African Entomology 2022, 30: e11455 (10 pages)
https://doi.org//10.17159/2254-8854/2022/a11455
RESEARCH ARTICLE

AFRICAN ENTOMOLOGY
ISSN (online) 2224-8854

Review of *Liriomyza huidobrensis* (Blanchard, 1926) (Diptera: Agromyzidae) on potatoes in South Africa, with special reference to biological control using entomopathogens and parasitoids

T Mugala[1], D Visser[2], AP Malan[1] and P Addison[1]

[1]*Department of Conservation Ecology and Entomology, Faculty of AgriSciences, Stellenbosch University, Stellenbosch, South Africa*
[2]*Agricultural Research Council, ARC-VIMP, Pretoria, South Africa*

Potatoes are among the four most widely consumed vegetable crops worldwide. However, a potato crop can be infested by various pests like the devastating leaf miner, *Liriomyza huidobrensis* (Blanchard, 1926) (Diptera: Agromyzidae). This leaf miner has, since the early 2000s, become an important pest of potatoes in South Africa. It is highly invasive, causing up to 70% damage of solanaceous crops. Direct damage results from the adult female flies feeding on the leaf mesophyll during oviposition, and the larvae mining the leaves. Indirect damage is induced through pathogens entering through perforations that act as vectors of plant diseases. Biocontrol agents, such as entomopathogenic nematodes (EPNs), entomopathogenic fungi (EPF) and parasitoids, have shown potential for control of *L. huidobrensis*. This review investigates the biology and morphological identification of *L. huidobrensis*, its host range and the potential of associated biocontrol agents, like EPNs, EPF and parasitoids, as future control options.

CORRESPONDENCE
T Mugala

EMAIL
tmugala@earth.ac.cr

DATES
Received: 14 June 2021
Accepted: 10 December 2021

KEYWORDS
biocontrol agents
entomopathogenic nematodes
entomopathogenic fungi
potato leaf miner
Diglyphus isaea

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INTRODUCTION

Insect invasions from one country to another are becoming commonplace, usually due to increased movement of goods and people (Pimentel et al. 2001; Seebens et al. 2018). Many factors contribute to insect invasions worldwide, although one of the common factors is climate change (Hill et al. 2016). Most economic damage and crop losses are the result of pest invasions (Oerke & Dehne 2004). The invasions have a negative impact on food security, and thus can increase levels of poverty (Umesha et al. 2018). To reduce crop losses associated with insect pests, synthetic pesticides are commonly used. However, the overuse of pesticides often results in negative impacts, like the development of insecticide resistance, soil contamination and adverse health problems (Pretty & Pervez 2015). Integrated pest management (IPM), which is an environmentally sensitive approach, includes multiple control strategies that are effective, ecologically compatible and above all, economically feasible (Norris et al. 2002).

Potatoes are among the most consumed non-grain commodity worldwide (Lutaladio & Castaldi 2009). In South Africa, it is one of the most important vegetable crops as it accounts for 60% of the vegetables grown (Joubert et al., 2010). In 2011 South Africa's potato industry represented three percent of the total value of agricultural products in the country's GDP (DAFF 2012). Over 50% of the potatoes that are produced in South Africa are consumed locally, whilst approximately 30% are exported to nearby countries, such as Zimbabwe, Zambia and Mozambique, with the rest exported to other countries (DAFF 2012).

Liriomyza huidobrensis (Blanchard, 1926) (Diptera: Agromyzidae), commonly known as the potato leaf miner, is a devastating pest of potato (*Solanum tuberosum* L.; Solanales: Solanaceae) in South Africa. The potato leaf miner, which originates from Central and South America, was first detected on other continents in the 1980s. After having been detected in Europe in 1987 (Lanzoni et al. 2002; CABI 2018), it was found to have invaded South Africa by the early 2000s (Visser 2009).

Gaining an in-depth understanding of the biology and control options for a devastating pest, like the potato leaf miner, is required prior to implementation of IPM. This review provides an overview of the current information available on the biology and ecology of *L. huidobrensis* and management practices for the pest under South African conditions, with special emphasis on biocontrol agents and their potential implementation in IPM.

INSECTS AFFECTING POTATOES

Globally there are many insects that target potato crops. Among these, 49 important pest species were recognised by Kroschel et al. (2020). Farmers in the tropical and subtropical regions tend to have more challenges with pests when compared to farmers in temperate regions, where pest densities are generally lower (Kroschel & Schaub 2013). *L. huidobrensis* and *Phthorimaea operculella* (Zeller, 1823) (Lepidoptera: Gelechiidae) (potato tuber moth) are major insect pests of potatoes in several countries (Table 1). *Liriomyza huidobrensis*, which is the pest of interest in this case, can cause about 70% crop loss (Visser 2005). Some studies suggest that, in some cases, the leaf miner can cause 100% crop loss (Rondon 2010; Mujica & Kroschel 2013).

In South Africa, more than 60 arthropod species have been identified infesting potatoes (Visser 2005). However, most are considered minor or nuisance pests. In a survey conducted on more than 100 commercial potato farms across South Africa, several insect species were identified as important causes of yield loss or as commonly occurring in potato fields (Table 1) (Potatoes South Africa 2017). The four most important pest species according to their grouping (Table 1), as reported by potato farmers (in order of importance) were: leaf miners, potato tuber moth, nematodes and aphids (as virus vectors).

LEAF MINERS

More than 10 000 leaf miner species have been reported worldwide from the insect orders Coleoptera, Diptera, Hymenoptera and Lepidoptera (Hering 1951). A leaf miner is defined as an insect that feeds within the leaf tissues for at least part of its life cycle (Hering 1951). During feeding the larvae form tunnels, or mines, which are feeding channels within the parenchyma (between the epidermal tissues) of infested leaves (Figure 1) (Hering 1951; Basij et al. 2011). With the exception of oviposition sites, both the epidermis and the outer wall remain intact during larval development (Hering 1951; Weintraub et al. 2017).

The feeding pattern of the larvae may be divided into two categories, i.e., facultative and obligate (Powell 1980). Facultative leaf miners are those that feed within the leaf and externally (in the case of the last larval instars) before they pupate. Obligate leaf miners, on the other hand, feed entirely within the leaves and may even pupate within the leaves (Hering 1951; Powell 1980; Ameixa et al. 2007). Other classifications of leaf miners depend on the shape of the mines (Weintraub et al. 2017).

Table 1. Major and common insect pests of potatoes in the potato producing regions of South Africa. Note that the pest group "Caterpillar" includes bollworms, semi-loopers and lesser army worm (adapted from Potatoes South Africa 2017).

Arthropod pest	Severity
Leaf miners	always a serious problem
Potato tuber moth	always a serious problem
Nematodes	always a serious problem
Aphids	always a serious problem
Caterpillars	sometimes a serious problem
Cutworms	sometimes a serious problem
Black maize beetle	sometimes a serious problem
White grubs	sometimes a serious problem
Red spider mites	sometimes a serious problem
Snout beetle	sometimes a serious problem
Millipedes	seldom a problem, but do occur
Sucking bugs	seldom a problem, but do occur
Thrips	seldom a problem, but do occur
Whiteflies	seldom a problem, but do occur
Wireworms	seldom a problem, but do occur
Grasshoppers	seldom a problem, but do occur

Figure 1. Typical leaf mines of *Liriomyza huidobrensis* observed on infested leaves in a potato field in the Sandveld region Western Cape province.

Some studies hypothesize that the leaf-mining habit protects the insect and, more broadly, acts as a defence against several natural enemies (Hering 1951; Connor & Taverner 1997). An alternative hypothesis suggests that leaf miners might have increased susceptibility to pathogens, due to the humidity within the leaf environment, which may be conducive to pathogens (Cornell 1989). However, Connor & Taverner (1997) found that leaf-mining insects are likely to encounter a lower pathogen incidence than those that feed externally on the foliage. The success rate attained with biological control options, like parasitoids, in relation to leaf-mining insects is greater than for externally feeding insects (Connor & Taverner 1997).

Abiotic changes affect leaf miner larval development. Therefore, the adult leaf miners' host choice is vital, due to the limited mobility of the immature stages, which means that they must feed on the plants where the eggs are laid (Zehnder & Trumble 1984; Musundire et al. 2012). Oviposition differs, depending on the insect order (Weintraub et al. 2017). Some insect orders leave puncture marks on the leaf surface when laying their eggs, while others do not (Hering 1951). In the case of *Liriomyza* leaf miners, a female will first make a puncture with her ovipositor, and then proceed to lay eggs in some of the punctures (Weintraub et al. 2017).

POTATO LEAF MINER, *LIRIOMYZA HUIDOBRENSIS*

Liriomyza, which is one of the largest genera of the order Diptera (Agromyzidae), consists of over 300 leaf miner species worldwide, of which only 23 are considered as economically important (Liu et al. 2009). Leaf mining occurs in nine different families of Diptera, with Agromyzidae having the largest number of species (Mujica & Kroschel 2011). Several leaf miner species have invaded agricultural landscapes across the world; some are key pests and cause significant damage to a variety of crops (Rauf et al. 2000).

Liriomyza huidobrensis is an invasive species, which is extremely polyphagous and is resistant to a variety of insecticides (Spencer 1973; Reitz et al. 2013; Weintraub et al. 2017). The potato leaf miner causes damage to crops both directly and indirectly. Direct damage to foliage is caused by feeding and oviposition punctures (Figure 2). In addition, infested/mined leaves become necrotic and eventually die. Chabi-Olaye et al. (2008) reported a 62% mean reduction in the photosynthetic ability of mined leaves, causing high yield losses. Indirect damage results from diseases, e.g., *Alternaria* spp., that enter the host through perforations made by leaf miner adults or larvae (Deadman et al. 2000). Despite *L. huidobrensis* itself not spreading pathogens,

Figure 2. Feeding and oviposition punctures of *Liriomyza huidobrensis* females on the leaves of a potato plant collected from the Sandveld region, in the Western Cape province.

they do increase the probability of secondary plant pathogen infections (CABI 2018). Few studies have tried to determine economic injury level and their economic threshold, but a quick life cycle and high fertility rates make this challenging (Rondon 2010). Alves et al. (2017) obtained an economic injury level of 0.07, and an economic threshold of 0.05 mines per plant, thus indicating the high damage potential even at low population densities and consequently the need to institute control measures timeously.

Pest description and biology

Liriomyza huidobrensis can be differentiated from other *Liriomyza* species by its relatively dark orange-yellow head and legs (Figure 3A), which, in other species, are mostly just yellow (Visser 2015; CABI 2018). The potato leaf miner is generally small, measuring two to three millimetres in length, with a characteristic division on the second abdominal segment (Weintraub & Horowitz 1995). Adult *L. huidobrensis* females can lay up to 400 eggs, measuring about 0.15 to 0.30 mm, with an off-white and slightly translucent colour (Visser 2015; CABI 2018). The eggs are laid in whitish leaf punctures, usually 0.05 mm in size, made by the female, which hatch within two to five days (Wei et al. 2000; Visser 2015; IPPC 2016; CABI 2018). The larvae hatch within the leaf, where they form mines while feeding (CABI 2018). The larvae stay within their mines during their early stages (Ge et al. 2019). However, in pea plants, the larva also tends to feed on the outer surface of the pods (CABI 2018; Ge et al. 2019). There are three larval instars: the first larval instar, which is colourless at hatching, later turns pale yellow orange. The colour of the last instar is yellow-orange (Weintraub & Horowitz 1995). The larvae can reach about 3.25 mm in length before pupating (CABI 2018). The larvae of some agromyzid species have been reported as leaving one leaf for another, although such behaviour has not been reported in the case of *L. huidobrensis* (Parrella & Keil 1984; CABI 2018). The final instar larva makes a slit on the leaf surface to exit the mine (Visser 2015; CABI 2018). The mines are irregular in shape (which is typically serpentine) and increase in size as the larva grows (Wei et al. 2000; CABI 2018). More than one larva may feed on a single leaf, thus leading to the production of a secondary 'blotch' type mine. This usually leads to wilting of the infested leaf (Spencer 1973). Larval damage is most severe when the plant is fully-grown and is less severe during the vegetative stages of the plant (Visser 2005; CABI 2018). Actively growing leaves contain fewer leaf mines compared to that of the older leaves on the same plant (Visser 2009; Mujica 2016). Additionally, they tend to pupate on the lower surface of the leaf, but usually fall to the soil to complete their pupation period (Visser 2009, 2015). The puparium, which has an oval shape (Figure 3B), measures between 0.5 mm and 1.3 mm in length, with a brown to almost black colour (CABI 2018). The pupal stage lasts for approximately 10 days (Visser 2009). The adults are between 1.3 mm and 2.3 mm in size, with a wing length of 1.3 mm to 2.3 mm (CABI 2018). The females are generally slightly larger than the males (Weintraub et al. 2017).

Figure 3. A. Female *Liriomyza huidobrensis*. **B**. *Liriomyza huidobrensis* pupae.

Although little information exists regarding the biology of the potato leaf miner, its life cycle is typical of all agromyzid species (Weintraub & Horowitz 1995, 1996). *Liriomyza* males usually emerge before the females and mating usually occurs 24 h after emergence (Mujica & Cisneros 1997; Migiro et al. 2011). A single mating can fertilise all of the eggs of one female (Mujica & Cisneros 1997; Migiro et al. 2011). Most adult activity occurs in the early morning just after sunrise, and then again before sunset (Weintraub & Horowitz 1995). In South Africa, leaf miner outbreaks are usually severe during summer when temperatures are high (Adendorff 2010; Visser 2009; Weintraub et al. 2017). Additionally, in a study by Videla & Valladares (2007), it was shown that the potato plant expresses a degree of mechanical resistance against the larvae and eggs of *L. huidobrensis*. In young actively growing leaves, eggs and young larvae are physically "pushed out" by an increase in the multiplication rates of leaf cells, thereby exposing the immatures to predation and increasing the risk of desiccation (Videla & Valladares 2007).

Host plants

Host selection is vital for most herbivorous insects, because it determines the progeny's feeding and the female's choice of oviposition site (Maharjan & Jung 2016). So far 365 plant species, from 49 different families, have been recorded as hosts (Weintraub et al. 2017). Only 32% of the host species are cultivated food crops, with most being weeds and cultivated flowers (Weintraub et al. 2017). The leaf miner affects both field- and greenhouse-produced vegetable crops, ranging from being sporadic to being prevalent throughout a growing season (Reitz et al. 2013). Local leaf miners have a strong preference for local plant species which was observed in Argentina, where *L. huidobrensis* was found to prefer local vegetable crops, like bean, beet, potato, sweet pepper and celery plants, when compared to other exotic vegetables (López et al. 2010). Other studies suggest that external factors, such as temperature and humidity, play a vital role in the host preference of *Liriomyza* flies (Fenoglio & Salvo 2009). Another study on host preference, which was carried out in China, found that the selectivity of the leaf miner is related to nutritional and physical factors (Liu et al. 2009). Other studies have suggested that host selectivity does not depend only on the amount of chlorophyll, soluble sugars, proteins and tannic acid concentrations present, but also leaf miner adaptability to the leaf conditions (Liu et al. 2009; Weintraub et al. 2017). There is little information regarding the extent of hosts susceptible to leaf miner attack in South Africa. However, within laboratory settings, plants like common beans, onions and tomatoes have successfully hosted *Liriomyza* species (Musundire et al. 2012).

MANAGEMENT OF DIFFERENT LEAF MINER SPECIES WITH REFERENCE TO THE POTATO LEAF MINER

Monitoring

Liriomyza huidobrensis is included on the A2 list of quarantine pests (EPPO 2005). In South Africa, it is one of the most important potato pests (Weintraub et al. 2017). An essential part of any IPM strategy is the adoption of monitoring for key pests (CABI 2018). Monitoring can give the farmer the necessary information to make decisions pertaining to which management practices to follow (Dara 2019; Sharma et al. 2020). Effective monitoring practices help to detect the presence and abundance of prevailing pests and may help to identify favourable conditions that facilitate increases in population abundance (Dreistadt et al. 1998; Lu et al. 2012). Monitoring of insect pests are achieved by using a variety of tools, including coloured sticky traps, light traps, pheromone traps, pitfall traps and suction traps (Epsky et al. 2008; McCravy 2018). No information is available regarding the use of sex pheromones for the potato leaf miner.

In the case of the potato leaf miner, the use of sticky traps coated with sticky adhesives in the monitoring of adult populations has proven to be successful. The traps have been designed in different colours, although yellow is mostly preferred (López et al. 2010). Sticky traps, however, also may trap natural enemies, such as parasitoids and lady beetles (Chavez & Raman 1987; Lu et al. 2012). In the potato plant, the adult feeding punctures present on the leaves can be used to foresee an outbreak (CABI 2018). The initial larval infestation begins in the lower third of the canopy, moving to the top canopy of the plant (Visser 2005). Hence, yellow sticky traps are usually placed at canopy level in potatoes. Thus, for fast-growing plants, the placement is usually a few inches above the canopy, while for slower growing plants just above, or at canopy level (Dreistadt et al. 1998; Atakan & Canhilal 2004). However, no study has documented how monitoring of the potato leaf miner is done in South Africa.

Chemical control

The most common method of control used against potato pests is synthetic pesticides (Rondon 2010; Mujica & Kroschel 2013). The use of contact insecticides is not effective as it only kills adult flies, thus to control the larvae growing inside the leaf, effective insecticides are systemic or translaminar (Pirtle et al. 2020). However, the use of most of these insecticides can lead to the development of insecticide resistance, increased cost of production, contamination of the environment and the loss of non-target organisms (Okoth et al. 2014). Most *Liriomyza* species rapidly develop resistance to certain conventional insecticides used in different countries (Weintraub et al. 2017). However, not all populations of *L. huidobrensis* have the same resistance profile (Weintraub et al. 2017). The larvae and adults are not susceptible to all insecticides equally, because the larval life stage is covered and protected inside the leaf, thus contact insecticides are not recommended for the control of larval populations (MacDonald 1991; Van der Staay 1992). In the early 1990s, the only effective insecticides used to control larval populations were abamectin, spinosad and cyromazine (Van der Staay 1992). Neem tree *Azadirachta indica* A.Juss. (Meliaceae) extract, proved to be highly effective against larvae (Weintraub & Mujica 2006). Pesticides that include pyrethroids and organophosphates are mostly ineffective against the potato leaf miner due to the development of insecticide resistance (Macdonald 1991; Weintraub & Horowitz 1995). Several insecticides containing different active ingredients have been registered against the potato leaf miner in South Africa (e.g. ciromazine, abamectin and spinosad). While the pest remains a challenge, these insecticides, if used according to the recommendations, can control, or reduce leaf miner populations (Weintraub et al. 2017).

Cultural control

Habitat management may play an important role in increasing the activity of a leaf miner's natural enemies (Gurr et al. 2017). The use of cover crops in pest management has been advantageous for maximizing interactions between insect predators and prey (Sharma et al. 2018). However, certain weeds near crops may act as reservoirs for leaf miner pests (Schuster et al. 1991; Chen et al. 2003). The cultural control of *L. huidobrensis* mainly involves the use of preventive measures (Weintraub et al. 2017). These measures include weeding of the fields (clean fields), ploughing, mechanical tilling and the adoption of other phytosanitary measures like trapping and monitoring (CABI 2018). Environmentally friendly strategies that play an important role in suppressing leaf miner populations include crop rotation, the selective removal and destruction of infested plant material, both before and after harvest, and the destruction of pupae before planting (Ben Husin 2017). In terms of agricultural crops, pruning and fertilisation have played an important role in reducing the size of lepidopteran and coleopteran leaf miner populations (Ateyyat & Mustafa 2001; Johnson et al. 2011). Practices like proper fertilisation could also be used in managing potato leaf miner, since the quality of the potatoes plays a vital role in leaf miner abundance (Fenoglio & Salvo 2009). *Liriomyza huidobrensis* has not been widely studied in South Africa. However, various cultural control strategies should be implemented and evaluated for their efficacy in pest management.

Biological control

A major objective of biocontrol is to reduce the number of crop pests present without contaminating the environment and disturbing other organisms (Ooi 1998). Environmental contamination is reaching greater heights (Pimentel 1995). Therefore, many biocontrol agents have been developed in recent years to control pests and to eliminate the need for harmful pesticides (Bhattacharya et al. 2003; Hassan et al. 2016; Gangwar 2017). The use of natural enemies like parasitoids, predators, pathogens and viruses are key options in biological control strategies ((Hajek & Eilenberg 2018). Novel options include the use of entomopathogenic fungi (EPF) and entomopathogenic nematodes (EPNs) (Malan et al. 2018). All these options aim to control pests without the use of harmful pesticides (Bhattacharya et al. 2003; Hassan et al. 2016).

Liriomyza species have a considerable cohort of natural enemies, with more than 80 different species reported (Liu et al. 2009). Most studies suggest that natural enemies are important in regulating *Liriomyza* species (Ode & Heinz 2002). The parasitoid, *Diglyphus isaea* (Walker, 1838) (Hymenoptera: Eulophidae), for example, is used to control agromyzid leaf miner populations in both their native and invaded areas (Rauf et al. 2000; Chen et al. 2003). In some parts of Africa, the best control of *Liriomyza* species achieved so far has been with augmentative release of *D. isaea* (Ode & Heinz 2002). In Kenya, mass production systems for parasitoids have been developed and used (Ode & Heinz 2002). In Germany, the most used parasitoid against *Liriomyza* in greenhouses, is *Dacnusa sibirica* Telenga, 1935 (Hymenoptera: Braconidae) (Leuprecht 1992). However, its effectiveness depends on the number of releases per week (between three and four releases recommended) (Leuprecht 1992). Other studies conducted in German-based greenhouses recommend the use of *D. sibirica* in combination with *Opius pallipes* Wesmael, 1835 (Hymenoptera: Braconidae) for effective control of the pests (Van der Linden 1991).

The use of biological control options helps in providing a stable and environmentally friendly pest management programme (Hajek & Delalibera 2009). The development of fungi as biocontrol agents against different pests, weeds and diseases has been an area of interest in recent years (Butt et al. 2001). Several entomopathogenic fungi (EPF) are common, and due to them being known to induce epizootics, they are very important in terms of regulating insect populations (Butt et al. 2001). EPF invade their hosts through the external cuticle, with some species being able to infect their hosts through their digestive tracts (Bonnie et al. 2004; Zimmermann 2007). The infestation process usually starts when the spores attach themselves to an insect's cuticle (Altinok et al. 2019). Spores germinate and penetrate the integument, through enzymatic degradation of the cuticle and physical pressure (Butt et al. 2001; Hajek & Delalibera 2009). After spore penetration, the fungi produce mycelia, which then ramify within the host haemocoele (Altinok et al. 2019). Due to the depletion of nutrients and the action of fungal toxins, the host dies (Butt et al. 2001; Bonnie et al. 2004). Under certain conditions hyphae, emerging from the dead cadavers, produce spores (Butt et al. 2001; Goettel et al. 2008).

The insect parasitic nematodes of the families Steinernematidae and Heterorhabditidae have been actively used since the 1990s (Poinar 1990; Navon & Ascher 2000). EPNs have been reported to show potential for use in different management strategies (Platt et al. 2020), due to their ability to locate, infect and kill several insect species actively (Campbell & Lewis 2002). The nematodes are obligate pathogens in nature, possessing a non-feeding phase that is also known as the infective juvenile (IJ) stage (Dillman et al. 2012; Shapiro-llan & Dolinski 2015). This free-living phase is the only stage that is able to survive outside the host and infect the insect host in soil substrates (Stock et al. 1999; Hazir et al. 2004). The IJs are only able to infect a host through natural openings like the mouth, the anus and the spiracles (Campbell & Lewis 2002; Hazir et al. 2004). After penetration, the IJs release a mutualistic bacterium, either through the anus or the mouth (depending on the genus) (Kaya & Gaugler 1993; Hazir et al. 2004). The released symbiotic bacteria colonise the insect and kill it within one to two days. The nematode then feeds on the bacteria and the bioconverted tissue of the dead larvae (Waterfield et al. 2009). Depending on its size, the nematode then develops through two to three more generations over a period of one to two weeks within the dead insect's body (Gözel & Gözel 2016).

EPF TO CONTROL LEAF MINERS

Entomopathogenic fungi (EPF) are an alternative to conventional chemical control of sap-feeding insects (Inbar & Gerling 2008). An increasing number of studies are being conducted to investigate the possibility of using biocontrol agents against leaf miners (Abd El-Salam et al. 2013). Several strains of *Beauveria bassiana* (Bals.-Criv.) Vuill. (Hypocreales: Cordycipitaceae) and *Metarhizium anisopliae* (Metschn.) Sorokīn (Hypocreales: Clavicipitaceae) have been reported as virulent against dipteran pests (Hallouti et al. 2020). However, few attempts have yet been made to investigate the use of EPF against dipteran leaf miners (Quesada-Moraga et al. 2006).

Consistent results have been reported on the pathogenicity and virulence of *M. anisopliae* to *Tuta absoluta* (Meyrick, 1917) (Lepidoptera: Gelechiidae) third-instar larvae, indicating its potential for use as a biocontrol method for the control of other leaf miners, e.g., *Liriomyza* spp. (Inanl & Oldargc 2012; Alikhani et al. 2019). Both *Metarhizium* and *Beauveria* species have been documented as being pathogenic to eggs and larvae (Inanl & Oldargc 2012). However, not all leaf miners can be controlled by EPF and EPNs (Progar et al. 2015). Progar et al. (2015) reported an increase in the number of the invasive leaf miner, *Profenusa thomsoni* (Konow, 1886) (Hymenoptera: Tenthredinidae), after the application of different fungal isolates. The EPFs that have been reported to infest *Liriomyza* species include *B. bassiana*, *Cordyceps fumosorosea* (Wize) Kepler, B. Shrestha & Spatafora (Hypocreales: Cordycipitaceae), *Purpureocillium lilacinum* (Thom) Luangsa-ard, Houbraken, Hywel-Jones & Samson (Hypocreales: Ophiocordycipitaceae), *M. anisopliae* and *Akanthomyces lecanii* (Zimm.) Spatafora, Kepler & B.Shrestha (Hypocreales: Cordycipitaceae) (Liu et al. 2009). *Metarhizium* and *Beauveria* species were found to be the most used EPF in previous studies (Gürlek et al. 2018).

A study by Migiro et al. (2011), investigating the pathogenicity of *M. anisopliae* and *B. bassiana* isolates against the adults of *L. huidobrensis* under laboratory conditions, found that all 17 isolates evaluated were pathogenic, causing mortalities of between 40% and 100% after five days of initial exposure. The LT_{50} of the isolates ranged from 2.6 and 5.4 days, depending on the isolate.

Noujeim et al. (2015) carried out pathogenicity tests to determine the effect of EPF (*Beauveria bassiana*) and EPN (*Heterorhabditis indica*) Poinar, Karunakar & David, 1992 (Rhabditida: Rhabditidae) on *L. huidobrensis* pupae. The results showed mortalities ranging between 73% and 97% at different concentrations of *B. bassiana*. Migiro et al. (2011) suggested a reduction in the oviposition potential of *Liriomyza* flies due to the applied fungal infection, thus supporting the use of entomopathogens for the control of *Liriomyza* spp. The above supports the success of entomopathogenic fungi against leaf miners (*T. absoluta*) under local conditions which has been reported in other studies (Erasmus et al. 2021). The similarity in the bioecology between *T. absoluta* and *L. huidobrensis* indicates that there is potential for entomopathogenic fungi to be used as a biocontrol agent of *L. huidobrensis*.

EPNS TO CONTROL LEAF MINERS

Following the degree of success attained in the use of EPNs against soil-based insect pests, their use as pest control agents of foliage pests has dramatically increased (Lacey & Georgis 2012; Platt et al. 2020). Several characteristics make it easy for EPNs to be widely used for controlling a variety of insect pests (Kerry & Hominick 2002), including their narrow host range, easy production on a large scale and the fact that they do not contaminate the environment (Kerry & Hominick 2002; Dunn et al. 2020). EPNs can enter leaf miners through oviposition sites and feeding punctures of the adults, making foliar application a viable option (Harris et al. 1990; Steyn et al. 2019).

Williams & Walters (2000) conducted a study to determine the susceptibility of three leaf miner species, namely *L. huidobrensis, Liriomyza bryoniae* (Kaltenbach, 1858) (Diptera: Agromyzidae) and *Chromatomyia syngenesiae* (Hardy, 1849) (Diptera: Agromyzidae), to *Steinernema feltiae* (Filipjev, 1934) (Rhabditida: Steinernematidae). All three species were highly susceptible to the EPN and pupal production was reduced compared to the control treatment. In addition, several species belonging to the genus *Steinernema* and *Heterorhabditis* have been tested against different leaf miner species (Garcia-del-Pino et al. 2018). In a South African study, Steyn et al. (2019) investigated the susceptibility of the leaf miner, *Holocacista capensis* Van Nieukerken & Geertsema, 2015 (Lepidoptera: Heliozelidae) to seven locally isolated EPN species. The bioassays showed that smaller sized nematodes *Heterorhabditis baujardi* Phan, Subbotin, Nguyen & Moens, 2003 (Rhabditida: Rhabditidae), *Heterorhabditis indica* and *Heterorhabditis noenieputensis* Malan, Knoetze & Tiedt, 2014 were the most virulent species as compared to the larger sized nematodes from the genus *Steinernema*. Therefore, efficiency of smaller sized nematodes to leaf mining insects is regarded as important (Bastidas et al. 2014). Nematode species like *Steinernema yirgalemense* Nguyen, Tesfamariam, Gozel, Gaugler & Adams, 2004 and *Steinernema feltiae* could also be used against micro-insect hosts, but virulence might be reduced due to the size of the IJs (Bastidas et al. 2014).

PARASITOIDS TO CONTROL LEAF MINERS

The success of parasitoids to control leaf miner pests can be attributed to the abundance of parasitoids associated with them (Rauf et al. 2000; Chen et al. 2003). In a survey on the species composition of the host crops of leaf miners and parasitoids in Indonesia, the most common parasitoid species associated with *L. huidobrensis* was found to be *Hemiptarsenus varicornis* (Girault, 1913) (Hymenoptera: Eulophidae), with 92% infestation recorded under field conditions (Rauf et al. 2000). One of the most used parasitoids around the world is *D. isaea*, which is a solitary larval ectoparasitoid of a variety of leaf miner species (Ode & Heinz 2002; Liu et al. 2009).

Rates of parasitism may depend on several factors. Studies of the rates of parasitism on the horse-chestnut leaf miner in different environments, including those near forests, villages, urban parks and streets in Switzerland were conducted for both first- and second-generation parasitoids (Girardoz et al. 2006). They concluded that the rates of parasitism increased during the pupal stage of the leaf miner in the first generation and decreased in the second generation. They attributed the poor rates of parasitism to a lack of synchronization, as the parasitoids attacking the first generation were probably old or emerging from the overwintering generation.

Parasitoids are affected by several different factors, both abiotic and biotic, with thermal conditions being found to be key (Rousse et al. 2009). Sugimoto et al. (2006) compared the thermal tolerance of different native species of parasitoids in Japan, when acting as biological control agents against the leaf miner *Liriomyza trifolii* (Burgess, 1880) (Diptera: Agromyzidae), a leaf miner belonging to the same genus as the potato leaf miner and affecting potatoes as well. A decrease in the length of the development period was observed, as the temperature rose above 25 °C. At temperatures above 30 °C, only male parasitoids emerged. The study also showed that the effects of temperature on host feeding and parasitisation differed, depending on the experimental temperature and the parasitoid species (Sugimoto et al. 2006). In addition, in a recent study *Diglyphus isaea, Eulophinae* sp., *Utetes africanus* (Szepligeti, 1910) (Hymenoptera: Braconidae), *Dacnusa sibirica* and *Alysiinae* sp. were recorded as parasitoids of the potato leaf miner in the Sandveld region in South Africa (Mugala et al. 2021), but most of the parasitoid species identified were not native (with the exception for *Utetes africanus,* which was described in 1910).

ALTERNATIVE CONTROL STRATEGIES

Sterile insect technique (SIT) is an environmentally conscious control strategy that aims to reduce pest populations by releasing overwhelming numbers of sterile male insects (Dyck et al. 2005). The population is suppressed through the sterility of the F1 generation, when sterile males mate with wild females to produce non-viable offspring (Knipling 1955). The Sterile Insect Techniques (SITs) programme has been present in South Africa since the 1990s, from single pest SIT programmes to multiple insect SIT programmes in recent years, for example against tortricid and tephritid pests (Barnes et al. 2015). Sterile insect technique has been used against a few lepidopteran insects, including the tomato leaf miner *T. absoluta* (Tarusikirwa et al. 2020), and used against several insect pests in South Africa, including *Ceratitis capitata* (Wiedemann, 1824) (Diptera: Tephritidae) on deciduous fruit and table grapes, *Thaumatotibia leucotreta* (Meyrick, 1913) (Lepidoptera: Tortricidae) on citrus, *Cydia pomonella* (Linnaeus, 1758) (Lepidoptera: Tortricidae) on apples and pears, and *Eldana saccharina* Walker, 1865 (Lepidoptera: Pyralidae) and *Chilo sacchariphagus* Bojer, 1856 (Lepidoptera: Crambidae) on sugarcane (Barnes et al. 2015). The efficacy of SIT in the management of other insects, its soundness with regards to the environment and its compatibility with different control measures, warrant investigation of the potential use of SIT on potato leaf miner management in South Africa. The use of sex pheromone-based strategies, like mass trapping and mating disruption are promising techniques for use against *T. absoluta* (Tarusikirwa et al. 2020), but have not yet been explored for potato leaf miner control.

CONCLUSION

Outbreaks of new pests in the agricultural industry requires baseline studies to understand their ecology and distribution, prior to development and implementation of proper management practices. A review of *L. huidobrensis* and its management on potatoes in South Africa is therefore vital for the enhancement of IPM. The severity of leaf miner outbreaks in South Africa is becoming a challenge and substantial losses are incurred by several farmers as a result. Potato production in South Africa faces potato leaf miner outbreaks over the summer period. The severe leaf damage, as a result of these outbreaks, highlights the need to develop potato plants mechanically resistant to the larvae and egg stages of *L. huidobrensis,* which could be planted during the summer period.

Insecticide overuse in potato production has led to the development of leaf miner resistance against several broad-spectrum insecticides. The latter is a reason to promote the implementation of IPM practices, including those supporting the use of EPF and EPNs. The possibility that EPNs, EPF and parasitoids can infect and colonise all the life stages of the leaf miner is a cardinal point to consider, requiring conformational research. Although previous studies on the effects of biological interventions on the potato leaf miner have concentrated on some of the larval stages, not all the life stages have been investigated in depth. For instance, in South Africa, only a few studies have been conducted regarding the potato leaf miner, especially in the Western Cape province. The current review combined the available information regarding the alternative methods of pest control of the potato leaf miner, *L. huidobrensis.* There is potential for most of these control strategies to be implemented locally. Furthermore, continued research will increase the current knowledge of *L. huidobrensis* and the use of emerging biocontrol options of *Tuta absoluta* in South Africa, as a reference for studies on *L. huidobrensis.*

ACKNOWLEDGEMENTS

The authors would like to thank The National Research Foundation and Potatoes South Africa for funding of the project.

ORCID IDS

T Mugala – https://orcid.org/0000-0001-6482-5974
D Visser – https://orcid.org/0000-0002-9034-0214
AP Malan – https://orcid.org/0000-0002-9257-0312
P Addison – https://orcid.org/0000-0002-8227-339X

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