# GENERAL DISCUSSION AND CONCLUSIONS

The current study forms part of a larger research project on self-sustaining pest management strategies for *Liriomyza* species in Kenyan horticultural systems. It specifically investigated factors related to biological control of agromyzids, specifically *Liriomyza* species, with hymenopteran parasitiods. However, the apparent paucity of information on the Agromyzidae, which include a number of pest species of horticultural importance, and their associated natural enemies in Kenya and the Afrotropical region at large, limits our knowledge concerning biological control approaches. To determine the potential of Afrotropical parasitoids for biological control, data on distribution of agromyzids, host plant records and associated parasitoid species in this region was collated from museum collections, available literature and own observations.

This is the first study in the Afrotropical region that summarizes available literature and provides a snapshot of our current knowledge. The review is critical in advancing biological control research and allows for a more informed approach towards biocontrol projects involving agromyzid species. Agromyzid and parasitoid records (Chapter 1) also provide a framework for collection of additional data on host plant, leafminer, parasitoid associations in the Afrotropical region and can be of great value to agromyzid and biocontrol workers in Africa and elsewhere.

Based on the review in Chapter 1, a wide diversity of agromyzid leafminers has been documented in the Afrotropical region with collection efforts mainly centered on the East and Southern African sub-regions. In contrast to agromyzids, few parasitoid species have been recorded. The number of parasitoid species is approximately 1/6 of the recorded agromyzid species, highlighting either a possible lack of parasitoid diversity associated with agromyzid species or perhaps most likely a lack of sampling effort in the Afrotropical region. There is, therefore, a need for more intensive collaborative research in the afrotropics to identify the causes of the observed pattern.

There are several reports on biological invasions and natural control of *Liriomyza* species from outside the Afrotropical region (Sivapragasam *et al*., 1999; Shepard *et al*., 1998; Murphy & LaSalle, 1999; Rauf & Shepard, 1999; Thang, 1999; Chen *et al*., 2003). According to these reports, local parasitoid species are capable of controlling leafminers in areas they invaded because agromyzid parasitoids, especially eulophids, are generally not host specific (Murphy & LaSalle, 1999). Unlike in regions outside the Afrotropics, only 14 parasitoid species have been recorded from *Liriomyza trifolii* (Burgess), three parasitoid species from *L. huidobrensis* (Blanchard) and only one species from *L. sativae* Blanchard (Chapter 1). Most of these records are likely to be a result of deliberate introduction from other parts of the world, e.g. *Diglyphus isaea* (Walker) (Hymenoptera: Eulophidae) and *Dacnusa sibirica* Telenga (Hymenoptera: Braconidae) from the Palearctic region, for classical biological control programmes or augmentative releases (Minkenberg & van Lenteren, 1986; Neuenschwander *et al.*, 1987; Minkenberg, 1989). On the other hand, a sizeable number of parasitoids have been recorded on *Ophiomyia phaseoli* (Tryon), a widely distributed agromyzid pest of legumes in the Afrotropical region. The relationship between the parasitoid species of *O. phaseoli* and the invasive *Liriomyza* species needs further investigation through more parasitoid collection efforts in this region.

According to previous studies, pest problems with *Liriomyza* species arose because of the use of broad-spectrum pesticides (Hills & Taylor, 1951; Spencer, 1973; Johnson *et al*., 1980; Parrella *et al*., 1984; Keil *et al*., 1985; Macdonald, 1991; Kotzee & Dennill, 1996; Murphy & LaSalle, 1999). According to the limited documentation available on pesticides, mostly broad-spectrum insecticides have been used for control of agromyzids in the Afrotropical region (Abate, 1990; Davies, 1998; Musundire, 2002). It is likely that in this region negative impact on natural enemies of *Liriomyza* species is associated with the indiscriminate use of insecticides in the agro-ecosystems while biological control of leafminers in the natural ecosystems is taking place but escaping notice. In light of this hypothesis, the recommendations made in Chapter 1, that there should be more concerted sampling efforts and capacity building in parasitoid taxonomy, are crucial in advancing biological control of agromyzid pests in the Afrotropical region.

In addition, parasitoid records of *L. huidobrensis*, *L. sativae* and *L. trifolii*, indicate that the presence of some of the parasitoid species is likely a result of deliberate introductions by humans (Neuenschwander *et al*., 1987), showing a willingness by stakeholders in agriculture to approach invasive *Liriomyza* control in a non-chemical way. Due to the ongoing large-scale disturbance of the natural ecosystems within some parts of the Afrotropical region because of expansion of land under agricultural production, it is unlikely that natural control of invasive *Liriomyza* species by parasitoids attacking sister agromyzid species in natural ecosystems will be realized in agro-ecosystems without human intervention. This provides a firm basis for advocating crop diversification and habitat management in Afrotropical agro-ecosystems while also providing an opportunity for implementing augmentative biological control techniques where parasitoids can be mass-reared and introduced into agro-ecosystems through inundative or inocultive releases.

Conservation biological control programmes have been successful in suppressing *Liriomyza* species to non-economic levels in celery, cucurbits, potatoes and tomatoes whose produce are not directly attacked by leafminers (Johnson *et al*., 1980; Heinz & Chaney, 1995; Murphy & LaSalle, 1999; Liu *et al*., 2009). On the other hand, augmentative releases of natural enemies have been successfully applied in greenhouses (van der Linden, 2004; van Linteren *et al*., 2006). Within the context of the existing large-scale commercial agricultural practices in some parts of the Afrotropical region, augmentative biological control seems suitable as the release of parasitoids can be synchronized with other management strategies within the agro-ecosystems, maximizing the efficiency of parasitoids during periods of their release. However, additional surveys of parasitoid candidates suitable for biological control are recommended to widen the base of parasitoids that can be used as biological control agents.

Production of sufficient and high quality hosts is essential for mass-rearing parasitoids (Liu *et al*., 2009). One of the requirements for successful rearing of *Liriomyza* species is production of good quality host plants under suitable environmental and nutritional conditions (Liu *et al*., 2009). The ideal host plants should be easily propagated and maintained, be attractive to females for oviposition and support high numbers of leafminer larvae (Liu *et al*., 2009). Results of the current study showed differences in host plant suitability for *L. trifolii* and to some extent for *L. sativae* but not *L. huidobrensis*, and as well as differences in host plant – host preference for *D. isaea*. These results highlight the importance of selecting suitable host plant species for mass- rearing leafminers for subsequent mass rearing of parasitoids. This is in accordance with Johnson & Hara (1987) that the best results for field application of *D. isaea* are obtained by matching the parasitoid with suitable host and host plant species. However, under field conditions and for mass rearing of *Liriomyza*, larval density per leaf may well exceed the larval densities/cm$^2$ leaf area used in this study. There are, therefore, research opportunities to investigate the effect of different larval densities on the size of the resulting leafminer and implications at the third trophic level.

Various host plants have been used to rear *Liriomyza* species including lima beans (Webb & Smith, 1970; Petitt & Wietlisbach, 1994), tomato (Ushchekov, 1994) and cowpea (Jeyakumar & Uthamasamy, 1997). In the current study the underlying factors of host plant preferences of *Liriomyza* species was not determined. Host plant characteristics, e.g. plant chemistry (Isman, 1992; Martin *et al*., 2005) and nutrition (Minkenberg & Ottenheim, 1990), affect life history parameters of *Liriomyza* as well as parastioid species. Future studies on *Liriomyza* and host plant interactions should involve methods that assess variation in larval size by using measurements of the cephalopharyngeal skeleton (Head *et al*., 2002) or measurements of pupal lengths (Via, 1984a,b; Via, 1986), combined with analyses of the nutritional content of the host plants.

Results of current study suggest that larval size of *Liriomyza* is not necessarily positively linked with parasitism by *D. isaea* (Chapters 2 and 3). It is likely that plant related factors other than size of the *Liriomyza* larvae influenced parasitism. Apart from indirectly affecting the quality of host larvae, host plants have also been shown to influence the degree of parasitism of *D. isaea* by affecting cues for parasitoids, which include visual, acoustic, contact, taste and olfactory cues (Feeny, 1976; Bergman & Tingey, 1979; Price *et al*., 1980; Elzen *et al*., 1983; Visser, 1986; Johnson & Hara, 1987; Gross & Price, 1988; Liu *et al*., 2009).

Olfaction is one of the many important factors involved in the search for a host by *D. isaea* (Zhao & Kang, 2002). Results from this study (Chapter 4) showed a positive response by parasitoids to all *L. huidobrensis*-damaged plant species evaluated. Although there was some variation in the response by parasitoids to plant species infested with *L. sativae* and *L. trifolii* (Chapter 4), overall parasitoids were attracted to leafminer-damaged plants. In addition, results show that indirect defensive compounds (allomones) were emitted by leafminer-damaged plants (Chapter 5). However, there is no discernable pattern between parasitoid response to damaged plants and parasitism and host feeding on the same plants. This suggests that olfactory preference is not necessarily linked with parasitism.

The apparent discrepancy between attraction of parasitoids to leafminer damaged host plants and parasitism or host feeding in the current study indicates that, while volatile cues are important in successful host location by *D. isaea*, a combination of other signals such as visual, acoustic, gustatory, and touch may be involved in successful parasitism or host feeding by the parasitoid. Therefore, the successful use of *D. isaea* in the field and mass rearing may depend on using suitable host plants for leafminers and parasitoids.

Using plant mixtures for manipulating host feeding, parasitism and sex allocation by *D. isaea* can contribute towards improving biological control of *Liriomyza* species. Firstly, crop mixtures are planted in many agro-ecosystems where *Liriomyza* species pose a problem for subsistence and small-scale farmers. It is, therefore, important to determine the dynamics of *D. isaea* in mixed cropping systems. Secondly, previous studies have shown that *D. isaea* adjusts the rate of parasitism according to the host size encountered previously (Ode & Heinz, 2002). Further research on manipulating *D. isaea* behaviour to maximize its efficiency in agro-ecosystems and improve female biased populations for mass-rearing using plant mixtures should be undertaken.

In conclusion, the current study showed that the suitability of *D. isaea* for controlling *Liriomyza* species is variable and depends mostly on host plant species and leafminer size. A need exists for more intensive regional collaborative research to identify other suitable biological control candidates.

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