combined with mass trapping recorded the lowest number of sweet potato roots (7.08%) compared to mass trapping only (9.18%) and highest in the control plots (17.38%) (Islam et al. 1992). Pheromones combined with one application of carbofuran on 45 days after planting is more effective in controlling the weevils than the insecticide treated 3 times (Kawasoe et al. 1993). Pheromone traps (40/ha) reduced sweet potato root damage by 65% and use of chlorpyrifos at 2.25 kg a.i. ha⁻¹ in addition to the pheromone reduced the damage by an additional 10% over the pheromone treatment (Hwang and Hung 1991).

BOTANICALS

Foliage of Croton linearis contain diterpene which showed insecticidal activity to adult C. f. elegantulus (72 h LD₅₀ was 0.32 µg insect⁻¹) (Alexander et al. 1991). Williams and Williams (1997) isolated sesquiterpene furan, epipangene by guided isolation of the crude ethanol extract of the leaves and stems of Bontia daphnoides and found it to have insecticidal properties to adult C. formicarius (72 h LC₅₀ of 0.8 µg insect⁻¹). Williams and Williams (1999) evaluated the toxicity of Rhi zophora mangle (Rhizophoraceae) crude extract and was found most toxic to C. formicarius (LC₅₀ of 70 µg insect⁻¹) and the extract is reported to contain triterpenoids. Tobacco decoction (1% a.i.) was toxic to SPW and effective for a period of two weeks (Palanswami and Mohandas 1996).

Botanical pesticides are effective against insect pests in vitro and have their toxic effects on target pests under specific climatic conditions. Pacheco et al. (2000) studied the adulticide effect (spray method) of the new bioinsecticide Neem/Azal 5 (Trifolio-M, Lahnau, Germany), at a dose of 0.05 % a.i. v/v and found that it did not result in any mortality (0.01 %). C. formicarius was more susceptible to the extract as compared to two applications of chlorpyrifos (80-85%), however, the opposite is seen when this substituent is placed at C2 or C14. The hydroxyl group at C13 increases the toxicity of the terpene, mortalities after 72 h. It would appear that the insertion of a hydroxyl group at C13 increases the toxicity of the terpene, all metabolites effected high mortalities after 72 h. It would appear that the insertion of a hydroxyl group at C13 increases the toxicity of the terpene, mortalities after 72 h. It would appear that the insertion of a
densa and B. bassiana (de Lima et al. 1999) and also with a limited number of bacteria (Abraham et al. 1992).

Jayaprakash et al. (2000) demonstrated the insecticidal effects of petroleum ether fraction of cassava seed extract against C. formicarius. Of the three concentrations tested on C. formicarius, the mortality was recorded as 17.7 and 86.7% on one day after treatment (DAT) in the batches treated with 1.0 and 5.0%, respectively. On 7 DAT, the mortality with petroleum ether with 0.1% was 40.0% each and it was complete in the treatment with 5.0%. However, only 22.0% weevils were found dead in the control batch. Facey et al. (2005, 2006) stated that the essential oils of leaves and stems as well as fruits of H. capitata are dominated by oxygenated sesquiterpenes (>50%) with viridiflorole being the major component. Both oils exhibited comparative insecticidal activity against C. f. elegantulus, with 72.9% LC₅₀ of 55 μg insect⁻¹ (leaves and stems) and 60 μg insect⁻¹ (fruits). However, the fruit oil had slower action at 24 and 48 h compared to the oil from leaves and stems.

Hexane extracts of leaves and stems of Cleome viscosea L. also showed pyrethroid type of contact insecticidal activity on adult C. f. elegantulus with 60% knock down effect (Williams et al. 2003). However, most of these insects (50%) recovered after 48 h. Formulation of C. viscosea extract containing 35% of essential oil of basil (O. basilicum) (PBO) 1.0% enhanced its toxicity to C. formicarius. The LD₅₀ determined for the extract on C. formicarius when applied in acetone was 89.0 μg insect⁻¹, compared with 43.0 μg insect⁻¹ for the PBO formulated extract. Their findings further support that the extract could be mediating its weak insecticidal activity via a disruption of the mixed function oxidase (MFO) enzyme system, which includes the P450 detoxification enzyme complex because PBO is a known selective inhibitor of these MFO enzymes (Bowers 1984).

CHEMICALS

Chemical insecticides were evaluated for the management of weevil which were used in the form of sprays, application at the base in the form of granules and also as vine dipping. Rajamma and Pillai (1991) showed that fenvalerate (0.05%), methomyl (0.03%) and deltamethrin (0.0003%) were the most effective insecticides; 0.05% heptachlor, chlorfenvinphos and fenitrothion, and 0.1% carbaryl plus molasses were found effective to control C. formicarius. In another study, dieldrin was found to be most effective compared to the untreated control (46.71%) (Islam et al. 1991b), though dieldrin is no more available in developing countries for their use on crops. Rajamma and Pillai (1991) showed that 0.05% endosulfan or endosulfan sprays (monthly intervals) in combination with or without pruning or soil application of carbofuran or phorate granules at 1 kg a.i. ha⁻¹, 45 days after planting were all effective in reducing infestation by C. formicarius and increasing marketable tuber yields. Phorate treatment resulted in the greatest cost benefit ratio. Dalvi et al. (1992) reported that soil application of carbofuran 3G and phorate 10G at 1.0 kg a.i. ha⁻¹ (applied at 45 DAP), and drenching with aldrin, fenithion or endosulfan at 0.05% (on 30, 50, 70 DAP each) were equally effective at reducing infestations. However, all the spray treatments failed to control the pest effectively. Significantly higher yields were recorded for treatments with carbofuran 3G (106.94 q ha⁻¹) and phorate 10G (91.71 q ha⁻¹). Field trials carried out in sweet potatoes cv. LA 206 in Jamaica showed that out of 5 insecticides tested against C. formicarius, heptachlor (23 EC) and chlorfenvinphos (73 EC) were the most effective (Williamson and Murray 1993). Teli and Salunkhe (1993, 1994b) found that dipping of vine cuttings in insecticide solution before planting and spraying the crop 1 month after planting, and a further 3 times at 3 week intervals with cypermethrin or fenvalerate at 375 g a.i. ha⁻¹, was most effective in reducing damage caused by the insect. The best cost:benefit ratio (1:1.19) was recorded for fenvalerate followed by cypermethrin and fenitrothion. Similarly many others have reported some more insecticides to achieve better control of SPW.
acephate (0.05%) and fenvalerate (0.001%) effectively reduced the vine and tuber damage by *C. formicarius* and increased tuber yields in Hyderabad. Among the insecticides, fenvalerate and monocrotophos were highly effective with cost:benefit ratio of 1:1.9 and 1:1.6, respectively. As few of the insecticides described above were banned in the recent years in India, search for new molecules with very low mammalian toxicity and environmental contamination is important.

**IRRADIATION**

Irradiation with gamma rays from different sources is one of the most frequently practiced method for sterilization of the SPW in tubers meant for export purposes and for long storage. Release of irradiated weevils formed the major part of its eradication programmes. Reproduction of over 30,000 adult SPW (*C. formicarius elegantulus*) was prevented with 165 Gy. (Hallman 2004). Dose response tests indicated that the most radiotolerant stage occurring in roots was adult *C. f. elegantulus* (summers). In large scale confirmatory tests, irradiation of 60,000 *C. f. elegantulus* adults at a dose of 150 Gy resulted in no production of F2 adults, demonstrating that this dose is sufficient to provide quarantine security (Fattett 2006).

Effects of gamma radiation on gametogenesis and embryogenesis in SPW were studied histologically (Sakurai et al. 1994; Sakurai et al. 1998). Spermatogenesis was inhibited by the treatment; the spermatogonia and spermatocytes almost completely collapsed and the number of spermatozoa in the seminal vesicles markedly decreased. In the spermatheca of normal females which had mated with irradiated males, spermatozoa were few. In eggs laid by normal females which had mated with irradiated males, the normal embryonic process was inhibited; the deposition of cleavage nuclei was followed by the degradation of the blastoderm, vacuolation of the ooplasm and necrosis of the egg cells, showing that gamma radiation resulted in a few abnormal spermatozoa in the males, which caused dominant lethal mutations in fertilized eggs. Gamma radiation of the females resulted in complete inhibition of oogenesis. Oocytes did not develop and pynosis and collapse of nurse cell nuclei occurred, which resulted in inhibition of ovisposition in sterilized females. The susceptibility of reproductive tissue to gamma radiation was greater in females than in males. In the midgut of irradiated adults, an abnormality was observed in the columnar cells of the epithelium. The midgut epithelium cells were damaged by the gamma radiation, which might cause a lowering of nutritive assimilation and result in a short lifespan. Hayashi et al. (1997) reported the longevity of three groups of SPW adults (irradiated with 80 Gy of gamma radiation) which emerged 29-30, 31-32 and 33-34 days after oviposition as 11.0, 11.2 and 11.2 days respectively in males, and 11.6, 12.6 and 14.4 days respectively in females. Detection rates of fluorescent dye were 60.5% in males and 55.2% in females, indicating that irradiated females live longer than males. Hayashi et al. (1994) and Ito et al. (1993) also demonstrated that SPW adults that emerged from 4 and 6 day-old pupae irradiated at 40 or 60 Gy were completely sterilized. Longevities of adults from 4 and 6 day old pupae were 19 and 31 days for pupae irradiated at 40 Gy, respectively, and 12 and 28 days for those irradiated at 60 Gy, respectively. The longevity of adults irradiated during the pupal stage at any dose was significantly reduced to 33-50% of the non-irradiated controls (Ito et al. 1993). Adults of *C. f. elegantulus* irradiated with a target absorbed dose of 150 Gy (maximum absorbed dose was 165 Gy) lived for 32 days, while at 32 days unirradiated weevils suffered 57% mortality (Hallman 2001). In Japan, SPW were irradiated with gamma ray 80 Gy on the 27th to 28th days after oviposition and released up to September 1995 and during September 1996 only a few unmarked weevils were found in sex pheromone traps which indicated that all the irradiated and marked adults were eradicated within one year in a 13 ha restricted area (Setokuchi et al. 2001).

Eggs and 3rd instar larvae of SPW present in the roots of sweet potato cv. ‘Jewel’ are more susceptible to gamma radiation when they are exposed to 100 to 1000 Gy. Dose-mortality data were analysed by logistic, Gompertz and normal probit probability density functions with and without logarithmic conversions. Gompertz probability density function analysis gave the best (99.9968%) mortality estimation (and 95% FL) against stages of *C. formicarius* in sweet potato roots: 37 Gy (35-42 Gy) for eggs (no log 10 conversion); 73 Gy (53-132 Gy) for 1st instar larvae (log 10 conversion); 38 Gy (31-55 Gy) for 2nd-inst larva (log 10 conversion); 28 Gy for 3rd instar larva (no log 10 conversion) and 1497 Gy (963-2229 Gy) for pupae (log 10 conversion). Pupae irradiated with more than 800 Gy produced no adults when efficacy tests were done. Irradiating adults in roots with 1000 Gy did not prevent adult emergence. However, males exposed to 150 Gy and females exposed to 300 Gy were sterile (Sharp 1995).

Irradiation of sweet potato with white and orange flesh differ significantly in their taste and appearance (McGuire and Sharp 1995) which seems to throw light on the use of irradiation as one of the best control strategies for production of orange flesh sweet potato varieties since they are reported to be more susceptible to SPW.

**CONCLUSIONS**

Sweet potato farmers are suffering from quantitative and qualitative loss of tubers because of *C. formicarius* infestation in several countries. For its effective management, identification of durable weevil resistance in the existing germplasm is of paramount importance. The existing screening methods for finding weevil resistance are to be strengthened by new approaches like ‘volatile assisted selection’ in which plants are selected based on the volatiles they release and the volatiles that are attractant or repellent to the weevil. Studies on understanding the complex infestation pattern of sweet potato vines or tubers and influence of climate change on structural and physiological changes in plant and weevil would result in identification of absolute and/or real resistance in plants. It is also essential to identify compounds from leaves, vines and roots of sweet potato from most susceptible and resistant genotypes that are most attractive to male and female weevils so as to design effective management strategies using push pull strategy. While repellent compounds can be used in the monocrops and attractant compounds can be used in periphery of the crop such that the weevil repelled from the centre of the crop are diverted to the periphery of the crop. Management of SPW reached an important milestone after the discovery of the sex pheromone and it became an important component in the control or eradication programmes in the West but not in the South. Sweet potato weevil became an important insect pest in the fields of poor and marginal farmers in developing countries like India, where sex pheromones are not commercially produced or available. Identification of the SPW resistant germplasm or sources could not be possible even after introduction of *Agrobacterium* plasmids into the cultivated species. The transformed plants were either unable to express the gene of interest or the weevil is tolerating the genes by production of defensive enzymes. Studies are required to identify more sources of resistance and the possible mechanism of action of plasmids in the plant and weevil. With the recent ban of endosulfan in India and the banned/restricted use of monocrotophos, carbofuran, methomyl, quinalphos and several other chemicals on horticultural crops, it is high time to focus on screening of new molecules, combination products and safer formulations in the form of tablets (example, deltamethrin 2.5 g tablet covers 400 m2 area) for effective management of the weevil. Until the new formulations and interventions are ready, farmers would adopt cultural, botanical and other feasible methods that suit to their incomes and farm holds.
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