AMBIO (2010) 39:325–335
DOI 10.1007/s13280-010-0041-4

REPORT

Community-Based Participatory Research Helps Farmers and Scientists to Manage Invasive Pests in the Ecuadorian Andes

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Received: 12 January 2009 / Revised: 28 July 2009 / Accepted: 17 November 2009 / Published online: 13 May 2010

Abstract Participatory research has not been a conspicuous methodology in developing nations for studying invasive pests, an increasing threat to the sustainable development in the tropics. Our study presents a community-based monitoring system that focuses on three invasive potato tuber moth species (PTM). The monitoring was developed and implemented by young farmers in a remote mountainous area of Ecuador. Local participants collected data from the PTM invasion front, which revealed clear connection between the abundance of one of the species (*Tecia solanivora*) and the remoteness to the main market place. This suggests that mechanisms structuring invasive populations at the invasion front are different from those occurring in areas invaded for longer period. Participatory monitoring with local people may serve as a cost-effective early warning system to detect and control incipient invasive pest species in countries where the daily management of biological resources is largely in the hands of poor rural people.

Keywords Insect pest · Developing countries · Participative monitoring · Farmer communities · Education · Andes

INTRODUCTION

Community-based participatory research involves a partnership between researchers and community members who collaborate on a research project to address social and environmental problems (Stoecker 2001; Wallerstein and Duran 2003). Unlike conventional research, community-based investigations are tied to the participation of community groups who have interest in applying the research findings to improve their quality of life (Jacobson et al. 2006). Over the past 10 years, an increasing number of conservation programs have involved native people to meet the twin goals of sustaining local livelihoods while simultaneously protecting the structure and function of the environment within which their community and culture are imbedded (Agrawal and Gibson 1999; Ambrose-Oji et al. 2002). Examples of environmental issues addressed by community-based research include the monitoring of water quality in the Philippines (UN Department of Economic and Social Affairs 2003), the testing of fishing methods to protect undersize fish in Benin (Afrol News 2003) and the monitoring of biodiversity in protected reef areas (Hill 2004). Community-based conservation has been particularly successful in developing countries where the daily management of biological resources is largely in the hands of poor rural people and local government staff with virtually no operational funding.

Community-based monitoring has therefore become widespread in the last few years, documenting many outcomes related to biological resource management (see Calheiros et al. 2000; Olsson and Folke 2001; Curtin 2002; Lawrence 2002; Danielsen et al. 2005 and related articles in the same issue). Surprisingly, community-based monitoring has not been a conspicuous focus for invasive pest species in developing nations, an increasing threat to the sustainable development in the tropics. Strategies to manage invasive species have been well implemented in developed countries (for example, "weed-watcher" groups have been collecting data on the distribution of invasive plant species in the United States; Mehrhoff et al. 2003). Although unpublished initiatives of invasive species management have been developed in a few third world countries, these nations have far fewer tools to face this global issue (Borgerhoff Mulder and Coppolillo 2005). Pest species that have become invasive contribute to exacerbating vulnerability of local communities and in some cases foreclosing livelihood and development options, especially when food security is at risk (Lockwood et al. 2007). Poverty, along with inequity, particularly in trade and access to technology make invasive pest monitoring programs particularly timely and challenging for developing countries. Monitoring programs are an important component of good environmental governance as they ensure that emergent threats are identified and addressed (Lovett et al. 2007).

Within the last 30 years, three species of potato tuber moths (PTM, Lepidoptera: Gelechiidae), *Phthorimaea operculella* (Zeller), *Tecia solanivora* (Povolny), and *Symmetrischema tangolias* (Gyen), have been assembled in combination of two of three species into the potato fields of the Northern Andes of Venezuela, Colombia, Ecuador, Peru, and Bolivia through successive introductions from different origins. *T. solanivora* was first described from Guatemala (Povolny 1973) and introduced to South America (Venezuela) via highly infested potato seeds imported from Costa Rica (Puillandre et al. 2008). It has then reached Colombia in 1985 and Ecuador in 1996. The invasion history of *P. operculella* and *S. tangolias* in Ecuador is far less clear but it is probable that they were sequentially introduced from Peru in the 1980's and 2001, respectively (Herrera 1998; Dangles et al. 2008). These putative different dates of introduction do not necessary mean that the three PTM species are in different phase of their invasion history. The three species indeed show singular population dynamics (Dangles et al. 2008) and complex inter-specific interactions (Dangles et al. 2009), which challenge our understanding of their spread in the country. It is, however, known that commercial exchanges of potato tubers at regional and local scales for both seeding and consumption are the main causes for the rapid expansion of the three pest species in all parts of Ecuador. At the larval stage, the three PTM species share the same resource, the potato *Solanum tuberosum* L. (Solanaceae), itself widespread between altitudes of 2400 and 3800 m a.s.l. In the highlands of Ecuador, potatoes are a major staple, and more than 90000 producers grow them on about 60000 ha of land (Pumisacho and Sherwood 2002). This complex of species represents one of the most serious agricultural pest problems in the Northern Andes with an estimated loss of 150 million dollars per year, principally in the poorest regions of Central Ecuador (Palacios et al. 2002; Pollet et al. 2003). In addition to threatening food security in the Northern Andes, these invasive species are a potential threat for wild Solanaceae found in the *páramos* (high-altitude tropical grasslands with high biodiversity and endemism), a threat facilitated by the rapid upward expansion of the agricultural frontier (Gondard and Mazurek 2001).

We had anecdotal evidence that local farmers facing this problem in different regions were willing to be involved in studying these invasive pests because they saw new "moth-like pests" in their field and also declines in potato production—although it was not clear whether the two factors were correlated. This participatory monitoring effort was developed in response to farmers' willingness to participate in the research, as well as a mutual desire among local people and scientists to quantify risk levels associated with PTM as a means of improving livelihoods in poor and remote regions of Ecuador. By accessing research at multiple levels (see Abay et al. 2008), this participatory study followed the traditional research process (objective definition, sampling, data analysis, discussion; see Stoecker 2002) but with the community involved at each step of the process. Some more complex data analysis was done by researchers, but the bulk of interpretation occurred with the involvement of community members (see below for further description). The overall goal of this study, which combines participative, scientific, and educational aspects, is to document how a community monitoring project can provide useful insights for invasive pest management in poor and remote tropical regions.

METHODS

Study Site and Farmer Communities

The study area was located in the central Ecuadorian province of Bolivar, canton of Guaranda, parish of Simiatug (Fig. 1). This parish comprised roughly 45 Kichwa communities living between 2800 and 4250 m of altitude, that share similar characteristics in terms of social organization, date of establishment, and agricultural practices (Culqui 2005). With about 1200 inhabitants, Simiatug is the economic center of the valley, and the communities outside Simiatug are smaller in size and density (50–700 inhabitants; see Table 1). Currently, about 25000 people, mainly subsistence and market-oriented farmers, live in the Simiatug parish. The main agricultural products are pasture, cereals (barley), legumes (fava bean), and potatoes (mainly the native varieties "Tulca," "Uvilla" and the commercial variety "Gabriela") as well as cattle and sheep. In 2005, only 2.9% of the potato production was commercialized outside Simiatug (Culqui 2005) thereby potentially limiting PTM introduction in the valley. The deteriorated road network together with the landscape configuration of the valley (squeezed between large areas of natural *páramos*; see Fig. 1) likely protected, to some extent, Simiatug communities from pest invasion. The rehabilitation of the road sections from Guaranda northward to Salinas was completed in 2006, and commercial

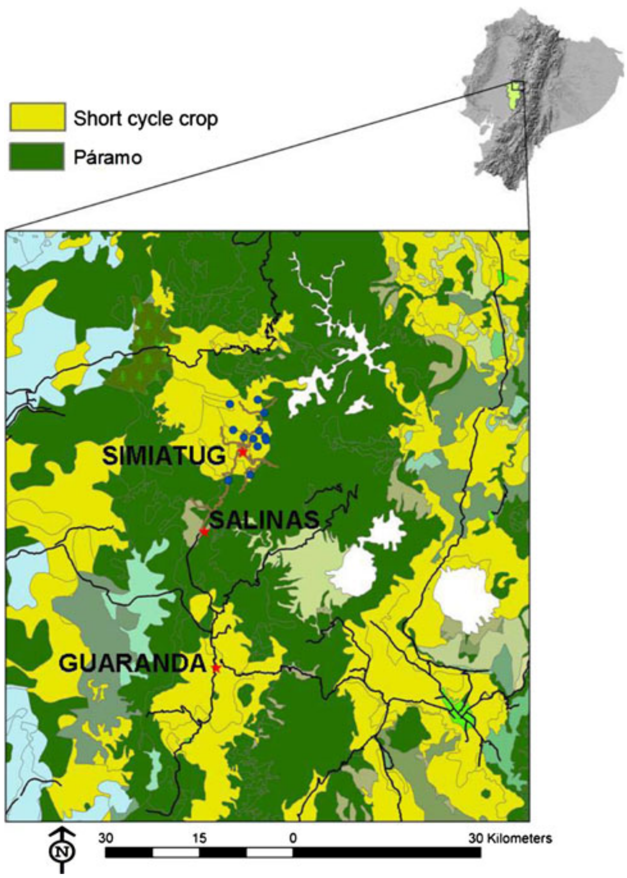

Fig. 1 Map of region of Simiatug (Bolivar, Ecuador) showing the location of the 13 villages (*blue dots*) involved in the participative monitoring. The figure also presents road network (*black lines*) and land use (páramos, some high altitude grasslands and short cycle crops such as potatoes)

exchanges from and to Simiatug are currently increasing as is the risk of PTM introduction. Because of the emerging threat from PTM, local farmers were interested in quantifying the densities of PTM species in the Simiatug valley, and to learn about potential risks associated with PTM and how to control them. This latter point was particularly important due to the low level of education in the communities: only 3% of the population has received formal training in insect pest management (Culqui 2005; Dangles and Carpio, unpubl. data).

First Session: Negotiation of Research Objectives and Processes

In order to attract local stakeholder participants and insure that research was driven by their interests, the objectives and process of the participatory research were developed together with farmers from Simiatug during a preliminary negotiation session. The farmers were neither paid nor given food or things (clothes, books) to enhance participation. At the beginning of the session, there was a consensus among farmers about the need of implementing a pest management program in their valley. Together with freeze, pests were indeed the most important problem putting at rick their crops, especially potatoes. The negotiation continued over the questions of process and practical outcomes of the program. Two main issues were outlined by the farmers: (1) their willingness of the involvement of young people from their community and (2) the need of practical results to control the pest at the end of the participatory research. From our part, we stressed the need of establishing a monitoring of PTM abundance and damages potato to quantify the extant of the problem in the valley. Based on these discussions, the following short-term objectives were established: (1) to monitor and analyze the abundance and distribution of PTM and damages to potatoes in storage with the help of young people from the community and (2) to propose solutions for effective control. Long-term objectives were to strengthen the local economy through integrated management of insect pests and decrease the risk of potato production collapse. Though lengthy, we think that this negotiation phase was important to build trust with farmers and to produce research conclusions that would be more relevant and more likely to be implemented by the community.

Second Session: Training and Monitoring

Thanks to the authorities of the College of Agriculture of Simiatug, 13 young farmers (age ranging from 17 to 25, 11 men, 2 women) were identified to be part of participatory monitoring of PTM abundances. In agreement with decisions taken during the negotiation session, farmers were selected so that the monitoring could include spatially dispersed communities allowing a relevant estimation of PTM distribution in the valley. Consequently, the 13 farmers belonged to 13 different Kichwa communities located at various altitudes and distances from Simiatug (see blue dots in Fig. 1; Table 1). In order to evaluate farmer knowledge on PTM before the training session, participants were asked to fill a questionnaire including 20 items, 10 on basic issues (biology and ecology of the pest) and 10 on applied issues (pest management). Based on filled questionnaires, we built a "knowledge index" for each farmer, which corresponded to the percent of questions answered correctly.

We first held a 2-h workshop with the 13 participants to introduce fundamentals of biological invasions and pest management. Our aim was to show farmers that the invasion problem they face locally is a widespread phenomenon. We then focused on describing the biology of the pests, presenting key morphological characters to

Table 1 Characteristics of the communities that participated in the PTM monitoring over the study period (October–December 2006)

Communities	Altitude (m)	Mean temperature (°C)	Rainfall (mm)	Main potato variety cultivated	Village size	Remoteness index
Simiatug	3300	12.8	133	Gabriela	3000	0.0
Yanaquero	3525	12.9	136	Tulca	50	0.15
Pambugloma	3075	13.2	102	Gabriela	100	0.08
Rayo Pamba	3725	11.1	145	Rosita	250	0.03
Jabas Pucho	3500	11.4	130	Tulca	700	0.05
Papaloma	3328	12.9	141	Rosita	300	0.05
Calvario	3225	13.1	127	Gabriela	250	0.05
Durazno	2750	15.5	107	Gabriela	100	0.04
Cascarrilla Grande	2555	16.2	124	Gabriela	600	0.2
Zuma Chupa	3150	13.0	111	Tulca	100	0.23
Pimbalo	3625	11.0	137	Rosita	300	0.05
Yuropacha	3750	10.9	143	Rosita	100	0.03
Tibulo	3400	12.5	137	Gabriela	100	0.05

All data have been acquired from community members except precipitations. Mean precipitation data for each site during the study period was interpolated from meteorological stations data using the Worldclim layers available in the geographical information system (GIS) software Arcview 9.1

differentiate the three PTM species (*T. solanivora*, *P. operculella*, and *S. tangolias*). We then moved to a 1-h field session presenting procedures for PTM monitoring. Each farmer assembled three traps (one for each PTM species) using materials we provided them (Fig. 2a): dome-like plastic containers, pheromones specific for each PTM species (Pherobank, Wageningen, NL), and metallic threads. Farmers were also provided with one minimum–maximum thermometer (ERTCO, Dubuque, IA) and a field book. Each farmer then went back to their community, fixed the traps on wooden sticks, and placed them in a potato field planted approximately 3 months earlier. Starting in October 2006, they recorded trap catches and temperatures every week for 8 weeks. Despite the lack of replicate sampling units in each community, it is likely that the extended time period and frequency of moth sampling allowed us to obtain a good estimation of the abundance of PTM in each locality. In each village, the 13 farmers also collectively evaluated damages (low, intermediate, and high) produced by PTM on potato tubers in stores by checking for holes made by young PTM larvae when burrowing into the tuber.

Third Session: Data Analysis

In December 2006, we met with the participants to compile and analyze their data. The approach used was largely that of learning-by-doing as local community teams and trainers jointly recorded, compiled, summarized, graphed, and discussed field observations. As a first step, data compilation was divided into two practical sessions. Step one was to check the identification of each PTM individual collected in the traps using stereomicroscopes provided during the sessions (Fig. 2b). The second step was to locate precisely on a map of the region where they had performed their monitoring (Fig. 2b), allowing for the documentation of spatial dimension of the distribution of the pest and also of altitudes of the different villages.

Then, we discussed the potential factors that could explain differences in measured abundance of the three PTM species among villages. In order to make the analysis of the results easier, it was limited to three variables that both showed evident variations among the 13 communities and had been identified as key drivers of PTM abundance: air temperature, number of inhabitants, and remoteness of the village from Simiatug (other parameters; see Table 1). During their field work, farmers had registered air temperatures and provided an estimation of the number of inhabitants (variable "village size") in their communities. This parameter was likely to be a good indicator of the intensity of commercial exchanges between the village and Simiatug and could potentially be correlated with PTM densities in the valley. In order to measure the variable of "remoteness," we asked each farmer the travel time from Simiatug to their community. For each village i, rank of remoteness, R_i, was then calculated by the normalized values of time, T_i as follows:

$$R_i = \frac{T_i}{\sum_i^{13} T_i}.$$

The possible range of R_i is from 0, the village Simiatug itself, to 1, the theoretical farthest community from Simiatug (see Table 1). The use of a normalized value of remoteness (see Eisenberg et al. 2006) allows potential

Fig. 2 Pictures of the participative monitoring performed with members of the Kichwa communities in the Simiatug valley. **a** Photograph showing 8 of the 13 participants with the material to perform the monitoring. Other people on the photograph are staff of the college and of the outreach project. **b** Community members checking adult moths identity with a stereomicroscope (*left*) and locating their own study site on a map of the region (*right*)

comparison with other studies. Despite of its relatively small scale, our study area therefore encompassed a wide range of remoteness values, some villages being as close as half an hour from Simiatug and other distant to up to 5 h.

Farmers then schematically plotted on blackboards PTM densities against each of these three variables (air temperature, village size, and remoteness) to identify potential relationships. Data analysis was a hard step for farmers. We facilitated this process by drawing the graph and then asking each farmer to plot the value of PTM abundance and the corresponding factor (e.g., temperature) recorded in the community of each farmer. In order to test the statistical significance of these graphical results, the authors further conducted additional statistical analyses using general linear models (GLM) to probe the significance of results found by farmers. GLMs were used to test for effects on numbers of male moths captured of all measured variables at each site (altitude, temperature, remoteness, village size, potato variety, and rainfall). None of these factors were significantly correlated among each others (Spearman rank test, $R < 0.5$, $P > 0.23$) except 'altitude' and 'temperature' ($R = 0.96$, $P < 0.01$). We included the term 'site' in the GLM analysis to allow within-site comparisons while controlling for variation resulting from unmeasured site-specific parameters. The change in abundance of species due to each effect was modeled as an interaction term between this effect and the species factor. For example, the interaction between remoteness and species models how the abundance of species changed with remoteness. The more parsimonious model was identified using the Akaike's Information Criterion (AIC; see Venables and Ripley 2002). We used the likelihood ratio test (LRT) to test the difference between the initial model and the reduced model dropping an 'effect' term (Breen et al. 2007). All analyses were performed using the mass library for R (R Development Core Team 2006).

Fourth Session: Evaluation and Recommendations for PTM Management

The last session consisted of (1) the oral evaluation of the participatory monitoring by each participant and (2) recommendations for the integrated pest management (IPM) of PTM. Recommendations were based on the infestation levels and species identity the farmers had monitored under field and storage conditions in their community. These guidelines followed classical approaches from integrated pest management: cleaning store rooms, keeping the harvested potatoes covered and using a biopesticide (e.g., *P. operculella* Granulovirus, PhopGV), exposing potato seed to the sun, hilling up of soil around plants or rotating crops (Pollet et al. 2004). In regions such as Simiatug where PTM densities are low, these simple recommendations are highly effective to control pest damages. However, in regions presenting high PTM densities, further IPM options such as participatory farmer field schools (see Pumisacho and Sherwood 2005) are necessary for an effective control of the pest. At the end of the session, we reevaluated participant knowledge on basic and practical PTM issues with the 20-item questionnaire used for the first session. We further assessed student learning by comparing their knowledge before and after the training session using a Wilcoxon Mann–Whitney test.

RESULTS

Participation and Learning of the Community Members

Because of their vested interest in the research results and familiarity with the outdoors and work in the field, young community members were highly motivated and especially conscientious and reliable field workers. Field notes on trap catches and temperatures were generally rigorously reported in book notes that they provided us, and PTM species sorting was satisfying during the hands-on sessions (regarding identification checking). Organized meetings and informal discussion with community members were useful to create trust between partners. As a consequence, high levels of commitment to the monitoring and data analysis of PTM species were displayed by all community members. In talking with farmers at community meetings, they acknowledged that they were not aware of the risks caused by PTM before the participatory research (this was conformed by our questionnaire; see Fig. 3). Adult captures in pheromone traps revealed, however, the existence of infestation by PTM in the Simiatug valley, which was confirmed by the detection of larvae in potato storage surveys. Data from the questionnaires filled by farmers before and after participative sessions confirmed that participants significantly learned from it (two-sided Wilcoxon Mann–Whitney *U* test, $U \leq 1$, $P < 0.001$, $N = 13$ for both types of knowledge), especially in practical terms (Fig. 3).

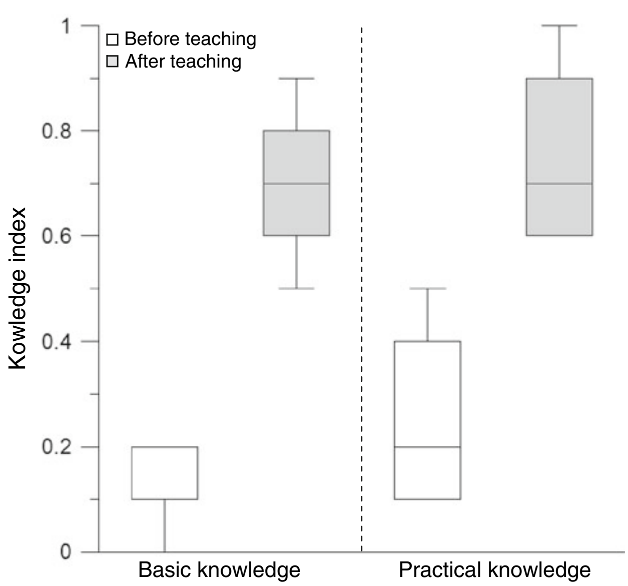

Fig. 3 Box-whisker plot of the basic and practical knowledge on tuber moth management of the local participants ($N = 13$) before and after sessions implemented in our community-based monitoring. The knowledge index was calculated based on a questionnaire including 20 items, 10 on basic issues (biology and ecology of the pest) and 10 on applied issues (pest management) (see "Methods" section). The three bars of the box consist of the median and the upper and lower quartiles in the distribution. The endpoints of both whiskers indicate minimum and maximum values

PTM Abundance in the Field

In general, the monitoring revealed low levels of catches of PTM species at all sites (<6 ind. day^{-1}). The most abundant species in the Simiatug valley was *S. tangolias* (1.71 ± 1.6 ind. day^{-1}, $N = 13$). *P. operculella* was rather abundant in three villages (1.16 ± 2.07 ind. day^{-1}, $N = 3$) but had very low densities in the 10 others (0.11 ± 0.26 ind. day^{-1}, $N = 10$). *T. solanivora* exhibited low density levels in all communities (0.72 ± 0.60 ind. day^{-1}, $N = 13$).

Farmers quickly pointed out the great variability in PTM densities among the different communities. In an attempt to explain this variability, participants investigated the influence of three variables, mean air temperature, village size, and village remoteness (see "Methods" section) that were markedly different among villages. Mean air temperature varied from 10.9 to 16.2°C, and village size ranged between 50 and 3000 inhabitants (Table 1). The least remote community has a remoteness value of 0.03, and the most remote village has a remoteness value of 0.23 (Table 1). Both air temperatures and village sizes were poorly correlated with PTM abundances (not shown). We found that the three PTM species were differently associated with remoteness of the 13 villages (Fig. 4a–c). *T. solanivora* showed a significant exponential decrease in abundance with an increase in remoteness from the closest to the farthest village to Simiatug (exponential, $R^2 = 0.62$, $P < 0.01$). In contrast, *S. tangolias* and *P. operculella* densities show no significant trend as a function of remoteness ($R^2 < 0.25$ and $P > 0.47$ for all models). Of the six factors included in the GLM analysis (see "Methods" section), only remoteness, species, and their interaction significantly affected the abundance of caught PTM adults (Table 2). Significant interactions with species indicated that the three PTM species responded differently to the remoteness from Simiatug.

DISCUSSION

Research Findings

In view of worldwide reports of increases in agricultural pest invasions with the movement of goods and people, it has become ever more important to incorporate the dynamics of interactions between societies and (agro)ecosystems in studies on pest dispersal (Scheffer et al. 2002; Lockwood et al. 2007). In many cases, however, surveys are performed once the invasive pest species has become established, and the link between its distribution and human movements is hardly detectable at a local scale (With 2002). In this context, anthropogenic environmental

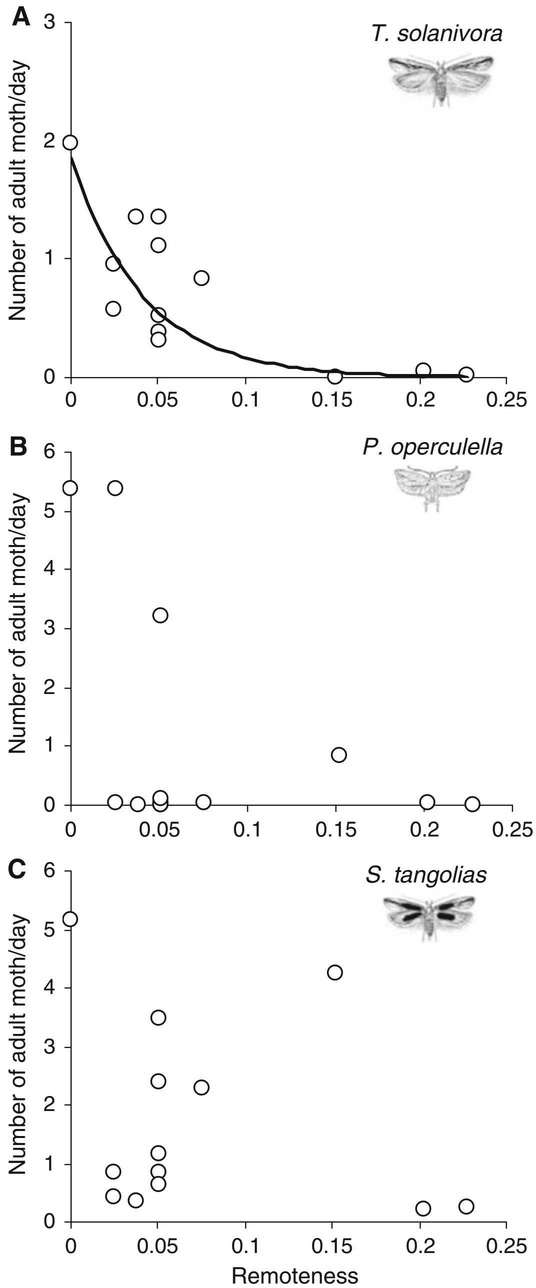

Fig. 4 Relationship between tuber moth densities and village remoteness from Simiatug. **a** *T. solanivora* (exponential fit, $R^2 = 0.62$, $P < 0.01$), **b** *P. operculella*, and **c** *S. tangolias* (non-significant relationships)

changes such as road rehabilitation that cause populations to move and settle in new ways can provide the opportunity to observe the relationship between environmental changes and invasive species dispersal (see Eisenberg et al. 2006 for a similar example with the dispersal of human pathogens). In our study, the rehabilitation of the road between Guaranda and Simiatug had recently increased the exchanges between the two places (Culqui 2005) and is likely responsible for the relatively high PTM densities found in the village of Simiatug, otherwise isolated by natural barriers. From this source population in Simiatug, *T. solanivora* showed significant trends in densities across a gradient of remoteness, even after adjusting for village size and temperature. Village size significantly affected PTM abundance in the Simiatug valley. Several factors are correlated with this variable, such as the area cultivated with potatoes or the presence of potato storages (tubers heaped under a basic shelter). In Ecuador, tuber infestation by PTM is habitually higher in potato storages than in the fields (Dangles et al. 2008). Storages indeed offer optimal conditions for PTM development, such as protection from coldest temperatures and against rainfall (Keasar et al. 2005). As the storages are located nearby the cultivated fields, part of the adult PTM population sampled in the traps probably undergoes its larval life cycle within storages. The significance of village size as a driving factor of PTM abundance may therefore be more related to the presence of storages than to the area of cultivated potatoes. Another important factor is that larger villages are more attractive to human flows and commercial exchanges than smaller ones (see Gilbert et al. 2004) and have therefore higher probabilities of being visited by people who transport infested potato seeds.

Our results indicated that villages farther from Simiatug had lower infestation rates by *T. solanivora* than villages closer to Simiatug. Why was this relationship observed only for *T. solanivora*? One reason maybe that in Ecuador, *T. solanivora* has been observed to develop only on tubers of *S. tuberosum*, whereas the two other species can grow on tubers, stems, or foliages of *S. tuberosum*, as well as on cultivated and wild Solanaceae (*S. lycopersicum* and *S. nigriscens*). The features of wide host plant spectra together with ample thermal tolerances (especially for *S. tangolias*) may increase the probability of a successful establishment in remote regions despite low dispersal rates. This could explain why *S. tangolias* was able to maintain populations in the more remote villages of the valley despite limited commercial contacts. Another interesting result of this study was that in contrast to a previous study in a high PTM invasion zone (Dangles et al. 2008), PTM species distribution was not related to air temperature. This suggests that mechanisms structuring invasive pest populations at the invasion front where PTM densities are low are different from those occurring in areas invaded for a longer period.

Obviously, these results are limited in space and time, and require further research and a greater range of results to permit a more robust analysis and validation. For example, additional analyses of insect population genetics could elucidate dispersal patterns across the landscape, and data on human migration patterns might provide information on

Table 2 Results of the generalized linear model's deviance analysis on PTM adult species catches in Simiatug

Effect	Terms included in the initial model	AIC	Δ AIC	LRT	*P* value
Remoteness × species	All	230.4	8.4	7.32	0.005
Species	Remoteness, variety, species	227.3	3.3	5.45	0.016
Remoteness	Remoteness, variety, species	228.0	4.0	5.85	0.011

The significance of each of the eight factors initially selected (altitude, temperature, remoteness, village size, potato variety, rainfall, site, and species; see "Methods" section) was computed using model simplification and Likelihood ratio test (LRT). We started with a model including the effect of all factors plus their interaction and then removed higher-order non-significant terms until all remaining terms were significant. The table gives the contribution of these remaining factors that significantly explain changes in the abundance of PTM in the valley. AIC = Akaike's information criterion of the initial model after the removal of the 'effect' term. ΔAIC corresponds to the difference between the AIC of the initial model and that of the reduced model

causal linkages between remoteness and risks of the propagation of invasive species. In a similar vein, looking at changes in incidence compared with changes in remoteness over time may provide additional causal information about how road development affects invasive pest dispersal, because the time scale of these social changes may take years or decades (Eisenberg et al. 2006). The remoteness and large number of possible sampling sites in populated rural areas such as the Andes demands that scientists develop collaborations with local communities to carry out such studies in a timely and rigorous way. Standardized, repeated, quantitative measures would be a useful way of determining the correlates of invasion success. It would also shed light both on attributes of species that make them likely to invade and have negative impacts, and on characteristics of the recipient environments that make them resistant or vulnerable to invasion. In turn, remote communities may be able to benefit from the more mechanistic pest management knowledge brought in by outside professionals to face emerging infestations by pests such as PTM. Monitoring would help these communities with the early detection of emergent invasions, within the window of opportunity where eradication efforts may be successful.

Practical Applications for the Communities

A participatory monitoring system of natural resources and associated threats is expected to be successful only if the local participants directly benefit from their involvement (Stuart-Hill et al. 2005). Several studies have reported the difficulties of involving local communities in resource management issues (see Borgerhoff Mulder and Coppolillo 2005; Williams 2007). Our experience in Simiatug was that farmers involved in the monitoring displayed a high level of commitment to the pest monitoring program although there are still challenges to reaching people in surrounding communities. Three main reasons may explain this result. First, and most importantly, community members were conscious of their dependence on their natural resources. Because they derive nutritional, financial, and even cultural benefits from harvesting potatoes (see Brush 2004), farmers were willing to contribute to any action for protecting that resource. Second, all of the participating farmers were also students in an adult high school program in Agriculture in the main town of Simiatug, thus they were more open to performing monitoring activities in their own communities than perhaps a non-student farmer would be. Third, the monitoring program we developed was simple, required a minimum of training and education, and was supported by local educational authorities. It also required little equipment, time, and financial resources, and had a short process time from data to management actions on-the-ground.

Both oral and written evaluations of the participative sessions revealed that farmers will be able to better manage their resources, after the participatory research implementation because they realized, from their own work, the spatial distribution of the pests in the valley and some potential mechanisms of their dispersal via the road network. A major benefit of our community-based research is therefore that future management interventions can be designed as a direct response to the results of monitoring activities and analyses of collected data, rather than just being based on perceptions of the PTM threat. More importantly, we think that the data on tuber moth trapping clearly enhanced local awareness about the need to control the pests before they became too numerous. The main specific management action taken by farmers was the systematic checking for PTM when buying potato tubers in the Simiatug market before transportation to their community. We also stressed the point with our local partners that benefits of the monitoring to the communities may also be over the longer term, in the form of a reduced probability of production collapse through PTM infestation. Unfortunately, we have no data about the transfer of knowledge from the participants to other community members in the valley of Simiatug. However, our group has evidence that each participant from farmer field schools similar to that we presented in this article can spread their knowledge to at least five people of their community (Villares 2008).

Participants and high school authorities expressed their interest of continuing with pest monitoring in the Simiatug region in the future. This monitoring program is currently continuing in the Simiatug valley and has been successfully extended to 42 participants in 2009. It provides farmers with information that allows them to predict more effectively potential threats to their crops and to quantitatively assess trends in agricultural landscape changes and the effects of pest control strategies. However, ensuring the sustainability of locally based monitoring systems, even when they have been designed to require minimal resources and to be reliant on locally available expertise and materials, is not an easy task. It will depend on the degree to which the participatory monitoring can increase the benefits to local farmers as a function of the cost incurred by monitoring. It will also depend on the extent to which farmers would spread their knowledge to other members of the community, an issue that we are currently studying through questionnaires and agent-based models. Further quantitative simulations of the net present value of potato harvests (the present value of the expected future revenues minus the present value of the expected future costs) with and without monitoring would also be useful to measure the benefit of following the monitoring on the long term (see Hockley et al. 2005).

Perspectives and Potential of Generalization

Monitoring is a fundamental part of environmental science, and long-term data are particularly crucial for documenting and predicting the spread of exotic pest species (Lovett et al. 2007). Community-based investigations in the context of invasive agricultural pest management can be a promising approach, especially in developing countries that often face limited funding and administrative capabilities. The experience from Simiatug is that collecting monitoring data using traps was a useful approach that can lead to better informed management interventions for controlling invasive pests, especially in remote invasion fronts. Given that these agricultural pests are essentially related to trade and human mobility, it would be essential to scale up a participatory monitoring approach similar to that we presented in order to improve regional cooperation to manage and reduce risks related to PTM. We are currently extending our community-based monitoring into other parts of Ecuador, with successful results in several communities of the Chimborazo and Bolívar Provinces. At a larger scale, it would be critical for developing nations of the Northern Andes and elsewhere in the world to invest in and cooperate toward building better understanding and capacity to deal with invasive agricultural pests (see Galindo-Leal 2001). Although the Andean countries have recognized the problems associated with invasive pest species for several years (see Ojasti 2001), a comprehensive approach to this issue still has to be developed. Establishing partnerships between national institutions will undoubtedly be a key issue in developing participatory research in the context of invasive pest management. In the present study, the establishment of a collaboration between research (Pontifical Catholic University of Ecuador, PUCE), technical (National Agronomy Institute of Ecuador, INIAP), and educational institutions (College of Agriculture of Simiatug) at both national and local levels revealed an effective strategy to empower local lay science. We believe that the implication of an international organism (Institute for Research and Development, IRD) and a foundation (McKnight Foundation) being involved in the project have also helped in supporting innovation to overcome the practices of local institutions that sometimes inhibit the interactive approach to science advocated above. It is likely that doing science separately at the local level would never produce the valuable outcomes presented in this study (see Fortmann 2008).

CONCLUSION

In this study, scientists would have hardly been able to study the dynamics of invasive population on a weekly basis in such remote invasion fronts without the help of local farmers (the whole tour through the 13 communities, many of which are only accessible by walking, required about 5 days). Reciprocally, farmers would not have been able to detect risks associated with PTM without scientists. As material and human means for ecological monitoring in developing countries are scarce there is a huge need for innovative solutions. Including local people in these activities is not just an opportunity to increase the effectiveness of early detection of invasive species but also a powerful education tool for growing awareness on the magnitude of the challenge they pose.

Acknowledgments This work was part of the research conducted within the projects "Biopesticide development and diffusion for the control of potato moths (C14-026)" and "Innovative Approaches to Manage Insect Pest Risks in Changing Andes (09-022)" both funded by the McKnight Foundation. We thank Lenin Lara, to have facilitated the monitoring with the College of Simiatug. The authors are also grateful to Cesar Aime, Manuel Azogues, Angel Azogues, Delia Chamaguano, Wilmer Chimborazo, Angel Cocha, Hernán Ichiquinga, Esteban Poaquiza, Mariano Poaquiza, Nicolas Sigcha, Carlos Tixilema, Hernán Yanchalaquin, and Norma Yanchalaquin for participating in the potato tuber moth monitoring in Simiatug. We thank Rebecca Nelson, Claire Nicklin, and Steven Vanek from the Cornell University and McKnight Foundation, the editor and two anonymous reviewers, for their helpful comments on a previous version of the manuscript.

REFERENCES

Abay, F., A. Waters-Bayer, and A. Bjørnstad. 2008. Farmers' seed management and innovation in varietal selection: Implications for barley breeding in Tigray, Northern Ethiopia. *Ambio* 37: 312–320.

Afrol News. 2003. Community-based research nets results in Benin. http://www.afrol.com/articles/10547.

Agrawal, A., and C.C. Gibson. 1999. Enchantment and disenchantment: The role of community in natural resource conservation. *World Development* 27: 629–649.

Ambrose-Oji, B., A. Lawrence, J. Wong, R. Lysinge, P. Fraser, J. Hall, H. O'Connor, and J. Healey. 2002. Obtaining local values for biodiversity: Protocols used by the ERP Mount Cameroon Project. Summarised case study. In *Internet Conference on Participatory Assessment, Monitoring and Evaluation of Biodiversity* (*PAMEB*), ed. ETFRN, 7–25 January 2002. Oxford: ETFRN, Environmental Change Institute DFID and Tropenbos International.

Borgerhoff Mulder, M., and P. Coppolillo. 2005. *Conservation: Linking ecology, economics, and culture*. Princeton, NJ: Princeton University Press.

Breen, S.L., S.P. Ellingsen, M. Johnston-Hollitt, S. Wotherspoon, I. Bains, M.G. Burton, M. Cunningham, N. Lo, C.E. Senkbeil, and T. Wong. 2007. A search for 22-GHz water masers within the giant molecular cloud associated with RCW 106. *Monthly Notices of the Royal Astronomical Society* 377: 491–506.

Brush, S.B. 2004. *Farmer's bounty*. New Haven: Yale University Press.

Calheiros, D.F., A.F. Seidl, and C.J.A. Ferreira. 2000. Participatory research methods in environmental science: Local and scientific knowledge of a limnological phenomenon in the Pantanal wetland of Brazil. *Journal of Applied Ecology* 37: 684–696.

Culqui, F. 2005. Estudio de línea base en producción, tecnología y comercialización, en el cultivo de papa (*Solanum tuberosum* L.), en cuatro zonas paperas de la provincia Bolívar. Dissertation, Technical University of Bolívar, Bolívar, Ecuador.

Curtin, C.G. 2002. Integration of science and community-based conservation in the Mexico/US Bordelands. *Conservation Biology* 16: 880–886.

Dangles, O., C. Carpio, A.R. Barragan, J.-L. Zeddam, and J.F. Silvain. 2008. Thermal niche partitioning of potato moths successively introduced in the tropical Andes. *Ecological Applications* 18: 1795–1809.

Dangles, O., V. Mesías, V. Crespo-Perez, and J.F. Silvain. 2009. Crop damage increases with pest species diversity: Evidence from potato tuber moths in the tropical Andes. *Journal of Applied Ecology* 46: 1115–1121.

Danielsen, F., A.E. Jensen, P.D.S. Balete, M. Mendoza, A.C. Custodio, and M. Enghoff. 2005. Does monitoring matter? A quantitative assessment management decisions from locally-based of protected areas. *Biodiversity and Conservation* 14: 2633–2652.

Eisenberg, J.N.S., W. Cevalos, K. Ponce, K. Levy, S.J. Bates, J.C. Scout, A. Hubbard, N. Vieira, P. Endara, M. Espinel, G. Trueba, L.W. Riley, and J. Trostle. 2006. Environmental change and infectious disease: How new roads affect the transmission of diarrheal pathogens in rural Ecuador. *Proceedings of the National Academy of Sciences United States of America* 103: 19460–19465.

Fortmann, L. 2008. *Participatory research in conservation and rural livelihoods*, 284 pp. Oxford: Wiley-Blackwell.

Galindo-Leal, C. 2001. Design and analysis of conservation projects in Latin America: An integrative approach to training. *Conservation Ecology* 5: 16. http://www.consecol.org/vol5/iss2/art16/.

Gilbert, E., J.A. Powell, J.A. Logan, and B.J. Bentz. 2004. Comparison of three models predicting developmental milestones given environmental and individual variation. *Bulletin of Mathematical Biology* 66: 1821–1850.

Gondard, P., and H. Mazurek. 2001. 30 años de reforma agraria y colonización en el Ecuador (1964-1994): dinámicas espaciales. In *Dinámicas territoriales: Ecuador, Bolivia, Perú, Venezuela*, *Estudio de Geografía 10*, ed. P. Gondard and J.B. León, 15–40.

Herrera, F. 1998. La Polilla Guatemalteca de la Papa: Biología, comportamiento y prácticas de manejo integrado. Colombia: CORPOICA.

Hill, J. 2004. Implementing reef check as a long-term monitoring program on the Great Barrier Reef, Australia. In 2nd international tropical marine ecosystem management symposium. Quezon City, Philippines: Department of Environment and Natural Resources.

Hockley, N.J., J.P.G. Jones, F.B. Andrianajaina, A. Manica, E.H. Ranabitsoa, and J.A. Randriamboahary. 2005. When should communities and conservationists monitor exploited resources? *Biodiversity and Conservation* 14: 2795–2806.

Jacobson, S.K., M. McDuff, and M.C. Monroe. 2006. *Conservation education and outreach techniques*. Techniques in ecology and conservation series. UK: OUP.

Keasar, T., A. Kalish, O. Becher, and S. Steinberg. 2005. Spatial and temporal dynamics of potato tuberworm (Lepidoptera: Gelechiidae) infestation in field stored potatoes. *Journal of Economic Entomology* 98: 222–228.

Lawrence, A. 2002. Participatory assessment, monitoring and evaluation of biodiversity: Summary of the ETFRN internet discussion 7–25 January 2002. http://www.etfrn.org/etfrn/workshop/biodiversity/index.html.

Lockwood, J.L., M.F. Hoopes, and M.P. Marchetti. 2007. *Invasion ecology*. London, UK: Blackwell Publishing.

Lovett, G.M., D.A. Burns, C.T. Driscoll, J.C. Jenkins, M.J. Mitchell, L. Rustad, J.B. Shanley, G.E. Likens, and R. Haeuber. 2007. Who needs environmental monitoring? *Frontiers in Ecology and the Environment* 5: 253–260.

Mehrhoff, L.J., J.A. Silander Jr., S.A. Leicht, E.S. Mosher, N.M. Tabak. 2003. *IPANE: Invasive plant atlas of New England*. Storrs, CT: Department of Ecology and Evolutionary Biology, University of Connecticut. http://www.ipane.org.

Ojasti, J. 2001. Estudio sobre el estado actual de las especies exóticas. Quito, Ecuador: Biblioteca Digital Andina.

Olsson, P., and C. Folke. 2001. Local ecological knowledge and institutional dynamics for ecosystem management: A study of Lake Racken watershed, Sweden. *Ecosystems* 4: 85–104.

Palacios, M., A. Lagnaoui, and O. Ortiz. 2002. En la necesidad de un proyecto regional andino para el control y la prevención de la polilla guatemalteca de la papa *Tecia solanivora* (Povolny) (Lepidoptera: Gelechiidae). In *Taller de la polilla de la papa*, ed. A. Pollet, G. Onore, F. Chamorro, and A.R. Barragán, 207–213. Quito: PUCE.

Pollet, A., A.R. Barragan, J.L. Zeddam, and X. Lery. 2003. *Tecia solanivora*, a serious biological invasion of potato cultures in South America. *International Pest Control* 45: 139–144.

Pollet, A., A.R. Barragan, and P. Iturralde. 2004. Conozca y maneje la polilla de la papa. Seria de divulgacion. Ecuador: Centro de Biodiversidad y ambiente, Escuela de Biologia, PUCE.

Povolny, D. 1973. *Scrobipalpopsis solanivora* sp. n.—A new pest of potato (*Solanum tuberosum*) from Central America. *Acta Universitatis Agriculturae, Facultas Agronomica* 21: 143–146.

Puillandre, N., S. Dupas, O. Dangles, J.L. Zeddam, C. Capdevielle-Dulac, K. Barbin, M. Torres-Leguizamon, and J.F. Silvain. 2008. Genetic bottleneck in invasive species: the potato tuber moth adds to the list. *Biological Invasions* 10: 319–333.

Pumisacho, M., and S. Sherwood. 2002. *El cultivo de la papa en Ecuador*. Quito, Ecuador: INIAP and CIP.
Pumisacho, M., and S. Sherwood. 2005. *Escuelas de Campo de Agricultores en América Latina*. Republic of Ecuador: INNIAP-Fortipapa.
R Development Core Team. 2006. *R: A language and environment for statistical computing*. Vienna, Austria: Foundation for Statistical Computing.
Scheffer, M., F. Westley, W.A. Brock, and M. Holmgren. 2002. Dynamic interaction of societies and ecosystems-Linking theories from ecology, economy and sociology. In *Panarchy*, ed. L.H. Gunderson and C.S. Holling, 195–239. Washington, DC: Island Press.
Stoecker, R. 2001. Community-based research: The next new thing. A report to the Corella and Bertram F. Bonner Foundation and Campus Compact. http://comm-org.wisc.edu/drafts/cbrreportb.htm.
Stoecker, R. 2002. Practices and challenges of community-based research. *Journal of Public Affairs* 6: 219–239.
Stuart-Hill, G., R. Diggle, B. Munali, J. Tagg, and D. Ward. 2005. The event book system: A community-based natural resource monitoring system from Namibia. *Biodiversity and Conservation* 14: 2611–2631.
United Nations Department of Economic and Social Affairs. 2003. Catalysing community participation: Water quality monitoring program in the Philippines. http://www.un.org/esa/sustdev/mgroups/success/1998/phil_pro.htm.
Venables, W.N., and B.D. Ripley. 2002. *Modern applied statistics with S-PLUS*, 4th edn. Berlin: Springer.
Villares, M. 2008. Implementación de un sistema de capacitación de agricultor en manejo integrado del complejo de polillas (*Phthorimaea operculella, Tecia solanivora* y *Symmetrischema tangolias*) de la papa (*Solanum tuberosum*) en la provincia de Bolívar. Dissertation, Technical University of Bolívar, Bolívar, Ecuador.
Wallerstein, N., and B. Duran. 2003. The conceptual, historical and practical roots of community based participatory research and related participatory traditions. In *Community based participatory research for health*, ed. M. Minkler and N. Wallerstein, 27–52. San Francisco, CA: Jossey Bass.
Williams, J. 2007. Linking science and practice: The pros and cons of the participatory research model. *Ecology, Management and Restoration* 8: 158–159.
With, K.A. 2002. The landscape ecology of invasive spread. *Conservation Biology* 16: 1192–1203.

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