J Pest Sci
DOI 10.1007/s10340-016-0807-y

ORIGINAL PAPER

Evaluating trap cropping strategies for insect pest control through simulation models

María S. Fenoglio[1] · Martín Videla[1] · Juan M. Morales[2]

Received: 4 April 2016 / Revised: 29 July 2016 / Accepted: 7 September 2016

Abstract Trap cropping is a habitat management strategy where the aim is to reduce damage to the crop of interest by mixing it with other plants that are highly attractive to insect pests. However, despite its potential, the application of this strategy has been limited mainly due to a lack of consistent effectiveness. Here, we developed an individual-based spatially explicit model that accounts for reproduction, movement and mortality of insects within a mixed crop system. This model was used to evaluate the effects of varying trap crop spatial configurations (border, stripes and patches), cover (2, 4 and 10 %) and supplemental management strategies (early harvest and pesticide application) to gain insight into the best control options offered by trap cropping. As a case study, we considered *Liriomyza huidobrensis*, a world known leafminer pest. Our results showed a maximum reduction of about 34 % in the pest population of the main crop when using trap plants. The supplemental management strategy had a stronger effect than other factors, with pesticide use being the best option. A sensitivity analysis showed that demographic parameters were more relevant than the behavioral ones in determining the success of the method. Our model suggests that trap cropping is only suitable for controlling *L. huidobrensis* if a pesticide application is added to the trap crop. Individual-based models, which are cheaper and less laborious than direct field testing, might provide an important tool to help define management schemes for the control of herbivorous pests.

Keywords Herbivores · Individual-based model · Movement · Pest management

Key message

- Trap cropping is a method of pest control, but its application is still limited due to a lack of consistent effectiveness caused by multiple factors.
- We developed a simulation model for a world known pest to test the efficiency of a highly attractive trap crop at different spatial configurations, cover and supplemental strategies.
- The supplemental strategy had a stronger effect than the other factors, with the trap crop having the potential to control pests if combined with a pesticide application.

Introduction

Environmentally friendly methods of pest control, such as habitat manipulation and diversification, have received increased attention in recent decades due to the problems generated by the overuse of pesticides (Landis et al. 2000; Pimentel 2001; Altieri et al. 2009; Letourneau et al. 2011; Vasseur et al. 2013). One of these strategies is trap

Communicated by M. Jonsson.

✉ María S. Fenoglio
mfenoglio@efn.uncor.edu

[1] Instituto Multidisciplinario de Biología Vegetal (IMBIV)-CONICET and Centro de Investigaciones Entomológicas de Córdoba (CIEC)- Facultad de Ciencias Exactas Físicas y Naturales, Universidad Nacional de Córdoba, Av. Vélez Sarsfield 1611, X5016GCA Córdoba, Argentina

[2] Laboratorio Ecotono, Instituto de Investigaciones en Biodiversidad y Medioambiente (INIBIOMA), Universidad Nacional del Comahue-CONICET, Pasaje Gutiérrez 1125. S. C. de Bariloche, 8400 Río Negro, Argentina

cropping, where certain plant species, cultivars or crop stages are used to attract the pests and thus reduce the damage on the main crop (Hokkanen 1991; Shelton and Badenes-Perez 2006). However, in spite of its potential in pest control the use of trap cropping in agriculture is still limited mainly due to a lack of predictability and reliability in its effectiveness, as well as economic and technical reasons (Banks and Ekbom 1999; Shelton and Badenes-Perez 2006). A review on the subject by Shelton and Badenes-Perez (2006) indicates that the majority of the trap crop systems examined had a good potential as a strategy of pest control in preliminary laboratory, greenhouse, screenhouse or field studies. Nevertheless, these authors state that this may not necessarily be successful at the commercial level, where additional variables and different environmental conditions may affect insect behavior. Thus, it is necessary to develop a general mechanistic framework in order to understand and predict the response of herbivorous pests to trap cropping (Hannunen 2005), and to the effects of habitat diversification in general (Ratnadass et al. 2012).

Establishing insect feeding and oviposition preferences is crucial for identifying an alternative (trap) to the main crop host plant when attempting to develop a successful trap cropping strategy, since it is the underlying behavioral mechanism that leads the pest to attack the trap crop and stay away from the main crop (Åsman 2003; Accinelli et al. 2005). As the immature distribution is related to adult movement patterns, a good insect dispersal capability is critical for pests to be able to reach the trap crop (Jones 1977). In addition, other factors apart from desirable life history traits of the herbivores are important in the arrestment of the target insect and should be taken into account when designing successful trap crop strategies (Hokkanen 1991; Potting et al. 2005). Related to this, environmental manipulations such as the spatial configuration of the trap crop (i.e., perimeter or intercropped trap crop) and the percentage of total area covered by the trap plant can have a significant effect on pest abundance (Banks and Ekbom 1999; Potting et al. 2005). Although perimeter trap cropping is one of the most common strategies used by farmers (Shelton and Badenes-Perez 2006), it would not be the best spatial design for herbivorous species which do not colonize the field from the side (Potting et al. 2005). General guidelines for trap cropping have suggested that about 10 % of the total crop area should be planted with the trap crop. However, the exact percentage of trap crop needed varies for each particular system (Shelton and Badenes-Perez 2006). A recent study has shown that in addition to elevated trap plant attractiveness, a very high retention is required for the effective reduction in pest densities (Holden et al. 2012). This necessitates additional practices to prevent insects from dispersing back to the main crop, such as the application of insecticides to the trap crop, the release of natural enemies or an early harvest (Correa-Ferreira and Moscardi 1996; Lu et al. 2009; Lin et al. 2014).

In order to improve our understanding of trap cropping strategies, it is essential to disentangle the interplay among all the involved factors, thereby determining how these can influence the distribution of the pest. However, considering the difficulty of experimentally testing all the variables together in the field, ecological modeling has emerged as a potential tool that may help to predict the outcome of trap cropping and to guide further experiments and data collection. These simulation models can be extremely useful since they allow virtual experiments to manipulate key variables, which is difficult under field conditions. For this purpose, it is possible to use available information on aspects related to preference–performance in herbivorous insects (i.e., Gripenberg et al. 2010) and on patterns of searching behavior (i.e., Bell 1990; Schoonhoven et al. 2005), to help predict the population dynamics of pests under variable conditions in trap crops.

To date, only a few simulation models have been developed in the context of trap cropping (Banks and Ekbom 1999; Hannunen 2005; Potting et al. 2005; Holden et al. 2012), and some of these have overlooked aspects that may limit the reliability of their results, such as ignoring pest reproduction (Hannunen 2005; Holden et al. 2012), mortality (Holden et al. 2012), not accounting for density dependence in behavioral patterns (Hannunen 2005; Holden et al. 2012), or assuming that the pest disperses by simple diffusion and is not attracted to the trap crop (Hannunen 2005). Moreover, certain investigations have considered that large portions of the cultivated surface are dedicated to the trap crop (Banks and Ekbom 1999; Potting et al. 2005), which is unrealistic in the majority of systems.

In the present work, we used a simulation model to evaluate the efficiency of a highly attractive trap crop at different spatial configurations, percentages of cover and supplemental management strategy scenarios, taking as a case study the world known pest species *Liriomyza huidobrensis* Blanchard (Diptera: Agromyzidae). Although the model was only developed for this pest species, we believe that the general framework could be used as a first approximation for other insect pests. To achieve our goal, we developed an individual-based spatially explicit model that accounts for reproduction, movement and mortality of insects to examine variations in the population of the pest in the main crop under different scenarios. We ran simulation experiments to try to gain insights into the best control options offered by trap cropping, and a sensitivity analysis was also performed to detect which parameters, demographical (i.e., mortality, fecundity) or behavioral (i.e., movement, preference), most affected the abundance of the pest in the main crop.

Materials and methods

Study system

Leafminers inflict damage to leaves through punctures made by females to feed and lay eggs and also by larval leaf mining in the mesophyll (Weintraub and Horowitz 1995). *Liriomyza huidobrensis*, known as the pea leafminer, is a highly polyphagous species that attacks a wide range of vegetable and ornamental crops throughout the world (Weintraub and Horowitz 1995). It is in fact the most important leafminer species of potatoes worldwide, being capable of completely destroying potato crops (Cisneros and Mujica 1997; Mujica and Kroschel 2013) and also infests horticultural and ornamental species such as beet, spinach, pea, lettuce, celery and bean crops (Steck 1996; Valladares et al. 1999). The *Liriomyza* species tend to be resistant to commonly used pesticides, which also have the undesirable effect of reducing natural enemy populations (Weintraub and Horowitz 1995). Thus, alternative strategies of control need to be found (Murphy and LaSalle 1999). Although the use of trap crops as a strategy for control of this species has not been tested, other cultural measures such as the use of "intercropping" have been shown to be suitable for the control of *L. huidobrensis* on pepper plants (Chen et al. 2011).

In Argentina, studies designed to evaluate the preference and performance of *L. huidobrensis* on different crops (broad bean, beetroot, potato, chard) have shown that the selection of the host plant appears to be driven primarily by variations in nutritional quality (Videla et al. 2006, 2012). The broad bean *Vicia faba* L. is highly preferred by *L. huidobrensis*, as the insect leaves a greater number of eggs and the offspring develop faster and tend to have a high survival rate, with emerging adults reaching larger body sizes in this plant than in other species such as chard or potato. Moreover, a study conducted in Guatemala suggests that the broad bean crop has an excellent potential as a trap crop for *L. huidobrensis* in bean fields (Sullivan et al. 2000). In the present investigation, we tested the efficiency of the broad bean as a trap crop for the control of the pea leafminer in potato cultures using a simulation model.

Model structure

We developed an individual-based and spatially explicit model that simulates the movement of *L. huidobrensis*, its reproduction and mortality to predict the population dynamics of the pest in a field with both the focal and the trap crop plants. This model keeps track of the age, movement and position of each individual, with predictions being made of the total number of leafmining larvae found on the main crop after the evaluation of different spatial configurations and cover of the trap crop, as well as supplemental management strategies of pest retention.

The environment is represented by a grid where each cell represents a plant of a specified crop species (i.e., potato for the main crop and broad bean for the trap crop), which can be occupied by none, one or more insects. The model proceeds at daily time steps, and the simulation lasts 120 days as this is the approximate duration of the cycle of a potato crop (Celis-Gamboa 2002).

An initial number of adults were chosen to have their origin on the main crop, and these were located randomly within the field. At each time step, the individuals (adult female) can remain in the plant (landscape cell) where they are, or they can decide to move away (Fig. 1). There are two types of movement that an insect can perform: (1) long-distance dispersal, where the insect moves into the air column and is then randomly relocated anywhere within the crop and (2) a local dispersal to any of the eight neighboring plants. These types of movements were selected based on evidence that agromyzid flies are considered to be "moderate fliers" (Yoshimoto and Gressitt 1964). In fact, leafminers tend to fly very short distances between host plants (Zehnder and Trumble 1984), but at the same time, they can move longer distances by wind dispersal (Yoshimoto and Gressitt 1964).

Individuals are more likely to decide to climb into the air column if they are on a crop plant than if they are located on a trap plant. Then, from the air column, they are then randomly relocated to any of the plants in the simulated area, as we assumed that although insects can control whether or not to disperse, they cannot decide where to land. This assumption is based on findings that very small insects, such as the one modeled here, depend on air currents to carry them to new sites and consequently have little control of landing sites (Pasek 1988). We also assumed that as many insects are leaving the simulated area as they are entering it from neighboring crops. Thus, every insect that decides to climb into the air column is relocated within the study area. For local dispersal, the probability of leaving a plant depends on the plant species that the individual came from, whereas the probability of choosing a new plant depends on the preference for or the attractiveness of the main or trap plants. This was based on the fact that adults of *L. huidobrensis*, as in the case of many other herbivorous insects, use visual and olfactory cues to recognize a preferred host plant while in flight (Prokopy and Owens 1983; Kang et al. 2009).

Once a female arrives at a plant, it lays a number of eggs according to a Poisson distribution, where the

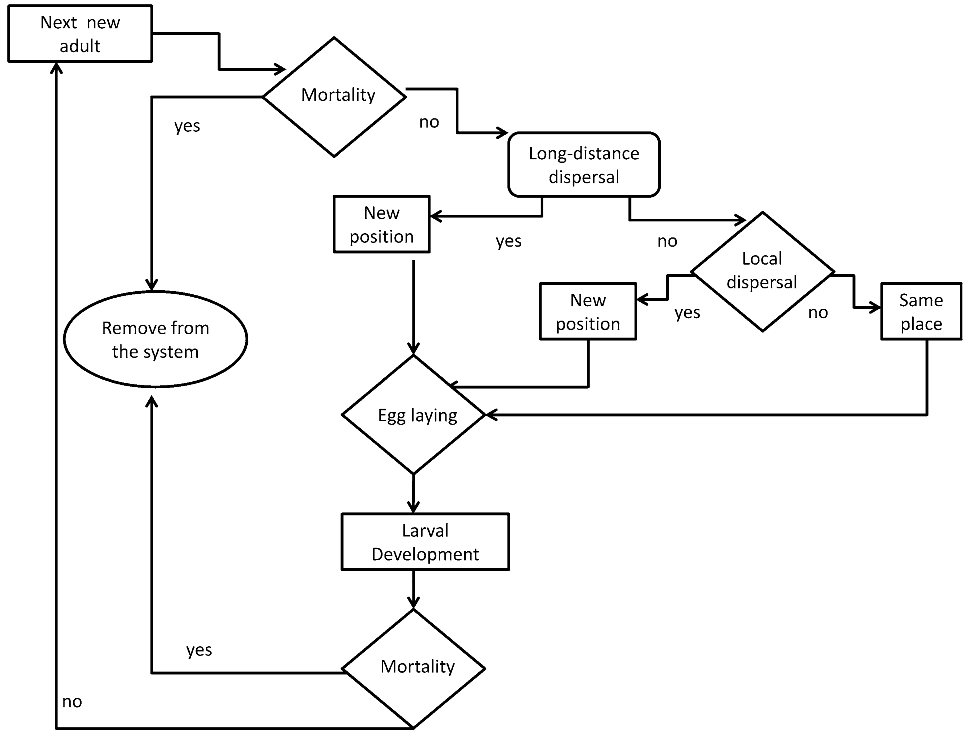

Fig. 1 Flow diagram of events for each individual for each time step in the simulation model

average was set to the amount of eggs that a female usually lays on potato or broad been (Table 1). We modeled density dependence at the larval stage by making daily larval survival an exponentially decreasing function of the number of competing larvae at the plant. The rate of decay in survival depended on the plant species where the larvae were located, with daily adult survival depending on whether the adult was born on a potato plant or on broad bean. Although parasitoids are an important source of mortality of *L. huidobrensis* (Videla et al. 2012 and references therein), they were not included in the model.

Each simulated individual leafminer passes through the different stages of egg, larvae and adult. The pupal stage, whose length is approximately of 7 days (Lizarraga 1990), was not modeled in order to simplify the simulation process. Thus, the model only takes into account the duration of the egg and larval stages, but is not differentiated by plant species. In addition, the model considers which plant species the adults have originated in, giving a higher chance of remaining on its original plant when this is the preferred host plant, and assumes that previous experience does not influence female decisions.

The parameters used in the model are summarized in Table 1, which were obtained from the literature for *L. huidobrensis*, from our own experience of the system or from estimates for related species. As the initial condition, the number of adult individuals starting the simulation was defined as $n = 400$, which was estimated using a study where adult fly populations were followed throughout the growing season of the potato crop and reported the number of adults found per plant 1 month after the planting of the potato crop (Cisneros and Mujica 1997).

Simulation experiments

We performed a simulation experiment (Fig. 2) following a factorial design and considering the following three levels of trap crop configuration: (a) plants located at the borders of the field, (b) plants located on strips in the field and (c) patches of plants placed at the edges and the middle of the field (Fig. 2). Regarding percentage of trap cover, the three levels tested were: (a) 2 %, (b) 4 % and (c) 10 %. The supplemental management strategies of pest retention applied to the trap crop were: (a) a control with no retention measure, (b) early harvest and (c) pesticide application.

Early harvest was applied on day 60 by removing all plants of the trap crop and allowing the model to keep running in the remainder of the plants. Under this condition, individuals in the air column were simulated to fall on the main crop, because if they fall into an empty space, then sooner or later, they will move to find a host plant. Pesticide application was simulated by considering egg and larval mortality caused by abamectin, which is a frequently used product that has shown to be effective in controlling leafminers (Mujica et al. 2000) (Table 1). A pulse of pesticide was applied on day 60 as well, whose effect lasted

Table 1 Details of parameters used in the simulation model to represent the different processes for the pest *L. huidobrensis* in the main (potato) and trap (broad been) crops

Process	Parameter description	Plant species	Parameter name	Value
Fecundity	Average number of eggs per female per day	Potato	ng_p	4[a]
		Broad bean	ng_b	20[b]
Survivorship	Adult survival rate	Potato	va_p	0.8
		Broad bean	va_b	0.9[c]
	Egg survival rate	Potato	vgn_p	0.7
		Broad been	vgn_b	0.9
	Coefficient for the larval survival model by denso-dependency	Potato	ddv_p	0.01
		Broad bean	ddv_b	0.01
	Egg survival rate after abamectin application	Broad been	vga	0.20[d]
	Larvae survival rate after abamectin application	Broad been	vla	0.25[d]
Dispersal	Probability of adults of getting in the air column from	Potato	c_p	0.5
		Broad bean	c_b	0.1
	Probability of adults of moving from	Potato	pa_p	0.1
		Broad bean	pa_b	0.01
	Probability of adults of choosing a plant species	Potato	m_p	0.1[a]
		Broad bean	m_b	0.9[a]
Development time	Number of days at egg stage	Both	gd	3[b,e]
	Number of days at larval stage	Both	vd	9[b,e]

[a] Videla pers. comm.

[b] Videla et al. (2012)

[c] Chien and Chang (2012)

[d] Mujica et al. (2000)

[e] Lizarraga (1990)

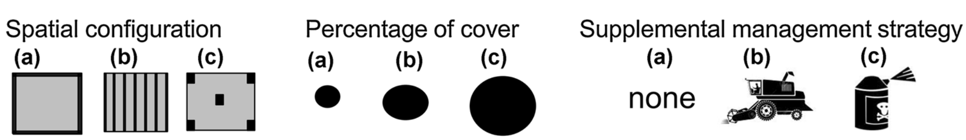

Fig. 2 Schematic representation of different factors regarding the trap crop used in experimental simulations. Spatial configuration: **a** plants in the border, **b** plants in strips **c** plants in patches. Percentage of cover: **a** 2 %, **b** 4 %, **c** 10 %. Supplemental management strategy: **a** none, **b** early harvest, **c** pesticide application

for 5 days. For the remaining days, the eggs and larvae on the trap crop were affected only by natural mortality.

Each combination of factors was replicated 100 times, and for each replicate, the total number of larvae on the main crop was registered at the end of the simulation time. Possible differences between treatments were assessed using a three-way ANOVA with a Tukey test a posteriori, with the relative importance of each factor being evaluated through partition of the sum of squares. A control without the trap crop was also generated and compared to the management strategy represented by the best previous combination of factors. The response variable was $\log_{10}$-transformed to achieve residual normality.

Sensitivity analysis

Tests of the sensitivity of the model were carried out to identify the most influential parameters. By varying the default value of individual parameters by 5 %, we were able to evaluate how each parameter influenced the outcome of the model. For discrete parameters, the default value was altered by adding or subtracting one. The sensitivity analysis was performed using the model that revealed the lowest pest abundance (see "Results"). The percentage of change on the final abundance of larvae (day 120) in the main crop was used to compare the effect of individual parameters on the simulation model.

Results

Our simulations showed that the lowest abundance of *L. huidobrensis* larvae on the main crop was recorded when the trap crop was placed in strips and covered 10 % of the field, with an insecticide also being applied as a supplemental management strategy for pest retention (Fig. 3). This trap cropping strategy accounted for a 34.32 % reduction in the pest population compared to a control scenario (without a trap crop) (Fig. 3).

The supplemental management strategy had a stronger effect than the spatial configuration or percentage of trap cover (Fig. 3) and accounted for 91.72 % of the variation in the final abundance of the pest in the main crop, whereas the other factors and their interactions explained <8 % (Table 2). Among the strategies evaluated, the application of pesticide to the trap crop at the middle of the season was the best option (Fig. 3) to retain the pest there, since a reduction of 29.86 % of pest abundance in the main crop was achieved compared to the control. Few differences were observed between early harvest of the trap crop and no application of a supplemental management strategy, which only reduced pest abundance by 5–6 % with respect to the control. Regarding the other two factors, the percentage of trap cover was more important than its spatial configuration, since the former accounted for a higher proportion of the variability (7.8 vs. 0.005 %; Table 2). A trap crop that covered 10 % of the field was the option where the lowest abundance of larvae in the main crop was registered (Fig. 3), resulting in a reduction of 18.64 % of the pest compared to the control. Related to this, when the trap crop covered 2 and 4 % of the landscape, the reduction in abundance in relation to the control was only between 10 and 12 %. The effects of spatial configuration, independent of other factors, were negligible (Fig. 3), with similar values in pest abundance reduction for the three configurations compared to the control being observed (border: 14.08 %, strips: 13.90 %, patches: 14.14 %).

The sensitivity analysis showed that five parameters had an important influence on the predicted pest population size (Fig. 4), of which the number of days at the larval stage, the average number of eggs per female per day in potato and the survival rate of adults originated in potato were the three parameters having the most impact (between 10 and 11 % of change) on the model outcome. The remaining two parameters, the coefficient for the larval survival model by denso-dependency in potato and the egg survival rate in potato, did not exceed a 5 % of change in the pest abundance in the main crop. The other parameters had an even smaller effect on the mean expected pest abundance.

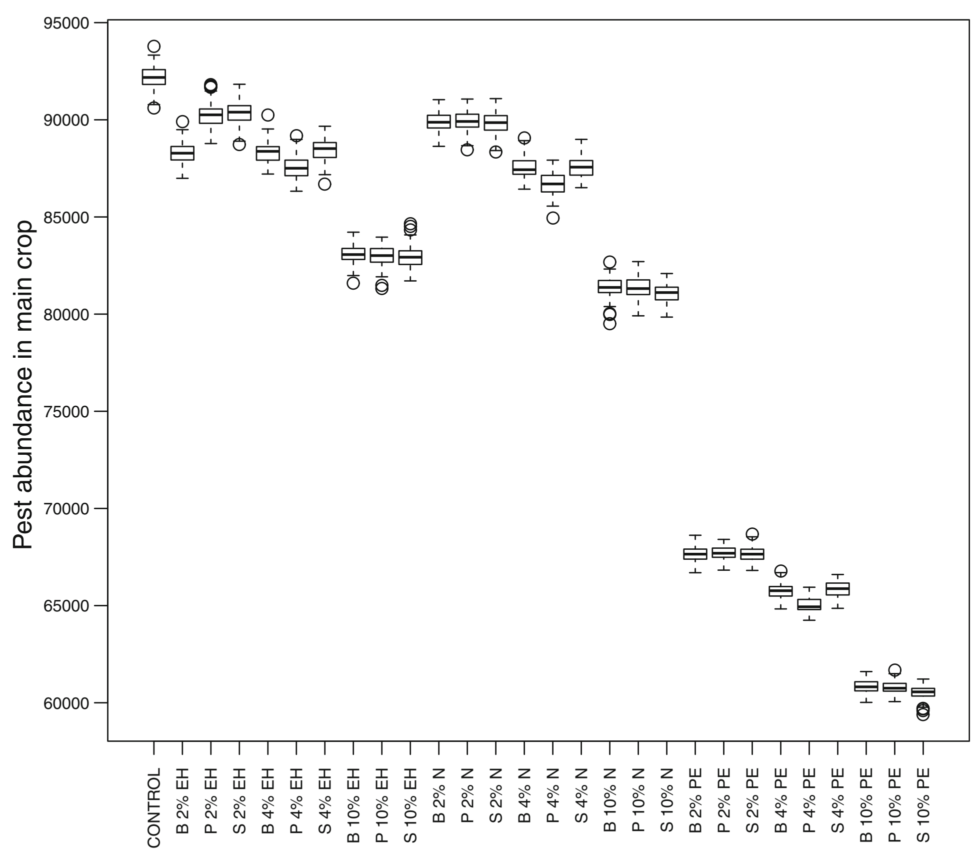

Fig. 3 Pest abundance in the main crop considering the combination of the three studied factors: spatial configuration (*B* borders, *P* patches, *S* strips), percentage of cover of the trap crop (2, 4 and 10 %) and different supplemental management strategies (*EH* early harvest, *N* none, *PE* pesticide application)

Table 2 Three-way ANOVA to test the effects of trap spatial configuration, percentage of trap cover, supplemental management strategy applied to the trap crop and interactive effects, on the final pest abundance in the main crop

Source	*df*	SS	*F* ratio	*P* value
Spatial configuration	2	6.2e−04	43.54	<0.0001
Percentage of cover	2	0.82	57,979.49	<0.0001
Supplemental management strategy (SMS)	2	9.64	677,823.68	<0.0001
Spatial configuration × percentage of cover	4	0.01	215.90	<0.0001
Spatial configuration × SMS	4	1.70e−03	60.29	<0.0001
Percentage of cover × SMS	4	0.02	546.30	<0.0001
Spatial configuration × percentage of cover × SMS	8	2.80e−03	48.79	<0.0001
Error	2673	0.02		
Total	2699	10.51		

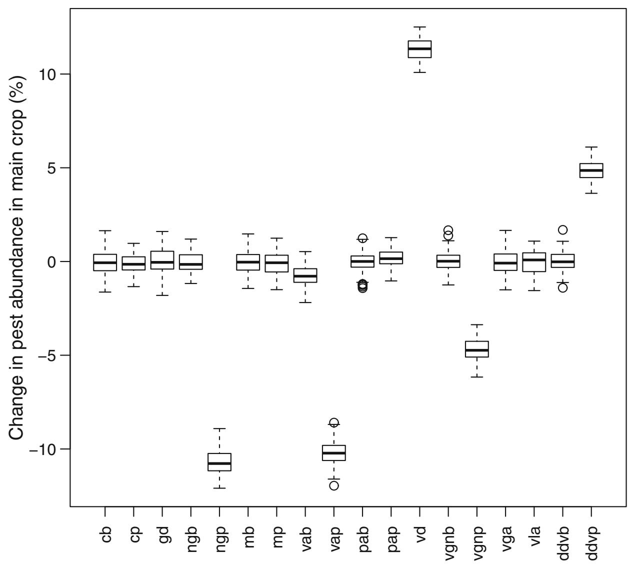

Fig. 4 Sensitivity of the simulation model to standardized changes in individual input parameters. The reference value is the average pest abundance in the main crop after using a trap crop of 10 % cover, in strips and with pesticide application on the trap crop. Model parameters: c_b probability of adults of getting in the air column from broad bean, c_p probability of adults of getting in the air column from potato, *gd* number of days at egg stage, ng_b average number of eggs per day per female in broad bean, ng_p average number of eggs per day per female in potato, m_b probability of adults of choosing broad bean, m_p probability of adults of choosing potato, va_b survival rate of adults originating in broad bean, va_b survival rate of adults originating in potato, pa_b probability of adults of moving from broad bean, pa_p probability of adults to move from potato, *vd* number of days at the larval stage, vgn_b egg survival rate in broad bean, vgn_p egg survival rate in potato, *vga* egg survival rate after abamectin application, *vla* larval survival rate after abamectin application, ddv_b coefficient for the larval survival model by denso-dependency in broad bean, ddv_p coefficient for the larval survival model by denso-dependency in potato

Discussion

General guidelines concerning the application of trap cropping have pointed out that it is very important to understand aspects of the behavior of the pest, the level of preference for the trap crop, as well as the different factors involved in the management of the trap crop (Ratnadass et al. 2012). Our results suggest that of the three factors we analyzed in relation to the trap crop management, the supplemental management strategy to pest retention was the most influential factor in determining the final abundance of the pest in the main crop, at least for the species studied here. In addition, pest demographic parameters were more relevant than behavioral ones in shaping the success of the trap crop.

Our simulations showed that trap cropping is a strategy that may be suitable for controlling *L. huidobrensis* if a pesticide is added to the trap crop. Under this scenario, a reduction of almost 35 % in the abundance of the leafminer in the main crop was obtained. Although various field studies have reported decreases of 50–70 % in population density or crop damage as the ideal values after the application of a trap crop (Åsman 2003; Michaud et al. 2007; Lu et al. 2009), other works have pointed out that reductions between 30 and 40 % are also useful (Accinelli et al. 2005; Moreau and Isman 2012). Thus, our finding is auspicious since it has demonstrated that a relatively simple model is able to produce estimated outcomes close to these empirical works. Moreover, if we consider that *L. huidobrensis* spends the winter as pupae in the soil's surface, a reduction of over 30 % in the population of larvae at the end of the season would therefore result in a lower abundance of adults the following year. The dynamics of the pest population using a trap crop should now be evaluated in a temporal series in order to have a complete picture of its impact.

In our model, the supplemental management strategy applied to control the pest in the trap crop played a fundamental role in the effectiveness of the method. This result is in agreement with other authors who have suggested that the use of supplemental management alternatives that can prevent insects from dispersing away from the trap crop is necessary to adequately reduce insect density (Shelton and Badenes-Perez 2006; Holden et al. 2012). Here, we found that the application of insecticide was the best way to prevent the redistribution of herbivores to the main crop, as previously suggested (Hokkanen 1991; Potting et al. 2002; Holden et al. 2012). In agreement, field studies that have used this approach have achieved a greater effectiveness of the trap crop (Dogramaci et al. 2004; Cavanagh et al. 2009; Lu et al. 2009; Lin et al. 2014). Sprays on trap crops are usually applied every 10 days, but our single pesticide application at the middle of the season was enough to moderately reduce insect abundance in the main crop. Thus, trap cropping with the assistance of pesticide treatments could be an important tool to complement other pest management strategies, since it eliminates the need to spray the entire field and minimizes negative effects on natural enemies in the main crop (Cárcamo et al. 2007). Moreover, considering that parasitoids of *L. huidobrensis* developing on broad bean can exert a control of 30 % (Videla et al. 2012), the frequent application of insecticide might not be necessary if parasitoids prefer the hosts that are on the trap crop (Kovacs et al. 2013; Kaasik et al. 2014).

The other factors evaluated in our model revealed that the fraction that the trap crop vegetation occupied in the environment was next in importance to the supplemental management strategy. In particular, we found that a 10 % cover for the trap crop resulted in the lowest herbivore population registered in the main crop, thereby corroborating theoretical suggestions concerning effective trap size (Hokkanen 1991). However, we cannot rule out that the relevance of the trap cover may depend on the selected scale of individual movement.

Regarding the spatial configuration of the trap crop, it seems from our results that this factor was not so important in determining the final level of the plague. The strip design has been previously mentioned as being the most useful way of obtaining a rapid reduction in pest population possibly because it maximizes the perimeter to area ratio of crop patches, whose significance depends on pest motility (Hannunen 2005). However, we were not able to corroborate this, despite our expectation that this system would be useful for *L. huidobrensis*, since it has been proved that this species does not start its attack from the edges of the fields (Neder de Román et al. 1993). In the case of herbivores that actively immigrate from a nearby source via the field edge, simulation studies have shown that a surrounding border trap crop is the optimal strategy, because it intercepts the population and reduces movement to the crop area (Potting et al. 2005).

Our sensitivity analysis revealed that the final pest abundance in the main crop was much more sensitive to demographic parameters than to behavioral ones, thereby contradicting a previous finding (Potting et al. 2005). For the three parameters that most influenced the pest abundance in the cultivar of interest, the number of eggs that females usually laid on potato was the only one related to pest behavior. Indeed, only a small increase in the number of eggs laid per female per day in the main crop could raise pest abundance by 10 %, which may signify a considerable change.

On the other hand, the movement tendency and movement rate of *L. huidobrensis* were irrelevant parameters for the final outcome of the model, which may in part be explained by some limitations of the developed model. In fact, it would be expected that the highest efficiency of a trap crop strategy would be for insect species that use visual cues to find their preferred host plants and move relatively fast (Potting et al. 2005). *Liriomyza huidobrensis*, as in the case of many other herbivorous insects, use both chemical and visual cues to find its host plants (Prokopy and Owens 1983; Kang et al. 2009), but adults need only move short distances to find acceptable hosts once they have landed in a habitat (Zehnder and Trumble 1984). In this regard, we assumed that the females of the leafminer made just one local movement per day and to neighboring plants, which may limit the probability of finding trap plants. Thus, a further step in developing this model should consist of incorporating several flights from plant to plant toward the preferred host. Moreover, for parameters associated with both types of dispersal (to and from different plant species) we did not have any previous information, except that the broad bean was the preferred host. Consequently, we assumed there would be a lower difference in leaving rates to the air column between potato and broad bean than for local movement, since dispersal to the air column it is not a completely voluntary movement. However, while it would be interesting to estimate what happens in reality, our sensitivity analyzes have shown that these parameters may not influence the outcome a great deal.

Concerning the demographic parameters, the number of days in the larval stage and the survival rate of adults born in potato were the most important ones. Although these findings might be due to a real effect of these processes on the dynamic of the pest under the trap cropping strategy, it could also imply that it is necessary to have a better specification of key biological parameters in order to improve predictions.

In conclusion, our model results demonstrated that trap cropping could be suitable as a strategy to control *L. huidobrensis* if a pesticide application is added. According to Holden et al. (2012), preventing insects from dispersing back onto the main crop is very important when reproduction is considered, as in our case. Therefore, individual-based models might be an important tool for developing management schemes for the control of herbivorous pests using trap crops. Considering that these types of models have rarely been used for such purposes on pests (Vinatier et al. 2009), we have highlighted the advantages of a method that allows different simulation scenarios to be used, by addressing pest reproduction and mortality in the main and trap crops, and simulating direct movement toward plants. Although our model would be best suited for the pest selected, we encourage its application to other agromyzid pests similar to *L. huidobrensis* in motility and sensory abilities, such as *L. trifolii* (Burgess), *L. brassicae* (Riley) and *L. sativae* Blanchard. Future studies are now necessary that field scale test the model, taking into account trap crop designs that appear to have the highest potential for controlling pest attacks (Hannunen 2005). The theoretical study of the trap cropping strategy is much less costly and laborious than direct field testing and provides a useful alternative in the search for more efficient methods of pest control that complement the conservation efforts in the context of an integrated pest management.

Author contributions

MF, MV and JM conceived and designed research. MF and JM developed the model. MS performed analyses and wrote the manuscript with contributions from MV and JM. All authors read and approved the text.

Acknowledgments We thank the Agencia Nacional de Promoción Científica y Tecnológica (ANPCyT) and Fondo para la Investigación Científica y Tecnológica (FONCyT) for providing the subsidy for this research (PICT 2012-No. 1846). We also would like to thank two anonymous reviewers for helpful comments on the manuscript and Dr. Paul Hobson, native speaker, for reviewing the manuscript. M.S.F., M.V. and J.M.M. belong to Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET).

Funding This study was funded by Fondo para la Investigación Científica y Tecnológica (PICT 2012-No 1846)- Agencia Nacional de Promoción Científica y Tecnológica. Ministerio de Ciencia, Tecnología e Innovación Productiva, Argentina.

Compliance with ethical standards

Conflict of interest All authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with animals performed by any of the authors.

References

Accinelli GA, Lanzoni AL, Ramilli FR et al (2005) Trap crop: an agroecological approach to the management of *Lygus rugulipennis* on lettuce. Bull Insectol 58:9–14

Altieri MA, Nicholls CI, Ponti L (2009) Crop diversification strategies for pest regulation in IPM systems. In: Radcliffe EB, Hutchison WD, Cancelado RE (eds) Integrated pest management. Cambridge Univ Press, London, pp 116–130

Åsman K (2003) Trap cropping effect on oviposition behaviour of the leek moth *Acrolepiopsis assectella* and the diamondback moth *Plutella xylostella*. Entomol Exp Appl 2885:153–164

Banks JE, Ekbom B (1999) Modelling herbivore movement and colonization: pest management potential of intercropping and trap cropping. Agric For Entomol 1:165–170

Bell WJ (1990) Searching behavior patterns in insects. Annu Rev Entomol 35:447–467

Cárcamo HA, Dunn R, Dosdall LM, Olfert O (2007) Managing cabbage seedpod weevil in canola using a trap crop—a commercial field scale study in western Canada. Crop Prot 26:1325–1334

Cavanagh A, Hazzard R, Adler L, Boucher J (2009) Using trap crops for control of *Acalymma vittatum* (Coleoptera: Chrysomelidae) reduces insecticide use in butternut squash. J Econ Entomol 102:1001–1007

Celis-Gamboa BC (2002) The life cycle of the potato (*Solanum tuberosum* L.): from crop physiology to genetics. PhD Thesis, Wageningen University, p 191

Chen B, Wang J, Zhang L et al (2011) Effect of intercropping pepper with sugarcane on populations of *Liriomyza huidobrensis* (Diptera: Agromyzidae) and its parasitoids. Crop Prot 30:253–258

Chien CC, Chang SC (2012) Effect of insecticides on survival and fertility of *Liriomyza huidobrensis* (Diptera:Agromyzidae) and its parasitoid, *Opius caricivorae* (Hymenoptera: Braconidae). J Taiwan Agric Res 61:316–329

Cisneros F, Mujica N (1997) The leafminer fly in potato: plant reaction and natural enemies as natural mortality factors. In: CIP program report, pp 129–140

Correa-Ferreira BS, Moscardi F (1996) Biological control of soybean stink bugs by inoculative releases of *Trissolcus basalis*. Entomol Exp Appl 79:1–7

Dogramaci M, Shrefler JW, Roberts BW et al (2004) Comparison of management strategies for squash bugs (Hemiptera: Coreidae) in watermelon. J Econ Entomol 97:1999–2005

Gripenberg S, Mayhew PJ, Parnell M, Roslin T (2010) A meta-analysis of preference-performance relationships in phytophagous insects. Ecol Lett 13:383–393

Hannunen S (2005) Modelling the interplay between pest movement and the physical design of trap crop systems. Agric For Entomol 7:11–20

Hokkanen H (1991) Trap cropping in pest management. Annu Rev Entomol 36:119–138

Holden MH, Ellner SP, Lee D-H et al (2012) Designing an effective trap cropping strategy: the effects of attraction, retention and plant spatial distribution. J Appl Ecol 49:715–722

Jones RE (1977) Movement patterns and egg distribution in cabbage butterflies. J Anim Ecol 46:195–212

Kaasik R, Kovacs G, Kaart T, Metspalu L, Williams IH, Veromann E (2014) *Meligethes aeneus* oviposition preferences, larval parasitism rate and species composition of parasitoids on *Brassica nigra*, *Raphanus sativus* and *Eruca sativa* compared with on *Brassica napus*. Biol Control 69:65–71

Kang L, Chen B, Wei JN, Liu TX (2009) Roles of thermal adaptation and chemical ecology in *Liriomyza* distribution and control. Annu Rev Entomol 54:127–145

Kovacs G, Kaasik R, Metspalu L, Williams IH, Luik A, Veromann E (2013) Could *Brassica rapa*, *Brassica juncea* and *Sinapis alba* facilitate the control of the cabbage seed weevil in oilseed rape crops? Biol. Control 65:124–129

Landis DA, Wratten SD, Gurr GM (2000) Habitat management to conserve natural enemies of arthropod pests. Annu Rev Entomol 45:175–201

Letourneau DK, Armbrecht I, Rivera BS et al (2011) Does plant diversity benefit agroecosystems? A synthetic review. Ecol Appl 21:9–21

Lin K, Lu Y, Wan P et al (2014) Simultaneous reduction in incidence of *Bemisia tabaci* (Hemiptera: Aleyrodidae) and *Sylepta derogata* (Lepidoptera: Pyralidae) using velvetleaf, *Abutilon theophrasti* as a trap crop. J Pest Sci 88:49–56

Lizarraga AD (1990) Biología de la mosca minadora *Liriomyza huidobrensis* Blanchard (Diptera, Agromyzidae). Rev Latinoam Papa 3:30–40

Lu YH, Wu KM, Wyckhuys KAG, Guo YY (2009) Potential of mungbean, *Vigna radiatus* as a trap crop for managing *Apolygus lucorum* (Hemiptera: Miridae) on Bt cotton. Crop Prot 28:77–81

Michaud J, Qureshi JA, Grant AK (2007) Sunflowers as a trap crop for reducing soybean losses to the stalk borer *Dectes texanus* (Coleoptera: Cerambycidae). Pest Manag Sci 63:903–909

Moreau TL, Isman MB (2012) Combining reduced-risk products, trap crops and yellow sticky traps for greenhouse whitefly (*Trialeurodes vaporariorum*) management on sweet peppers (*Capsicum annum*). Crop Prot 34:42–46

Mujica N, Kroschel J (2013) Pest intensity-crop loss relationships for the leafminer fly *Liriomyza huidobrensis* (Blanchard) in different potato (*Solanum tuberosum* L.) varieties. Crop Prot 47:6–16

Mujica N, Pravatiner M, Cisneros F (2000) Effectiveness of abamectin and plant-oil mixtures on eggs and larvae of the leafminer fly, *Liriomyza huidobrensis* Blanchard. In: CIP program report, pp 161–166

Murphy S, LaSalle J (1999) Balancing biological control strategies in the IPM of New World invasive *Liriomyza leafminers* in field vegetable crops. Biocontrol News Inf 20:91–104

Neder de Román LE, Arce de Hamity M, Quincoces de Guerra V (1993) Mecanismo de invasión de *Liriomyza huidobrensis* (Blanchard) (Diptera: Agromyzidae) a un cultivo de *Vicia faba*. Idesia 12:25–29

Pasek JE (1988) Influence of winds and windbreaks on local dispersal of insects. Agric Ecosyst Environ 22(23):539–554

Pimentel D (2001) Overview of the use of genetically modified organisms and pesticides in agriculture. Indiana J Glob Leg Stud 9(1): 4. http://www.repository.law.indiana.edu/ijgls/vol9/iss1/4

Potting RPJ, Perry JN, Powell W (2002) Possibilities and constraints of agroecosystem management as a pest management strategy: a simulation approach. In: Proceedings of the BCPC conference, pests and diseases, Brighton, pp 91–96

Potting RPJ, Perry JN, Powell W (2005) Insect behavioural ecology and other factors affecting the control efficacy of agro-ecosystem diversification strategies. Ecol Modell 182:199–216

Prokopy RJ, Owens ED (1983) Visual detection of plants by herbivorous insects. Annu Rev Entomol 28:337–364

Ratnadass A, Fernandes P, Avelino J, Habib R (2012) Plant species diversity for sustainable management of crop pests and diseases in agroecosystems: a review. Agron Sustain Dev 32:273–303

Schoonhoven LM, van Loon JJA, Dicke M (2005) Insect-plant biology. Oxford University Press, Oxford

Shelton AM, Badenes-Perez FR (2006) Concepts and applications of trap cropping in pest management. Annu Rev Entomol 51:285–308

Steck GJ (1996) Pea leafminer, *Liriomyza huidobrensis* (Diptera: Agromyzidae). In: Florida Department of Agriculture and Consumer Services, Entomology Circular No. 378, 1996. http://doacs.state.fl.us/~pi/enpp/ento/peamin4.htm

Sullivan GH, Weller SC, Edwards CR et al (2000) Integrated crop management strategies in snow pea: a model for achieving sustainable NTAE production in Central America. Sustainable development international, 3rd edn. ICG Publishing, London, pp 107–110

Valladares G, Salvo A, Videla M (1999) Moscas minadoras en cultivos de Argentina. Horticult Argent 18:56–61

Vasseur C, Joannon A, Aviron S et al (2013) The cropping systems mosaic: How does the hidden heterogeneity of agricultural landscapes drive arthropod populations? Agric Ecosyst Environ 166:3–14

Videla M, Valladares G, Salvo A (2006) A tritrophic analysis of host preference and performance in a polyphagous leafminer. Entomol Exp Appl 121:105–114

Videla M, Valladares GR, Salvo A (2012) Choosing between good and better: optimal oviposition drives host plant selection when parents and offspring agree on best resources. Oecologia 169:743–751

Vinatier F, Tixier P, Le Page C et al (2009) COSMOS, a spatially explicit model to simulate the epidemiology of *Cosmopolites sordidus* in banana fields. Ecol Modell 220:2244–2254

Weintraub P, Horowitz A (1995) The newest leafminer pest in Israel, *Liriomyza huidobrensis*. Phytoparasitica 23:177–184

Yoshimoto CM, Gressitt JL (1964) Dispersal studies on Aphididae, Agromyzidae and Cynipoidae. Pac Insects 6:525–531

Zehnder GW, Trumble JT (1984) Intercrop movement of leafminers. Calif Agric 38:7–8