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Research

The Azteca Chess experience: learning how to share concepts of ecological complexity with small coffee farmers

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ABSTRACT. Small-scale coffee farmers understand certain complex ecological processes, and successfully navigate some of the challenges emerging from the ecological complexity on their farms. It is generally thought that scientific knowledge is able to complement farmers' knowledge. However, for this collaboration to be fruitful, the gap between the knowledge frameworks of both farmers and scientists will need to be closed. We report on the learning results of 14 workshops held in Chiapas, Mexico during 2015 in which 117 small-scale coffee farmers of all genders (30% women) and ages who had little schooling were exposed by researchers to a natural history narrative, a multispecies network representation, a board game, and a series of graphical quizzes, all related to a nine-species complex ecological network with potential for autonomous control of the ongoing and devastating coffee rust epidemic that was affecting them. Farmers' retention and understanding of direct and indirect bilateral interactions among organisms was assessed with different methods to elucidate the effect of adding Azteca Chess gaming sessions to a detailed and very graphical lecture. Evaluation methods that were better adapted to farmers' conditions improved learning scores and showed statistically significant age effect (players older than 40 had lower retention scores) and gaming effect (lower retention of interactions included in the lecture but not in the game). The combination of lecture and game sessions helped participants better understand cascades of trait-mediated interactions. Participants' debriefings confirmed qualitatively that they learned that beneficial organisms and interactions occur on their farms, and that gaming was enjoyable, motivating, and critical to grasp complex interactions. Many of the farmers concluded that the outcome of these interactions is not unique and not always in favor of rust control but is context dependent. Many concluded that there are feasible things they can do on their farms, derived from what they learned, to favor potential autonomous pest control.

Key Words: *autonomous pest control; coffee farmers; ecological complexity game; educational board-game; farmer scientist interaction; learning complexity; shade coffee; trait-mediated interactions*

INTRODUCTION

Small-scale shade-coffee producers and community ecologists studying coffee farms share a familiarity with the ecological complexity of diverse agroecosystems. The convergence and complementarity of farmer and academic "ecological knowledge frameworks" is an active field of inquiry with potential to inform research agendas and production processes in landscapes composed of small coffee farms (Vandermeer and Perfecto 2013). In the past three decades, there has been an acknowledgment that the standard top-down "transfer of technology" approach to agricultural research is frequently inadequate, and a transition to participatory-action research became common (Kindon et al. 2007, Blackstock et al. 2010). One of the most conspicuous of these programs is based on the idea of "farmer-to-farmer" knowledge-sharing (Holt-Giménez 2006), evidenced in the experiences of Farmer Field Schools (Damtie et al. 2011). Such knowledge-sharing implicitly and sometimes explicitly deals with complex social and ecological networks. However, most frequently, the ecological complexity has been reduced to simple and generalized recommendations—for example, integrated pest management techniques or nature-friendly and organic production. For coffee farmers, this translates into farmers exchanging knowledge concerning direct applications of materials or techniques aimed at very specific consequences—soil amendments, shade management, and judicious use of herbicides, fungicides, and insecticides (Damtie et al. 2011).

Farmer-to-farmer and farmer-to-scientist experiences in coffee farms have frequently focused on biological pest control (Jarquin et al. 2006). Most cases thus far explored have involved a single pest and one or two (sometimes exogenous) natural enemies (e.g., Gómez et al. 2012). Results of producing and liberating natural enemies into the field, commonly referred to as "classical biological control," have been modest because of ecological and logistic reasons but also, we argue, due to a knowledge and communication gap between scientists and farmers (Segura et al. 2004, Jarquin et al. 2005). The challenges of building common ecological knowledge increase significantly when dealing with more sophisticated programs of pest management (e.g., Lewis et al. 1997), such as so called "autonomous pest control" (Vandermeer et al. 2010). By their very nature, these more sophisticated programs acknowledge the existence of complex interactions involving many species. In their management practices, experienced farmers deal effectively with certain complex ecological processes, but most pay little attention to, or have little knowledge of, the behavior of the many small inconspicuous organisms that may be key to the operation of autonomous pest control, let alone those forces that indirectly, but significantly, relate to pest outbreaks (Perfecto and Vandermeer 2015). Conversely, ecologists committed to unraveling the details of pest management in coffee frequently lack the knowledge and tools to develop effective ways of incorporating their frameworks and findings into farmer-to-farmer and other participatory experiences

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in ways that help farmers (a) continuously update their management strategies based on a deep understanding of the specific case, and (b) develop better insights about the ecological complexity of other social-ecological processes that they must navigate (García-Barrios et al. 2016).

We report on the results of a series of workshops held in the Sierra Madre de Chiapas, Mexico during 2015 in which small-scale coffee farmers of all genders (30% women) and ages who had little schooling were exposed to (a) a natural history narrative, (b) a multispecies network representation and graphical analysis, and (c) a board game, all related to a complex ecological network with potential for autonomous control of the ongoing and devastating coffee rust epidemics (*Hemileia vastatrix*) affecting them. Pre- and post-game graphical quizzes were administered to evaluate the learning process that occurred through these activities. The basic ecological interactions of the nine-species network have been extensively researched empirically and theoretically by Perfecto and Vandermeer, with collaboration from other scholars and farmers (Vandermeer et al. 2010, Perfecto et al. 2014) as part of a broader coffee agroecology project (Perfecto and Vandermeer 2015). The game Azteca Chess—designed by the authors and named after the key ant species *Azteca sericeasur*—has been successfully tested with students for playability, engagement, and learning (García-Barrios et al. 2016).

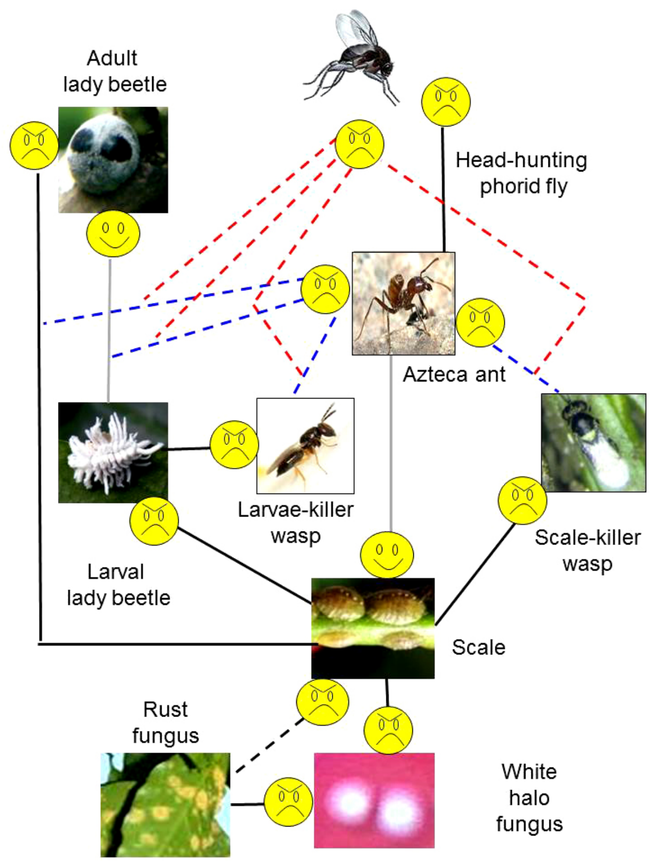
Our objectives are to (a) share our workshops and “gaming methodology” with small-scale farmers as a resource to be added to more comprehensive and long-term field-based educational processes, (b) explain why and how our network-learning evaluation tools had to be better adapted to farmers’ conditions during the process, (c) describe (in their and our terms) what farmers learned from this experience, and (d) define to what extent the gaming sessions made a difference in being able to understand and remember the network’s interactions and deduce some of its consequences for autonomous pest management.

METHODS

The Azteca autonomous pest management network

We provide a stylized and brief description of the Azteca network. For more details and ecological depth, see Vandermeer et al. (2010), Perfecto and Vandermeer (2015), and García-Barrios et al. (2016). Fig. 1 depicts a network of empirically verified interactions occurring among organisms on shade-coffee bushes. This is the network that has the potential to aid in the control of the coffee rust fungus. The sessile coffee scale insect, *Coccus viridis*, serves as alternative prey/host to the white halo fungus *Lecanicilium lecanii*, and thus facilitates the latter’s predatory action on the coffee rust. However, the scale is heavily consumed by the adults and larvae of a lady beetle, *Azya orbigera*, and by a group of parasitoid wasps (in Fig. 1 represented by the “scale-killer wasp”). But a tree-nesting ant (*Azteca sericeasur*; *Azteca* hereafter) protects scales in exchange for the honey dew they extrude. *Azteca* patrols scale colonies and scares away all but the beetle’s larva, which is protected from the ants by the waxy filaments that cover its body. The beetle larva is controlled by parasitoid wasps (mainly *Homalotylus shaviakane*, plus other wasps in the family Encyrtidae; in Fig. 1 represented by the “larvae-killer wasp”). This complementary ant/wasp protection of the scale is compromised by (a) the ant itself, since the *Azteca* ant does not discriminate and also scares away larvae-killer-wasps, and (b) the parasitoid fly, *Pseudacteon lascinosus* (in Fig. 1 represented by the “head-hunting phorid fly”), that attacks *Azteca* ants when they are moving and triggers a temporary halt in the patrolling activity of the ant as a defense mechanism. The reduced activity of the ant when the parasitoid flies are present provides a window of opportunity for the adult lady beetle to oviposit under the scales (and also eat scales), and for the scale-killer and larvae-killer wasps to approach their hosts. Thus, we see two main types of interaction: predatory (X consumes Y), and

Fig. 1. Each organism projects an action (face) through a line directed toward another organism(s) or interaction(s) which it affects. An angry face signifies harm. Black solid lines mean harm by consumption. The black dashed line means the scale facilitates harm done by the white halo fungus to the rust fungus. The behavior of the ant that changes the behavior of predators is represented by dashed blue lines (trait-mediated interactions) projected upon predation interactions. The behavior of the fly that changes the behavior of the ant is represented by dashed red lines projected upon blue lines. Happy faces with gray solid lines represent the capacity of the scale to provide honey dew to the ant, and of the adult lady beetle to oviposit and produce its larvae. Species marked with an asterisk are included in the workshop lectures but not in the game. (Figure modified after Fig.5.14 in Perfecto and Vandermeer 2015.)



trait-mediated (Z's behavior modifies X's behavior, which changes X's predatory efficiency over Y). Various levels of interaction occur. In the first level, X harms Y by eating, parasitizing, or scaring it; in the second level, Z benefits Y by harming X, an enemy of Y; and finally, a higher level that is represented by the cascading effects from levels 1 and 2. The predatory and trait-mediated interactions that cascade through different pathways from the fly to the coffee scale can ultimately lead to one of two attractors (local exuberant coffee scale colonies and local coffee scale extinction). The theoretical and empirical relations between coffee scale and rust dynamics are even more complex, and are explored in Vandermeer et al. (2014) and McCook and Vandermeer (2015).

Azteca Chess

The features and rules of this board game are thoroughly described in García-Barrios et al. (2016). We explore its use as a learning and communication tool between farmers and researchers. Nevertheless, in Appendix 1, we provide a graphic summary of the game and links to the manual, for the reader's convenience. In Fig. 2, we display the hexagonal-cell game board, which highly stylizes a transversal section of a coffee bush. It exposes the initial spatial display of tokens representing different organisms.

First set of workshops

Two sets of workshops with coffee farmers were organized: five in the Sepultura Reserve in April and nine in Sepultura and Tacaná reserves in July–August 2015 (Fig. 3).

LGB and JCM had conducted previous work in the region and were trusted by many of the participants. In the first workshops, family members of all genders and ages were invited by public broadcast to a lecture that addressed the rust problem, followed by Azteca Chess training, a game tournament with prizes, and a small dinner followed by a reflection session. With a limit of 16 players per workshop, a total of 72 people aged 12–70 and with a deficient rural primary school level attended and played, and 67 completed all quizzes. Workshops lasted 4 hours.

During a 45-minute PowerPoint-supported lecture, we:

1. presented the basics of the rust's biology and data on regional damage caused to coffee producers in the region;
2. explained and practiced with farmers a "happy-face grammar" to establish the notion and graphical representation of first- and second-level ecological interactions. For this purpose, we used the simplest network: the rabbit harms [angry face—first level] a crop; the fox harms [angry face—first level] the rabbit; the fox benefits [happy face—second level] the crop; and
3. constructed step-by-step—and thoroughly explained—the natural history and network representation of each element in Fig. 1. At intervals, volunteer participants were asked to come up to the stage and use the grammar to follow the interaction paths down to the scale and rust to deduce if a given organism had the potential to indirectly benefit or harm the farmer (Fig. 4). The lecture's goal was to familiarize farmers with the diversity of organisms involved, their elaborate behaviors and choices, their types and levels of interactions, and their ultimate effect on scales and, potentially, on rust.

Fig. 2. Azteca Chess board game with initial display of tokens. Pink circles are exclusively for the phorid fly to move clockwise in each round.

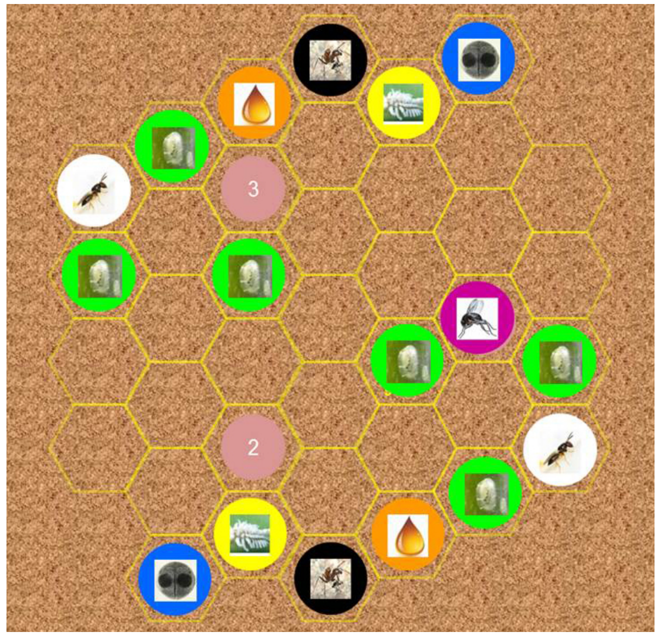
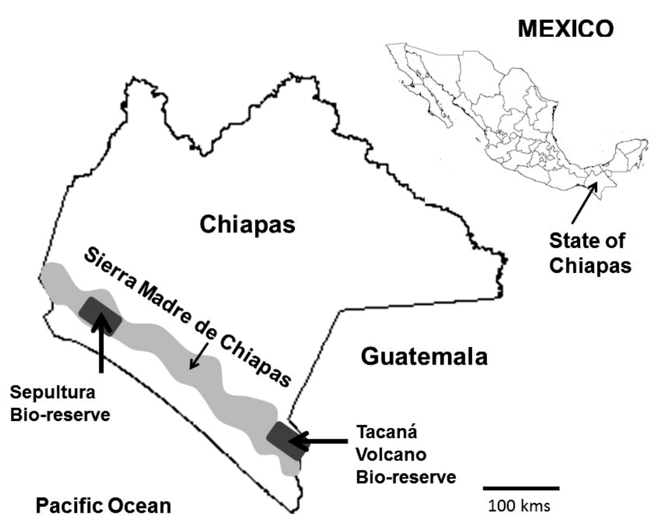


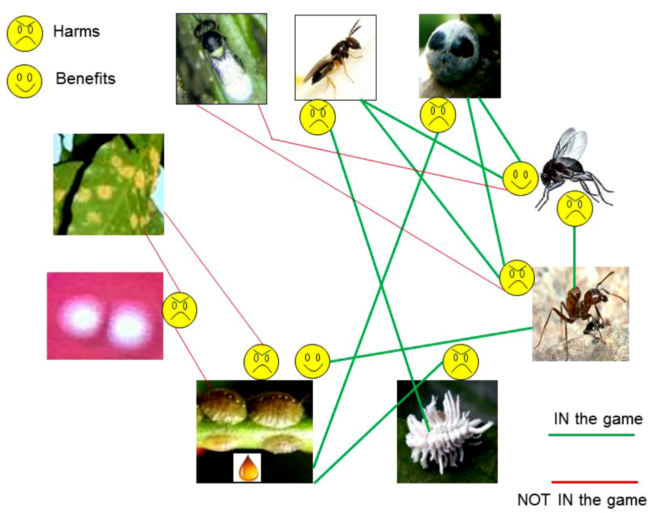
Fig. 3. Map of Chiapas in southern Mexico. Shade-coffee is produced in the mid-altitudes of the mountain range called Sierra Madre de Chiapas (light gray). The study sites are within the buffer zones of the "Sepultura" and "Tacaná Volcano" Man and the Biosphere Reserves (dark gray).



Immediately after the lecture, participants were asked without previous notice to answer a graphical, semi-open quiz "A" in 7 minutes. The same procedure was repeated after the gaming sessions (approximately 3 hours later). Quiz A (Figs. 5 and 6) explored mainly retention (memorization) and understanding, the first two of Bloom's taxonomy of learning levels (Anderson

Fig. 4. Participants explain how interactions cascade down the network (e.g., the fly harms the ant that harms the beetle that harms the scale…).

Fig. 5. Quiz A. Network elements of Fig. 1 are redisplayed in a circle. The quiz was handed out without the red and green lines in this figure. Players were asked to connect, with lines, the beneficial and harmful faces departing from each organism to one or more organisms affected by such behaviors. For analysis, we counted only matches with those connections represented in the figure, and which correspond with 14 of the 18 lines in Fig. 1 (i.e., the presence of these lines in the player's quiz was considered correct; their absence incorrect).



et al. 2001). Players were asked to connect beneficial and harmful faces departing from each organism to one or more organisms affected by such behaviors. To obtain retention scores per player, we counted only matches with 14 of the 18 bilateral interactions presented in Fig. 1. The 14 were selected to make the average interaction levels of the nine "in the game" interactions and the five "not in the game" interactions as similar as possible.

Fig. 6. Participants answering quiz A. Above: closeup. Bellow: 16 players filling in the pre-game quiz.

Comparing pre- and post-gaming quiz scores does not immediately yield the gaming effect because the difference in scores results from the lecture's learning effect minus the forgetting effect plus the positive effect of quizzes on countering the forgetting effect (Roediger and Karpicke 2006) plus the gaming effect itself. Comparison of pre- versus post-gaming quiz scores only allows knowing if all post-lecture activities were able to counter or even overcompensate the lecture-forgetting effect. We will call it the post-lecture effect. To isolate the gaming effect, two performance scores (0–10 scale) were calculated per player: one for the nine "in the game" interactions and another for the five "not in the game" interactions. This was done separately for the pre- and post-game quiz A. Fifty-six of the respondents were younger than 41, and 11 were between 41 and 68 years of age. We noticed that the second age group more commonly struggled to follow the workshop activities and to do the quizzes, so in all statistical analysis, age group was considered as an additional explanatory factor. The pooled set of "in the game" and "not in the game" scores obtained in the pre- and post-game A quizzes was subject to a three-way Univariate General Linear Model analysis; i.e., a UGLIM (pre/post quiz x "in the game?" x age group). Additionally, paired *t* tests were performed to compare pre- versus post-game sets of scores for each age group. All tests were performed in SPSS (Version 16, 2007, SPSS Inc., Chicago, Illinois, USA).

Participants were trained in Azteca Chess by LGB through a 20-minute lecture and a step-by-step hands-on demonstration, followed by personalized clarifications during the game by JCM and LGB. Each participant played three times (Fig. 7). Post-game collective reflections were conducted by JCM. They were not tape recorded; only notes were made on paper.

Fig. 7. Happy moments during Azteca Chess sessions.

Second set of workshops

A different set of 50 players from the Sepultura and Tacaná subregions participated in these workshops, again conducted by LGB and JCM. Interesting findings, inconclusive results, and perceived weakness of the learning evaluation process motivated six changes in our learning evaluation tools, which were decided by all authors:

First, the Azteca network and game-training lectures—and the game itself—were unaltered, but the nine workshop groups were limited to six players each to allow people to perform three supervised post-game quizzes through question and answer (Q&A) dialogues with a researcher. Groups were formed by open invitation made by a local contact-farmer in each community. Participants were informed they were considered to be working collaborators who were exploring a learning method, so each received a 1-day rural salary of US$10. Fifty participants completed all activities. Half were aged 12–40 and half were 41–68, again with a deficient primary school level as average schooling. Participants played three times in rotation with others. Workshops lasted 4–5 hours.

Second, before starting the workshop, each player was interviewed briefly by JCM about his/her knowledge of species dwelling on coffee bushes, their interactions, and their effect on pest problems.

Third, the semi-open "A" quiz was substituted with a closed "B" quiz (Figs. 8 and 9) that was meant to capture in a step-by-step, unambiguous, and less overwhelming way the same information, as well as to familiarize the participant with responding quizzes. The player held the graphical quiz, and the researcher asked them to decide, for each of 16 bilateral interactions, (a) if it was included in the game, (b) if species X benefited or harmed species Y, and how (to distinguish knowing from guessing). Researchers were extremely careful not to hint, approve, or disapprove responses. Two performance scores (0–10 scale) were calculated per player: one for the 10 "in the game" interactions and another for the six "not in the game" interactions. The pooled set of scores was subject to a two-way UGLIM (age group x "in the game?") to reveal the game effect.

Fig. 8. Quiz B. In each of the 16 rows, participants circle the correct face, and later cross the square if the interaction is in the game.

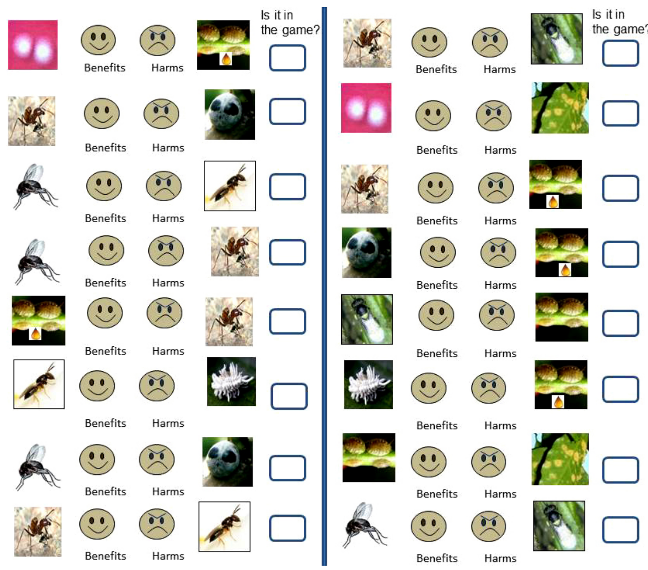


Fig. 9. One of the researchers (LGB) assisting a farmer who is filling in quiz B, through a Q&A dialogue.

To test if this quiz "B" procedure was better able to capture the possible gaming effect than was quiz "A", we pooled the two workshop set data and performed a three-way UGLIM, comparing scores from post-game quizzes "A" and "B".

Additionally, the frequency of players correctly answering each of the 16 bilateral interactions was calculated and arc-sin transformed. A linear regression model with dummy variables was used to explore how such frequencies were affected by age group (0 = young; 1 = older), "in the game?" (0 = no; 1 = yes), level (1, 2), and type of interaction (predatory = 0; trait-mediated = 1).

Fourth, to explore if players recognized trait-mediated interactions in the game, the researcher offered the player a board with tokens and asked them to make the proper moves to show (a) how an ant scares away a beetle, (b) how an ant scares away a wasp, (c) how a fly favors a beetle by killing a contiguous ant, and (d) how a fly's mere presence deters ants from approaching a beetle. All except (c) are trait-mediated interactions.

Fifth, high-level cascades along the Azteca network were explored qualitatively and briefly with farmers during the lecture (e.g., the fly harms the ant that harms the beetle that harms the scale that benefits the fungus that harms the rust). We developed a post-game hands-on quiz (the cascade quiz) (Fig. 10) in which six medium-sized cards of the sequence (fly–ant–larvae-killer wasp–larval beetle–scale–rust) were presented to the player as an initial condition. We then changed the current state of the network by increasing the fly's population (the size of the card) and asked the player to propagate the consequences on other species' populations by changing, if necessary, the size of the subsequent cards (smaller and bigger card were available). Players were asked the reason for each change they made to discriminate correct answers from guessing. We registered how many steps the player propagated correctly along the sequence and built the frequency distribution of correct steps for all players. Before taking the cascade quiz, the farmer practiced with a similar story using fox–rabbit–plant cards. As with the Lotka-Volterra dynamical model, the Azteca network exhibits complicated oscillatory behaviors due to its many predator–prey interactions, which were not discussed with the farmers. In this exercise, we obviously avoided such complications and focused on a very stylized form of cascading quantitative effects in a single time step.

Sixth, after players were personally interviewed for quizzes, we held a collective reflection session about the workshop, the game, and the practical implications of the experience. Unlike the first set of workshops, all reflection sessions were recorded and transcribed. Thirty-five farmer quotes were selected for this paper.

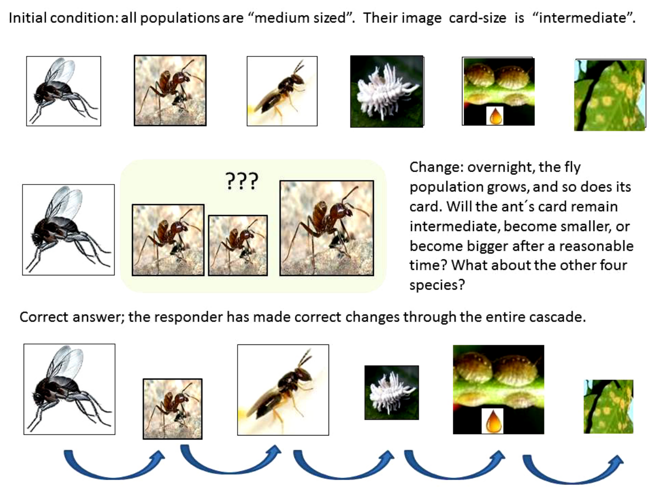
RESULTS

First set of workshops

The five tournament sessions were successful in that all 72 participants engaged in the lecture and game, and 67 completed both "A" quizzes and participated in reflection sessions.

The average pre- and post-game quiz scores, which measured retention of bilateral interactions, were both low (around 50% correct answers). Table 1 shows there was a significant age group effect (younger did better than older) but no gaming effect, as measured both by the pre- versus post-game score comparison and the "in" or "not in" the game comparison. The younger age group performed slightly better than the older group. For the younger group paired t tests, "in the game" post-game scores were marginally higher (5.73; p = 0.09) than "in the game" pre-game scores (5.32). This first set of gaming experiences revealed an important age group effect, but only slight and statistically marginal post-lecture effects and gaming effects that could not counter the effect of partially forgetting the lecture details after 3 hours.

Fig. 10. The cascade quiz. The initial condition, the change in the fly population, and the correct dynamic consequence. See text for further explanation.



Participants were surprised to know how many small organism live and actually interact on a coffee bush, were interested in the fact that these animals act pro or against coffee rust control both directly and indirectly, and were amazed and amused by some of the insects' elaborate behaviors. Overall, only one-fifth of participants recalled and/or could graphically represent 60% or more of the direct and indirect relations in the Azteca network. Yet in all debriefings and reflection sessions, players commented positively on more general aspects of the learning experience. They concluded that insecticides should be applied carefully or not at all to avoid killing beneficial insects. Finally, they considered that learning the game was challenging at first, but later it was fun and rewarding, and some noted that the game complemented the lecture or was absolutely necessary to understand the interactions.

Second set of workshops

A different group of 50 farmers from the Tacaná and Sepultura subregions participated in this second set of workshops. While more than 80% of players could list, before the workshop, five or more vertebrates and invertebrates that could be found on their coffee bushes, 75% were unaware of some of the interactions, and the same proportion did not know that some interactions can control pests. Interestingly, unawareness was somewhat lower in the younger group. Thirteen percent of young players and twenty percent of older players spontaneously said that most species found on coffee bushes are pests.

Table 1. Variables explaining quiz "A" scores. Univariate General Linear Model. Note: Dependent variable: retention scores obtained by players for interactions in and not in the game, before and after playing Azteca Chess (pre- and post-game "A" quizzes applied during the first set of workshops).

Source	Type III sum of squares	df	Mean square	F	Significance
Corrected model	187.15[†]	7	26.737	7.800	0.000
Intersection	2734.025	1	2734.025	797.618	0.000
Age group	154.016	1	154.016	44.932	0.000
In the game?	5.549	1	5.549	1.619	0.204
Pre- vs. post-game quiz	10.830	1	10.830	3.159	0.077
Age group * In the game?	0.001	1	0.001	0.000	0.986
Age group * Pre vs. post	0.006	1	0.006	0.002	0.966
In game? * Pre vs. post	1.800	1	1.800	0.525	0.469
Age group * In the game? * Pre vs. post	4.111	1	4.111	1.199	0.274
Error	891.212	260	3.428		
Total	7773.926	268			
Corrected total	1078.370	267			

[†] R^2 = 0.174 (corrected R^2 = 0.151)

Note: Age groups: scores of younger and older players. In the game?: score for interactions in the game vs. score interactions not in the game. Pre vs. post: pre-game quiz "A" total score vs. post-game quiz "A" total score.

The average player had 73% correct answers in the single quiz applied post-game (i.e., average score = 7.3). Sixty percent of players got a score between 8 and 10 (i.e., good to excellent). Table 2 shows significant age group and gaming effects on quiz "B" performance. Younger players got higher scores than older players (8.1 versus 6.5; $p < 0.0001$), and "in the game" scores were higher than "not in the game" scores (8.4 versus 6.1; $p < 0.0001$)

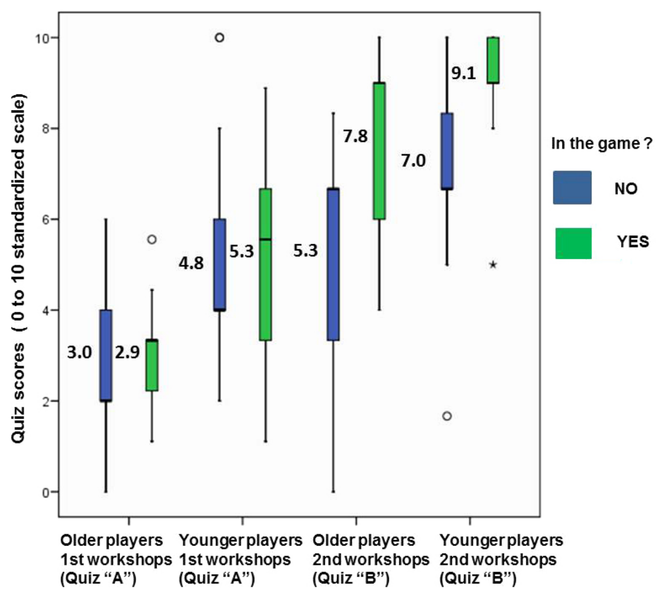
Table 2. Variables explaining quiz "B" scores. Univariate General Linear Model. Note: Dependent variable: retention scores obtained by players for interactions in and not in the game (post-game "B" quiz applied during second set of workshops).

Source	Type III sum of squares	df	Mean square	F	Significance
Corrected model	190.492[†]	3	63.497	15.876	0.000
Intersection	5207.937	1	5207.937	1302.129	0.000
Age group	59.302	1	59.302	14.827	0.000
In the game?	129.801	1	129.801	32.454	0.000
Age group * In the game?	0.894	1	0.894	0.224	0.637
Error	375.958	94	4.000		
Total	5753.889	98			
Corrected total	566.450	97			

[†] R^2 = 0.336 (corrected R^2 = 0.315)

Table 3 compares the post-game quiz scores of the two sets of players that were exposed to quiz "A" and quiz "B", respectively. It confirms significant age group effects across both workshop sets and a significant effect of the second set of workshops on capturing the gaming effect (see the "workshop x gaming" interaction effect). Thus, with the new and unambiguous quiz "B" format, filled through a step-by-step Q&A interaction between player and researcher, the effect of the game and of age group on the player's capacity to retain and understand network interactions became starkly apparent. Fig. 11 graphically summarizes the various statistical trends presented, and the positive effect of the quiz "B" procedure.

Fig. 11. Comparison of learning performance measurements (post-game quiz "A" and "B" scores) as affected by workshop set and its quiz type, by age group, and by gaming effect. For each of the eight combinations of these three variables, we provide the box and whiskers distribution and, in bold, the average score. Open circles are statistically atypical data. Asterisks are statistically very atypical data.



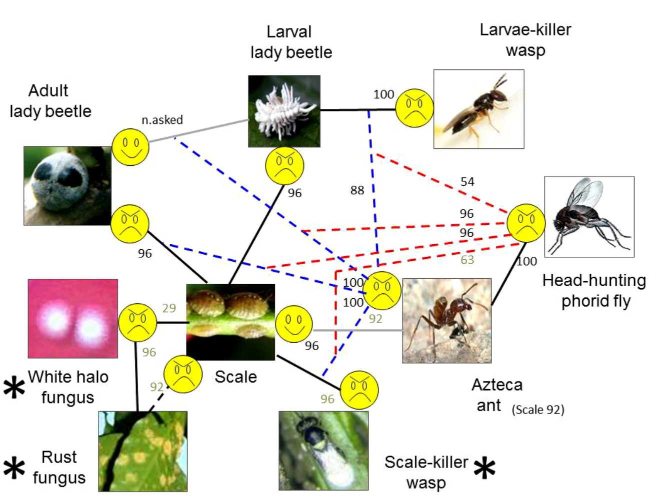
Figs. 12 and 13 show, for the younger and the older group, respectively, the frequency of players who recalled each of the 16 bilateral interactions in the lecture. According to the linear regression model (Table 4), the frequency of correct answers to a given interaction was significantly increased by being an "in the game" interaction, was reduced by being the answer of an older player, and was not influenced by the interaction's level (1 or 2)

Table 3. Variables explaining quizzes “A” and “B” scores. Univariate General Linear Model. Note: Dependent variable: retention scores obtained by players in post-game “A” and “B” quizzes applied during first and second set of workshops.

Source	Type III sum of squares	df	Mean square	*F*	Significance
Corrected model	641.889[†]	7	91.698	25.158	0.000
Intersection	5393.825	1	5393.825	1479.829	0.000
Age group	137.282	1	137.282	37.664	0.000
In the game?	64.044	1	64.044	17.571	0.000
Workshop set	444.167	1	444.167	121.860	0.000
Age group * In the game?	0.199	1	0.199	0.055	0.815
Age group * Workshop set	2.660	1	2.660	0.730	0.394
In the game? * Workshop set	47.873	1	47.873	13.134	0.000
Age group * Workshop set * In the game?	2.839	1	2.839	0.779	0.378
Error	816.457	224	3.645		
Total	9279.074	232			
Corrected total	1458.346	231			

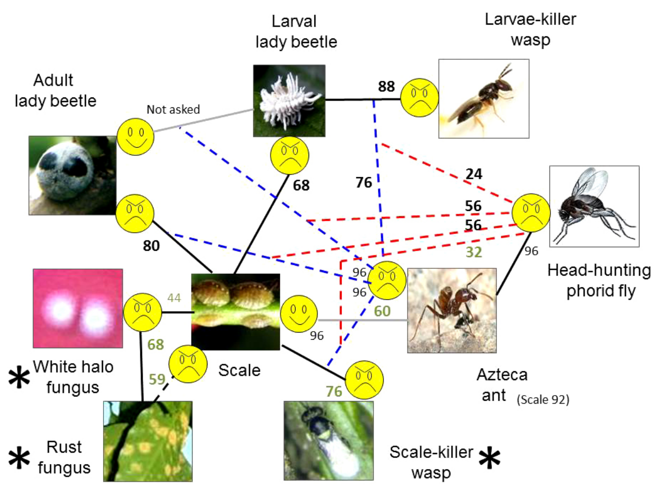
[†] R^2 = 0.440 (corrected R^2 = 0.423)

Fig. 12. Frequency of 25 younger participants (%) who correctly identified each of the 16 interactions in quiz B. The network is the same as in Fig. 1 but has a different spatial arrangement to reduce number crowding as much as possible. Black lines = first-level interaction, predatory effect; gray lines = first-level interaction, beneficial effect; dashed black line = second-level interaction. The coffee-scale facilitates rust predation by the white halo fungus; dashed blue lines = trait-mediated, first-level interactions through which the ant harms two wasps and the adult beetle (as predator and as egg layer). Dashed red lines = trait-mediated, second-level interactions through which the fly reverts the ant’s potential harm on the wasps and adult beetle. The three species marked with an asterisk are not included in the game. Number colors: black = the interaction is in the game; green = the interaction is not in the game.



and type (trait-mediated or predatory). In other words, the frequency of correct answers did not change significantly by being a higher level interaction or a trait-mediated interaction.

Fig. 13. Frequency of 25 older participants (%) who correctly identified each of the 16 interactions in quiz B. Symbols as in Fig. 12. Larger bold number = frequency was lower than in the younger group.



Most players did not have trouble distinguishing in the quiz which bilateral interactions were included in the game (92% of answers were correct). Table 5 shows that almost every young person could translate the most relevant trait-mediated level 1 interactions into token moves on the board, while only two-thirds could do so for the trait-mediated level 2 interactions. Older players followed the same pattern but at lower frequencies.

After the game, 64% of players were able to elucidate the cascading effects of a change (sudden fly increase) on a six-level interaction pathway, while 25% did not understand the exercise and/or could not go beyond [more fly -> less ant]. Performance was not significantly related to age group.

In Appendix 2, we present 35 selected farmer quotes on the different topics addressed during post-game reflection sessions. Here, we reproduce five:

Table 4. Frequency of players who correctly identified each of 16 bilateral interactions, as a function of age group, interaction in or not in the game, and level and type of interaction, for the second set of workshops.

ANOVA of the regression model (b)					
Model	Sum of squares	df	Square mean	*F*	Significance
Regression	4116.5	4	1029.1	5.71	0.002 (a)
Residual	4886.2	27	180.2		
Total	8982.7	31			

a Predictor variables: (Constant), TRAIT MEDIATED, AGE GROUP, IN GAME, INTERACTION LEVEL
b Dependent variable: ARCSIN OF THE FREQUENCY OF PLAYERS CORRECTLY IDENTIFYING THE INTERACTION

Regression coefficients (a)					
Model	Nonstandardized coefficients		Standardized coefficients	*t*	Significance
	B	Std error	Beta	B	
CONSTANT	76.1	8		9.5	0
AGE GROUP (0 = younger; 1 = older)	-14.5	4.7	-0.43	-3.1	0.005
IN GAME (0 = no; 1 = yes)	15.3	5	0.44	3.1	0.005
INTERACTION LEVEL (1, 2)	-7.3	5.2	-0.21	-1.4	0.17
TRAIT MEDIATED (0 = no; 1 = yes)	-6.9	5.2	-0.2	-1.3	0.19

b Dependent variable: ARCSIN TRANSFORMATION OF THE FREQUENCY OF PLAYERS CORRECTLY IDENTIFYING THE INTERACTION

1. “With the game I understood a bit better, because with words only, I get drowsy—that’s the truth—every time I attend a workshop. In the game, as I look at the board and move the tokens, and as I see how the good and the bad animals eat each other, I really get to understand which helps me and which doesn’t.”

2. “On the wall we only see [PowerPoint] figures. But once in the game, it’s as if we were seeing it in reality: each animal did his act, defending his life, giving life to others he helps. It benefits our minds because we have to think, we have to analyze what we are about to do; it clears our mind because in our mind everything is so tangled, but once our mind can focus on how we are going to deal with the situation…so yes, it was great!”

3. [The youngest player 12 years old; already a farmer]: “The fly helps the beetle by killing the ant. The fly also helps the beetle by hovering above the ants so that they can’t approach; this way of helping the beetle is more difficult to perceive. The beetle is freed from the ant and now has no problem to eat the scales, and without these, the rust can better reproduce. Now, the wasp kills the larva beetle so the rust won’t reproduce, but if ants become abundant again, they frighten the wasp and it flees from the coffee bush.”

4. [Researcher]: “Which outcome do you expect more frequently on a coffee bush: the scale population flourish and rust is somewhat controlled; scale population remains low; scale population is eliminated and rust flourishes.” Answers: (1) “It depends on what animals are there: for example, if the fly is absent the beetle is busted; it depends.” (2) “When there are more ants and wasps, scales increase, but ants are in danger also, so sometimes they win and sometimes they lose. Sometimes they are more abundant and sometimes less.”

5. “We are very aggressive with ants and all animals, but today we are learning about them, and I will take to my family the message that dear God sent us today through you. You came today to awaken our belief that our coffee farms are not 100% lost to rust: We have defenders, ants that are struggling for us. We are very rude with them, but starting today, we are going to give ants a little bit of freedom; we won’t mess with them, just let them be there.”

DISCUSSION AND CONCLUSIONS

Farmer Field Schools (FFS) and other “farmer to farmer” learning experiences with scientists’ involvement have contributed to strengthening the capacity of legions of rural people to develop and share with others control strategies that seek to promote comprehensive knowledge and adaptive management. Yet, results are mixed, such learning is not easy to evaluate, and many challenges remain (Henk van den Berg: FFS evaluation 2004 report for the Global IPM Facility). The situation described is similar for small-scale coffee farm experiences (Damtie et al. 2011). In Sierra Madre de Chiapas coffee farms, important efforts have been made by researchers to (1) identify the relevant insects and fungus (e.g., Barrera 2008), (2) explore pest versus natural enemy bilateral interactions (e.g., Gómez et al. 2012, Jackson et al. 2012), and (3) describe farmers’ knowledge and develop coffee FFS and participatory biological control programs (e.g., Segura et al. 2004, Jarquín et al. 2006, Barrera 2008). The ongoing rust epidemics are exhibiting processes that invite the actors involved to gain an even broader and shared understanding of the complexity of autonomous pest control, emerging from cascading, multispecies trait-mediated interactions.

The coffee rust pandemic that started in 2012 in the Sierra Madre de Chiapas has been devastating for coffee farmers. Many resorted to heavy use of fungicides during the acute phase and are partially or totally substituting varieties of *Coffea arabica*, which are rust susceptible, high quality, and shade-tolerant, with varieties that are rust resistant but reportedly of lower quality. Some are

Table 5. Frequency of younger and older players who could translate interactions into moves on the board. Younger = 12–40 years old; Older = 41–68 years old.

The player can show on the board:	Type of interaction	% of 25 younger players	% of 25 older players
How an ant captures (scares away) a beetle	Trait-mediated	94	72
How an ant captures (scares away) a wasp	Trait-mediated	90	62
How the fly favors beetles by killing an ant	Predatory	96	40
How a fly's presence deters ants from approaching a beetle	Trait-mediated	65	38

planting the resistant (thus far) species *Coffea canephora* (also known as robusta), well known to be of low quality. Others are waiting for the epidemics to pass and are substituting dead coffee plants with the same or less susceptible *C. arabica* varieties (Valencia, *personal communication*). While short-term responses alleviate the crises generated by the rust epidemic, in the long term it is strategic to pay more attention to complex networks of species that interact with each other and keep pests under control. It is important to convey that autonomous pest management is not a simple recipe or a "magic bullet" but rather a complex, context-dependent process (Lewis et al. 1997, Vandermeer et al. 2014) that can be embraced and explored adaptively through long-term building of a collective agroecological culture among the different actors involved.

Small-scale coffee farmers have sophisticated ecological knowledge about many processes occurring in their farms (Vandermeer and Perfecto 2013, Valencia et al. 2015), but as the literature reports and our preworkshop survey confirms, they know their shade-coffee farms thrive with life but pay little attention to many organisms unless their harm is significant (Segura 2004, Jarquín 2005, 2006, López-del-Toro et al. 2009); they are rarely aware that some pesky organisms (e.g., ants and scales) and their inconspicuous ecological associates indirectly exert potential autonomous control over rust and other coffee pests (Perfecto and Vandermeer 2015). Furthermore, they generally lack a framework for learning about subtle ecological processes that would improve pest control at broad spatial and temporal scales (Rebaudo and Dangles 2015).

In our case, a first small step in providing such a framework to farmers was to explore with them the learning effects of combining (1) a natural history narrative of the Azteca ant network (as a temporal surrogate of long-term field observation and experimentation by farmers themselves), (2) a basic training in acknowledging and analyzing multilevel indirect interactions in network diagrams, and (3) a board game that mobilizes such multilevel interactions and reveals the resulting network's qualitative attractors (i.e., local Azteca network persistence or extinction).

Ecological dynamics are complex and difficult to share (Leiba et al. 2012), more so with people who have no formal training. In the process, we had to learn what works for small-scale coffee farmers and what needs to be further adapted. Most reports on educational games assume that learning has taken place given that these methods and tools are problem-solving oriented, interactive, and motivating, and require players to focus, think, collaborate, and be creative. These claims are frequently consistent with players' self-evaluations (Etienne 2014). Very few studies statistically compare learning methods and/or pre- and post-game specific knowledge (e.g., Cushman-Roisin et al. 2000, Speelman and García-Barrios 2009, Loula et al. 2014).

The first set of workshops revealed an important age group effect on quiz scores, favoring younger players, but only slight and statistically marginal differences between pre- and post-game quizzes. Overall, the average quiz score was significantly lower than the average score of high school urban students (García-Barrios et al. 2016)—and only 20% of participants recalled and/or could graphically represent 60% or more of the direct and indirect interactions. Results suggested that either the learning evaluation tool was not adequate or that forgetting the interactions as presented in the lecture was not prevented by the subsequent activities. We observed that the open-ended quiz "A" for recalling and reconstructing bilateral interactions was prone to different interpretations, and/or it created challenges that not all players could deal with when left alone to work with this tool. We decided to modify, adapt, and expand our evaluation procedures to avoid overwhelming farmers and to probe and better understand their learning.

In the resultant, second set of workshops, quiz "B" addressed explicitly and systematically the interactions to be recalled. Scores improved significantly for both age groups, and the effect of the game and of age group on the player's capacity to retain and understand network interactions became starkly apparent. Regression results suggest that the workshop and game might have countered the difficulty of grasping and retaining level 2 and trait-mediated interactions. Most players did not have trouble distinguishing which bilateral interactions were included in the game, and almost every young player could translate the most relevant trait-mediated level 1 interactions into token moves on the board, while only two-thirds could do so for the trait-mediated level 2 interaction. Older players followed the same pattern but at lower frequencies. After the game, two-thirds of players (both younger and older) were able to elucidate the cascading effects of a population change.

Farmers' comments during reflection sessions confirmed qualitatively that participants learned that potentially beneficial organisms and interactions occur on their farms, and that gaming was enjoyable, motivating, and critical to grasp complex interactions. Many of the farmers concluded that the outcome of these interactions is not unique and not always in favor of rust control, but is context dependent. Most saw that there are feasible actions derived from what was learned (tolerate ants and keep the trees they use to nest, tolerate scales, reduce pesticides, pay more attention to small organisms and their behaviors, etc.). Farmers also gave researchers insights on how they learn; how they sometimes struggle with lectures, gaming rules, and quizzes; how more practice and time could allow them to master the topic; and how field visits would consolidate the learning process. Overall, the effects of learning and evaluation tools displayed in the second set of workshops show that a significant proportion of small-scale coffee farmers were capable of dealing with a complex ecological interaction network, and deriving general lessons, changes in attitudes, and potential actions. The general learning experiences will probably persist in participants' minds, even as the details might fade away. Any actions that farmers might take as a result of this experience are not part of our study's framework, but the literature reports a significant effect of coffee farmer learning on their subsequent actions (Damtie 2011). To better define these actions and their actual pest control capacity, some farmers requested future discussion and work in the field about specific conditions and managements that could foster a significant effect of white halo fungus over coffee rust in their farms. As stated in the Introduction, these are context-dependent, open questions which need—and offer the opportunity for—collaborative on-farm research.

Diniz et al. (2015) report that it is unusual and difficult to involve farmers in multilevel interaction network analyses, and Mani et al. (2013) discusses how financial worries partially impair poor farmer's capacities for such complex cognitive task. Therefore, it is encouraging that younger farmer participants performed very well with the B quiz, and as well as outstanding urban students did in a previous set of workshops using the A quiz (García-Barrios et al. 2016). Azteca workshops need to be further adapted, and complemented with field visits, more so for older participants who struggled with this learning approach.

We are confident that farmers and their allies will become interested in Azteca workshops, both for understanding this specific network but mainly for a better appreciation of the complexity of agroecosytem ecological networks (Benitez et al. 2014, Perfecto and Vandermeer 2015). We expect others to significantly contribute to further adapting these workshops and to incorporating them into broader participatory research and learning experiences in small-scale coffee farmer territories. The kind of abilities Azteca workshops seek to promote in small-scale farmers (observing subtle elements and processes, conceiving and integrating their networked interactions, and mobilizing the latter through game simulations) might be a stepping stone toward even more ambitious goals such as empowered and effective small-scale farmers' participation in multiactor social-ecological analysis and decision-making processes (e.g., Etienne et al. 2011, d'Aquino and Bah 2013, Diniz et al. 2015).

If the knowledge framework gap between ecologists and farmers regarding complex agroecological issues is to be reduced in both directions, farmers' interests and capacities to better understand the ecology of their farms should not be preconceived, overestimated, or underestimated. As researchers, we need to go further in our dialogue with farmers, be sensitive to cultural differences in dealing with complex processes (Strohschneider 2002), and learn how to facilitate learning in ways that empower small-scale coffee farmers, both to understand and take action in their own fields and to allow them to fully participate in both mainstream and critical multiactor deliberations and decisions about complex social-ecological processes that strongly affect them (García-Barrios et al. 2015).

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.php/9184

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Appendix 1.

A graphical manual of Azteca Chess movement and capture rules.

This appendix reproduces images of the Azteca chess manual, which describe rounds, movements and capture rules. The full manual is available on line at http://www.ecosur.mx/academico/wp-content/uploads/sites/8/2016/11/AZTECA-CHESS-RULES-ONLINE.pdf; further enquires can be made to the authors. (luis.garciabarrios@gmail.com).

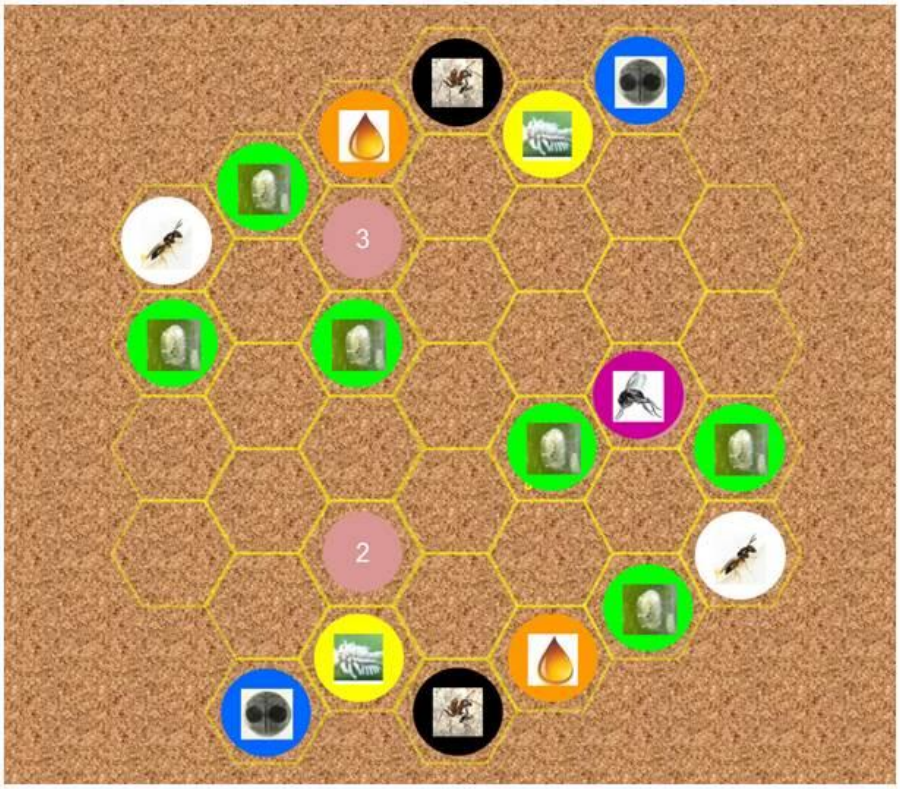
These images were also published previously as figures 2 and 3 in:

García-Barrios L., I.Perfecto and J.Vandermeer. 2016. Azteca Chess: Gamifying a Complex Ecological Process of Autonomous Pest Control in Shade Coffee. *Agriculture, Ecosystems and Environment* 232: 190-198

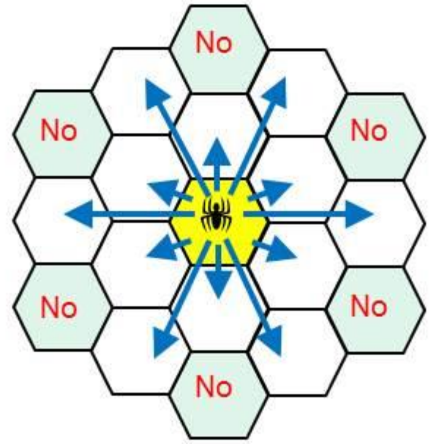
For a brief explanation of other general features and objectives of the game see the methodology section of this paper and, for a detailed description, see the results section of García-Barrios et al. 2016.

Appendix 1. Figure 1. (a) Azteca Chess Board-Game with initial display of tokens. Pink circles are exclusively for the phorid fly to move clockwise at the end of each round. (b) A generic species in a given cell can move to any of the white cells in this diagram. (c) A generic species in a given cell can affect species or consume resources in any of the white cells in this diagram. (d) Tokens and order of moves in a round. The phorid fly is moved systematically and this can be done by any of the two players.

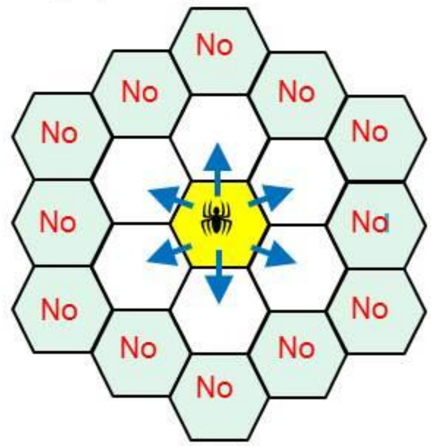
(a) Table Board and initial conditions

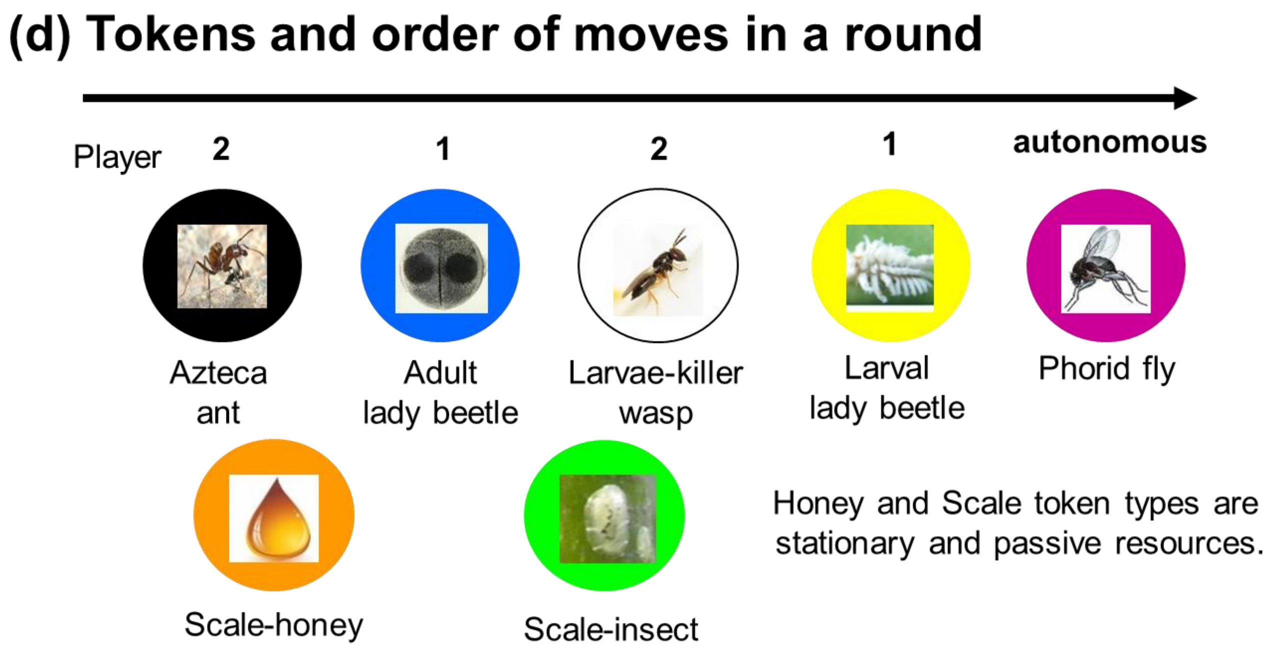


(b) Movements



(c) Captures



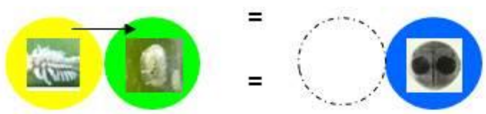


The Azteca Chess hexagonal-cell board stylizes a transversal section of a coffee bush. It exposes the initial spatial display of coffee-scale insects, adult beetles, beetle larvae, larvae-killer wasps, ants and one phorid fly. Honey-dew drops can eventually be traded for additional ants. Neither the two fungi nor the scale-killer wasp are included explicitly in the game. It is a turn-based two-player strategic game. One player decides the moves of the adult and larval beetles; the other those of the ants and wasps. The fly moves autonomously to a new pink cell of the board on each round. Scale insects and honeydew do not move; they are passive tokens to be consumed by the beetles and ants respectively. Player-one´s goal is to have its beetle tokens capture/consume all six scale insects on the board; she strives to drive the dynamics towards the scale extinction attractor (no rust control). Player-two´s goal is to have ant and wasp tokens capture all beetles on the board before they can eat all the scale insects; she strives to attract the dynamics towards a persistent scale colony (potential rust control). Whichever player meets her goal first wins. If both players meet their goals in the same round, the game ends in a draw (all locally extinct; no potential rust control). A draw can also be declared by agreement among players based on time limit (commonly 30 min.) or if more rounds mean an endless pursuit with no winner (i.e. a threshold between attractors).

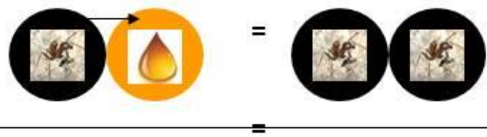
Appendix 1. Figure 2. On its turn, an organism-token can choose to capture another token according to the following rules. In the last two rules, capture is not optional but obligatory.

How tokens capture and affect other

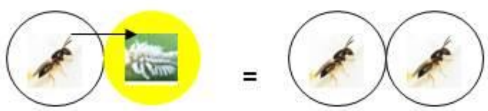
If an adult lady beetle captures a contiguous SCALE, it oviposits and the young larvae eats the scale while the adult flies away. Thus, the adult token is flipped as a LARVA in the scale´s cell.



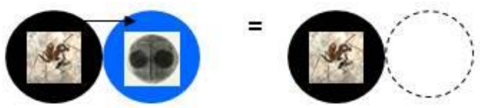
If a larval beetle captures a contiguous SCALE, it eats it and grows to adult. For this purpose the larva token is flipped to set itself as an adult in the scale´s cell.



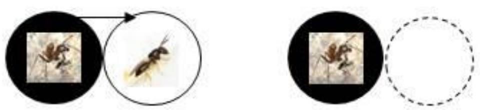
If AZTECA ANT eats contiguous HONEY, the Ant remains on the board, and produces another ANT in the cell where the honey is. The HONEY token is removed from the board.



If WASP eats contiguous LADYBEETLE LARVA, the WASP remains on the board, and produces another WASP in the LARVA´s cell. The LARVA token is removed from the board.



If ADULT LADYBEETLE becomes contiguous to ANT, the ANT – on its turn- MAY chase her off of the board; ANT remains in Its current cell, and the ADULT LADYBEETLE token is removed from the board.



If on its turn any ANT has a WASP contiguous to it MUST use its turn to chase out of the board. Thus, the ant gets distracted from other

At the end of a round, the FLY eats one of any contiguous AZTECAs Then it moves clockwise to the next pink cell before the next round. In this level of the game, the FLY does not reproduce when it eats ANT.

APPENDIX 2.

Thirty five selected farmers´ quotes during post-game collective reflections in the second set of workshops

Lessons from the workshop

We learned new things, played, had fun and now know which insects harm us and which help us. We can now share this with others.

In our coffee farm, there are many insects that help us against rust, but they too have enemies. Like we have many enemies of our coffee: rust, middlemen and pesticides.

When I used to see so many little animal on my coffee bushes, I thought they were all pests, but no: some are protecting and our friends; they struggle with the other that damage coffee.

Value of including the game

Workshops for coffee farmers are very long and very boring; including a game makes a difference.

With the game I understood a bit better, because with words only, I get drowsy (that's the truth; every time I attend a workshop). In the game, as I look at the board and move the tokens, and as I see how the good and the bad animals eat each other, I really get to understand which helps me and which doesn't.

On the wall we only see [powerpoint] figures. But once in the game, it's as if we were seeing it in reality: each animal did his act, defending his life, giving life to others he helps. It benefits our minds because we have to think, we have to analyze what we are about to do; it clears our mind because in our mind everything is so tangled, but once our mind can focus on how we are going to deal with the situation….. so yes, it was great!

I learned by playing. I exercised the knowledge and the mind. I learned what we just saw on the screen or what we see in the coffee farm but to which we pay little attention.

It's different to just see than to practice; by practicing one elaborates more.

When we are practicing through the game it's like being by the coffee bush, deciding what´s convenient and what is not.

Struggling with the game

Learning the game takes time and effort, but slowly my mind clarified.

If you continue to visit and we invite others to play, after two or three tournaments I would learn it much better.

Interaction Awareness

There are so many little animals in our coffee farms that we prefer to ignore them. I had no idea there was a chain and each animal has a function and they compete.

We realized that an insect helps another insect; if it didn't exist, it wouldn't help the whole chain. Every insect needs the help of other.

Apparently it's just a game but through it I learned, for example, that there is interaction between those that harm and those that help us.

The youngest player (12 y.o.) The fly helps the beetle by killing the ant. The fly also helps the beetle by hovering above the ants so that they can't approach; this way of helping the beetle is more difficult to perceive. The beetle is freed from the ant and now has no problem to eat the scales, and without these, the rust can better reproduce. Now, the wasp kills the larva beetle so the rust won't reproduce, but if ants become abundant again, they frighten the wasp and it flees from the coffee bush.

The ant the scale and the wasp are my friends; the mother and daughter beetles my enemies.

When I´m the wasp and I´m about to eat the beetle´s daughter, I think: that's good ! But then she eats, grows into a mother beetle and the token I was going to eat…. is gone! And that makes it fun!

The complexity of controlling scales & rust

We used to think that rust could be eliminated. We now see that there are many animals that defend it and few that help combat it. We learned that Its impossible to eliminate rust.

Researcher: Which outcome do you expect more frequently on a coffee bush: the scale population flourish and rust is somewhat controlled; scale population remains low; scale population is eliminated.

Answers: (1) It depends on what animals are there: if the fly is absent the beetle is busted; it depends. (2) When there are more ants and wasps, scales increase, but ants are in danger also, so sometimes they win and sometimes they lose. Sometimes they are more abundant and sometimes less.

How we learn

L: all I just told you required the field observations and analysis of a team of researchers for many years. Farmer´s remark: If we observe, we can all learn and teach.

At times I did get bored during the workshop, but we learned to protect our plants and not destroy the animals that are there.

We were unaware of what's really going on in our coffee farms; we haven't been curios to see who lives on our plants.

We used to focus on the ant itself, and as such it's bad because it stings us so we destroy them; because we were unaware of all these interactions; the workshop has been very interesting and beneficial.

We don't know the white (halo) fungus much. I think we should now go to the coffee fields so that we can get to know them very well, because for me this course is something new, and although we have been in our fields we don't know them, we don't see them; its like we had abandoned them. But through this workshop and activities we will start paying attention to them, and knowing them.

I was telling others that It would have been good to organize ourselves to go to the coffee farms to see exactly which animal is which, because we had some confusion with the beetle larva and a caterpillar called "little chick".

What really made me think was when you asked me questions during the individual quiz.

Both the game and the knowledge you shared is very good, but we really need more time to meet. [Researcher: how should we give it more time?] Well, actually for me what I learned today was enough, because I wouldn't just leave it at that: I would go home and recall the chain [network] and make it more understandable to myself, in my own way, however I can; practice it. Now what I still want to understand is how I need to manage my coffee so that the harmful animals do not exist; that´s something that wasn't clear: we saw the relation between all those insects but we did not discuss how we can avoid rust. I understand that if there is rust, all those insects will show up, and if not, they won't; that relation will not exist.

Action from knowing

Thanks to this game we now know which little animals help us and which do not. Before, I used to take scales off my coffee bushes. Now I´ll better take care of them so that they will get rid of rust.

Through the game we can learn how to combat rust; it's difficult but with effort we can. Effort means not applying so many chemicals so that the insects that help us won´t run away.

What we need to learn is how to produce more coffee-scales

These little coffee scales do their work to finish the rust problem; but they too have their enemies. Let's not bring down the ants´ trees: there can be an alternative against the rust.

We just have to let all these animals go on with their lifes; with chemicals we destroy them all, good and bad. We only have to make sure the plant grows properly and let these little animals combat each other.

In our mind and in yours, we are extremely aggressive with ants and with all animals. If a little snaked crawled in just now, we would jump for a stick to kill its head. You on the contrary as biologists are really good friends of animals, you let snakes and spiders and cockroaches go on with their life. We are very aggressive with animals, but today we are learning about them, and I will take to my family the message that dear God sent us today through you. You came today to awaken our belief that our coffee farms are not 100% lost: We have defenders, ants that are struggling for us. We are very rude with them, but starting today, we are going to give ants a little bit of freedom; we won't mess with them, just let them be there.

I think I'm going to stop using pesticides; if I want to leave anything good for my children for the future, I'm the one who has to start.