

Rajinder Peshin · David Pimentel
Editors

Integrated Pest Management

Experiences with Implementation,
Global Overview, Vol.4

 Springer

Integrated Pest Management

Rajinder Peshin • David Pimentel
Editors

Integrated Pest Management

Experiences with Implementation,
Global Overview, Vol.4

 Springer

Chapter 15

Agent-Based Models and Integrated Pest Management Diffusion in Small Scale Farmer Communities

François Rebaudo, Carlos Carpio, Verónica Crespo-Pérez, Mario Herrera, María Mayer de Scurrah, Raúl Carlos Canto, Ana Gabriela Montañez, Alejandro Bonifacio, Milan Mamani, Raúl Saravia and Olivier Dangles

Contents

15.1	Introduction	368
15.2	Diffusion Theory and Integrated Pest Management	370
15.3	Agent-Based Models in Social-Ecological Systems	371
15.4	Application Within Farmer Communities in the Northern Andes	372
15.4.1	Preliminary Session with Farmers	374
15.4.2	Presentation	375
15.4.3	Initialization	375
15.4.4	Role-Playing Session and Discussion	376
15.4.5	Impact of Role Game Sessions on Farmers' Knowledge	376
15.5	Conclusion and Discussion	377
	References	380

Abstract The purpose of this chapter is to present how agent-based models can be used for the diffusion of Integrated Pest Management (IPM) information in small scale farmer communities, using the potato tuber moth in the North Andean region as a study case. This issue was addressed through an international project called INNOMIP (*INNOvación en el Manejo Integrado de Plagas*, 2009–2012, funded by the McKnight Foundation), which operated in three Andean countries (Ecuador,

O. Dangles (✉) · F. Rebaudo
 Institut de Recherche pour le Développement UR072, CNRS-UPR9034, UPXI,
 CNRS-IDEEV-FR3284, 91198 Gif-sur-Yvette Cedex, France
 e-mail: olivier.dangles@ird.fr

Universidad Mayor San Andrés, La Paz, Bolivia

C. Carpio, · V. Crespo Pérez, · M. Herrera
 Pontificia Universidad Católica del Ecuador, Quito, Ecuador

M. M. de Scurrah, · R. C. Canto, · A. G. Montañez
 Yanapai group, Huancayo, Perú

A. Bonifacio, · M. Mamani, · R. Saravia
 PROINPA Foundation, Cochabamba, Bolivia

R. Peshin, D. Pimentel (eds.), *Integrated Pest Management*,
 DOI 10.1007/978-94-007-7802-3_15,
 © Springer Science+Business Media Dordrecht 2014

Peru, and Bolivia). This project involved scientists from a broad range of disciplines, from agronomists to modelers to extensionists. With the specific objective of proposing innovative IPM extension tools, we first developed a role-playing game relying on an agent-based model to simulate the consequences of individual behaviors on pest control in a theoretical landscape. We then tried this role-playing game with 90 farmers belonging to 6 communities in three countries. Briefly, the training sessions consisted of a board game where farmers could exchange and discuss information about IPM practices and visualize the benefits of IPM adoption and cooperation within a theoretical landscape. Based on farmer interviews and comparison of IPM level of knowledge before and after the sessions, our study suggests that the role-playing game sessions significantly increased the IPM knowledge score in the community and also reduced farmers' knowledge heterogeneity. Moreover, our analyses suggest that farmers' age and extension experience significantly affected role-playing game success, with younger participants (and among them, those with higher initial knowledge) more inclined to increase their IPM knowledge after the session. While we have no evidence of the long (mid)-term benefits of our sessions in the adoption/changes of IPM practices, farmers revealed themselves more predisposed to understand and realize the importance of the cooperative basis of IPM and therefore disseminate to their peers IPM information they had acquired. At a broader scale, this study exemplifies how a computer simulation model can be used for teaching purposes and may represent a promising complement to existing IPM diffusion programs. More broadly, our experience with ABM (Agent-Based Models) for IPM issues suggests that new approaches in pest management extension practices should include topics such as group decision making, intergroup relations, commitment, and persuasion which deal directly with how other farmers influence each other's thoughts and actions and consequently with the level of insect infestation in the community.

Keywords Role-playing game · Potato tuber moth · Andes · Social-ecological systems · INNOMIP program

15.1 Introduction

Food security of millions of people in the third world has faced a growing number of challenges in recent years including risks associated with climatic change and extreme events, unprecedented price hikes for basic food and the continuing growth of the human population (Gregory et al. 2009). If future world demand is to be met, food production must virtually double by the year 2050 (Thomas 1999). One potential approach of meeting part of this demand is the control of insect pests and diseases, which are estimated to cause losses approaching 60–70 % in available crop production and storage in developing countries (Nwilene et al. 2008); farmers cannot afford to feed pests in addition to themselves. In the Andes, climate and habitat changes are considered to be one of the most serious threats to sus-

tainable development, with adverse impacts expected on the environment, human health, economic activity and food security (Young and Lipton 2006). Over the last decade, the tropical Andes have also experienced socio-economic and institutional changes that have increased the pressure on natural resources, weakened the internal social organization and caused cultural erosion in the Andean society, reducing the capacities of populations to overcome these challenges (Perez et al. 2010). At the interface between environmental and social changes, the risks related to agricultural pests are of major concern for the food security of thousands of Andean farmers. For example, the emergence and spread of new invasive insect pests (e.g., potato tuber moths in Ecuador, *Tecia solanivora*) are a consequence of both climatic and socio-economical factors (Dangles et al. 2008, 2009). The risks related to agricultural pests in a changing climate will be of major concern for the food security of thousands of Andean farmer communities for at least two reasons. First, effects of temperature increase on insect pests is expected to be greater in the mountainous regions than in lowlands, reflecting the prediction of much larger proportional temperature rises in the mountainous regions (Hodkinson 2005). Second, the wide range of thermal environments found along altitudinal gradients in the Andes may increase the risks presented by invasive pest species in the near future (Hagen et al. 2007; Dangles et al. 2008). More species can “be packed” into a long thermal axis than into a shorter one. Small differences in elevation can also create strong microclimatic differentials over short distances and allow persistent microclimatic refuges for pests to develop (Bale et al. 2002).

However, given the paucity of studies on Andean pest response to climate and the complexity of agro-ecosystems and farmer mitigation response, mid- to long-term predictions regarding the effect of climate change on pests in the Andes remain uncertain. In view of recent developments in empirical data analysis and modeling (Gelman and Hill 2007), new approaches are now available to better understand and predict pest dynamics. A transfer of this knowledge to local technicians is a great way to strengthen the resilience of the Andean region to pest problems; technicians have a key role in transferring advances in scientific knowledge to farmers (Feder et al. 2004).

Because of important limitations such as access to technology and funding, low levels of education, or village inaccessibility, the transfer of integrated pest management (IPM) knowledge through pest management programs is a difficult task in developing countries and policy makers have long been in search of new and better strategies to promote IPM (Oerke 2005). During the last decade, several participatory research, management and teaching programs have been implemented in the Andes to help small farmers facing risks presented by agricultural pests (Thiele et al. 2001). Among them, farmer field schools (FFS) are an intensive training approach extensively applied in the last decade to promote knowledge of agroecological concepts, apply IPM practices, reduce the use of pesticides and improve crop yields (Pumisacho and Sherwood 2005). Because of the high training cost, the success of FFS depends on the effectiveness of knowledge diffusion from a limited number of trained farmers (graduate farmers) to other farmers (exposed farmers). Graduate farmers are therefore encouraged to share their knowledge with

other farmers within their communities. Although this aspect is fundamental for the progress of knowledge enhancement programs, theoretical studies on diffusion from FFS have received little attention and empirical evidences provide conflicting conclusions (Feder et al. 2004). The way acquired information is spread by exposed farmers is a complex process that can be affected by a number of factors such as the structure of the interaction social network, the size of the community, the level of homophily (common interests among farmers) or the spatial organization of the community (Feder and Savastano 2006). A better understanding of the processes by which new knowledge spreads through farmer communities is of crucial importance for the success of farmer training programs (Dangles et al. 2010; Rebaudo and Dangles 2011). We believe that new approaches, such as agent-based models (Bonabeau 2002; Rebaudo et al. 2010, see definition thereafter), would strengthen the role of education in reducing community vulnerability to pest risks, and spur adaptation to ongoing climate-driven changes in pest distribution and abundance.

15.2 Diffusion Theory and Integrated Pest Management

For almost half a century, the theory and practice of agricultural extension has been dominated by Rogers' "diffusion of innovation theory" (Peshin et al. 2009). As mentioned above, the success of IPM programs depends on the effectiveness of information diffusion from farmers to farmers, a precept that has demonstrated varying results (Rebaudo and Dangles 2013; Matteson 2000). These may be due to the very nature of the information being disseminated: is it the philosophy of IPM (i.e., an integration of all elements of the agro-ecosystem and their interaction leading to a given set of practices in a given context) or rather advised practices in an IPM context for a given problem? As exemplified by Peshin et al. (2009), there are several levels of integration that constitute the IPM approach. Along with these considerations, there are several technical and socio-economical factors that must be taken into account, from the trialability and risk perceived by farmers, to the farmers' social network. Trialability (one of the criteria for acceptance of innovation according to Rogers (2003) is the perceived degree to which an innovation may be tried on a limited basis or small-scale, and thus reduce risk, which would enhance the chance of acceptance. Such complexity can however be represented in a simplified way using different modeling approaches. The common approach is mathematical and relies on the Bass model (Mahajan et al. 1990; Bass 1969), describing the "S-curve" of cumulative adopters as follows:

$$\frac{dN(t)}{dt} = \frac{q}{m} \cdot N(t)(m - N(t)) + p \cdot (m - N(t)) \quad (15.1)$$

Where $N(t)$ represents the cumulative number of adopters and $dN(t)/dt$ the variation of the cumulative number of adopters as a function of time t , p and q the coeffi-

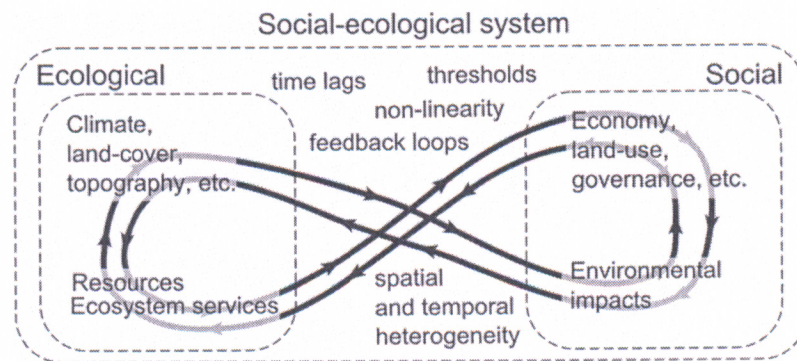


Fig. 15.1 Representation of a social–ecological system that is affected by ecological (*left-hand side*) and social properties (*right-hand side*), and exhibits time lags, thresholds, non-linearity, feedback reciprocity loops and heterogeneity. (based on Chapin et al. 2009; Liu et al. 2007)

cient of external (*e.g.* marketing, television, radio) and internal (world-of-mouth, mimicry) influence, respectively, and m is the number of potential ultimate adopters.

In the Bass model, however, social networks through which the innovation is disseminated, are not taken into account, while the importance of social networks has been recognized to influence information diffusion (Fowler and Christakis 2010), with different networks favoring the spread of new ideas or technologies (Montanari and Saberi 2010). In this context, another modeling approach, using agent-based simulations, seems particularly promising (Kuandykov and Sokolov 2010).

15.3 Agent-Based Models in Social-Ecological Systems

In most countries around the globe, land is dedicated to crops, so that agriculture plays a major role in shaping landscapes (Firbank et al. 2008; Ziegler et al. 2011). These landscapes constitute social-ecological systems (SES), *i.e.*, systems where environment and human activities are tightly linked (Hufnagl-Eichiner et al. 2011; see Fig. 15.1). SES are characterized notably by non-linear dynamics, thresholds, feedback loops or delays in time (Liu et al. 2007), and are consequently susceptible to unexpected changes (Chapin et al. 2009).

However, questions related to the interactions between ecological dynamics and social dynamics have been examined for many years either as “an ecological system subject to anthropogenic disturbance” or, as “a social system subject to natural constraints” (Bousquet et al. 1999). In this context, agent-based models appeared to be a good alternative to integrate knowledge from both social and ecological sciences (Smajgl et al. 2011). This type of computer model is composed of autonomous entities able of acting upon themselves and their environment (Daudé 2003). When considering human agents, it allows the integration of behavioral heteroge-

neity, which in the case of IPM programs, is a key issue to understand and predict the success of pest control information diffusion on a large scale (Paredes 2010; Rebaudo and Dangles 2013).

Agent-based models (ABM) in a social-ecological context have been widely used to represent the management of commons, for example natural resources like water (Becu et al. 2003), bush meat (Bousquet et al. 2001), or forests (Bonaudo et al. 2005). ABM have also been employed to represent land-use and land-cover changes (Parker et al. 2003), but less often to simulate farmers' behaviors facing a pest (Carrasco et al. 2012), or as an educational tool for sustaining functional agrobiodiversity in farming systems (Speelman and Garcia-Barrios 2010). Moreover, ABM have proven to be excellent support for teaching and role-playing games, as exemplified by the Cormas group (*e.g.* Guyot and Honiden 2006; Dray et al. 2006; Mathevet et al. 2007; Barnaud et al. 2008), and seemed promising in the case of IPM diffusion among small scale farmers of the Northern Andes.

15.4 Application Within Farmer Communities in the Northern Andes

We designed a computer model of the Andean agricultural system as a support to realize a role playing game with potato growers of the Andean region facing pest problems. The main objective was to use the model to enhance the farmers' awareness that pest problems should be considered at the regional scale and that individual actions should be coordinated to reduce pest populations to an acceptable threshold. A key factor of coordination was underlined as being the wide sharing of information regarding integrated pest management among community members. The pest model consists of a cellular automaton which represents pest densities on a spatially explicit landscape, implemented on the basis of previous work of our team on the potato tuber moth *Tecia solanivora* (see Crespo-Pérez et al. 2011). The farmers (mainly subsistence and market-oriented farmers, see Dangles et al. 2010 for a description of Ecuadorian potato growers of the Andean region) were represented through an agent-based model where actions of each participant were updated at each time step, depending on their selection of practices. Briefly, IPM technologies for the potato tuber moth *T. solanivora* consist of prophylactic measures targeting fields and storage facilities (see Pollet et al. 2003 for a complete description). These technologies were developed taking into account farmers' local constraints whenever possible. Their implementation requires a low economic investment and is reasonably time-consuming compared to existing practices, to ensure sustainability of the production system. A board game was used to represent the landscape, the farmers and pest densities in grid cells represented farms. The formation was divided into five parts: (i) preliminary session with farmers (Fig. 15.2, part c and d); (ii) presentation of the role-playing session and appropriation of the board game by participants (Fig. 15.2, part e and f); (iii) initialization according to inquests among participants (Fig. 15.3, part a and b); (iv) role-playing session (Fig. 15.3, part c, d and e); and (v) discussion and diffusion of information (Fig. 15.3, part f).

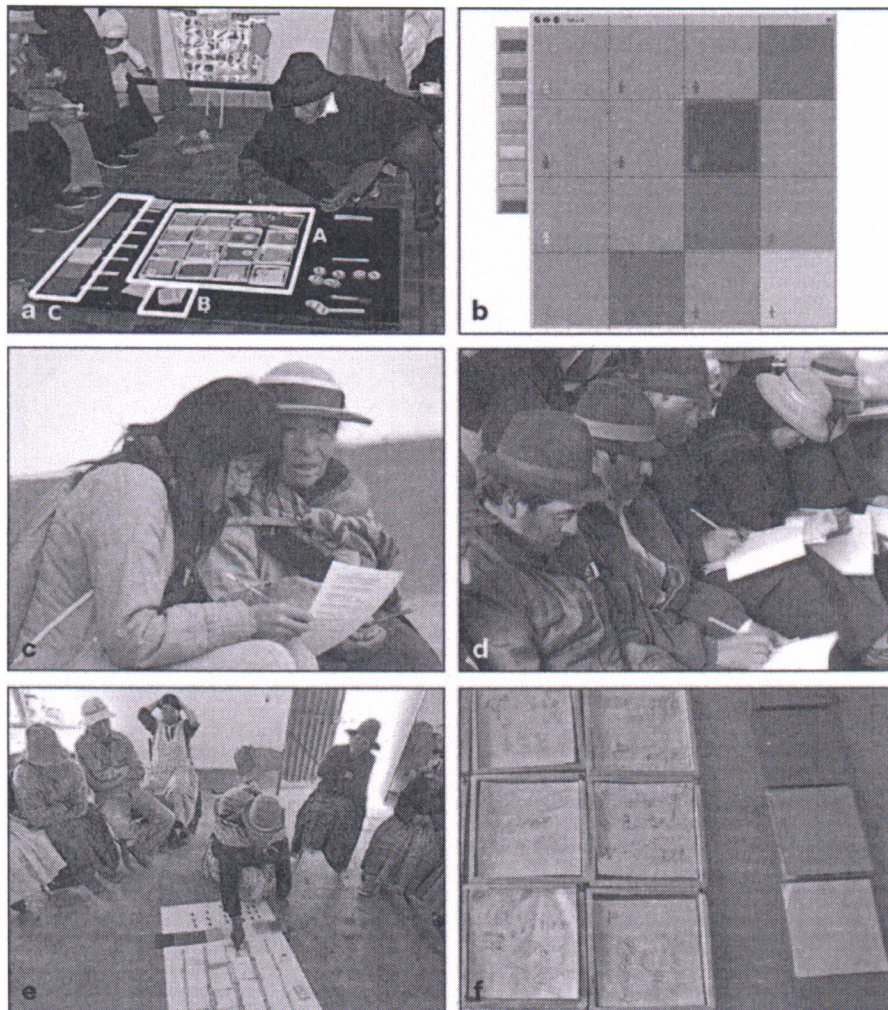


Fig. 15.2 Pictures of the role-playing game sessions. *Part (a)*: board game with participants of the Marcopamba community in Ecuador. **(A)** theoretical landscape composed of 16 grid cells where farmers managed the pest. **(B)** playing cards representing management decisions. **(C)** set of colored cards used to update pest abundance in each grid cell (based on the simulation model outputs). *Part (b)*: Screenshot of the agent-based model computer simulation. The gradient of colors indicates the severity of pest infestation, from blue (no infestation) to red (high infestation). *Part (c)* and *Part (d)*: preliminary sessions in Bolivia and Ecuador, respectively, with participants filling out the questionnaire. *Part (e)* and *Part (f)*: Presentation of the game board in Bolivia and Peru, respectively. Participants localize their farm in the board game and appropriate the space thanks to drawings representing their main activities



Fig. 15.3 Pictures of the role-playing game sessions. Initialization of the game board is realized thanks to questionnaires and dispersal of the pest from one farm to another (part (a) and (b) in Peru and Ecuador, respectively). Then a specific pest management practice is discussed according to playing cards (Part (c) in Peru and (d) in Ecuador). Each participant's practices can then be updated according to their choices which consequently are updated in the board game thanks to the computer simulation (Part (e) in Peru). When all pest management practices have been discussed, a general discussion is opened between farmers (Part (f) in Bolivia)

15.4.1 Preliminary Session with Farmers

The preliminary session with farmers was organized about two weeks prior to the role-playing game session in order to get a first contact with farmers involved. At the beginning of the session, there was a consensus among farmers about the need of implementing a pest management program in their area. In order to evaluate

farmers' IPM knowledge, participants were asked to fill in a questionnaire including 11 items on pest management practices during different stages of the potato crop (seed selection, field practices, harvest, storage, see Fig. 15.2, part c and d). We also registered on the questionnaire the participant's age and sex for further analyses (see Sect. 15.4.5). Based on the completed questionnaires, we built a "knowledge index" for each farmer, which corresponded to the percent of questions answered correctly. These data were later used to initialize the model. Note that some partners of our group (in Peru) had been promoting IPM among farmer communities, and documenting this process over several years and, in this case, the preliminary session was not necessary and the whole session was realized in a single day (instead of two days).

15.4.2 Presentation

The computer model consisted of a coupled cellular automaton (CA) representing pest dynamics and agricultural landscape (see Crespo-Pérez et al. 2011), with an agent-based model representing potato farmers facing the pest. Briefly, the CA was a spatially explicit simulation model accounting for the pest dynamics (reproduction, survival, and dispersion), in a theoretical landscape divided into grid cells. The farmers of the agent-based model behaved accordingly to participants' decisions which were updated at each time step in the model (information diffusion and control practices). These decisions influenced pest dynamics which were used to update the role-playing game in return (see Rebaudo and Dangles 2011 for a detailed description of the model).

The role-playing game consisted of a game board divided into grid cells (similar to the computer simulation model), used in parallel with the computer model (see Fig. 15.2 part a and b). The game board itself was composed of 16 square cells representing participants' farms (see Figs. 15.2 and 15.3). Note that if more than 16 farmers came to the session they were observers, but conceivably they could team up to play in pairs. The cells were disposed to form a grid of four by four cells. Each participant was responsible for one cell representing a potato production unit (i.e., a farm). Participants' pest management decisions were made within pre-defined options through playing cards and pest abundances were represented through a set of colors (from no pest to severe abundance, see Fig. 15.2, part a). Once participants were familiar with the representation of the landscape and the management options, we initialized the simulation model.

15.4.3 Initialization

In the preliminary session (see above), each participant was asked to answer questions about theoretical and practical aspects of integrated pest management (Fig. 15.2, part c and d). Answers were used to initialize the level of pest infestation in each farm. One of the 16 participants in the role-playing game was systematically

an extension agent whose role was to adopt unsuitable control strategies to foster the heterogeneity among agents regarding control practices, and consequently underlined the negative effect of individual behavior at the community scale.

15.4.4 Role-Playing Session and Discussion

Once levels of pest infestation were initialized for each farmer, a computer simulation was run to determine a scenario of pest dynamics, given the spatial configuration of all participants in the role-playing game (dispersion of the pest to neighborhood farms, see Fig. 15.2 part b). Levels of pest infestation were updated accordingly in the board game and a discussion was opened among farmers, which focused on hypotheses to explain the new situation. In any case, the presence of the extension agent participating as a farmer without good control practices led to the necessity of: (1) integrating more components in control practices to ensure a better control of the pest (e.g., IPM practices, vision of the landscape as a whole); and (2) diffusing the IPM information to neighbors so that fewer pests would disperse from neighborhood farms (see Fig. 15.3 part c and d).

Using a set of playing cards (see Fig. 15.3 part d), farmers were then offered the possibility of changing their practices. Each card, read collectively among all participants, represented a key point of potato production regarding the pest in question. Then different control strategies were offered to reduce pest incidence and a discussion was opened to let farmers exchange information and decide which strategy they wanted to apply (see Fig. 15.3, part c and d). Then, decisions were updated in the computer model and levels of pest infestations were updated in the board game. The role-playing game continued as long as there were remaining playing cards. Finally, a general discussion ensued.

At the end of the role-playing session, a majority of the theoretical landscape contained low levels of pest infestation, except for the extension agent's farm and farms neighboring it. A general discussion among all participants stressed the need of diffusing information to all farmers of the community to reduce pest incidence at the landscape level (see Fig. 15.3, part f). To conclude, we reevaluated participant knowledge on pest management issues with the 11-item questionnaire used for the first session.

15.4.5 Impact of Role Game Sessions on Farmers' Knowledge

Our sessions gathered both male (64%) and female (36%) participants, young and old (39% less than 40 years, 41% between 40 and 60 years, and 20% more than 60 years). Their mother language was Spanish (30%), Quechua (35%) or Aymara (35%); the sessions were carried out in Spanish with translation to Quechua and Aymara. Most participants had received limited IPM training sessions in all countries. We assessed participants' learning by comparing their IPM knowledge before

and after the training session using a pair t-test (knowledge scores before vs. after training). Results for the six studied communities (total of 90 potato growers directly participating in the role game) and for each of the four stages of pest control practices (during seed selection, crop production, harvest, and storage) are given in Table 15.1. Overall, we found that all participants increased their pest management knowledge after the training session (significantly in 66% of the surveys, t-test, $P < 0.05$, Table 15.1). Importantly, our data also show that training sessions decreased farmers' knowledge heterogeneity in the community, as evidenced by lower standard deviation and min-max range values after the training session than before (see Table 15.1).

We further used generalized linear models (GLMs) to test the effects on farmers' learning (expressed as the difference between their knowledge after the session and before the session) of five variables: participant age, sex, initial knowledge, community, and country (Ecuador, Peru, and Bolivia). We used standard model simplification procedures to identify significant terms of the initial models, by starting with the most complex model (including all variables and interactions) and subsequently eliminating higher-order terms. Of the five variables included in our GLM analysis, age and country best explained differences in farmers' learning among the six training sessions (see statistics in Table 15.2). Overall, older participants (>60 years) had lower learning scores than younger ones. Also, learning scores differed among the three countries (they were higher in Peru, followed by Ecuador and Bolivia), suggesting that factors associated with the experience of the local training team (e.g., long-term interaction with the communities, experience of the extensionist to lead the session, etc...) is likely to influence the success of the sessions. IPM knowledge, sex, and community were not significant predictors of farmers' learning after the role-playing game session ($P = 0.167$, 0.198 , and 0.251 , respectively). Interestingly the GLM revealed a significant interactions term between age and initial knowledge (see Table 15.2) suggesting that young (<40 years) participants with high initial IPM knowledge had the highest probability to increase their IPM knowledge during the session ($P = 0.023$).

All this suggests that while role game-based sessions had an overall positive impact on the IPM knowledge of the whole community (both increasing mean IPM knowledge score and decreasing heterogeneity among farmers), their effectiveness increased with young participants and when the extensionist group has a long experience in pest management training.

15.5 Conclusion and Discussion

A key achievement of the role-playing game based on an ABM was that, by providing farmers with evidence that pests propagated through their community not as the result of isolated decisions by individuals but rather as the result of repeated interactions between multiple individuals over time, our ABM pointed at key psychological and social issues that were highly relevant for efficient management

Table 15.1 Farmers' pest management knowledge (% correct answers) before and after their participation in the role-game-based training session in six communities of three Andean countries (Ecuador, Peru, and Bolivia). Focus pests were the Gelechiid potato moths for all communities except Ccasapata and Quiripujo; in these cases the insect pest was Andean weevil as tuber moth which although present so far has not shown damage. Data are means $\pm$ standard deviation (SD) of 15 farmers' marks for four different stages of the potato crop: seed, field, harvest, and storage. Minimum and maximum IPM knowledge values are given between brackets.

	Ecuador				Peru				Bolivia			
	Marcopamba		Santa Ana		Quilcas		Ccasapata		Callisaya		Quiripujo	
	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
Seed	34 $\pm$ 16 (0-70)	68 $\pm$ 10* (10-100)	37 $\pm$ 18 (0-70)	77 $\pm$ 9* (40-100)	64 $\pm$ 37 (0-100)	98 $\pm$ 7* (80-100)	68 $\pm$ 39 (0-100)	72 $\pm$ 32 (0-100)	22 $\pm$ 12 (0-50)	58 $\pm$ 10* (5-85)	43 $\pm$ 25 (0-90)	62 $\pm$ 12* (30-100)
Field	50 $\pm$ 19 (0-80)	79 $\pm$ 13* (45-90)	31 $\pm$ 22 (0-70)	69 $\pm$ 11* (30-100)	59 $\pm$ 18 (25-85)	91 $\pm$ 7* (80-100)	66 $\pm$ 16 (45-95)	89 $\pm$ 9* (65-100)	38 $\pm$ 11 (0-60)	42 $\pm$ 10 (5-70)	50 $\pm$ 23 (10-80)	55 $\pm$ 17 (15-90)
Harvest	52 $\pm$ 23 (0-100)	78 $\pm$ 12* (55-100)	56 $\pm$ 22 (0-90)	64 $\pm$ 11 (10-85)	47 $\pm$ 19 (0-70)	80 $\pm$ 18* (50-100)	39 $\pm$ 19 (0-70)	59 $\pm$ 11* (30-70)	29 $\pm$ 12 (0-60)	51 $\pm$ 8* (20-90)	30 $\pm$ 15 (10-80)	39 $\pm$ 15 (10-80)
Storage	49 $\pm$ 21 (0-80)	79 $\pm$ 14* (43-90)	42 $\pm$ 23 (0-80)	78 $\pm$ 12* (25-100)	76 $\pm$ 28 (20-100)	89 $\pm$ 17 (50-100)	95 $\pm$ 5 (70-100)	100 $\pm$ 0 (100-100)	44 $\pm$ 11 (0-65)	50 $\pm$ 12 (10-80)	39 $\pm$ 17 (20-70)	59 $\pm$ 9* (30-90)

* denotes significant increase in pest management knowledge after the training sessions (Pair t-test, $P < 0.05$)

Table 15.2 Results of the generalized linear model (GLM) analysis on farmers' learning (expressed as the difference in pest management knowledge after vs. before the training session). Data include 15 farmers in six communities in three countries (total 90 farmers). For each analysis, all terms and their interactions are included in the model. AIC is the Akaike's Information Criterion for the initial model after removal of the "effect" term. Δ AIC corresponds to the difference between the AIC of the initial model and that of the reduced model. Likelihood ratio test (LRT) and associated P-values test the hypothesis that the suppression of the 'effect' term provides no better fit than the initial model. Only significant interaction terms of the GLM analysis are shown. Analyses were performed using the MASS library for R (R Core Research Team 2009)

Effect	AIC	Δ AIC	LRT	P-value
Initial knowledge	161.3	1.8	1.439	0.167
Age	157.9	5.2	4.551	0.032*
Sex	161.3	1.8	1.654	0.198
Community	161.6	1.5	1.320	0.251
Country	158.7	4.4	3.897	0.043*
Age $\times$ initial knowledge	155.7	7.4	6.091	0.023*

* denotes significant likelihood ratio tests (p-value < 0.05)

of invasive pests, and a central point of integrated pest management (Peshin et al. 2009). ABM may therefore be a powerful tool to advance the application of social psychology theory by stakeholders in rural communities (Smith and Conrey 2007) and to change individual attitudes (Jacobson et al. 2006), all of which is needed for the adoption of IPM in remote areas of developing countries. This suggests that new approaches in pest management extension practices should include topics such as group decision-making, intergroup relations, commitment, and persuasion which deal directly with how other farmers influence each other's thoughts and attitudes toward cooperation and actions (Mason et al. 2007; Urbig et al. 2008). By examining group- and population-level consequences on the invasion process, agent-based modeling may therefore reveal its potential as a powerful pedagogical approach to change behaviors across large populations, a long lasting issue in pest management outreach programs worldwide (Feder et al. 2004). While we have no evidence of the benefits of our sessions in the adoption/changes of IPM practices, farmers revealed themselves more predisposed to understand and realize the importance of the cooperative basis of IPM and therefore disseminate to their peers IPM information they acquired. This suggests that more than being a support for teaching IPM, role-playing games served as a support for discussion between farmers facing the same problems but with different perceptions (Meulen et al. 1996). Moreover, the theoretical landscape can be perceived as a unique tool for virtual experiments (Macy and Willer 2002; Grimm et al. 2005), especially relevant in the case of agriculture and IPM, where adoption is conditioned by trialability (Peshin et al. 2009). In this context, any farmer can evaluate the consequences of his/her collaboration, enhancing collaboration of others (Fowler and Christakis 2010). Because ABM telescopes the time of training sessions and expands the discussion at a landscape level, with a minimal time cost for participants they may represent a useful complement to farmer field school extension events. At a broader scale, this study exemplifies how a computer simulation model can be used for teaching purposes and may represent a promising complement to existing IPM diffusion programs. More broadly, our

experience with ABM for IPM issues suggests that new approaches in pest management extension practices should include topics such as group decision making, intergroup relations, commitment, and persuasion which deal directly with how other farmers influence each other's thoughts and actions. In this context, understanding to what extent ABM-based farmer thinking and discussion could be used more directly to support increasing adoption remains a promising area of research to assess how ABM may help strengthen food security in small-scale farmer communities.

Acknowledgements This work was conducted within the project “Innovative Approaches for Integrated Pest Management in Changing Andes” (C09-031) funded by the McKnight Foundation. We are grateful to all farmers who participated to the training sessions and to all members of the McKnight Foundation's Andean community of practices for useful discussions. We warmly thank Carlos Perez and Claire Nicklin for useful comments and English editing on a preliminary version of the manuscript.

References

- Bale, J. S., Masters, G. J., Hodkinson, I. D., Awmack, C., Bezemer, T. M., Brown, V. K., Butterfield, J. E. L., Buse, A., Coulson, J. C., Farrar, J., Good, J. E. G., Harrington, R., Hartley, S., Jones, H., Lindroth, R. L., Press, M. C., Symrnioudis, I., Watt, A. D., & Whittaker, J. B. (2002). Herbivory in global climate change research: Direct effects of rising temperatures on insect herbivores. *Global Change Biology*, 8(1), 1–16.
- Barnaud, C., Bousquet, F., & Trebuil, G. (2008). Multi-agent simulations to explore rules for rural credit in a highland farming community of Northern Thailand. *Ecological Economics*, 66(4), 615–627.
- Bass, F. M. (1969). A new product growth model for consumer durables. *Management Science*, 15.
- Becu, N., Perez, P., Walker, A., Barreteau, O., & Le Page, C. (2003). Agent based simulation of a small catchment water management in northern Thailand: Description of the CATCHSCAPE model. *Ecological Modelling*, 170(2–3), 319–331.
- Bonabeau, E. (2002). Agent-based modeling: Methods and techniques for simulating human systems. *Proceedings of the National Academy of Sciences of the United States of America*, 99(3), 7280–7287.
- Bonaudo, T., Bommel, P., & Tourrand, J. F. (2005). Modelling the pioneers fronts of the transamazon highway region. In *SMAGET, multi-agent modelling for environmental management*. France: Bourg St Maurice.
- Bousquet, F., Barreteau, O., Le Page, C., Mullon, C., & Weber, J. (1999). An environmental modelling approach: The use of multi-agent simulations. In F. Blasco & A. Weill (Eds.), *Advances in environmental and ecological modelling*. France: Elsevier.
- Bousquet, F., Le Page, C., Bakam, I., & Takforyan, A. (2001). A spatially explicit individual-based model of blue duikers population dynamics: Multi-agent simulation of bushmeat hunting in an eastern cameroonian village. *Ecological Modelling*, 138(1–3), 331–346.
- Carrasco, L. R., Cook, D., Baker, R., MacLeod, A., Knight, J. D., & Mumford, J. D. (2012). Towards the integration of spread and economic impacts of biological invasions in a landscape of learning and imitating agents. *Ecological Economics*, 76(0), 95–103.
- Chapin, F. S., Kofinas, G. P., & Folke, C. (2009). *Principles of ecosystem stewardship: Resilience-based natural resource management in a changing world* (pp. 401). Springer.
- Crespo-Pérez, V., Rebaudo, F., Silvain, J. F., & Dangles, O. (2011). Modeling invasive species spread in complex landscapes: The case of potato moth in Ecuador. *Landscape Ecology*, 26(10), 1447–1461.

- Dangles, O., Carpio, C., Barragan, A., Zeddani, J.-L., & Silvain, J.-F. (2008). Temperature as a key driver of ecological sorting among invasive pest species in the tropical Andes. *Ecological Applications*, 18(7), 1795–1809.
- Dangles, O., Carpio, F., Villares, M., Yumisaca, F., Liger, B., Rebaudo, F., & Silvain, J. F. (2010). Community-based participatory research helps farmers and scientists to manage invasive pests in the Ecuadorian Andes. *AMBIO: A Journal of the Human Environment*, 39(4), 325–335.
- Dangles, O., Mesías, V., Crespo-Perez, V., & Silvain, J. F. (2009). Crop damage increases with pest species diversity: Evidence from potato tuber moths in the tropical Andes. *Journal of Applied Ecology*, 46(5), 1115–1121.
- Daudé, E. (2003). Apports de la simulation multi-agents à l'étude des processus de diffusion. *6èmes Rencontres de Théo Quant*. Besançon, France.
- Dray, A., Perez, P., Jones, N., Le Page, C., D'Aquino, P., White, I., & Auatapu, T. (2006). The atollGame experience: From knowledge engineering to a computer-assisted role playing game. *Journal of Artificial Societies and Social Simulation*, 9(1), 6.
- Feder, G., Murgai, R., & Quizon, J. B. (2004). The acquisition and diffusion of knowledge: The case of pest management training in farmer field schools, Indonesia. *Journal of Agricultural Economics*, 55(2), 221–243.
- Feder, G., & Savastano, S. (2006). The role of opinion leaders in the diffusion of new knowledge: The case of integrated pest management. *World Development*, 34(7), 1287–1300.
- Firbank, L. G., Petit, S., Smart, S., Blain, A., & Fuller, R. J. (2008). Assessing the impacts of agricultural intensification on biodiversity: A British perspective. *Philosophical Transactions of the Royal Society B*, 363, 777–787.
- Fowler, J. H., & Christakis, N. A. (2010). Cooperative behavior cascades in human social networks. *Proceedings of the National Academy of Sciences*, 107(12), 5334–5338.
- Gelman, A., & Hill, J. (2007). *Data analysis using regression and multilevel/hierarchical models*. Cambridge: Cambridge University Press.
- Gregory, P. J., Johnson, S. N., Newton, A. C., & Ingram, J. S. I. (2009). Integrating pests and pathogens into the climate change/food security debate. *Journal of Experimental Botany*, 60(10), 2827–2838.
- Grimm, V., Revilla, E., Berger, U., Jeltsch, F., Mooij, W. M., Railsback, S. F., Thulke, H. H., Weiner, J., Wiegand, T., & DeAngelis, D. L. (2005). Pattern-oriented modeling of agent-based complex systems: Lessons from ecology. *Science*, 310(5750), 987–991.
- Guyot, P., & Honiden, S. (2006). Agent-based participatory simulations: Merging multi-agent systems and role-playing games. *Journal of Artificial Societies and Social Simulation*, 9(4), 8.
- Hagen, S. B., Jepsen, J. U., Ims, R. A., & Yoccoz, N. G. (2007). Shifting altitudinal distribution of outbreak zones of winter moth *Operophtera brumata* in sub-arctic birch forest: A response to recent climate warming? *Ecography*, 30(2), 299–307.
- Hodkinson, I. D. (2005). Terrestrial insects along elevation gradients: Species and community responses to altitude. *Biological Reviews*, 80(3), 489–513.
- Hufnagl-Eichner, S., Wolf, S. A., & Drinkwater, L. E. (2011). Assessing social–ecological coupling: Agriculture and hypoxia in the Gulf of Mexico. *Global Environmental Change*, 21(2), 530–539.
- Jacobson, S. K., McDuff, M. D., & Monroe, M. C. (2006). *Conservation education and outreach techniques* (pp. 480). Oxford: Oxford University Press.
- Kuandkyov, L., & Sokolov, M. (2010). Impact of social neighborhood on diffusion of innovation S-curve. *Decision Support Systems*, 48(4), 531–535.
- Liu, J., Dietz, T., Carpenter, S. R., Alberti, M., Folke, C., Moran, E., Pell, A. N., Deadman, P., Kratz, T., Lubchenco, J., Ostrom, E., Ouyang, Z., Provencher, W., Redman, C. L., Schneider, S. H., & Taylor, W. W. (2007). Complexity of coupled human and natural systems. *Science*, 317, 1513–1516.
- Macy, M. W., & Willer, R. (2002). From factors to actors: Computational sociology and agent-based modeling. *Annual Review of Sociology*, 28, 143–166.
- Mahajan, V., Muller, E., & Bass, F. (1990). New product diffusion models in marketing: A review and directions for research. *Journal of Marketing*, 54(1).

- Mason, W. A., Conrey, F. R., & Smith, E. R. (2007). Situating social influence processes: Dynamic, multidirectional flows of influence within social networks. *Personality and Social Psychology Review*, 11(3), 279–300.
- Mathevet, R., Le Page, C., Etienne, M., Lefebvre, G., Poulin, B., Gigot, G., Proréol, S., & Mauchamp, A. (2007). BUTORSTAR: A role-playing game for collective awareness of wise reed-bed use. *Simulation & Gaming*, 38(2), 233–262.
- Matteson, P. C. (2000). Insect pest management in tropical Asian irrigated rice. *Annual Review of Entomology*, 45, 549–574.
- Montanari, A., & Saberi, A. (2010). The spread of innovations in social networks. *Proceedings of the National Academy of Sciences*, 107(47), 20196–20201.
- Nwilene, F. E., Nwanze, K. F., & Youdeowei, A. (2008). Impact of integrated pest management on food and horticultural crops in Africa. *Entomologia Experimentalis et Applicata*, 128(3), 355–363.
- Oerke, E. (2005). Centenary review: Crop losses to pests. *The Journal of Agricultural Science*, 144(1), 31–43.
- Paredes, M. (2010). *Peasants, potatoes and pesticides. Heterogeneity in the context of agricultural modernisation in the highland Andes of Ecuador*. Wageningen University, published doctoral dissertation.
- Parker, D. C., Manson, S. M., Janssen, M. A., Hoffmann, M. J., & Deadman, P. (2003). Multi-agent systems for the simulation of land-use and land-cover change: A review. *Annals of the Association of American Geographers*, 93(2), 314–337.
- Perez, C., Nicklin, C., Dangles, O., Vanek, S., Sherwood, S. G., Halloy, S., Garrett, K. A., & Forbes, G. A. (2010). Climate change in the high Andes: Implications and adaptation strategies for small-scale farmers. *The International Journal of Environmental, Cultural, Economic and Social Sustainability*, 6, 71–88.
- Peshin, R., Vasanthakumar, J., & Karla, R. (2009). Diffusion of innovation theory and integrated pest management. In R. Peshin & A. K. Dhawan (Eds.), *Integrated pest management: Dissemination and impact* (Vol. 2). Dordrecht, the Netherlands: Springer.
- Pollet, A., Barragán, A., & Iturralde, B. P. (2003). Conozca y maneje la polilla de la papa (*Tecia solanivora*). Centro de Biodiversidad y Ambiente, Escuela de Biología, Pontificia Universidad Católica del Ecuador, Serie Divulgación 3.
- Pumisacho, M., & Sherwood, S. (2005). *Guía Metodológica sobre ECAs: escuelas de campo de agricultores*. Quito: FAO/CIP/INIAP/WN.
- R Development Core Team. (2009). R: A language and environment for statistical computing. Vienna: R Foundation for Statistical Computing. <http://cran.r-project.org/>.
- Rebaudo, F., Crespo-Pérez, V., Silvain, J. F., & Dangles, O. (2010). Agent-based modeling of human-induced spread of invasive species in agricultural landscapes: Insights from the potato moth in Ecuador. *Journal of Artificial Societies and Social Simulation*, 14(3), 7.
- Rebaudo, F., & Dangles, O. (2011). Coupled information diffusion–pest dynamics models predict delayed benefits of farmer cooperation in pest management programs. *PLoS Computational Biology* 7(10), e1002222. doi:10.1371/journal.pcbi.1002222.
- Rebaudo, F., & Dangles, O. (2013). An agent-based modeling framework for integrated pest management dissemination programs. *Environmental Modelling and Software*, 45, 141–149. DOI: 10.1016/j.envsoft.2012.06.014.
- Rogers, E. M. (2003). *Diffusion of innovations* (5th edn.). New York: The Free Press.
- Smajgl, A., Brown, D. G., Valbuena, D., & Huigen, M. G. A. (2011). Empirical characterization of agent behaviours in socio-ecological systems. *Environmental Modelling and Software*, 26(7), 837–844.
- Smith, E. R., & Conrey, F. R. (2007). Agent-based modeling: A new approach for theory building in social psychology. *Personality and Social Psychology Review*, 11(1), 87–104.
- Speelman, E. N., & García-Barrios, L. E. (2010). Agrodiversity v.2: An educational simulation tool to address some challenges for sustaining functional agrodiversity in agro-ecosystems. *Ecological Modelling*, 221(6), 911–918.

- Thiele, G., van de Fliert, E., & Campilan, D. (2001). What happened to participatory research at the International Potato Center? *Agriculture and Human Values*, 18(4), 429–446.
- Thomas, M. B. (1999). Ecological approaches and the development of “truly integrated” pest management. *Proceedings of the National Academy of Sciences of the United States of America*, 96(11), 5944–5951.
- Urbig, D., Lorenz, J., & Herzberg, H. (2008). Opinion dynamics: The effect of the number of peers met at once. *Journal of Artificial Societies and Social Simulation*, 11(2), 4.
- van der Meulen, H. A. B., de Snoo, G. R., & Wossink, G. A. A. (1996). Farmers’ perception of unsprayed crop edges in the Netherlands. *Journal of Environmental Management*, 47(3), 241–255.
- Young, R., & Lipton, J. K. (2006). Adaptive governance and climate change in the tropical highlands of western South America climate change. *Climatic Change*, 78(1), 63–102.
- Ziegler, A. D., Fox, J. M., Webb, E. L., Padoch, C., Leisz, S. J., Cramb, R. A., Mertz, O., Bruun, T. B., & Vien, T. D. (2011). Recognizing contemporary roles of swidden agriculture in transforming landscapes of Southeast Asia. *Conservation Biology*, 25(4), 846–848.