How do insecticides affect potato yield and ecosystem resilience to manage potato pests? An ecological assessment from the central highlands of Peru

J. Kroschel and **V. Cañedo**

International Potato Center, P.O.Box 1558, Lima 12, Peru; j.kroschel@cgiar.org

Abstract

In potato (*Solanum* sp.) production in the Andes, farmers mainly apply insecticides to control Andean potato weevils (*Premnotrypes* sp.). The objective of our research was to make an insect inventory in potato agroecosystems and to explore the effects of insecticide applications on potato pests and natural enemies in an altitude gradient between 2800 to 3850 m in the central highlands of Peru. Potato fields were equally divided into insecticide-treated (farmers' practice) and insecticide-free plots. Active and passive evaluation methods were used to monitor arthropods. Phytophagous insects were the most numerous functional group constituting 75.4% of total arthropods. Predatory insects and parasitoids represented 23% and 1.4% of the total insect population, respectively. Of yet 36 identified phytophagous insects, 23 species are phytophagous on potato. Of 23 predator species, ground-dwelling predators were most numerous (21.7%); plant inhabiting predatory species only represented 1.3% of the total insect population. Although a total of 16 parasitoids were identified, parasitism of potato tuber moths was low (0.4%). Insecticide treatments reduced about 50% of the arthropod population compared to non-treated fields; however, no significant differences were found in predator and parasitoid species abundance and diversity. In non-insecticide treated fields, very striking were higher infestations with flea beetles (*Epitrix yanazara*) with up to 70% of potato foliar damage causing yield losses of up to 72%. Without insecticides, tuber damage by Andean potato weevils and potato tuber moths ranged between 74% to 95% and 5% to 35%, respectively. Insecticide applications were not always effective to control Andean potato weevil and tuber infestations ranged between 0 to 70%.

Keywords: Andean potato weevil, Premnotrypes suturicallus, potato tuber moth, Phthorimaea operculella, flea beetle, Epritrix yanazara, carabidae, natural enemies, Andean region.

Introduction

Potato (*Solanum tuberosum* L.) production in the Peruvian Andean highlands at altitudes between 2800 to 4200 m is severely constrained by many pest problems. Farmers mainly respond with the application of hazardous class Ia and Ib (aldicarb, carbofuran, methomyl, metamidophos) insecticides to control the most important pests which are Andean potato weevils (Orozco *et al.*, 2009). Andean potato weevils belong to the genera *Premmnotrypes, Rhigopsidius* and *Phyrdenus.* With 11 species the genus *Premnotrypes* is most important and most widely distributed. *P. suturicallus* Kuschel occurs mainly in the central highlands, *P. vorax* (Hustache) in the northern and *P. latithorax* (Pierce) in the southern highlands of Peru (Kaya *et al.*, 2009). Other important pests are the common potato tuber moth *Phthorimaea operculella* (Zeller) and the Andean potato tuber moth *Symmetrischema tangolias* (Gyen.), both native to South America, but which are mainly controlled in potato stores (Keller, 2003).

For Peru, several beneficial insect predators and parasitoids that could play an important role in the integrated pest management of potato pests have been reported. These include predators of the families Carabidae, Coccinelidae, Nabidae, Lygaeidae, Chrysopidae, and Syrphidae (Cisneros, 1995). The carabids *Harpalus turmalinus* Van Emden and *Notiobia schmusei* Van Emden have been reported as predators of Andean potato weevils (Cisneros, 1995; Loza, 1999); recently, Kroschel et al. (2009) reported of high numbers of carabids of the genera *Blennidus*, *Metius, Pelmatellus, Incagonum, and Notiobia peruviana* (Dej.) in the central highlands of Peru that greatly affect Andean potato weevil. *Apanteles subandinus* Blanchard, *Dolichogenidea gelechiidivoris* (Marsh), *Copidosoma koehleri* Blanchard, and *Incamyia cuzcensis* Townsend are parasitoids of the potato tuber moths; *Gonia peruviana* Townsend as well as *Patelloa robusta* (Wied.) are larval parasitoids of cutworms (Cisneros, 1995).

Depending on the complexity and species richness, agroecosystems can have a good potential to provide a high level of natural biological control, and hence ecosystem complexity can increase ecosystem resilience to pest outbreaks (Risch et al., 1987). However, various insecticides especially pyrethroids, organophosphates and carbamates are well known to be highly toxic to a wide range of natural enemies (Devine and Furlong, 2007) and hence may negatively interfere with natural control in agroecosystems. The objective of our research was to make an insect inventory in potato agroecosystems of the central highlands of Peru and to explore the effects of insecticide applications on potato pests and natural enemies in different potato agroecosystems in an altitude gradient.

Materials and methods

Study areas

The study was conducted in Huasahuasi (province of Tarma) and the Rio Mantaro valley (province of Concepcion, Jauja and Huancayo). In Huasahuasi, the main potato-cropping season lasts from June to December, in which about 90% of the fields are cultivated with potato. With some exceptions of irrigated potato, the Rio Mantaro valley has one potato-cropping season from November to June, in which period our study was conducted. At each location 5 fields were selected; in Huasahuasi, fields were located at an altitude between 2800 to 3600 m and in the Rio Mantaro valley between 3250 to 3850 m.

Experimental design

In each region and altitude, each of the experimental fields had a size of approximately 1300 m^2, which were divided into two equal plot sizes. One plot served as control (insecticide-free) while the other plot received 3 to 5 insecticide applications with aldicarb, carbofuran and fipronil according to farmers' pest management practice. Fungicides (Propineb plus Cimoxanil, dimethomorph, chlorothalonil, and mancozeb) were applied to control late blight (*Phythopthora infestans* (Mont) De Bary), if required. All fields were planted with potato (var. Yungay). In the Mantaro valley, the two plots were separated by a 3 m strip of oat (*Avena sativa* L.). Each experimental site was considered as one individual experiment.

Inventory and assessments of potato pests and natural enemies in insecticide-treated and non-treated field plots

Direct assessments of pests and natural enemies on potato plants. For direct assessments, ten plants were randomly selected in each field plot by crossing the field in a zig-zag course. The presence of potato pests and their natural enemies was assessed by shaking potato plants and collecting falling insects in 1 m^2 sheets of plastic placed under the plants, direct counts on the plant and using sweeping net sampling methods. Direct counting comprised the evaluation of the whole plant for pest damage (e.g., number of potato tuber moth mines; percentage of leaves damaged by flea beetles, *Epitrix* spp., or other type of damage). All instars of pests were collected and reared in the lab until the adult stage. The sweeping net was applied five times (repetitions) along three meters of 10 consecutive potato plants by making ten strokes. The samples of each repetition were placed in a small container and processed in the laboratory.

Evaluation of natural enemies of the potato tuber moths. Leaf and stem infestations by the potato tuber moth species *Phthorimaea operculella* and *Symmetrischema tangolias* are generally very low and do not allow collecting immature stages in larger quantities to study larvae parasitism throughout the season. Hence, plants were artificially infested with eggs and neonate larvae derived from CIP's insect rearing. In each field, at 10 randomly selected points three consecutive plants were infested either with 30 neonate larvae or 30 eggs (laid on board cards and pinned) of the *P. operculella* or *S. tangolias* in four development stages of the potato crop (emergence, hilling, flowering and pre-harvest). In addition, eggs were placed on the ground in Petri dishes covered by a fine wire-mesh. In total, 48,000 larvae and 113,000 eggs of each moth species were exposed to monitor parasitism. Infested plants were marked, removed and processed after three weeks of exposure to assess larvae infestation. Larvae were placed onto potato tubers (var. Peruanita) until hatching of either adults of moths or parasitoids.

Evaluation of ground-dwelling insects. Pitfall traps were used to sample and monitor ground-dwelling insects, consisting of phytophagous insects (e.g., Andean potato weevil) and predators (e.g., carabids). Apart, also a large number of saprophagous insects, spiders and some parasitoids were found, of which only spiders (Aranea) were considered in the present evaluation. The traps consisted of 1-l plastic pots with a funnel on top.

Inside the pot, a smaller jar (0.25 l) was placed to take out collected insects of the trap. The pitfall traps were buried into the soil and slightly covered with a wooden plate (18 x 18 cm) to protect traps from rainfall, but leaving sufficient space for insects to enter. In all treatments, ten traps were installed at planting inside each of the experimental plots, at field borders and in the middle of the fields and monitored throughout the experiment. The captured insects were stored dry in Petri dishes and sealed with Parafilm® until processing and taxonomic identification.

Taxonomic identification of insect species. Taxonomic identification was performed through comparisons with CIPs' existing collections, with available taxonomic keys or by various experts for each insect group. Reference specimens have been pinned and stored in CIP's Entomological Museum at the La Molina Experimental Station, Lima, Peru.

Evaluation of potato damage and yield

In each experimental plot, five subplots (five repetitions) of an area of 5 x 5 m (25 m^2) were randomly selected to evaluate tuber damage and yield. Tubers were counted, graded into three categories according to size, weight and evaluated for damage by Andean potato weevil, the two potato tuber moth species, *Epitrix* spp. and cutworm determining for each pest species infestation rate and intensity, respectively. Since potato tuber moth infestation cannot be finally determined at harvest, a sample of 100 tubers per subplot was stored in paper bags to evaluate infestation again one month after harvest.

Statistical analysis

The potato pest and natural enemy occurrence and infestation affected by the insecticide treatments were compared among individual experimental sites. High variability existed between plots and sites and the data showed no homogeneity and normal distribution. Hence, the Friedman non-parametric statistical test was applied to detect differences in insect population, damage of plants and tubers, and tuber yield between treatments at a significant level of $P \leq 0.05$, using R program (R, 2008). The effect of the insecticide applications on the community of arthropods was assessed by analyzing the communal variables abundance, dominance, and diversity (Shannon) (Southwood, 2000).

Results

Arthropod inventory

A total number of 27,308 individual insects from 9 orders and 56 families were collected from direct plant evaluation, sweeping net and pitfall traps comprising 20,581 phytophagous, 6,302 predators and 425 parasitoids in the study regions of Huasahuasi and the Rio Mantaro valley (Table 1). With 15,474 insects, pitfall traps proved being the most effective method for collecting phytophagous insects and predators. Only 15 pollinators were collected using sweeping net and pitfall traps (data not shown). However, we found a high number of saprophagous and omnivorous insects (13 families of Coleoptera and 23 families of Diptera, mainly). Further, also spiders (Aranea) with the families Lyniphiidae, Clubionidae and Lycosidae were very abundant in pitfall traps (Table 1). At present, we were able to identify 36 phytophagous insects (Table 2), 21 predators and 15 parasitoids to the genus or species level (Table 3), however, the taxonomic identification of many collected insects is still pending.

Table 1. Insect numbers of three functional groups sampled with different evaluation methods in insecticide-treated (I) and non-treated plots (C) in potato cropping systems of Huasahuasi and the Rio Mantaro valley, Peru

Functional group	Methods of evaluation	Huasahuasi			Mantaro valley		
		I	C	% of reduction	I	C	% of reduction
Phytophagous	Plant evaluation	193	615	69	1989	4133	52
	Sweeping net	25	21	-19	1331	2655	50
	Pitfall trap	1350	2844	53	1468	3957	63
Parasitoids	Plant evaluation + sweeping net	35	45	22	120	225	47
Predators	Plant evaluation	68	131	48	55	112	51
	Plant evaluation[1]	26	50	48	35	84	58
	Sweeping net	0	0	0	40	41	2
	Pitfall trap[2]	1654	2654	38	871	752	-16
	Pitfall trap[1]	335	453	26	162	197	18
TOTAL		**3686**	**6813**	**46**	**6071**	**12156**	**50**

[1]Araneae, [2] Mainly Carabidae and Staphylinidae

Phytophagous insects

The group of phytophagous insects includes 23 species that feed on potato; of those, 9 species can cause severe damage to potato reaching pest status. Most important is the Andean potato weevil *Premnotrypes suturicallus* in all cropping regions, especially above an altitude of 3000 m. In both study regions, 8 species of the family Curculionidae were identified yet, of which the Andean potato weevil was most abundant (about 95% of all Curculionidae collected). Other weevil species were *Amitrus alutaceus*, *Puranius* sp., *Cryptochrynchine* sp., *Adioristus* sp., *Cylydrorhinus* and many un-identified species, which feed on plants (roots and foliage) other than potato. The Chrysomelidae *Diabrotica* sp. and *Epitrix yanazara* occurred in the Rio Mantaro valley in higher numbers. The two potato tuber moth species *Phthorimaea operculella* and *Symmetrischema tangolias* as well as the cutworms *Agrotis ypsilon* and *Copitarsia decolora* are also wide-spread in both regions and altitudes. In total we collected 14 cutworm species of which five are identified yet. The aphids *Myzus persicae* and *Macrosiphum euphorbiae* occurred in all regions, but with a higher abundance in the region of Huashuasi. Although the leafminer fly is generally an important pest of potato at the coast of Peru, in the highlands it only causes feeding punctures on potato leaves; it is however an important pest of faba bean (*Vicia faba* L.) and therefore very common in the study region.

Parasitoids

Generally, the abundance of parasitoids was very low in all regions and altitudes although artificial infestation of potato plants with eggs and neonate larvae of *P. operculella* and *S. tangolias* were used, but which resulted only in a low parasitism percentage between 0.30 and 0.50% in all study areas, although 13 and 9 species were identified in Huasahuasi and the Rio Mantaro valley, respectively. Among the yet identified species are the Braconidae *Dolichogenidea gelechiidivoris* and the Encyrtidae *Copidosoma koehleri,* which both parasitize potato tuber moths, as well as the Tachinidae *Incamyia cuzcensis* (Table 3). *Halticoptera arduine* is a wide-spread parasitoid of leafminer flies in Peru.

Table 2. Phytophagous insects sampled with different evaluation methods in potato cropping systems at different altitudes in Huasahuasi and the Rio Mantaro valley, Peru

Functional group	Family	Species	Huasahuasi (m a.s.l.)			Mantaro (m a.s.l.)	
			3550	3350	2800	3850	3300
Phytophagous	Chrysomelidae	*Calligrapha curvilinea* Stal					*
		Diabrotica* sp. cerca *nigropuncta		**		**	**
		***Diabrotica* sp.**		*			*
		***Epitrix yanazara* Bechyne**	*	*	**	***	****
		Phyllotreta sp.				*	*
	Curculionidae	*Adioristus* sp.	*	*	*	*	**
		Amitrus alutaceus Schoenherr	*	*	*	*	*
		Cryptorhynchine sp.	*	*	*	*	*
		Cylidrorhinus sp (three species)	***	***	***	**	*
		***Premnotrypes fractirostris* Marshall**					*
		***Premnotrypes pusillus* Kuschel**				*	*
		***Premnotrypes suturicallus* Kuschel**	****	***	**	****	***
		Puranius sp. (two species)	**	**	*	*	*
	Meloide	***Epicauta latitarsis* Haag**				*	*
		***Epicauta willei* Denier**				*	*
	Melyridae	***Astylus luteicauda* Champ**				*	**
	Scarabaeidae	*Lygirus mainom* Erichson		*	*	*	*
	Agromyzidae	*Amauromyza* sp.				*	*
		***Liriomyza huidobrensis* Blanchard**	*	*		*	**
		***Phytoliriomyza papae* Spencer**	*	*	*	*	***
	Anthomyiidae	*Delia platura (Meigen)*	**	**	*	*	**
	Cecidomyiidae	***Prodiplosis longifila* Gagné**			*	*	*
	Aphididae	***Macrosiphum euphorbiae* (Thomas)**	**	*		*	*
		Myzus persicae (Sulzer)	***	**	*	*	**
	Cicadellidae	*Agallia* sp.	*	*	*	*	*
	Lygaeidae	***Nysius* sp.**	*			*	*
	Membracidae	*Heranice miltoglypta* (Fairmaire)	*				
	Psyllidae	***Russelliana solanicola* Tuthill**	*			1	***
	Gelechiidae	***Phthorimaea operculella* (Zeller)**	*	*	**	*	*
		***Symmetrischema tangolias* (Gyen)**	*	*	**	*	*
	Noctuidae	***Agrotis ypsilon* (Hufnagel)**	*	*	**	*	*
		***Copitarsia decolora* (Guenée)**	*	**	*	*	*
		***Copitarsia incomoda* (Walker)**			*		
		***Peridroma clerica* (Butler)**			*		*
		***Scania* sp.**		*		*	
	Plutellidae	*Plutella xylostela* (L.)		*			

**** Very abundant > 500; *** abundant [100-500]; ** moderate [10-100]; * scarce <10. Species in bold are phytopagous on potato

Predators

In the group of predators, only ground-dwelling predators of the family Carabidae and Staphylinidae occured in higher numbers; in Huasahuasi and the Rio Mantaro valley we found 16 and 18 species of carabids, respectively, but only some of the species are identified yet (Table 3). In Huasahuasi, *Pelmatellus* sp. was the most abundant species (74% of all species collected). In contrast, *Blennidus* sp. was more common in the Rio Mantaro valley (79% of all species collected). Other carabids were *Incagonum* sp. (near *chilense*), *Metius* sp., *Notiobia peruviana*, and *Pelmatellus columbianus*. Plant inhabiting predators, e.g. of the family Coccinellidae, Syrphidae or Lygaeidae, were very rare or even absent at specific locations or altitudes.

Table 3. Parasitoids and predators sampled with different evaluation methods in potato cropping systems at different altitudes in Huasahuasi and Rio Mantaro valley, Peru

Functional group	Family	Species	Huasahuasi (m a.s.l.)			Mantaro (m a.s.l.)	
			3550	3350	2800	3850	3300
Parasitoids	Tachinidae	*Eucelatoria* sp.	*	*			
		Incamia cuzcensis Townsend	*	*			
		Incamia sp.	**	**	**	*	*
		Leucostoma sp.					*
		near *Phasmonfrontina* sp.	*	*			
		Peleteria sp.		*		*	
		Prosopochaeta anomala Aldrich	*	*		*	*
		Trichophoropsis sp.	*				
	Braconidae	*Aphidius* sp. (two species)	*	*	*	*	*
		Dolichogenidea gelechiidivoris (Marsh)	*	* ▲	* ▲	*	*
	Cynipidae	*Ganaspidium sp.*	*				
	Encyrtidae	*Copidosoma koehleri* (Blanchard)		* ▲	*		*
	Ichneumonidae	*Enicospilus sp.*	*	*			
		Thymebatis sp. (two species)	**	**		*	*
	Pteromalidae	*Halticoptera arduine* Walker				*	*
Predators	Carabidae[1]	*Blennidus* sp. (two species)	*	*		***	*
		Incagonum sp. (near *chilense*)	**	**	*	*	***
		Metius sp. (five species)	*	**	*	**	**
		Notiobia (Anisotarsus) peruviana (Dej.)	**	**	*	*	**
		Notiobia (Anisotarsus) sp.		*			
		Pelmatellus columbianus (Reiche)	**	**	*	**	*
		Pelmatellus sp.	***	****	**	**	*
	Coccinellidae	*Eriopis conexa conexa* Mulsant					*
		Eriopis sp.	*	*		*	*
		Hippodamia convergens Guérin-Méneville				*	*
	Staphylinidae	*Oligota* sp.	*	*		*	*
		Paederus irritans	*	*	*	*	
		Paederus sp.	**	**	*	*	*
	Syrphidae	*Platycheirus saltana*	*				*
		Scaeva prob. *punctata* Shannon	*				
		Toxomerus prob. *mutum*					*
		Toxomerus sp.					*
	Lygaeidae	*Geocoris punctipes* (Say)	*				
	Nabidae	*Nabis punctipennis* Blanchard					*
	Hemerobiidae	*Hemerobius bolivari* Banks	*	*	*		
		Hemerobius tolimensis Banks	*	*		*	

**** Very abundant > 500; *** abundant [100-500]; ** moderate [10-100]; * scarce <10. ▲ found with artificial infestation.

[1] May include herbiovorous species

Insecticide effects on potato pests and natural enemies

Insecticide effects on potato pests

Compared to non-treated fields, the total number of phytophagous insects collected by three different evaluation methods (direct plant evaluation, sweeping net and pitfall traps) was reduced by 55% in insecticide-treated plots (Table 1). This means that insecticides controlled more than half of the pest population. The species number of the family Curculionidae was not affected by the insecticide treatments although abundance was reduced by 70% and 61% for Huasahuasi and Mantaro valley, respectively. Significant differences were observed in the dominance and diversity of species (Table 4A).

Insecticide treatments most heavily affected the Andean potato weevil population (Fig. 1). In the Rio Mantaro valley, the Andean potato weevil abundance was significantly higher at higher altitudes of 3800 m; here, three insecticide applications were needed to reduce the weevil population significantly. In Huasahuasi, treatment effects were similar (data not shown).

Table 4. Abundance and species diversity of ground-dwelling insects in insecticide-treated (I) and non-treated (C) fields as monitored in pitfall traps. Huasahuasi: Total of 5 fields at elevations between 2800 m and 3600 m; Rio Mantaro valley: Total of 5 fields at elevations between 3300 and 38050 m.

Biodiversity indices	Huasahuasi		Mantaro Valley	
	I	C	I	C
A Curculionidae				
Taxa S	18	12	15	13
Abundance	714	2210	1250	3779
Dominance	0.2979	0.4756 *	0.7938	0.9175 *
Shannon H	1.48	1.015 *	0.487	0.2475 *
B Carabidae				
Taxa S	16	17	18	16
Abundance	945	1795	731	629
Dominance	0.4389	0.4509	0.1645	0.1833
Shannon H	1.312	1.267	2.073	2.006
C Staphylinidae				
Taxa S	9	8	8	8
Abundance	686	837	93	73
Dominance	0.1993	0.249 *	0.3299	0.3898
Shannon H	1.715	1.549 *	1.422	1.279
D Araneae				
Taxa Family	7	11	12	11
Abundance	320	411	152	133
Dominance	0.7827	0.7815	0.2371	0.232
Shannon H	0.5071	0.5319	1.69	1.732

* $P < 0.05$

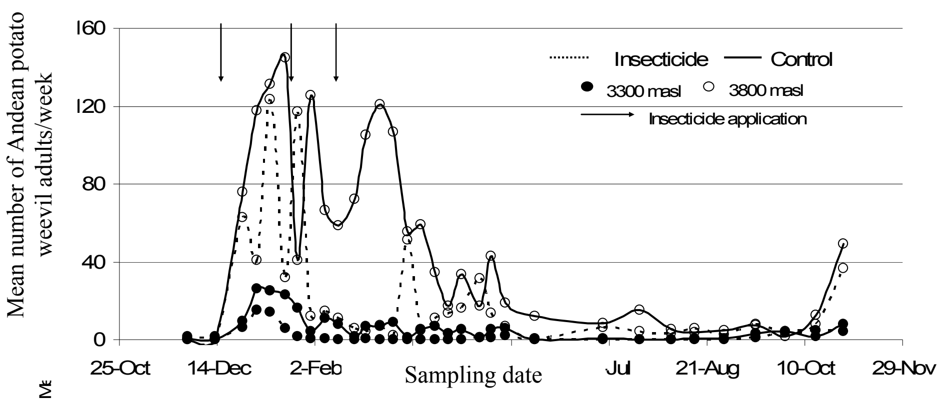

Figure 1. Effects of insecticide applications on Andean potato weevil (*Premnotrypes suturicallus*) population dynamics as monitored by pitfall traps in the Rio Mantaro valley at altitudes of 3300 m and 3800 m, Peru. At 3300 m: mean of three fields; at 3800 m: mean of two fields for each evaluation date

The non-application of insecticides caused a strong increase of the population of flea beetles (*Epitrix yanazara*) and of a stem borer fly (probably *Phytoliriomyza papae*) especially in the Rio Mantaro valley at altitudes of 3300 m. The flea beetle adult population increased up to 7 times (from 22 to 158 adults/plant) intensifying significantly the damage to the potato foliage of up to 70% (Fig. 2). Larvae of stem borer flies caused a plant infestation of up to 50% (data not shown).

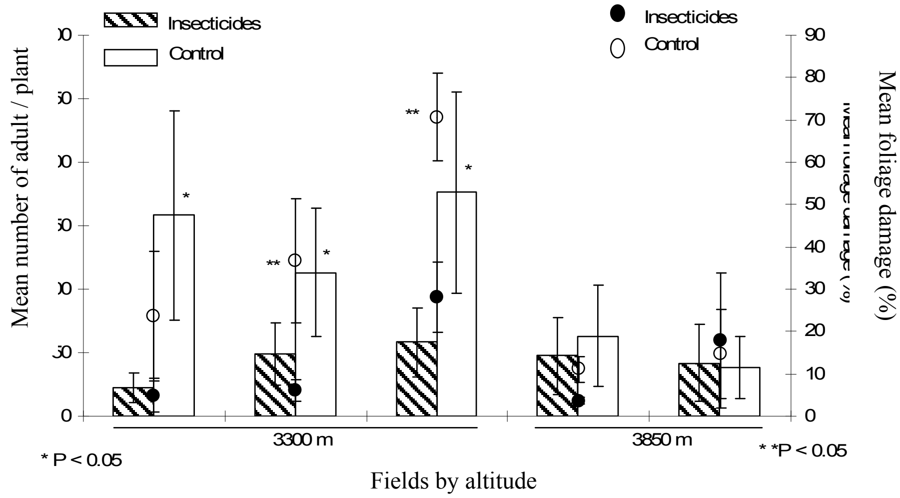

Figure 2. Flea beetle (*Epitrix yanazara*) adult population and mean potato foliage infestation in five insecticide-treated and non-treated fields at two altitudes of the Rio Mantaro valley, Peru

Effects on parasitoids and predators

The abundance of parasitoids (total of 424 individuals) and plant inhabiting predators (total of 336 individuals) was very low throughout the potato growing season in both study regions. Although a mean overall reduction of both functional groups by 35% and 49.5% could be found in insecticide-treated field plots, no significant differences could be established (Table 1). Ground-dwelling carabids, rove beetles (Staphylinidae) and spiders (Aranea) were found in higher numbers in Huashuasi in non-insecticide treated fields, but significant differences with regard to family or species number, abundance, dominance or diversity were not found (Table 4B, C, D).

Treatment effects on potato damage and yield

In Huasahuasi at altitudes of 2800 m, potato tubers were severely infested by the potato tuber moth, both in insecticide-treated and non-treated fields with 25% and 40% of tubers infested, respectively (Fig. 3A). At altitudes above 3350 m, Andean potato weevil infestation ranged between 60 to 70% in the non-treated control fields. The application of insecticides controlled weevil infestation almost by 100%. Without insecticide treatments, a total yield reduction of 40% was determined at lower altitudes of 2800 m, above 3350 m yield reduction ranged between 6 and 26% (Fig. 3B), however, differences were statistically not significant. In the Rio Mantaro valley, tuber infestation by the potato tuber moth complex was less than 5% (Fig. 3C). Andean potato weevil infestation differed greatly between experimental sites at an altitude of 3300 m. In two of the experimental sites Andean potato tuber infestation was very low (<5%) in the non-treated fields, but reached 90% at the third site. At 3850 m, both fields were highly infested by Andean potato weevil resulting in a tuber infestation of 80 and 100% in the non-treated control plots. Interestingly, also the insecticide-treated plots had a very high Andean potato weevil infestation of 20 and 76%, respectively. In three of the sites, total potato yields were significantly different between insecticide-treated and non-treated plots, which can be explained by the high flea beetle infestation on potato leaves especially at one site at 3300 m. In this cases, the total potato yield was reduced by 72% (Fig. 3D).

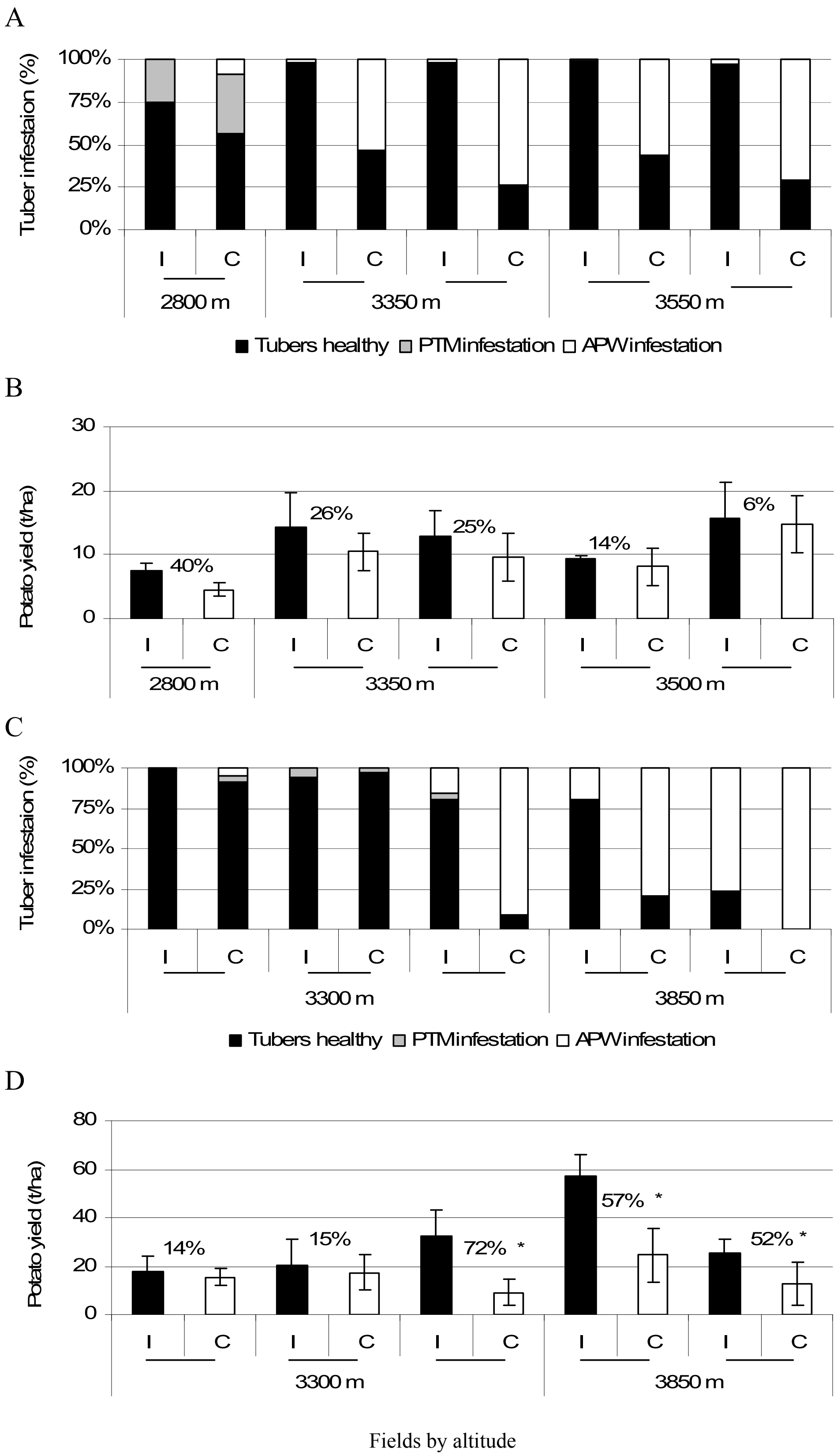

Figure 3. Tuber infestation by the potato tuber moth complex, *Phthorimaea operculella* and *Symmetrischem tangolias*, and the Andean potato weevil, *Premnotrypes suturicallus*, and total potato yield in insecticide-treated and non-treated fields in the potato growing regions of Huashuasi (A, B) and the Rio Mantaro Valley (C, D). *=P • 0.05

Discussion

Arthropod inventory and diversity

Our study presents the first detailed inventory on arthropods in potato agroecosystems of the high Andes at altitudes between 2800 and 3850 m. Phytophagous insects have been found being the most numerous functional group constituting of 75.4% of the total arthropods collected from direct plant evaluation, sweeping net and pitfall traps. In contrast, predatory insects and parasitoids represented 23% and 1.4% of the total insect population, respectively. Of all predators, ground-dwelling Carabidae and Staphylinidae were the most abundant families with 21.7%; instead predators inhabiting potato foliage like species of the families Coccinellidae, Syrphidae, Lygaeidae, Nabidae, and Hemerobiidae only represented 1.3% of the total insect population. Previously we reported of the high abundance and importance of carabids in Andean potato weevil natural control in the Rio Mantaro valley (Kroschel et al. 2009). The general very low abundance of parasitoids and plant inhabiting predators might be due to the low availability of hosts and preys (e.g., aphids) as a result of the high altitude and the harsh Andean climate. Moreover the landscape especially in the Rio Mantaro valley is poorly structured and consists mainly of introduced trees (*Eucalyptus globulus* Labill.) and bushes (Spanish broom, *Spartium junceum* L.) grown in hedgerows. We found that those hedgerows suppress the growth of annual flowering plants and hence are not ideal refugees for those species. Instead, flowering plants are mainly found as weeds along agricultural fields, which are more frequently inhabited by beneficial insects compared to hedgerows.

Effects of insecticides on potato pests and potato yield

The frequent insecticide applications are directed to control Andean potato weevil infestation. In the region of Huasahuasi insecticide efficiency reached almost 100% whereas in the Rio Mantaro valley a high weevil infestation was still found in insecticide-treated fields. Previously, we already reported that farmers' insecticide applications are often not very successful and that infestations of 10-30% are very common (Kroschel et al. 2009). The two potato tuber moth species *Phthorimaea operculella* and *Symmeytrischema tangolis* are important potato pests at lower altitudes up to 3400 m. The insecticide applications resulted in only minor reductions of tuber infestation. Generally, the infestation of potato leaves and stems is not very severe in the study areas, but an increase in tuber infestation is highly correlated to late potato harvest; main potato damage occurs during potato storage (Keller, (2003).

In non-insecticide-treated fields the flea beetle (*Epitrix yanazara*) population increased enormously in the Rio Mantaro valley; at some sites high tuber yield losses could be explained by the high flea beetle foliage infestation. Flea beetles overwinter as adults in the soil or under plant debris in undisturbed areas. Adults feed on potato foliage, producing numerous minute circular holes. Further, larvae feed on roots, and tubers causing superficial injury. *Epitrix* species are quite common in potato production in Peru; apart of *Epitrix yanazara,* Bravo et al. (1986) reported of *E. parvula* (Fab.), *E. subcrinita* Le Conte, *E. ubaquensis* (Harold) and *E. harilana rubia* Bech. & Bech. Our study revealed that flea beetles may become a very serious potato pest if alternative control measures for Andean potato weevil control would be applied. In our study we could not identify natural enemies of flea beetles. Ohashi and Urdampilleta (2003) identified predatory bugs in tobacco (*Nicotiana tabacum* L.) production in Argentina such as *Cosmoclopius nigroannulatus* and *C. poecilus, Apiomerus* sp., *Repipta flavicans* and *Zelus* sp. (Hemiptera: Reduviidae) as well as two species of *Campyloneuropsis* (Hemiptera: Miridae). Further it was reported that entomopathogenic nematodes (*Steinernema carpocapsae*) (Ambrosino, 2008) and fungi (*Beauveria bassiana*) (Rojas, 1982) can reduce flea beetle larvae infestation.

Another emerging pest is the stem borer fly *Phytoliriomyza papae*, which also occurred mainly in non-treated fields. Adult flies lay eggs in the leaf axils and hatching larvae bore into the stem where they destroy the vascular system.

In the region of Huashuasi, no statistically significant differences in total potato yields were found between insecticide-treated and non-treated fields. However, in the Rio Mantaro valley significant differences occurred, but which can be only partly attributed to the high flea beetles infestation. Generally, insecticide-treated potato plants looked healthier and greener than non-treated plants; hence yield stimulation may have also result directly from the insecticide application as it is described for carbofuran (Waibel, 1983).

Effects of insecticides on non-target organisms

Since decades the frequent use of insecticides is farmers' main practice to manage potato pests in the study area (Ewell et al. 1990). Considering all study sites, insecticide treatments reduced about 50% of the arthropods population compared to non-treated fields within one vegetation period. Since potato is the most widely grown crop especially at altitudes above 3800 m, the regular use of insecticides may have caused long-term negative effects on insect populations, especially where no effective recovery from unsprayed fields or hedgerows was given; however, no earlier reference base line studies exist that could give evidence for this assumption.

Long-term field studies in the United Kingdom in a range of arable crops found few adverse long-term effects of pesticides on non-target organisms including insects, spiders, earthworms and soil microbes (Young et al., 2001). Here, the application of broad-spectrum insecticides resulted in declines in the number of many non-target arthropods, but these usually recovered within the same growing season. Less temporary effects were seldom noted and affected only soil-dwelling collembolans (springtails). Numbers of these organisms remained comparatively low in treated plots up to two years after application (Devine and Furlong, 2007). Apart from the persistence of the insecticide, the degree to which affected populations can recover is also dependent upon the recruitment of new individuals from unaffected populations, which permit often the rapid recovery of species in insecticide-treated fields (Jepson and Thacker, 1990). Especially in small experimental areas the probability for a reinvasion increases compared to larger field sizes. In our study we used field sizes of 1300 m^2 divided into two equal plot sizes. Further, insecticide effects on natural enemies may be complex to interpret or fail to detect if only small areas within a field are monitored or if species exhibit either low numbers or spatial heterogeneity (Mead-Briggs, 1998). Such a distribution has been shown for most groups of beneficial arthropods including Carabidae, Staphylinidae, Araneae and parasitic wasps (Holland et al., 1999). The taxonomic level at which results are analyzed is also important because no effects may be detected at the family level but individual species may vary considerably in their response (Büchs et al., 1997).

The impact of insecticides is not limited to a decrease in number of individuals and taxa richness, but also changes species composition. In studies on the carabid community, species richness was a consistent indicator of change; dominance not (Teodorescu and Cogalniceanu, 2005; Dritschilo and Erwin, 1982). Also, precipitation or irrigation may play an important role on how insecticides are affecting insects. Residual toxicity tests suggest that post treatment irrigation reduces insecticide exposure to adult predators such as carabids. The insecticides bendiocarb or imidacloprid have an acute toxicity to the carabid *Harpalus pensilvanicus,* but applications followed by irrigation were found to have relatively little impact on season-long pitfall trap captures in golf courses roughs (Kunkel et al., 2001). In our study regions, potato is grown during the rainy season with not less than a mean precipitation of 750 mm during the potato vegetation period.

Apart from soil-dwelling predators, parasitoids and predators were too scarce in the study area to find significant differences in insecticide-treated and non-treated fields. However, several studies have shown that parasitic wasps are susceptible to insecticides. Gao et al. (2008) found that application of monocrotophos and methomyl in cotton (*Gossypium hirsutum* L.) affected the abundance of parasitoids, but not their diversity. Kao and Tzeng (1992) found a mortality of more than 90% of *Cotesia plutellae* (Kurdjumov) (Hymenoptera: Braconidae) adults (parasitoid of *Plutella xylostella* L.) after carbofuran and methomyl applications while effects to immature stages were less hazardous. In laboratory studies Zu-hua et al. (2004) confirmed that fipronil and methomyl caused over 93% mortality of *C. plutellae* within 24. Further, dimethoate and metamidophos were toxic to *Orgilus lepidus* Muesebeck and *Copidosoma desantisi* Annecke and Mynhardt, both parasitoids of *Phthorimaea operculella* in lab conditions (Keeratikasikorn and Hooper, 1981). According to other studies the effects on predators are mixed. Chlorpyriphos and cypermethrin affected predators like spiders, brown earwigs and carabid beetles in Australia (Curtis and Horne, 1995). The predator *Orius insidious* Say was significantly affected by the insecticides bifenthrin, ethyl-parathion, permethrin, and λ-cyhalothrin in corn (*Zea mays* L.) with more than 40% reduction compared to untreated controls (Al-Deeb et al., 2001). On the other hand, applications of dimethoate had less toxic effects on *Tachyporus* sp. in wheat in Germany and Great Britain (Holland et al., 2000). The pyrethroids fluvalinate and esfenvalerate did not significantly reduce hoverfly (Syrphidae) larvae in field plots but did affect ladybird larvae (*Adalia* spp.) and reduced the Coccinellidae population. By contrast, applications of carbamates such as pirimicarb had no effects on ladybirds' larvae but reduced the number of hoverflies significantly (Jansen, 2000).

Conclusion

Intensive potato production in the Central highlands in Peru is associated with the excessive use of highly toxic insecticide applications to control Andean potato weevil. These insecticide applications also control other pests such as flea beetles. The population of natural enemies is very low in the highlands and main predators are ground-dwelling carabids. Although the number of individual insects of all functional groups was reduced in insecticide-treated fields we could not found a significant direct reduction but assume that the long-term use of insecticides has contributed to a degradation of predators and parasitoids. Potato production with less use of insecticides could become possible by using plastic barriers installed at field borders, which showed a high efficacy to stop the migration of flightless Andean potato weevil adults to potato fields and thus to reduce Andean potato weevil tuber infestation effectively (Kroschel et al., 2009; Alcazar and Kroschel, 2009). No natural enemies of flea beetles could be identified in our study, which could provide effective natural control. However, compared to Andean potato weevils, flea beetle infestations on potato leaves could be more easily controlled by farmers applying economic damage thresholds and thus only applying insecticides, if needed. Augmentation strategies for parasitoids and predators could be applied to increase their population and hence natural control of potato pests.

Acknowledgement

We are grateful to The Regional Fund for Agricultural Technology (FONTAGRO), Washington, USA for providing financial support for this research. Further, we thank Javier Alvarado for his great support in the taxonomic species identification and the preparation of pinned samples for CIP's Entomological museum. Further, we acknowledge the support of Piere Moret for the identification of species of the family Carabidae.

References

Alcázar, J.; Kroschel, J. 2009. Plastic barriers control Andean potato weevils (*Premnotrypes* spp.): Large-scale testing of efficacy, economic and ecological evaluation and farmers' perception. 15th Triennial Symposium of the International Society for Tropical Root Crops. Tropical roots and tubers in a changing climate: A convenient opportunity for the world. 2-6 November 2009.

Al-Deeb M.; Wilde, G.; Yan-Zhu, K. 2001. Effect of insecticides used in corn, sorghum, and alfalfa on the predator *Orius insidiosus* (Hemiptera: Anthocoridae) J. Econ. Entomol. 94(6): 1353–1360.

Ambrosino, M. 2008. Flea beetle pest management for organic potatoes. Oregon State University, Extension service, USA.

Bravo, R.; Carhuamaca, J.; Aldana R. 1986. Pulguilla de la papa, *Epitrix* spp. Biologia, daños y control. Serie Boletin tecnico INIPA Año V No. 517pp.

Büchs, W.; Harenberg, C.; Zimmermann. J. 1997. The invertebrate ecology of farmland as a minor of the intensity of the impact of man? – An approach to interpreting results of fields experiments carried out in different crop management intensities of a sugar beet and an oil seed rape rotation including set-aside. Biol. Agric. Hort. 15: 83-108.

Cisneros, F. 1995. Control de Plagas Agrícolas. Full Print S.R.L. 313pp.

Curtis J.; Horne, P. 1995. Effect of chlorpyrifos and cypermethrin applications on non-target invertebrates in a conservation-tillage crop. Aust J Entomol 34(3): 229 – 231.

Devine, G.; Furlong, J. 2007. Insecticides use: Contexts and ecological consequences. Agric Human Values. 24: 281-306.

Dritschilo, W.; Erwin, T. 1982. Responses in abundance and diversity of cornfield carabid communities to differences in farm practices. Ecology 63(4): 900-94.

Ewell P.; Fano, H.; Raman, K.V.; Alcázar, J.; Palacios, M.; Carhuamaca, J. 1990. Farmers' management of potato insect pests in Peru. Lima, International Potato Center. 87p.

Gao, F.; Ge, F.; Liu, X.; Song, Y. 2008. Impact of insecticide on the structure and productivity of insect pest and natural enemy communities associated with intercropping in cotton agroecosystems. Int. J. Pest. Manage. 54(2):103-114.

Holland J.; Perry, J.; Winder, L. 1999. The within-field spatial and temporal distribution of arthropods in winter wheat. B. Entomol. Res. 89:499-513.

Holland J.; Winder, L.; Perry, J. 2000. The impact of dimethoate on the spatial distribution of beneficial arthropods in winter wheat. Ann. Appl. Biol. 136 (2): 93-105.

Jansen, J. 2000. A three-year field study on the short-term effects of insecticides used to control cereal aphids on plant-dwelling aphid predators in winter wheat. Pest Manag. Sci. 56 (6): 533 – 539.

Jepson, P.; Thacker, J. 1990. Analysis of the spatial component of pesticide side-effects on non-target invertebrate populations and its relevance to hazard analysis. Func. Ecol. 4:349-355.

Kao, S.; Tzeng, C. 1992. Toxicity of insecticides to *Cotesia plutellae*, a parasitoid of diamondback moth. In: NS Talekar (ed.) *Diamondback moth and other crucifer pests*. Proceedings of the Second International Workshop, Taiwan, 10-14 December 1990, Asian Vegetable Research and Development Center, Shanhua, Taiwan, AVRDC Publication No. 92-368, pp. 287-296.

Kaya, H.; Alcazar, J.; Parsa, S.; Kroschel, J. 2009. Microbial control of the Andean potato weevil complex. In: Tennant P, Benkeblia N (Eds.) Potato II. Fruit, Vegetable and Cereal Science and Biotechnology 3 (Special Issue 1): 39-45.

Keeratikasikorn, M.; Hooper. G. 1981. The comparative toxicity of some insecticides to the potato moth *Phthorimaea operculella* (Zeller) (Lepidoptera: Gelechiidae) and two of its parasites *Orgilus lepidus* Muesebeck and C*opidosoma desantisi* Annecke and Mynhardt. Aust J Entomol 20(4): 309–311.

Keller, S. 2003. Integrated Pest Management of the potato tuber moth in cropping systems of different agro-ecological zones. In: Kroschel, J (ed.) Tropical Agriculture 11– Advances in Crop Research 1, Margraf Verlag, Weikersheim, Germany. 153pp.

Kroschel, J.; Alcazar, J.; Poma, P. 2009. Potential of plastic barriers to control Andean potato weevil *Premnotrypes suturicallus* Kuschel. Crop Prot. 28 (2009): 466–476.

Kunkel, B.; Held, D.; Potter, D. 2001. Lethal and sublethal effects of bendiocarb, halofenozide, and imidacloprid on *Harpalus pennsylvanicus* (Coleoptera: Carabidae) following different modes of exposure in turfgrass. J. Econ. Entomol. 94(1):60-67.

Loza, A. 1999. Población y ecología alimentaria de carabidos (Coleoptera) en agroecosistemas del altiplano. MSc thesis, Universidad Nacional del Altiplano, Puno, Peru.

Mead-Briggs, M. 1998. The value of large-scale field trials for determining the effects of pesticides on the non-target arthropod fauna of cereal crops. In P T Haskell and P McEwen (eds.) Ecotoxicology; Pesticides and Beneficial Organisms, Dordrecht, Kluwer Academic Publishers, pp. 182-190.

Ohashi, D.; Urdampilleta, J. 2003. Interacción entre insectos perjudiciales y benéficos en el cultivo de tabaco de Misiones, Argentina. Ria 32(2):113-124.

Orozco, F.; Cole, D.; Forbes, G.; Kroschel, J.; Wanigaratne, S.; Arica, D. (2009). Monitoring adherence to the International Code of Conduct – highly hazardous pesticides in central Andean agriculture and farmers' rights to health. Int. J. Occup. Environ. Health. 15 (3): 255-268.

R Development Core Team (2008). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org.

Risch S.J.; Andow D,; Altieri M.A. 1983. Agroecosystem diversity and pest control: data, tentative conclusions, and new directions. Environ. Entomol. 12: 625-629.

Rojas, J. 1982. Metodos de aplicación del hongo *Beauveria* para el control de la pulga saltona *Epitrix* sp. Turrialba 32(1): 91-92.

Southwood, T.; Henderson, P. 2000. Ecological methods. Third edition. Blackwell Science Ltd.

Teodorescu I.; Cogălniceanu, D. 2005. Rapid assessment of species diversity changes after pesticide application in agricultural landscapes. Appl. Ecol. Env. Res. 4(1): 55-62.

Waibel, H. 1983. Die Okonomik des chemischen Pflanzenschutzes im bewässerten Reisanbau der Philippinen. PhD thesis, University of Hohenheim, Germany.

Young, J.; Griffin, M.; Alford, D.; Ogilvy, S. 2001. Reducing agrochemical use on the arable farm: The Talisman and Scarab Projects, 416pp London: DEFRA.

Zu-hua, S.; Shi-jian, G.; Wen-cai, L.; Shu-sheng, L. 2004. Evaluation of selective toxicity of five pesticides against *Plutella xylostella* (Lep: Plutellidae) and their side-effects against *Cotesia plutellae* (Hym: Braconidae) and *Oomyzus sokolowskii* (Hym: Eulophidae). Pest Manag. Sci. 60(12): 1213–1219.