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Short paper

Review of soldier flies in sugarcane and identification of some key research gaps

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Abstract Soldier flies (*Inopus* spp.) (Diptera: Stratiomyidae) feed on the root system of sugarcane and in some cane-growing regions of Australia, especially Central and Southern Queensland, are considered an economic pest complex. Past studies and some current research gaps for sugarcane soldier flies are presented. Low numbers of soldier fly larvae can cause significant damage to sugarcane due to their ability to cause poor ratooning that ultimately leads to poor growth and reduced yield. Soldier flies have a complex life cycle of up to 2 years, unpredictable outbreaks, relatively uncharacterised varietal choice, and patchy distribution. These factors make research activities and management options challenging. Most studies on the biology, ecology and control approaches for soldier fly have focused on a single species *I. rubriceps*, even though a further species *I. flavus* is also known to attack sugarcane. These studies are reviewed here. However, there are at least five major genetic groups of soldier fly in Queensland cane fields and at least a further four uncharacterised species. Their geographical distribution and relative economic significance in terms of crop damage across regions have not been determined. This diversity of soldier flies highlights the need to further improve knowledge on the biology, genetic diversity, and ecology of these insect pests, and insufficient baseline information on the soldier fly complex is a potential barrier for development of targeted control methods. Currently, only cultural practices for control of soldier flies are recommended, and reports of infested localities are increasing. Hence, new approaches to research are required. One new approach is the development of an *in vitro* rearing method using an artificial diet for sugarcane soldier fly larvae to compare the nutritional requirements of species, which would inform varietal selection. Development of a rearing methods is also a prerequisite to establish rapid screening of pesticides, including chemical and biorational options, against healthy soldier fly larvae in the laboratory prior to field trials and varietal screening. A new research approach, focusing on the development of an artificial diet and characterising species distribution, is outlined.

Key words Alternative control, ecology, sugarcane soldier fly, *in vitro* rearing, species composition, geographical distribution

INTRODUCTION

Soldier flies, *Inopus* spp. (Diptera: Stratiomyidae), are native root-feeding insect pests. Of the two species known from sugarcane fields, sugarcane soldier fly *Inopus rubriceps* and yellow soldier fly *I. flavus*, only *I. rubriceps* has been widely studied. Larvae feed on the roots of sugarcane, causing poor growth and weak ratooning post-harvest. The change in the pest status of soldier fly, from that of minor importance in the 1920s and 1930s to major importance in the subsequent decades, is well known (Allsopp and Robertson 1988). An unpublished review of soldier fly research (Matthiessen 2014) indicated that soldier flies affected between 1.1% and 1.7% of harvested area for the Bundaberg and Mackay regions, respectively. However, this is likely to be an underestimation due to a paucity of accurate soldier fly survey data. In recent years, anecdotal reports have indicated an increase in their damage, but which species is causing the damage in each locality and how much damage is done has not been quantified.

Here, we review the biology, ecology and control options related to sugarcane soldier fly and outline the research gaps for future opportunities to develop a sustainable control management of this long-standing pest of sugarcane.

BIOLOGY OF SUGARCANE SOLDIER FLY

Studies on biology of sugarcane soldier flies have been conducted in the past decades mostly on (purportedly) *I. rubriceps.*

Life cycle

Soldier flies are slow-growing insects and complete their development in 1-2 years. Descriptions of the general biology of *I. rubriceps* are given by Irwin-Smith (1920, 1921), Campbell and Koehler (1971), Hitchcock (1976), Wilcocks and Oliver (1976) and Gerard (1978) (reviewed by Allsopp and Robertson 1988).

Larvae

Soldier flies spend most of their life-cycle as larvae (Hitchcock 1976). Most individuals reach the adult stage within a year after developing through 8-9 larval instars. Larvae that fail to pupate in March to June develop over two years and go through a total of 10-12 larval instars (Hitchcock 1976; Samson and McLennan 1995). About 90% of larvae mature into adult flies in one year (Figure 1), and the remainder take two years (Sugar Research Australia 2022). Larvae are present all year round but are largest during summer and mostly very small and found with difficulty in winter; hence, monitoring for them beneath ratoon stools is practical from September onwards (Sugar Research Australia 2022).

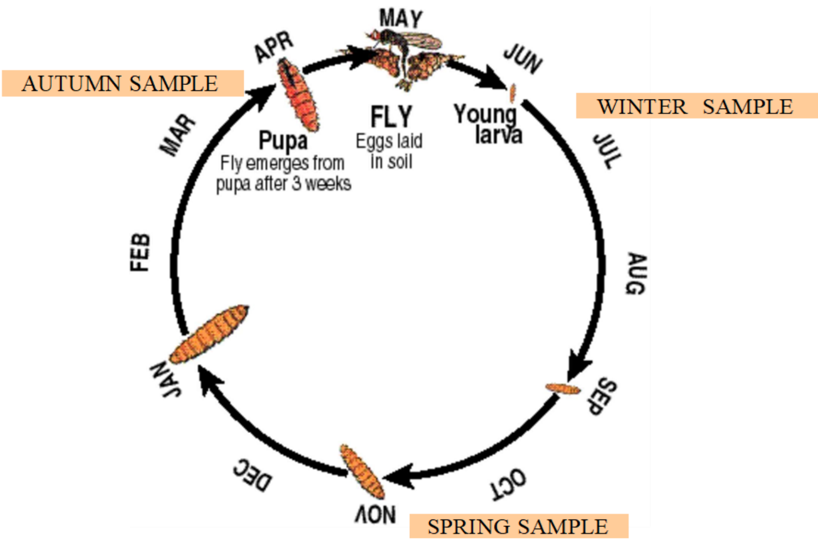

Figure 1. Life cycle of sugarcane soldier fly (Sugar Research Australia 2013).

Pupae

The pupal stage lasts for about three weeks before the adult fly emerges (Sugar Research Australia 2022). Samson and McLennan (1995) studied the timing of pupation of *I. rubriceps* and showed that the pupation period coincided with mean soil temperatures of 20-25°C, and male pupae were smaller than female pupae.

Adults

The male soldier fly is smaller than the female and has prominent black eyes. Females of *I. rubriceps* have black bodies and orange red heads, whereas the yellow soldier fly (*I. flavus*) female's body, head and legs are orange yellow. The sugarcane soldier fly male has a dark-brown body and head, and the yellow soldier fly male has a black body with brown-black head and yellow legs. Adult soldier flies may be seen in the leaf canopy, soil surface or on weeds soon after hatching, usually from March to July, depending on the weather (Figure 1). Adult soldier flies emerge from March to July, later in the north and earlier in the cooler south. Each female emerges, mates, and lays their complement of 100-400 eggs on the day of emergence. They die within 1-2 days. However, males live for up to 1 week. The females are not strong fliers and tend to lay their eggs close to where they emerged (Elder 1969; Osborn and Forteath 1972; Osborn and Halbert 1972; Hitchcock 1976; Wilcocks 1973; Gerard 1978; Dixon and Gerard 1979; Sugar Research Australia 2022).

NATURE OF DAMAGE

Soldier fly larvae are root-feeders and even low to moderate levels of feeding damage can lead to reduction in sugarcane growth and ratooning ability (Samson 2001) that leads to economic loss due to yield reduction and premature plough-out of affected blocks (Lenancker and Powell 2021). Poor ratooning may result from injection of inhibitory substances by larvae into sugarcane plants while feeding (Samson 2001). Etebari *et al.* (2020) found some venom proteins in the salivary glands of soldier flies, but their role in soldier fly biology and/or host plant interactions has not been determined.

ECOLOGY OF SUGARCANE SOLDIER FLIES

Past studies on ecology of soldier flies have included species composition, geographic distribution, abiotic and biotic factors of population dynamics.

Species composition and distribution

The assumption that there are only two species of *Inopus* as pests of sugarcane may not be correct as their taxonomy and distribution have not been well defined. According to Robertson (1985), there are six described species of *Inopus* of which *I. rubriceps* is the most common and widespread. However, he did not report whether all these six species are associated with sugarcane. *I. rubriceps* alone has been recorded from the central eastern coast of Australia (southeast Queensland, northern NSW), whilst *I. flavus* (James) and *I. hitchcocki* (James) are known only from north Queensland.

Allsopp and Robertson (1988) indicated that there might be several species of *Inopus* and/or other genera present in sugarcane. Braithwaite *et al.* (2019) conducted limited studies based on molecular analysis of larvae. They reported that there were five major genetic groups of soldier fly in Queensland cane fields, not two as expected. Morphological studies on 30 adult *Inopus* spp. indicate at least six species, including four uncharacterised species, have been detected on sugarcane and their geographic distribution varies (Powell 2020).

According to Robertson (1985), soldier fly populations have a discontinuous distribution. Sugarcane soldier fly apparently occurs over a wide area from Innisfail, Burdekin, Bundaberg, Mackay and the Atherton Tablelands in Queensland to Harwood in New South Wales. Yellow soldier fly apparently has a more limited distribution, mainly occurring around Proserpine, Mackay, and Plane Creek (Sugar Research Australia 2013; Kevin Powell, SRA, unpublished).

Biotic and biotic factors regulating population dynamics

Abiotic factors

Soil structure: Soldier flies live in a wide range of soil types from red volcanics and heavy clays to sandy alluvials, which are friable and free draining soils (Sugar Research Australia 2013; Robertson 1984).

Temperature and rainfall of habitat and soil: Biogeography studies of *I. rubriceps* across different regions such as Queensland (Mackay) and New South Wales revealed that warm temperatures (> 12.8°C mean annual temperature) and high rainfall (> 750 mm/yr in warm temperate or > 1000 mm/yr in subtropical/tropical regions) are suitable for growth and development of soldier fly (Robertson 1984). He suggested that severe flooding or drought can affect natural enemies of soldier flies. Samson and McLennan (1995) found that pupation was earlier in New South Wales than in Queensland due to cooler soil temperature. Samson (1991) showed that small larvae (<7.5 mg) were closest to the soil surface in winter while large larvae (>7.5 mg) were closest to the surface during the pupation period of March-May.

Biotic factors

Different faunal group interactions with soldier flies were studied by Morris and Samson (2006) as discussed in the control strategies section.

CONTROL STRATEGIES FOR SOLDIER FLY

Chemical control of soldier fly

Most efforts towards management of soldier flies have been directed towards insecticide trials and hence, many field trials had been conducted targeting different active ingredients. Until the 1970s, highly persistent organochlorines, such as lindane and dieldrin (Mungomery 1967; Moller 1968, Bull 1976), were used to control soldier fly in sugarcane. These compounds were subsequently banned worldwide due to environmental, residual and health concerns (Allsopp and Robertson 1988). Since then, despite significant research investment, no effective chemical insecticide for soldier fly control has been identified due to the absence of proven efficacy of a wide range of products (Moller 1968; Samson 2002b, 2015). Actives tested in trials were chlorpyrifos (Samson and Harris 1994), neonicotinoids (thiamethoxam, imidacloprid, clothianidin) (Samson and Eaton 2009; Samson 2015) and carbamates (aldicarb, carbofuran) (Allsopp and Robertson 1988; Samson 2002b). Several controlled-release formulations were also unsuccessful in controlling the pest (Samson and Harris 1997). Field trials conducted more recently between 2015-2018 using a range of actives were also inconclusive with no effective control identified (Powell 2020; Lenancker and Powell 2021).

Microbial insecticide

A *Metarhizium anisopliae* insect-pathogenic fungus isolate FI-322, which was proven to be the most virulent strain from previous bioassays, was applied in field trials at Mackay against soldier fly (Samson *et al.* 2004). There was no effect of *Metarhizium* on soldier fly numbers, even at very high application rates. Consequently, there was no further development of this approach (Samson *et al.* 1994, 2000; Samson and Milner 1997).

Contribution of biological control agents such as predators and parasitoids

Morris and Samson (2006) studied the population dynamics of soldier fly and potential predators, and the influence of other soil fauna and various abiotic factors in cane fields from plant crops to young third ratoons and in grasslands. Numbers of soldier fly larvae were lower in a late-planted field and trash blanketing appeared to favour an increase in earthworms and staphylinid beetles in a fallow field.

Cultural control

Cultural practices are the only recommended control for soldier flies in sugarcane fields. Current control recommendations, by Sugar Research Australia, include taking out the affected block early in the season. Adjusting the planting date, that is, planting the next sugarcane crop late in the season after the adult flight period and fallowing the block to give it a grass-free break from sugarcane or a rotation with soybeans or spraying out the old crop with herbicide can be effective control options (Moller 1968; Samson *et al.* 1991; Morris and Samson 2006; Samson 2007). Other control options that can be followed are minimal cultivation and planting varieties with strong root systems that ratoon quickly (Sugar Research Australia 2004). All these cultural control strategies have been reviewed by Samson (1995) and he suggested that these should be included in an IPM (Integrated Pest Management) program for the control of sugarcane soldier flies.

Host-plant resistance

No sugarcane variety has been identified as resistant or tolerant to soldier fly damage despite evidence that some varieties can better withstand soldier fly pressure (Samson 2002a; Samson *et al.* 2004; Powell 2020). It is unclear whether the resistance mechanism is prompted by physical or chemical properties of the plant.

ARTIFICIAL DIET

Development of an artificial diet for sugarcane soldier flies is essential for evaluating nutrient requirements for different species of soldier flies. This could lead to the selection of varieties based on host plant susceptibility. A soldier fly-specific diet can assist greatly in the development of a stable and sanitized system for rearing larvae in a controlled laboratory environment and subsequently allow rapid screening of chemical and biorationals. Moreover, direct field trials are costly due to huge labour and management costs and take prolonged periods of time to test several products simultaneously. In addition, they are subject to the vagaries of weather and pest infestation. Hence, screening of insecticides before the field trials with laboratory reared larvae fed on artificial diet is both cost and time effective due to less management and labour cost and provide testing of wider range of products within a shorter time.

Artificial diets for laboratory rearing of different dipteran insects, including black soldier fly *Hermetia illucens* (f. Stratiomyidae), blow fly *Lucilia sericata* (f. Calliphoridae) and hover flies (f. Syrphidae), have been reported (Singh 1977; Tachibana and Numata 2001; Gobbi *et al.* 2013). None has been developed for *Inopus* spp. However, an artificial diet has already been developed for another root-feeder of sugarcane, greyback canegrub (*Dermolepida albohirtum*) (Lenancker and Powell 2023), which potentially could be modified for sugarcane-feeding soldier flies.

CONCLUSIONS

Although, the areas specifically damaged by soldier fly appear to be relatively small and outbreaks are sporadic, reports of damage are being reported increasingly due to evidence of poor ratooning in fields. Most studies have been focused on the biology and ecology of *I. rubriceps*, and potential control options. However, in the light of recent detection of several species of sugarcane-feeding soldier flies, we are conducting further research on the species composition and biology and ecology of the respective dominant species in the field. Furthermore, to select resistant varieties, screen chemical pesticides and other novel control options effectively and rapidly, prior to the field trial, laboratory trials with a fully characterised artificial diet are required to be established for this sugarcane pest complex.

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