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Azteca chess: Gamifying a complex ecological process of autonomous pest control in shade coffee

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ABSTRACT

Science-based board games can help people grasp the ecological complexity of autonomous pest control (APC) in the shade-coffee agroecosystem. Azteca Chess is a board-game that captures in a stylized way the fascinating natural history and the dynamics of a complex network of direct, indirect and cascading trait-mediated interactions among five species of arthropods dwelling in shade coffee bushes (a coffee-scale, an ant, an adult and larval lady beetle, a parasitoid wasp and a parasitoid fly). In exchange for honey-dew, the Azteca ant protects scale-insects that help control the devastating coffee-rust disease. The ant repels the adult ladybeetle but inadvertently protects its larvae, which devour scales to local extinction. The head-hunting fly paralyzes Azteca and opens a window of opportunity for the adult beetle to oviposit under scales, but also for a parasitoid wasp to kill the beetle larvae. Interactions can cascade or not towards APC. Experimental test-driving shows Azteca Chess meets good modeling and game-design standards and is proved statistically to enhance understanding and application of relevant complex ecological processes.

1. Introduction

Capturing the inherent complexity of ecological systems has long been a perplexing problem for pedagogy. Massive networks of interactions, so commonly displayed in nature centers and power point presentations, do not really convey what most professional ecologists understand about ecological complexity. The reality is that ecology is complex and therefore is difficult to teach, learn and apply (Leiba et al., 2012; Proctor and Larson 2005). This is more so when those that are supposed to use the knowledge to solve practical problem, have not been trained in the formal science of ecology, which is the case of most stakeholders involved in natural resource management, including the millions of farmers in the world. "Preaching" to local impoverished farmers about the "ecological services" provided by the local nature preserve is not, in our experience, effective.

One pedagogical tradition that has seen many science classroom applications is gaming (e.g. Honey and Hilton, 2011; Stevenson et al., 2014), where students play either board or computer games designed to represent various natural phenomena, most frequently physical principles or human behavior (e.g., classical economics). We propose that such an approach could be useful in an extension outside of the classroom also, especially with the purpose of teaching an appreciation of some basic principles of ecological complexity with very practical consequences for shade-coffee and other agroecosystem management involved. Indeed, board-games have recently emerged as participatory education tools that facilitate communication and reflection among those involve in resource management, and promote a common knowledge ground from where to build effective management and governance (Sandker et al., 2010; Etienne, 2014; García-Barrios et al., 2015). To this end we have taken a particular ecological system with which we are intimately familiar (Perfecto and Vandermeer, 2015), developed a set of rules that capture the central essence of the interactions involved, and cast it as a two-person board game called "Azteca Chess." We here report on the game itself and on the results of test-drive "tournaments" we have organized in Mexico.

Shade-coffee grown by Mesoamerican farmers in tropical mountains has been claimed as an archetypical example of a complex ecosystem capable of sustaining a significant proportion of the local biodiversity (Perfecto and Vandermeer, 2015). Unfortunately, the farmers who construct and manage these

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systems are riddled with livelihood problems, most recently due to the coffee rust epidemic (*Hemileia vastatrix*) (Vandermeer et al., 2014; McCook and Vandermeer, 2015). Such dramatic moments are perhaps not as rare as thought when considering a longer time frame and more extensive area (e.g., only a few years earlier, it was the coffee berry borer that created the drama and the coffee leaf miner, a trivial problem in Mexico, is currently a major problem in Puerto Rico). There is, of course, an important message here – populations of agriculturally relevant organisms in general explode to pest levels only occasionally. This is due, at least in part, to the emergence of self-organized (and therefore autonomous) networks of organisms, including natural enemies of the pests, that are interacting directly and indirectly resulting in oscillating populations that are kept within certain bounds (e.g. autonomous pest control; APC). Small-scale coffee farmers have sophisticated ecological knowledge of many processes occurring in their farms (Valencia et al., 2015) but are rarely aware of the subtle yet critical interactions among the smaller inconspicuous organisms that contribute to APC (Perfecto and Vandermeer, 2015).

Over the past twenty years various research teams have combined to provide an appreciation of the complex ecology of neotropical shade coffee (Perfecto et al., 1996; Greenberg et al., 1997; Perfecto and Vandermeer, 2008, 2015; Philpott et al., 2009; Vandermeer et al., 2010; Karp and Daily, 2014; Perfecto et al., 2014). In southern Mexico, where many of the studies have been conducted, they have unraveled the fascinating natural history and the qualitative dynamics of a self-organized network of at least 21 interacting species of fungi, ants, beetles, parasitoid wasps and parasitoid flies capable of exerting autonomous pest control over coffee-berry borers (*Hypothenemus hampei*), leaf miners (*Leucoptera coffeella*), scale insects (*Coccus viridis*) and rust fungus (Vandermeer et al., 2010; Perfecto and Vandermeer, 2015). Our two-player strategic board-game, Azteca Chess, deals with a keystone subset of this community involving a scale insect pest and a fungal rust disease and the purported autonomous pest control (APC) therein (Fig. 1). A full accounting of the system is found elsewhere (Vandermeer et al., 2010; Perfecto and Vandermeer, 2015), and Supplementary Online Materials (Appendix A in Supplementary materials) presents a synthesis.

The APC in this system emerges from direct and indirect interactions and from the cascading effects of the mere presence and behaviors of some species (trait-mediated interactions). The following is a list of those interactions shown in Fig. 1 and how they contribute (or not) to APC:

In shade coffee plantations, high-density colonies of the green coffee scale (*Coccus viridis*) – a minute sessile insect – are found sucking the sap out of twigs, leaf and fruits of a few coffee bushes. Why? Swarms of the tree-nesting ant *Azteca sericeasur* (Azteca hereafter) actively patrol these bushes tending the scale insects. This is a typical ant-hemipteran mutualism where the ant protect the scales by harassing and chasing away scale parasitoids and predators, in exchange for energy-rich honeydew that the scale insects extrudes. High-density scale colonies harbor its "predator" the white halo fungus (*Lecanicillium lecanii*), an entomopathogen known to also attack other fungi. *Lecanicillium* proliferates on these scale colonies, which provides spores that disperse from these nuclei to attack the coffee rust. The scale helps exert prevention and partial control on rust at the farm level.

The lady beetle, *Azya orbiguera* is a major predator on the scale. *Azteca* harasses the adults and sometimes kills them. However, the beetle larvae are protected from ant predation by abundant waxy filaments that cover their soft bodies and deter the ants from biting them. Furthermore, *Azteca,* by chasing away all the parasitoids that come close to the general area where the scales are located,

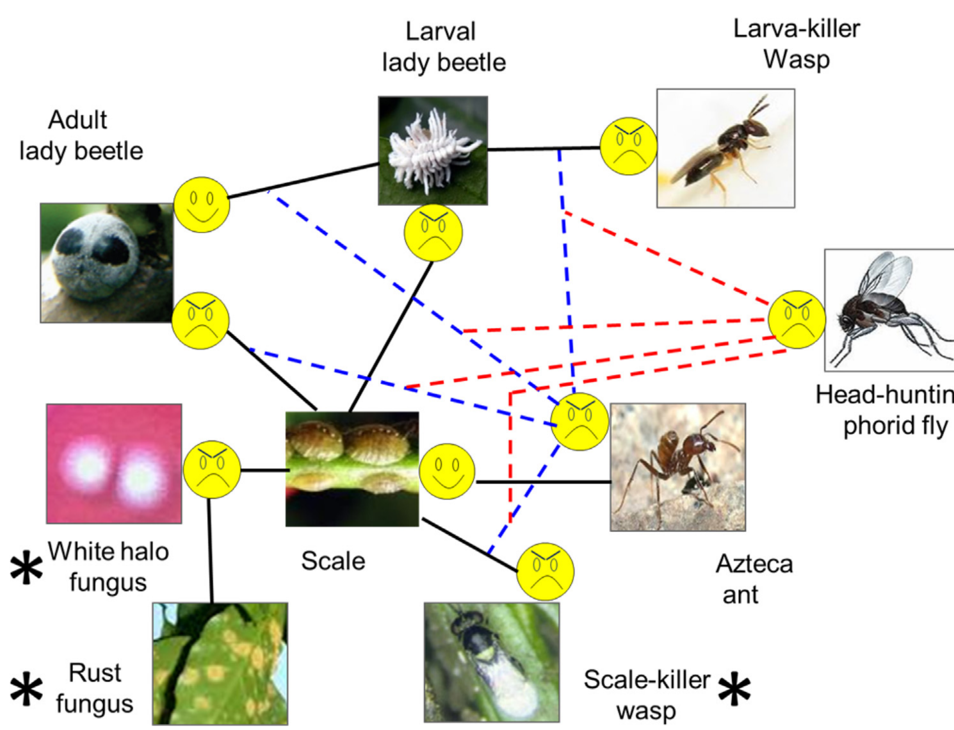

Fig. 1. Each organism projects an action (face) through a line directed towards another organism(s) or interaction(s) which it affects. An angry face signifies harm and a happy face benefit. Solid lines mean predation or parasitism (eating the prey or laying eggs that will hatch and eat the prey). For example: the larval lady beetle projects a harmful face towards its prey, the scale. Trait-mediated interactions are represented by dashed lines. The capacity of the ant to change the behavior of predators is represented by dashed blue lines projected upon predation interactions. The capacity of the fly to change the behavior of the ant is represented by dashed red lines. Happy faces in the figure 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. (Figure modified after Fig. 5.14 in Perfecto and Vandermeer, 2015. In the latter, standard ecological symbols (dot and arrow) are used to denote consumer-resource relations. Species marked with an asterisk are included in workshop lectures but not in the game.). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

inadvertently protects the beetle larvae from their own parasitoid wasps (e.g. *Homalotypus spp*). Gravid female beetles instinctively seek ant/scale clusters and oviposit underneath scale insects. How do they manage to breach the ant line of defense which will later protect their larvae? Through the behavioral interaction of *Azteca* and its own parasitoid, the phorid fly, *Pseudacteon lascinosus*. The fly can detect an ant swarm but needs ant movement to be able to locate an individual ant to oviposit. The ant swarm reacts to the hovering fly by becoming motionless. This provides beetles with a short window of opportunity to approach the scale insects and hide their eggs under them.

Thus we see in this sub-network consumptive (and therefore density dependent) interactions that can be both direct (e.g. beetle larvae consume scale-insects) and indirect (e.g. parasitoid wasp reduces consumption of scale insects by consuming its predator, the beetle larvae). But there are other interactions – more subtle, non-consumptive and not strictly density dependent- known as trait-dependent indirect interactions. In the latter, the mere presence and (nonconsumptive) behavior of a third species modifies the intensity and efficiency of the interaction among two other species (Railsback and Harvey, 2012; Trussell et al., 2003; Perfecto and Vandermeer, 2015)

A first set of trait-mediated indirect interactions (TMII) results when the ant's presence and its (non-predatory) behavior interferes with the ability of the female beetles to oviposit under the scales and the parasitoid wasps to parasitize the beetle larvae. The effects of these TMIIs on scale and beetle populations can be reverted by the second set of TMIIs derived from the phorid fly's effect on the ant.

If *Azteca* is effective in protecting scales from beetle oviposition (but not as effective against the larvae-killing wasp), ant-scale clusters might locally persist longer, white halo fungus nuclei will thrive and better control rust, and beetles will exert less control over scales at the farm level. If *Azteca* is not effective enough because of frequent presence of the fly, and the beetle takes more advantage of this than its wasp parasitoid, the opposite might hold true. Thus, the net autonomous pest control effect of these cascading TMIIs could be neutral under some conditions or strongly positive or negative under others. In short, the *Azteca* sub-network – and an educational board game that can capture its cascading TMIIs – can be an excellent way to convey the fact that autonomous pest control is not a simple recipe nor magic bullet but rather a quite complex, context dependent possibility that can be embraced and navigated adaptively through long term building of a collective agro-ecological culture among the different human actors involved.

The objectives of this paper are: (1) to present Azteca Chess as an effort to stylize, model and gamify cascading TMIIs for educational purposes, (2) report on test-drive evaluations of playability and basic learning effects, and (3) demonstrate the potential of using gaming as a novel tool to better communicate the concept of ecological complexity to students, farmers and other resource managers and policy makers.

2. Game design and workshop methods

TMIIs can be conveyed to others by hands-on processes where learners embody the interacting organisms and experience the consequences of their behaviors. Yet, modeling and gamifying TMIIs is uncommon and not easy (e.g. Railsback and Harvey, 2012; Loula et al., 2014). Bringing together all the elements and requirements of a complex scientific board-game is a long, arduous, nonlinear tinkering process of trial and error (Speelman and García-Barrios, 2009; García-Barrios et al., 2015; Meza-Jiménez and García-Barrios, 2015; Chiarello and Castellano 2016). It emerges more out of messy vitality than of ordered recipes. Nevertheless, it needs guiding principles. Based on our understanding of the ecological system and our educational objectives we decided that the Azteca Chess game/model should:

(a) Represent *Azteca* network processes occurring at the individual coffee bush level, where farm-level effects originate.
(b) Increase awareness that a diversity of frequently inconspicuous but relevant small organisms actively interact directly and indirectly at this level
(c) Highlight and increase awareness of trait mediated interactions by making users embody the insects on the board, experience their needs and hardships, and discover the individual and cascading consequences of their (stylized) behavioral choices (search and approximate a prey; eat and reproduce; harass and expel; respond to the current or eventual proximity of an enemy; succumb to a predator or harasser).
(d) Allow for, and focus on, three qualitative outcomes, as example of the multi-attractor nature of the network's dynamics at the coffee bush-level (beetles consume all scales and the *Azteca*/scale association is locally dissolved; beetles and *Azteca*/scales coexist locally; beetles are locally excluded).
(e) Be attractive, playable and educational for a wide range of users (a diversity of genders, ages, cultures, relations with farming activity, incomes, power, academic education, etc.). This required making the previous points compatible with the

Table 1
Game evaluation by 20 teenagers interested in science.

Have you played chess?	no 6	ocassionally 11	frequently 3
I found the game rules	very difficult to keep in mind 0	a bit difficult to keep in mind 11	not difficult to keep in mind 9
The length of a game session is	too long 3	adequate 15	too short 2
The turns move at a proper pace	never 0	sometimes 7	most of the time 13
(Flow) The game is	too easy 1	an interesting challenge 19	too difficult 0
The game is entertaining	not much 0	acceptably 11	very 9
I feel the game is biased towards	the beetle 2	none 13	the ant/wasp 5
Actual outcome of 22 game sessions	the beetle won 7	ended in a draw 8 (mostly time limit)	azteca/wasp won 7
Knowing I would play a game was important to motivate me to pay attention to the introductory lecture on the Azteca ant network.	not much 3	somewhat 9	very much 8
Was a game necessary to understand the powerpoint lecture?	No 0	It helped understand the lecture 16	I only understood till I played the game 4
Did the workshop as a whole (lecture, game explanation, playing the game twice) allow me to understand the network of interactions?	Very little 0	More or less 4	Very much 16

principles of successful strategy-board-game design (Adams and Dormans, 2012; Pulsipher, 2012): clear goal and rules; trajectories and challenges not prescribed but emerging; balance among potential outcomes; possible trajectory change during all or most of the game to avoid early dominance; minimum use of randomness; entertainment; flow (not too hard and not too easy for the average player); immersion and engagement; simple and swift mechanics; minimum or no need for calculations and number tracking; adequate board geometry and size; board and tokens attractive and easy to manipulate; appropriate duration of turns, of rounds and of the whole game; appropriate number of players.

(f) Allow for evaluation of the most basic learning skills (retention, understanding, application; Anderson et al., 2001).

In two workshops a total of 44 highschool students were first exposed to a lecture where the natural history and the Azteca network was constructed step by step and slowly explained through a very graphical power point presentation. Immediately after they were asked without previous notice to answer two graphical quizzes (quiz A in seven minutes; quiz B in three). The same procedure was repeated after the gaming sessions (approximately 3 h after having heard and seen the lecture). For the game, player roles and goals were defined and movement and capture rules were explained and practiced step by step with an auxiliary power point presentation. Participants played three game sessions. After the games, students answer in written form a few questions (see Table 1) and held with them a 20 min reflection session. Appendix B in Supplementary materials describes in detail these Azteca Chess workshops and evaluation methodologies.

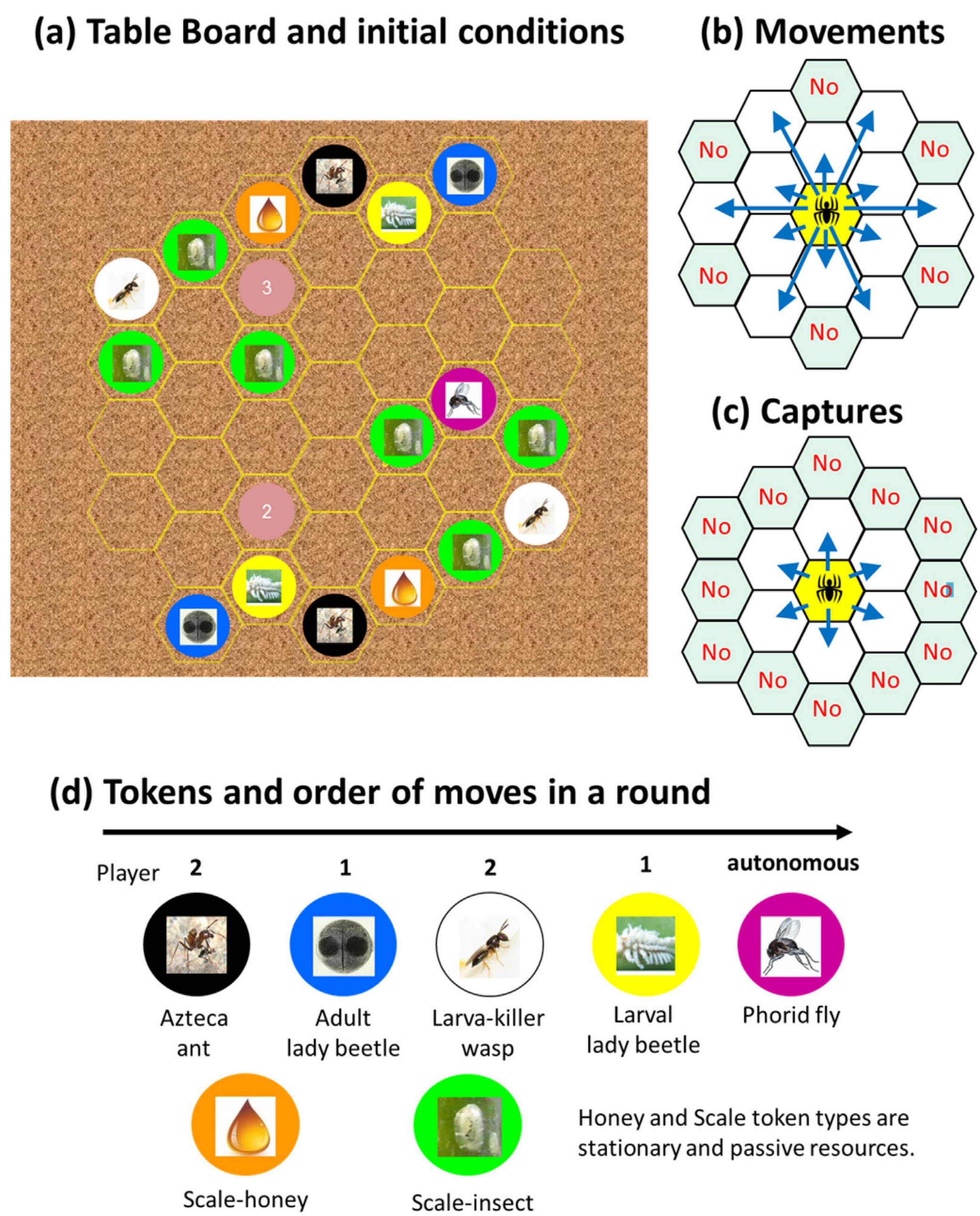

Fig. 2. (a) Azteca Chess Board-Game with initial display of tokens. Pink circles are exclusively for the phorid fly to move clockwise in each round. (b) A generic species in a given cell can move to any of the white cells in this diagram. (c) A generic species in a given cell can affect species or consume resources in any of the white cells in this diagram.

3. Results

3.1. The Azteca game

The Azteca Chess board game is a 39-hexagonal-cell surface representing in a quite abstract form a mid-height transversal section of a coffee bush. It exposes the initial spatial display and numbers of organisms: six scale insects, two adult beetles, two beetle larvae, two wasps (that parasitize beetle larvae), two ants and one phorid fly. Two honey-dew drops on the board can eventually be traded for two additional ants. Note that neither the two fungi nor the parasitoid wasp of the scale are included in the game. Initial token number and positions were carefully selected to avoid imbalance and dominance by design (Fig. 2a).

Azteca Chess is a two player game, played by turns with unlimited (but reasonable) time per player/move. The first or "lady beetle" player (P1) decides the moves of the adult and larval beetles. The second or "anti-lady beetle" player (P2) decides the moves of the ants and the wasps. The fly belongs to no one; it moves autonomously to a new section 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. Having each player deal with two token types that can both cooperate and interfere with each other results in a more interesting game and can produce more awareness of the complexity of the network's dynamics.

The first player's goal is to have its beetle tokens consume all six scale insects; the second player's goal is to have its ant & wasp tokens eliminate from the board all beetles before they can eat all the scale insects. Whichever player meets her goal first wins. If both players meet their goals in the same round, the game ends in a draw. 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.

In a round the sequence of game-play is: ant (player 2) – adult beetle (player 1) – wasp (player 2) – larval beetle (player 1) – fly (moved by any player to a predetermined cell). The organism in turn makes one move with one of its available tokens (e.g. player 1 moves one of her two adult beetles). A player cannot "pass" on her turn unless there are currently no pieces on the board for that type of token. Captured tokens leave the board. Movement and capture rules are shown in Fig. 2b and c, and the consequences of token captures are shown in Fig. 3. The way we have stylized the natural history of bilateral interactions between arthropods and translated them into capture rules is presented in more detail in Appendix C in Supplementary materials.

Note that the player's opportunity to make context-dependent decisions on each token's turn reflects to a certain extent the fact that the arthropods she impersonates are not automata but complex organisms capable of choosing among a suite of possible behaviors, sometimes successfully and sometimes not.

3.2. Coupling of bilateral interactions through trait-mediated indirect effects; cascades as emergent properties in Azteca Chess

A typical Azteca Chess game can follow many different specific trajectories towards one of its three general outcomes, and all trajectories exhibit frequent trait-mediated cascading episodes. Playing the game is the best and only way to get a full sense of the possibilities. Here we present an example to illustrate these attributes of the game that emerge from its spatial structure and coupling of its capture rules.

Fig. 4a and b shows how Azteca Chess captures the ability of the lady beetle to use to its advantage the ant's non-predatory but aggressive behavior against intruders. The beetle's consumption of scales secures a life cycle (the larva-adult token-swapping cycles in the game) that allows it to escape harm from both the ant's trait-mediated effect and the wasp's predatory effect: by capturing a scale, the adult beetle can prevent imminent capture by the ant, and the larval beetle can prevent imminent capture by the wasp. Fig. 4c and d shows however that when both ant and wasp are protecting the same scale, the magic of beetle swapping is broken,

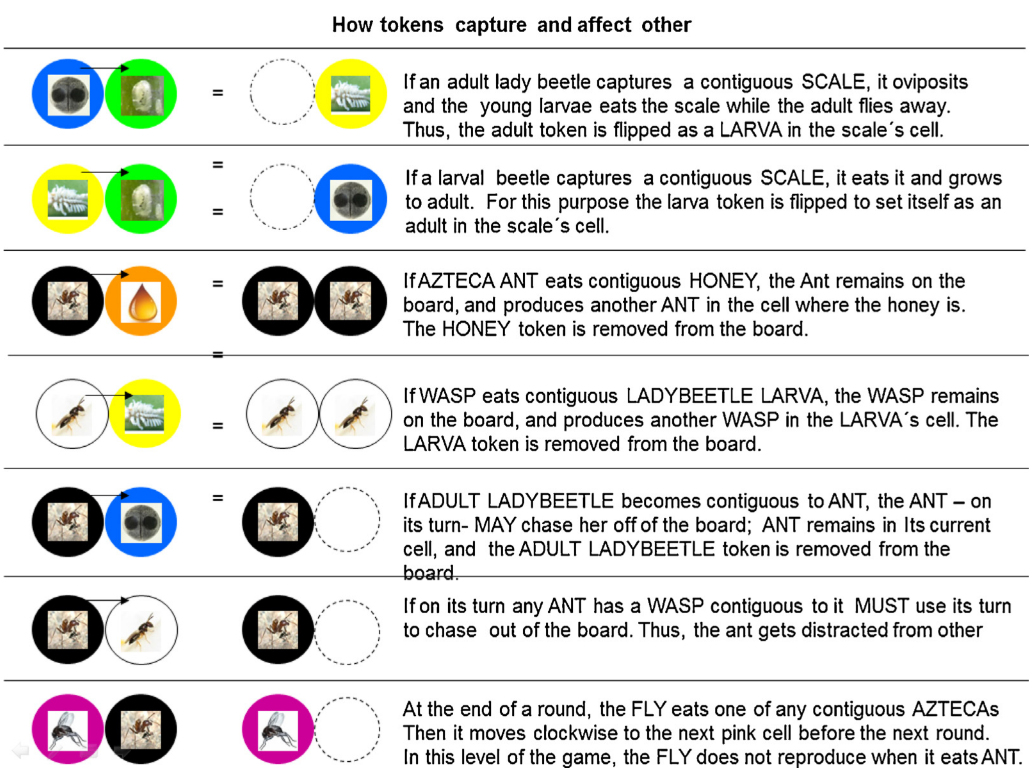

Fig. 3. Each row in the figure shows the consequences of a token capture by another token.The text to the right explains the graphical equations to the left.

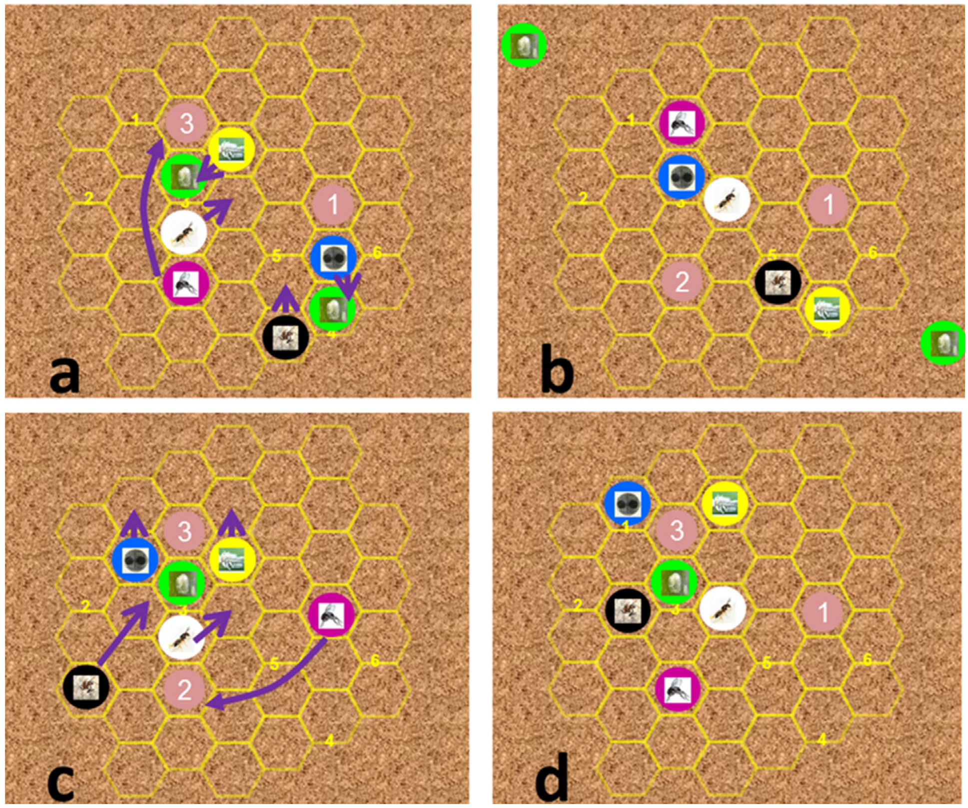

Fig. 4. Examples of two rounds with contrasting outcomes for beetles. In a (and b, its outcome) the beetles escape capture by eating scales and swapping to the next life-stage; in c (and d its outcome) scales are protected so beetles escape capture by fleeing. The sequence of turns in a round is ant-adult beetle-wasp-larval beetle-fly. Arrows denote the best or the only possible move. (a) Azteca approximates adult beetle; adult beetle could flee but still has the opportunity to oviposit under scale, swap for a larva and become immune to ant; wasp approximates larva beetle; larva beetle could flee but still has the opportunity to feed and grow to adult stage, becoming inmmune to wasp; fly heads toward position 3. (b) The ant approximates both adult beetle and wasp; the adult beetle could swap for a larval beetle by eating the scale but fears the wasp would immediately capture its daughter, so it chooses to flee; the wasp can still flee from the ant and approximate the larval beetle; the larval beetle could flee the wasp or eat the scale and swap to adult, but then it would be immediately captured in the next round by the ant; the fly heads towards position 2.

unless the wasp and ant get too near each other and their resulting behavioral interactions break the shield they had jointly constructed around the scale. Thus, the ant-wasp trait mediated interaction can trigger effects in two opposite directions: weakening or strengthening scale protection.

The ant's trait-mediated response to the vicinity of the fly is not captured in Azteca Chess by freezing the ant token during a turn, but the cascading consequences of the mere presence of the fly on the ant's activity are well captured. In Fig. 5, the network is poised in configurations that in the next round will cascade through trait mediated interactions to define the fate of the game and therefore of the local ant-scale association on a specific bush. In Fig. 5a (and 5b, its outcome), the fly is not present so in this round both adult and larval beetle are eliminated. In Fig. 5c (and 5d, its outcome), we have the same configuration at the beginning of the round, but with the fly present- the trait-mediated interaction cascades in the opposite direction and the scales are eliminated. In this latter case, the presence and behavior of the fly cascades by interfering with the trait-mediated effect of the ant against the beetle's effect on the scale.

3.3. Playability and basic learning

Between 2014 and 2015 we organized a couple of Azteca Chess workshops/tournaments with 22 teenager Chess players and 20 outstanding high school students respectively Twenty one of the 22 teenage Chess players considered the game flows appropriately because it poses an interesting challenge, and found it acceptably (9) to very entertaining (13). Half sensed a bias towards the dynamic attractor "beetles are excluded and *Azteca*/scale prevails". In 29 games played by them the beetle won 12 times and *Azteca*/wasp won 17, indicating that the potential bias is much lower than believed. Avoiding such bias as much as possible is a crucial matter for this game. A few weeks later, a young but seasoned board and computer game aficionado shared us an important insight. "If the beetles (larvae or adults) are overly defensive and are never or rarely willing to capture a scale at the cost of themselves being captured, they will lose the game." In the second test-drive workshop teenagers interested in science who played the beetle were instructed to avoid being overly defensive. Their perception of bias was less frequent and the actual outcome of 29 games was unbiased (Table 1).

Teenagers interested in science were much less familiar with chess, and they found the *Azteca* Chess rules to be either not difficult or sometimes a bit difficult to remember. This second group of players found the duration of turns and game to be mostly adequate, and the great majority of them found the game acceptably or very entertaining. Anticipation of a game motivated them to pay more attention to the lecture and helped them understand it. However, some only grasped the message of the lecture during the game (Table 1). The workshop as a whole helped them understand that there are a diversity of small organisms that interact in an elaborate network in coffee bushes and that these organism influence pest outbreaks in a complex way.

Table 2 shows the results of the retention quiz done by adolescents interested in science. In the pre-game test, the average player recalled equally subsets of interactions included and excluded in the game. In the post-game quiz, they scored

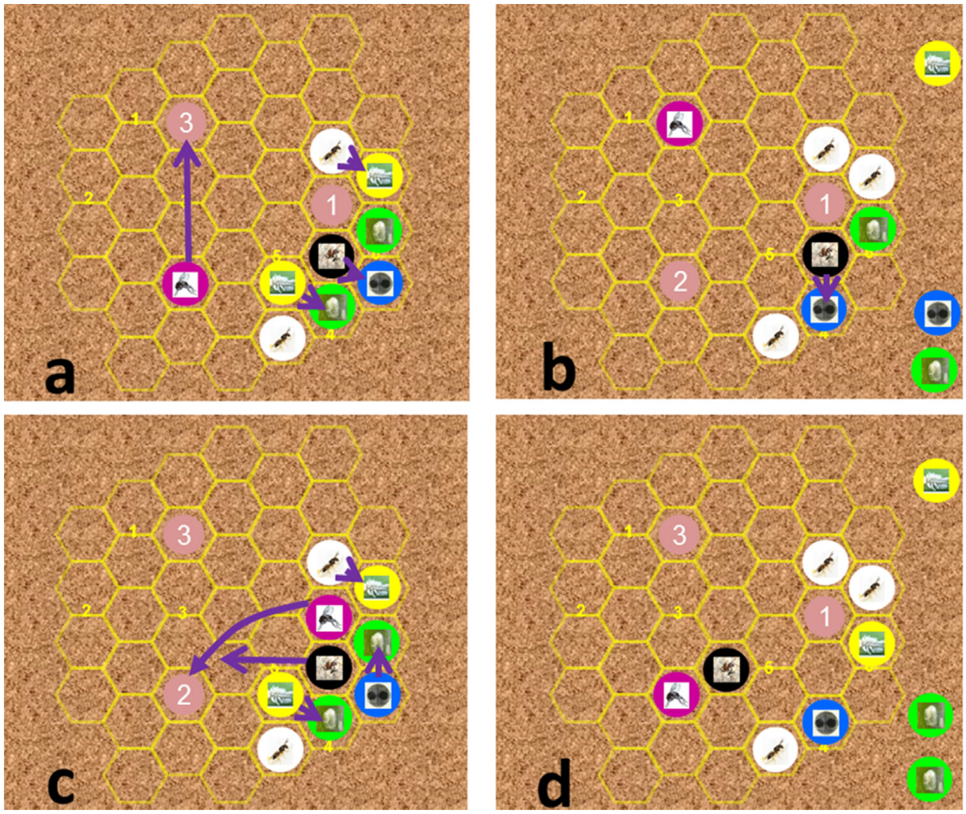

Fig. 5. Examples of two rounds with contrasting game outcomes. In a (and b, its outcome) the fly is absent and Azteca's TMII effect creates conditions for the beetle to lose in the next round. In c (and d, its outcome) the same round-condition but with presence of the fly produces TMII effects that revert the previous scenario and the beetle wins. The sequence of turns in a round is ant-adult beetle-wasp-larval beetle-fly. Arrows denote the best or the only possible move. (a). The ant expels the adult beetle from the coffee bush; the adult beetle turn is void; the wasp eliminates the larval beetle and reproduces; a second larval beetle feeds on a scale and grows to adult; the fly heads towards position 3.] (b) Outcome of described round: two beetles and a scale have been eliminated; at the beginning of the next round the ant expels the last beetle from the board and wins. (c) The ant perceives the contiguity of the fly and must 'stand still' by seeking a safe position, giving up other possible moves like staying put and expelling the adult lady beetle or approximating the upper wasp; the adult lady beetle captures the scale and swaps to larval beetle; the upper wasp captures de upper larval lady beetle and reproduces; the lower larval lady beetle captures the last scale and grows to adult; the fly heads towards position 2. (d) Outcome: all scales have been eliminated and the beetle wins the game.

Table 2
Pre and post-game retention and understanding of a subset of direct and indirect bilateral interactions in the *Azteca* network. The relative score registers the proportion of such interactions the player recalled and reconstructed by connecting species in SOM Panel 3; Fig. S1. The score is relative, to allow for the "In the game" vs "not in the game" comparisons.

Group of studied bilateral interactions	Performance retaining information. BEFORE playing Azteca Chess	Performance retaining information. AFTER playing Azteca Chess
Six bilateral interactions IN THE LECTURE BUT NOT IN THE GAME.	Average student relative score for these six interactions = 0.65	Average student relative score for these six interactions = 0.74 Before-after pair-wise T test $p > 0.05$ Not Sig.
Nine bilateral interactions IN THE LECTURE AND IN THE GAME	Average student relative score for these nine interactions = 0.69	Average student relative score for these nine interactions = 0.86 Before-after pair-wise T test $p < 0.02$ Sig.
	IN vs. NOT IN THE GAME comparison; General linear model test $p > 0.05$ Not Sig.	IN vs. NOT IN THE GAME comparison; General linear model test $p < 0.05$ Sig.

significantly better than in the pre-game quiz for interactions included in the game but not for those excluded. This suggests that playing the game twice after the lecture improved *ceteris paribus* mid-term retention of bilateral interactions.

Retaining direct interactions between the scale and its predators did not differ between the pre and post-game for organisms both included and not included in the game. Yet performance increased significantly after playing the game when applying knowledge of direct and indirect (predatory and trait-mediated) interactions to elucidate cascading effects on the scale insect (Table 3).

4. Discussion and conclusions

In this study we described the development of the board game, Azteca Chess, based on known complex ecological interactions that occur in coffee farms in Mexico and that influence pest control. The objective of the game is to facilitate communication and

Table 3
Pre and post-game performance while retaining direct bilateral interactions with the scale insect and applying them to elucidate indirect interactions with the latter. The absolute score registers the average player's correct answers in each section of SOM Panel 3; Fig. S2.

Group of studied organisms related to the scale insect	Performance retaining and applying information. BEFORE playing Azteca Chess	Performance retaining and applying information. AFTER playing Azteca Chess
DIRECT effects of white halo fungus and parasitoid wasp of scale on scale insect. (IN THE LECTURE BUT NOT IN THE GAME)	Average student absolute score for these two questions = 1.75	Average student absolute score for these two questions = 1.65 Before-after pair-wise T test p = 0.43 Not Sig.
DIRECT effects of larval and adult beetle on the scale insect (IN THE LECTURE AND IN THE GAME)	Average student absolute score for these two questions = 1.90	Average student absolute score for these two questions = 1.90 Before-after pair-wise T test p = 1.00 Not Sig.
INDIRECT (predatory or trait mediated) effects of the parasitoid wasp of beetle, of the ant and of the fly on the scale insect. (IN THE LECTURE AND IN THE GAME)	Average student absolute score for these three questions = 2.00	Average student absolute score for these three questions = 2.75 Before-after pair-wise T test p = 0.002 Sig.

understanding of the concept of ecological complexity and how it can influences management outcomes in agricultural systems. We use Azteca Chess as an example of a novel educational and management tool that can potentially make farmers and other natural resources managers aware of the complexities of nature. In the specific case of Azteca Chess, workshops structured around the game are aimed at helping farmers and other resource managers co-construct a set of specific messages and experiences: (a) both pest control and pest outbreaks can emerge in shade-coffee plantations; (b) many inconspicuous organisms live on coffee bushes and interact in complex ways that create or affect such outcomes; (c) some organisms affect relevant predatory interactions by their mere presence and behavior which adds to the complexity; (d) while some organisms affect others directly, discovering more subtle and indirect effects among them (and on pest outbreaks) requires careful network thinking (and games can make this easier); (e) ant/scale symbiosis at the bush level is important for scale and rust autonomous pest control; (f) ant-scale-beetle-wasp-fly direct and indirect interactions can cascade to produce two qualitative outcomes at the bush level: local persistence or dissolution of ant/scale symbiosis; (g) similar APC process must occur in other biodiverse agroecosystems.

Our workshops combined a lecture, pre and post-game quizzes, game explanation, game-play and debriefing/reflection. In our pre-game lecture, the fascinating natural history amazes and amuses all listeners; they easily understand each bilateral interaction but struggle to assimilate its full structure and consequences. Quizzes evaluate certain forms of learning and, interestingly, have been found to reduce the steepness and final level of the forgetting curve (Roediger and Karpicke, 2006). Explaining the many rules of the game without losing player's attention and assimilation has been successful but sometimes challenging and shows the game is at the limit of rule complexity. Like the few scientific board-games dealing with complex processes (Loula 2014, Chiarello and Castellano, 2016), Azteca Chess was designed and tinkered trying to reconcile the need to convey relevant scientific messages, to stylize and gamify the network's dynamics and to elicit learning in players. Major design concerns were striking a balance between possible outcomes, keeping rules and mechanics as simple as possible, and creating engagement and entertainment. Through two pilot workshops with high school urban teenagers from Mexico, we found out that these players consider that the game meets these goals. We still expect that in the future some players might suggest changes that could improve the game.

Most reports on educational games assume that learning has taken place given that these methods and tools are problem-solving oriented, interactive, 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 compare statistically between learning methods and/or pre-post game specific knowledge (e.g. Cushman-Roisin et al., 2000; Speelman and García-Barrios, 2009; Loula et al., 2014). In Azteca Chess workshops, the learning effects of a lecture and pre-game quiz might have left little space for further improvement of retention, understanding and comprehension among scientifically inclined teenagers; yet such improvements were statistically significant, more so those related with indirect, trait-mediated interaction. Collective discussion with Azteca Chess workshop participants exposed and fostered other dimensions of learning; teenagers considered the workshop an eye-opener to ecological research as a fascinating intellectual and social endeavor.

We are currently developing Azteca Chess workshops with different groups of Mesoamerican coffee farmers and adapting, with their participation, the way lectures, quizzes and rules are delivered to them. We have developed and are test-driving game level 2 which stylizes and incorporates the highly non-linear effects of interaction between the scale, the white halo fungus and the coffee rust, following Vandermeer et al. (2014). We welcome the readership of AGEE and the (agro) ecology community to contact us, use the Azteca Chess worskshop and game, and contribute to their further development. To get Azteca Chess workshop manuals and playing kits (with 2D chips or 3D wood-carved tokens) contact the first author at

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2016.08.014.

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