Exploring How Knowledge and Communication Influence Natural Resources Management With REHAB

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Abstract

Background and Aim. It is often assumed in **natural resources management** that communication helps with solving the '**tragedy of the commons**' by way of **shared knowledge** and better **coordination**. ReHab is a **role-playing game**, both **cooperative and comp**etitive, exploring the role of knowledge production and communication for the conservation and management of **natural resources** through **experiential learning**.

Method. ReHab pitches players as ***Harvesters*** or ***Rangers*** in an abstract landscape representation where a resource is distributed in discrete units of *Biomass*. The **landscape** is also a nesting and breeding ground for a protected migratory *Bird*. The *Rangers*' task is to maximize *Bird* reproduction by creating protected areas, while *Harvesters* have to collect *Biomass*. Rules about biomass regeneration, distribution amongst harvesters, and bird reproduction are not disclosed to the players. A typical **game session** includes two successive **scenarios**: No communication between players, followed by open communication. A final **debriefing session** with all players focuses on eliciting a common understanding of the hidden rules, as well as the influence of **individual or collective strategies** on **scenario outputs**. The analysis includes records from 45 sessions played since 2008.

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Results. Our results show that in most cases **communication** improves the outcomes for both roles, *Harvesters* and *Rangers*, even though players construct and articulate rational decisions based on limited or even flawed **understandings** of the rules. In the absence of **enforcement mechanisms**, **trust** and **communication** prevail over knowledge and understanding when it comes to **managing natural resources** and resolving **trade-offs** between **conservation and development**.

Keywords

agency, communication, computer-supported role-playing game (CRP), conservation, Cormas, natural resources management, development, ReHab, stakeholder, tragedy of the commons

Introduction

Most issues in natural resources management are described as wicked problems to denote their resistance to resolution, due to complex social and environmental interdependencies. Efforts to solve one problem often result in the creation of new ones (Rittel & Webber, 1973). Klabbers (2009) argued that managing wicked problems consists of handling both conflicting certainties about knowledge and dissension about values at stake. Wicked problems typically involve multiple stakeholders (i.e. Government agencies, social and economic actors) with different perspectives and interests, acting in a changing and often unpredictable environment. As a consequence, solutions are rarely right or wrong by nature, but rather more or less acceptable to the stakeholders. Some solutions produce associated costs and entail unforeseen consequences. Tackling wicked problems requires a generic approach that does not aim at finding particular instrumental solutions, but at triggering an adaptive process of collective learning, exploration and experimentation (Xiang, 2013).

Linked human agencies are pivotal in shaping the complex web of interactions between social actors and ecological components happening at multiple temporal and spatial scales (Stepp, Jones, Pavao-Zuckerman, Casagrande, & Zarger, 2003). Understanding the rational for decisions made by stakeholders is therefore critical to explain the behavioral patterns being observed and to analyze the consequences of interventions being implemented (Pahl-Wostl, 2002). Unfortunately, the direct elicitation of mental models underlying behavioral patterns has proven highly challenging, due to methodological shortcomings (Jones, Ross, Lynam, Perez, & Leitch, 2011), as well as usual discrepancies between espoused theory and theory in use (Argyris & Schon, 1974). It is often assumed that better and widely shared information should improve natural resources management, although many other factors - such as power, trust or buy-in relationships - influence management outcomes, particularly when natural resources are perceived as a public good shared under weak governance. In extreme cases, stakeholders even refuse to consider existing evidence, taking decisions under the highest level of uncertainty. Research on social learning has demonstrated that communication and social interactions are key to reducing conflicts and reaching amenable solutions (Scholz, Dewulf, & Pahl-Wostl, 2013). However, this can only happen when social actors have already agreed on values; otherwise, communication and interaction can only exacerbate conflicts.

Role-playing games (RPGs) can assist with re-framing these wicked conditions by design, in order to emulate associated behaviors in a controlled and safe environment (Barreteau, Le Page, & Perez, 2007). Well-designed RPGs allow players and observers (individually and collectively) to shape, learn about, and reflect upon responses from the socio-ecological system to various management regimes. Moreover, as stated by Klabbers (2009), participants in a game often perform symbolic acts, which constitute our ways of understanding major aspects of the world, including ways to think and feel about the world, and how we act on those feelings. During a session, the underlying models (either computer-assisted or -supported) can be progressively understood or revealed to the actors as part of a learning process that focuses on substantive information (Bousquet et al., 2002).

Our role-playing game, called ReHab, has been designed as an ice-breaker and teaching tool in academic courses and training workshops dealing with ecosystem management, wicked problems and participatory modelling. It also helps to introduce through experiential learning (Kolb, Boyatzis, & Mainemelis, 2000), the two main tools used by the Companion Modelling (ComMod) approach, namely role-playing games and agent-based models. ComMod aims at: understanding complex socio-ecological systems and their dynamics, facilitating collective learning processes, enhancing stakeholders' decision-making capabilities and elaborating possible scenarios for the future. By taking equal account of the different perspectives and interests, it enhances dialogue, collective decision-making and knowledge and information sharing in order to co-construct a simplified representation (a model) of the problem meaningful for all stakeholders (Bousquet, Barreteau, Le Page, Mullon, & Weber, 1999).

ReHab allows players to test whether or not communication between the actors may influence and improve natural resources management in a context of high inter-player competition with divergent values, weak regulation, asymmetry of information between players and limited knowledge of the system. This article successively presents a description of the model, procedural aspects of a typical gaming session, and finally, shares the results from 45 gaming sessions recorded since 2008.

Methods

Model Description

The core engine of the ReHab game is an agent-based model (ABM). Therefore, we use the ABM-dedicated **O**verview-**D**esign-**D**etails (ODD) protocol (Grimm et al., 2006; Grimm et al., 2010) to provide an in-depth and standardized description of our model in order to make the description more understandable and complete, thereby making the model easier to replicate.

Overview

The name of the model (ReHab) comes from the concatenation of both biomass *resource* and breeding *habitat*. The model consists in an abstract landscape containing different levels of *biomass*. It is also a nesting and breeding ground for a protected migratory *Bird*. The two decision-making entities, representing the stakeholders, are the *Harvesters* and the *Ranger.*

Purpose

The ReHab model's main purpose is to support experiential learning about the role of knowledge production and communication among interacting stakeholders in the realm of renewable resource management. The model is meant for organizing role-playing game sessions to explore, through direct participation, the effectiveness and challenges of communication in improving management of an abstract environment under high levels of uncertainty and information asymmetry. The objectives of the game is to find a balance between conservation (bird reproduction) and development (maximizing harvest) to prevent a spatialized tragedy of the commons (Hardin, 1968).

Entities, State Variables and Scales

A virtual landscape is represented as a spatial grid of 20 cells (4x5), each cell containing a given number of *Biomass* units, from 0 to 3. *Biomass* represents a natural and renewable resource.

Actors will either control a Household *or act as a* Ranger. Cells with either 2 or 3 units of *Biomass* represent a suitable breeding habitat for a protected species of *Bird*. The reproductive success of a *Bird* nesting in a suitable breeding habitat is expressed by a number of newborns (0, 1 or 2). The number of newborns is related to the disturbance caused by *Harvesters* in the cell where the *Bird* nested and in its neighborhood.

There are 20 *Harvesters* in the model, each having the capacity to harvest *Biomass* units in a given cell each round. They are grouped into *Households* of up to 4 *Harvesters*. Each *Household* actor decides where to send its *Harvesters*. Harvesting is the only available activity and source of income (expressed in units of harvested *Biomass*), and each *Harvester* requires 1 *Biomass* unit/round to sustain itself.

The *Ranger* actor, usually played in a 2 or 3-member team, is in charge of monitoring and protecting the *Birds*. The *Ranger*'s objective is to maximize the number of newborn *Birds*. From Round 2 onwards, the *Ranger* may decide to delineate up to 3 cells on the grid as *Protected Areas*. The *Ranger* does not need *Biomass* to sustain him or herself. No other prerogatives or capabilities are defined in the rules given to players. Figure 2 summarizes below those interactions amongst the various actors and resources of the model.

Klabbers (2009) defines three categories of role-playing games: Rule-based, principle-based or free-form. We argue that ReHab is a hybrid form of the three

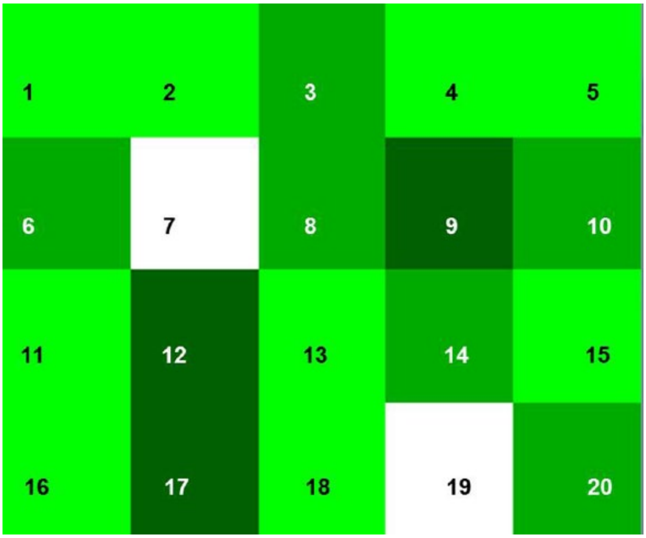

Figure 1. REHAB's initial spatial configuration.
Note. Twenty numbered locations. Colors indicate the number of available Biomass units. White= 0, Light green=1, Medium green=2 and Dark green=3.

categories. In ReHab, actors are facing *laws of Nature* (biomass regeneration, bird reproduction) that they cannot question. Actors are given a few indications about their objectives only as a general guidance. They are free to re-interpret them, based on their own norms and values, like in principle-based games. For example, a Harvester actor may decide to opt for a maximizing strategy, when he is only asked to avoid food scarcity. Finally, as with participating in free-form games, actors can invent, challenge, discard or improve social rules or constraints (law enforcement, incentives or new roles). The combination of the three categories allows room for creativity and innovation, while controlling for replicability and comparison aspects. Actors often distance themselves from rules and resources to challenge them, construct theories around them or devise strategies, for either their maintenance or their transformation (Mouzelis, 1989).

Scheduling

One modelling time-step (a round), represents a hypothetical season during which the harvesting activities coincide with bird nesting and breeding. For each round, the model first allocates nesting cells to the *Birds.* The *Ranger* delineates, from Round 2 onwards, protected areas having up to 3 cells. Then *Households* simultaneously place their *Harvesters* on the grid. Finally, the model calculates breeding outcomes, harvested biomass, and updates the number of *Biomass* units on each cell.

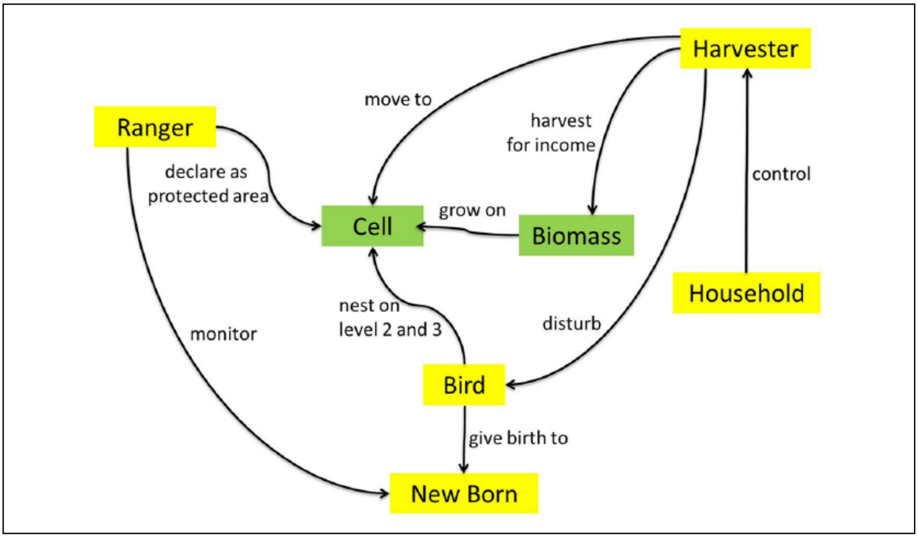

Figure 2. Diagram of interactions between actors (yellow boxes) and resources (green boxes) in the ReHab model.

A typical session includes two successive scenarios of 5 rounds each. The first one prevents any communication or direct interactions between players. The second scenario allows for and encourages communication between players.

Design Concepts

ReHab is a distributed access game, both competitive and cooperative, dependent on the learning goals of the players/actors (Klabbers, 2009). The information available to the players is limited and specific to each role. The rule for *Biomass* regeneration is unknown to everyone, as are the rules controlling the nesting and breeding of the *Birds*. Information and knowledge gaps not only relate to the rules of the system, but also to the outcomes of the decisions. The only publicly available information are the numbers of *Biomass* units in each cell, updated every round, and the locations where *Harvesters* were sent. However, the *Household* affiliation of a given *Harvester* is not revealed and the amount of *Biomass* collected is known to his *Household* only. Similarly, the locations of *Bird* nesting and the breeding results are only given to the *Ranger*. This asymmetry of information is kept all through the 5 rounds of a scenario. However, *Household*'s results and *Bird* reproduction figures are shared and discussed during an end-of-scenario debriefing.

The only stochastic event in the model is related to the sharing of the *Biomass* among *Harvesters* located on the same cell at the same time, whereby the *winner takes all* rule is randomly enforced.

Implementation Details

ReHab is implemented using the agent-based simulation platform Cormas (n.d.). Cormas is devoted to participatory agent-based simulation for renewable resource management (Bousquet, Bakam, Proton, & Le Page, 1998; Le Page, Becu, Bommel, & Bousquet, 2012). More recently, ReHab has also been implemented with NetLogo (n.d.). Both Cormas and NetLogo run on the main operating systems (Mac, Windows, Linux), so with one of these two open-source multi-agent programmable modeling environments installed on a computer, the ReHab model can be loaded and run. Additionally, a packaged version of ReHab implemented with Cormas is available as a standalone .exe file that straightforwardly works on Windows platform without having to install the Cormas platform. These three distributions of the software are freely available for download in the model library of the Computational Modeling for Socio-Ecological Science network (Openabm, n.d.).

Initialization

The initial condition of the abstract environment, as shown in Figure 1, is always the same from one session to another. The resources available (9x1 + 6x2 + 3x3 = 30 units of *Biomass*) account for one-half of the landscape carrying capacity (20x3 = 60 units of *Biomass*). The number of *Harvesters* is set to 20. The number of players being a minimum of 5, one *Household* controls 1 to 4 *Harvesters*. These initial figures were determined through trial and error of the model's calibration process. These values avoid a rapid collapse of the *Biomass* while creating enough tension between *Households*. This point is further discussed in this article's Sensitivity and analysis section.

Input Data

ReHab requires the inputting of player's decisions, namely, the location of each individual *Harvester* for every *Household*, and the location of the cells delineated by the *Ranger*. These decisions are initially recorded in a game sheet provided to each Household, and then collected and transferred to the computer. The *Ranger* communicates his decision orally – it is public and the outcome visible immediately.

Sub-Models

Harvesting. *Households* make a profit from harvesting. The harvesting capacity is limited to 2 units of *Biomass* per round per *Harvester*. When two or more *Harvesters* share the same cell, the order of harvesting is set randomly, and the loser(s) can only harvest the leftovers, if any are available.

Resource Dynamics

The evolution of Biomass depends upon the history of harvesting that has been done in each cell. Table 1 gives the Laws of Nature in the absence of Harvester on a cell at round t.

Table 1. Evolution of Biomass Change.

Round			
t-2	t-1	t	Δ *Biomass*
At least one *Harvester*	No *Harvester*	No *Harvester*	0
No *Harvester*	No *Harvester*	No *Harvester*	−1
Harvester(s) or not	At least one *Harvester*	No *Harvester*	+1

Note. Change in the absence of Harvester in a cell at Round t.

Biomass increases (Δ=1) if the cell was harvested at round (*t-1*); it decreases (Δ=−1) if the cell was not harvested at round (*t-1*) and (*t-2*); it remains unchanged in any other case (Δ=0). Hence, *Biomass* requires harvesting to regenerate.

When at least one *Harvester* is located on a cell at round *t*, state-transition rules apply based on the current number of *Biomass* and the number of *Harvesters* as presented in Figure 3.

When a cell is occupied by only one *Harvester*, its *Biomass* remains stable as natural regeneration compensates for the harvest. With two or more *Harvesters*, the Biomass decreases by the number of *Harvesters*. When a Harvester is alone on a level 2 or 3, the Harvester collects 2 levels of biomass. Likewise, on a level 1, the player gets one level. When two or more harvesters are on a level 3, the model randomly selects one harvester who gets 2 levels of biomass, another one who gets 1 level. All others remaining are left empty-handed. On a level 1 or 2 of biomass, one harvester (randomly selected) gets all the resource, all others get nothing.

Bird Reproduction

Cells with 2 or 3 units of *Biomass* represent a suitable nesting habitat for the *Bird*. Although portrayed as protected, the *Bird* population is considered locally abundant and stable enough to allow for nesting on each and every suitable cell throughout the game. At the end of a round, *Birds* and any possible newborns are assumed to fly away from their nesting cell. Breeding success depends upon the nest disturbance caused by *Harvesters*. Any presence of harvesters on the nesting cell prevents hatching and breeding = 0. In the absence of *Harvester* in the cell, the success of hatching depends on a disturbance rate set as the percentage of neighboring cells occupied by *Harvesters*. Above 50% (breeding = 0), between 20% and 50% (breeding = 1), or below 20% (breeding = 2). We opted for a neighborhood defined by the eight cells surrounding a central cell and for closed boundary conditions. Therefore, the breeding success is also influenced by neighboring/corner of the environment edge effects. All possible configurations are listed in Table 2.

An example is given in Figure 4. Two newborns are in cell #17 because all five surrounding cells are unexploited but only one newborn in cell #12 because the disturbance rate is 3/8 (37.5%). No newborn exist in cell #13 because the disturbance rate is 5/8 (62.5%).

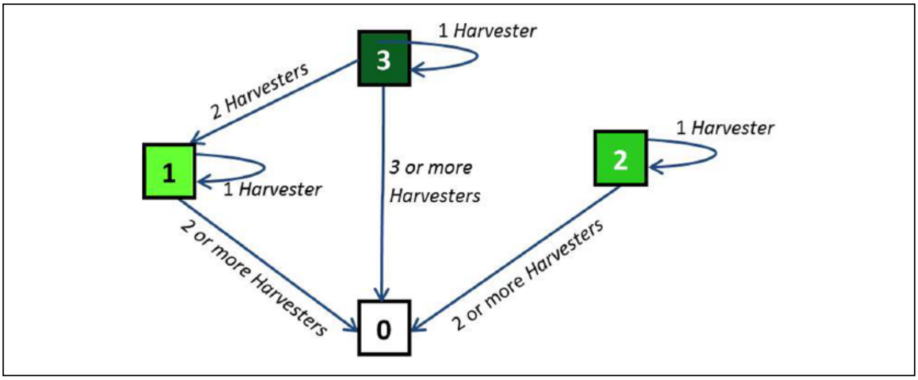

Figure 3. Biomass evolution levels in presence of harvester.
Note. Four possible levels, between 0 and 3 given in boxes. Arrows show the transition from one biomass level to another based on the number of harvesters.

Table 2. Number of Newborn Birds Based on Neighboring Conditions and Surrounding Cells.

	Number	
Neighborhood Condition	Unoccupied Surrounding Cells	Newborn Birds
Eight neighbors	7-8	2
	5-6	1
	<5	0
Five neighbors	4-5	2
	3	1
	<3	0
Three neighbors	3	2
	2	1
	<2	0

Briefing and Facilitation

ReHab follows a strict protocol of play, starting with a 5-minute-brief in plenary using a dedicated 3-slide presentation. The abstract environment, color-coding, levels of biomass, and the roles and rules are explained to the participants. Actors are given some complementary information on a profile's sheet containing specific, yet limited information. The game unfolds and is followed by a debriefing session. The entire process lasts about two 2 hours.

ReHab is facilitated by a Game Master who is in charge of introducing the game, controlling time management and promoting a lively and engaging atmosphere. As stated by Prouty (2000), playfulness is instrumental in stimulating creativity as the brain moves from a cognitive, rule-based state to a more relaxed state where the whole body is engaged in problem solving. The Game Master also strives to accommodate new

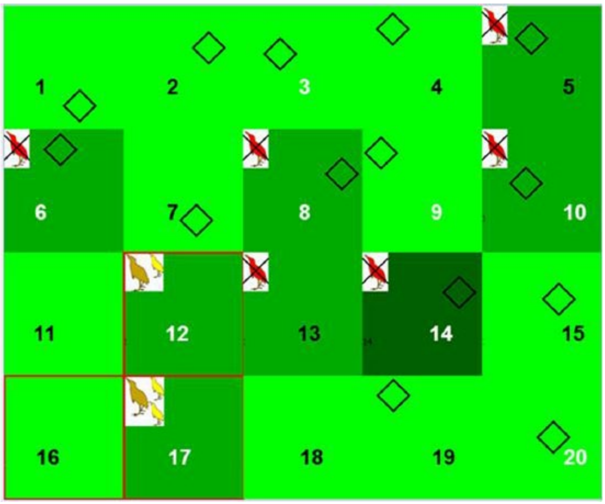

Figure 4. *Bird* breeding success.
Note. Breeding depends on disturbances made by black diamonds *Harvesters*.

propositions from the actors (introduction of new roles, policies, institutions, norms). Other tasks that need to be covered by the facilitating team include : collecting player's game sheets, data entry using a dedicated computer interface, feeding back results to players, and keeping track of the nature and verbatim of interactions between actors.

Data Collection

At the start of a gaming session, players are provided with a game sheet on which they record their decisions, indicating for each round the targeted cells where they send their *harvesters*. Once collected, these private decisions are transferred to the computer by the operator and the simulation proceeds forward to the next step. The outcome of the decisions - the amount of *Biomass* harvested – is then privately given back to players, using the same game sheet. A modified version of the game sheet is used with players acting as *Rangers*: they record the protected cells and receive the number of newborn *Birds*. Round by round, all results from each simulation is stored by the simulation software and can be recalled in playback mode during debriefing or used for further analysis later on in the debriefing section presented below.

During a session, social interactions are recorded according to three protocols. These protocols have evolved during the course of our work, and are meant to support the debriefing and the learning process rather than testing hypotheses in a controlled environment. These protocols are: (i) taking pictures of interactions and passive audio recording (Figure 5a); (ii) collecting verbatim later on organized in snippets of conversation relevant to various themes such as knowledge, rights, enforcement, collaboration or attitude (aggression, empathy or puzzlement) (Figure 5b) and (iii) organizing a team of external

Figure 5a. A *Ranger* trying to convince *Households* to respect a protected area.
Source. Session 45, Bogor 2015.

Figure 5b. Observer records discussion.
Source. Session 39, Montpellier 2014.

Figure 5c. An observer records striking social interaction elements.
Source. Session 39, Montpellier 2014.

observers in charge of recording on dedicated sheets player's attitudes, body language, power games and alliances, leadership, tipping points, knowledge production and sharing (Figure 5c).

Indicators

Three indicators and their evolution over time are particularly useful to analyze with players: the total level of *Biomass*, the cumulative number of newborn *Birds*, and the cumulated harvest. Figure 6 shows these three indicators for Session 45 (session is titled Boger 2015) for the *no-communication* scenario.

In this example, the level of *Biomass* was almost divided by two while only 2 new *Birds* were born in total. The cumulated harvest did not reach the threshold of 100, indicating that total *Household* needs were not met.

In addition to these global indicators, participants get to see how each actor performed through the analysis of results from individual *Households* as shown in Figure 7.

Global and individual indicators are presented to the players at the end of each scenario and serve as a springboard to launch the *communication scenario* and to initiate the debriefing.

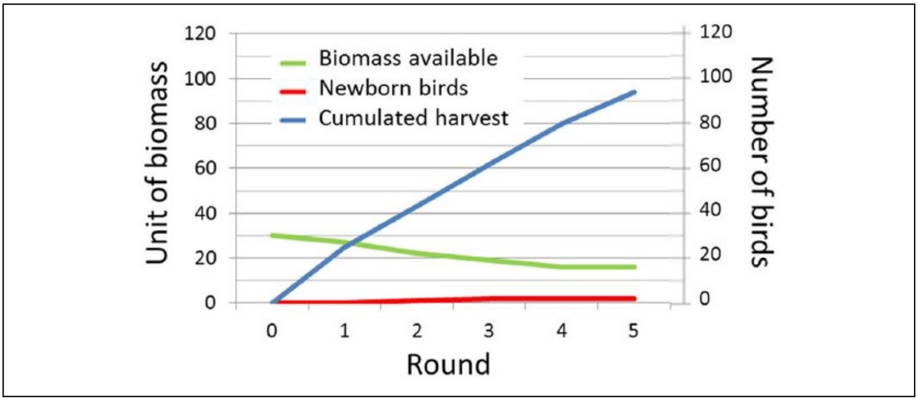

Figure 6. Recorded indicators.
Source. Session 45, Scenario 1 (Bogor, 2015).

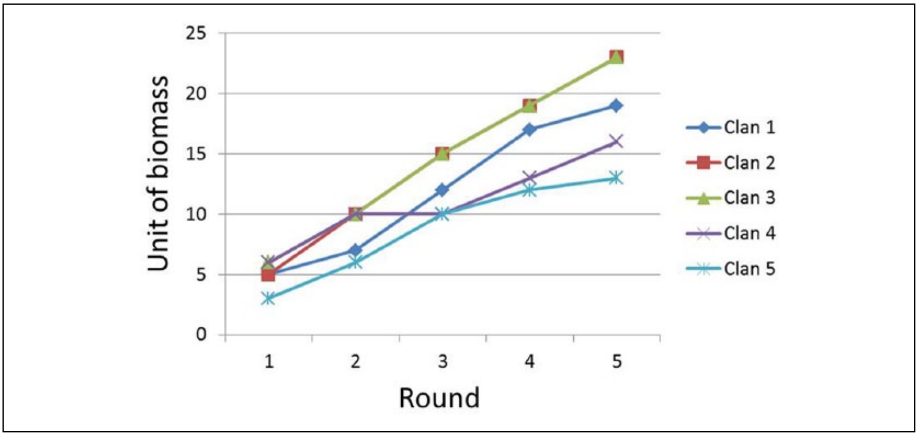

Figure 7. Individual results of cumulated harvested *Biomass* per *Household* (Session 45, Bogor 2015).

Debriefing

The debriefing session is structured in 5 steps with the corresponding set of questions, inspired by Crookall (1995) and Lederman (1992):

1. Immediate emotional response of the participants to the game and its outcomes.
   How did you feel during the game? And now?
2. Visualization of the evolution of gaming indicators: level of biomass, harvest per household and number of newborn birds. Results are then compared with

those from past sessions (as explained below). The use of global indicators (Cumulated Harvest, Total Biomass and Total Newborn Birds) allows jumping from individual to collective outcomes during the debriefing.
How do you assess your collective result?
How do you assess your individual result?

3. Using the replay mode to analyze harvesting strategies and unfold hidden rules and dynamics. Time allowing, a playback mode allows participants to visualize and comment on the game that has been recorded by the computer software. In this mode, specific clans can be highlighted to pinpoint and discuss their strategies and behaviors.
What did you understand?
What were the hidden rules?
What did you learn?
4. Collective analysis of group dynamics (quality of communication, knowledge sharing and emergence of leaders).
Did you reach agreements and how?
How were conflicts resolved?
5. Bridging gaming context and reality of the tragedy of commons by selecting striking features of the session
What similarities & differences do you see between the game and reality?

Sessions

We have organized and recorded 45 sessions worldwide since 2008, 29 in France and 16 abroad (see Appendix A). The number of participants per session varied from 6 to 37. The most frequent setting for a ReHab session consisted in playing with master students as a practical exercise in a short module on Companion Modelling within a longer-term curriculum. 30 ReHab sessions correspond to this category, with students belonging to three main disciplines (11 in ecology; 7 in agronomy; 6 in geography). Five ReHab sessions were played with researchers and managers involved in a common environmental project. Finally, four ReHab sessions were played during professional development workshop with researchers. In all cases, acquaintances between participants were established prior to the sessions. The six remaining ReHab sessions were organized during international training courses. In this case, the heterogeneity among participants was higher because of the diversity of disciplines and status (postgraduate students, postdoctoral fellows or senior researchers). With most participants meeting for the first time, the sessions were organized as an ice-breaker exercise on the first day of the training course.

Results

Eliciting Individual Strategies

As players' decisions and outcomes are recorded in the model, it is possible to run playback versions of each session. The *no-communication* scenario allows for the identification of the individual strategies whereas the second one, *with communication*, enables the elicitation of collective strategies or the emergence of conflicts.

The following analysis was conducted on a sub-set of the 45 sessions (Canberra sessions only). Participants were asked to fill a strategy sheet to explain their initial strategy and mention any changes of strategy throughout the game, together with the underlying motivation. Comparing these self-reports to the actual decisions of the players, checking for patterns in the placement of their Harvesters, the research team identified the major individual strategies for *Household* and *Ranger* players. These strategies were discussed and validated with the same trainees that had provided the input. The main four *Household* strategies are:

- Maximizer: The *Household* targets cells with high level of biomass
- Lone Rider: The *Household* avoids cells with high level of biomass
- Explorer: The *Household* spreads his harvesting effort across biomass levels
- Poacher: The *Household* targets cells labelled as protected by the *Ranger*

Most *Household* players switch from one strategy to another depending on shifting circumstances. Overall, each round, 38% of players displayed a Maximizer strategy, 32% a Lone Rider strategy and 29% an Explorer strategy. The Poacher strategy could be associated with any of the three previous ones and was used, on average, by 30% of the players on a given round. Further analysis of the relationship between selected strategies and the units of harvested biomass did not bring any statistically significant differences between strategies.

We analyzed the strategies used by *Ranger* players trying to maximize breeding outcomes. Four major strategies were also identified:

- Crusader: The *Ranger* protects cells with high level of biomass
- Negotiator: The *Ranger* protects cells with mid-level of biomass
- Manager: The *Ranger* protects connected cells (including at least one with high biomass)
- Naturalist: The *Ranger* protects cells with previous bird nesting

Unlike the *Households*, most players taking on the role of *Rangers* tried to stick to a given strategy but often had to change due to the lack of compliance displayed by the *Harvesters*. Each round, on average, 9% of players displayed a Crusader strategy, 18% a Negotiator strategy, 45% a Manager strategy and 27% a Naturalist strategy. Like in the case of the *Households*, further analysis of the relationship between selected strategies and the number of newborns did not bring any statistically significant differences between strategies.

Sensitivity Analysis and Calibration

As described in the Initialization section, we used three major indicators (1) Total Harvest, (2) Final Biomass and (3) number of Newborn *Birds* to qualify the simulations' outcomes. The initial calibration of the model, particularly the total population of *Harvesters* (20) and the initial *Biomass* (30) was done through sensitivity analysis aimed at keeping the game in a solution space that would allow for the possible emergence of collective action. Previous research has shown that the rate of evolution of the *Biomass* was a critical factor. A rapid and general collapse leads players to abandon any hope of improving the system through collective action, while a very slow decline doesn't provide any incentive for concertation.

In order to calibrate the model, a first automated version was created whereby *Households* allocate their *Harvesters* at random, ignoring *Biomass* levels or protection status. This version aims at simulating a game without cooperation or individual strategies. Figure 8 shows statistical results from 30 simulation runs (5 rounds each) with three different levels of initial *Biomass* (20, 30 or 40 units). As expected, with an initial level of *Biomass* of 30 units, results are particularly poor: 78.9 ± 11 for Total Harvest, 19.73 ± 3.8 for Final *Biomass* and 1.73 ± 1.4 Newborn *Birds*.

To assess the capacity of the game to respond to various strategies, depending on the initial level of *Biomass*, we developed a new automated version with *Households* being allocated one strategy (Explorer, Lone Rider, Maximizer or Fixed Plan) and *Rangers* being allocated one strategy as well (Crusader, Negotiator or No Action). All *Household* and *Ranger* strategies are crossed with each other, resulting in 12 configurations (3x4). Each configuration is run 30 times. Figure 9 presents the results of these simulations (XLSTAT Version 2015.1.03.15449). Each dot represents average values (over 30 runs) for one configuration. In all cases, *Households* respect protected areas (no Poacher strategy allowed). Results show highly linear correlations between all permutations of a given initial *Biomass* level (r^2=0.79), indicating the existence of a structural trade-off between the amount of *Biomass* that can be collected and the total number of newborn *Birds*. In the absence of coordination and without retroactive feedback and cognitive capacities that would allow them to respond and adapt their behavior, agents navigate along this baseline. Higher levels of initial *Biomass* simply lift the baseline of this trade-off. These two sensitivity analyses led us to select an initial level of *Biomass* of 30 units. Coupled with a stated collective level of self-sufficiency set at 100 units of *Biomass* harvested, it confronts players with a difficult, yet solvable challenge.

Learning and Sharing Knowledge

Table 3 shows the global positive impact of communication. All three indicators improve when players can freely interact and communicate: lower mean *Biomass* depletion, higher mean *Bird* reproduction, and higher mean Total Harvest. However, results show a higher level of variability (standard variation) when communication is allowed.

Appendix B summarizes results from the 45 sessions across the 3 indicators. In 25 cases, all indicators have improved from the first scenario (*no-communication*) to the second one (*with-communication*). In 12 cases, the available Resource at the end of the session even reached or topped the initial value of 30 units of *Biomass* (best

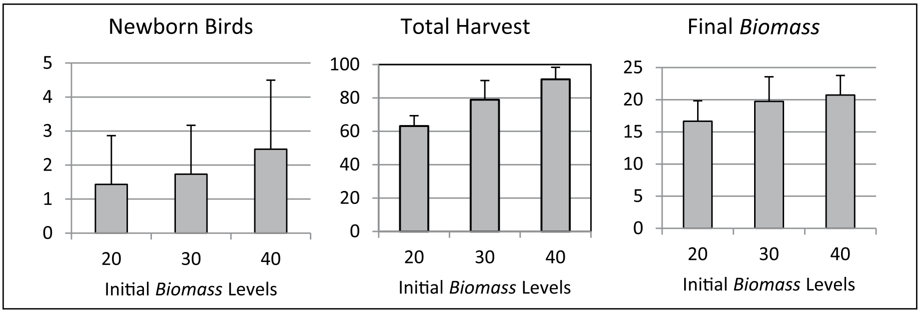

Figure 8. Simulation outcomes of a fully automated multi-agent ReHab model with dummy *Household* strategies, and different levels of initial *Biomass* (20, 30 and 40).

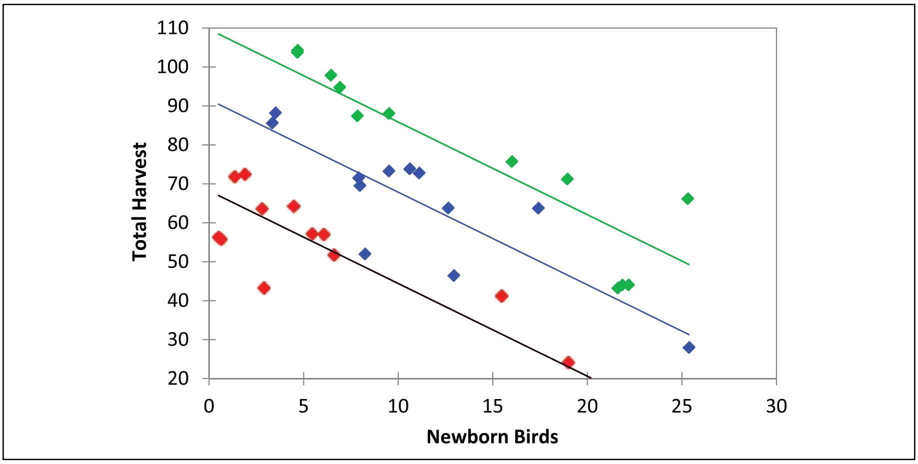

Figure 9. Simulation outcomes of a fully automated multi-agent ReHab model with specific *Ranger* and *Household* strategies, and different levels of initial *Biomass* (20 in red, 30 in blue and 40 in green). The results of the simulations pitching Crusader, Negotiator and Absent *Rangers* against Explorer, Lone Rider, Maximizer and Planner *Households* exhibit a structural trade-off between Total Harvest and Total Newborn *Birds*, represented by the slope of the linear regressions (slope $=-2.379$, std $= 0.247$, $p < 0.0001$). Higher initial levels of Biomass simply shift the resulting trade-offs up. Results based on 30 simulations per combination of variables ($r^2 = 0.797$; $F=4.868$, $p < 0.0001$).

score: +66.7%). Overall, there are a limited number of cases where indicators worsen during the second scenario: 7 sessions for the Resource indicator, 12 sessions for the Bird indicator and 12 sessions for the Harvest indicator.

Three paired t-tests were performed to determine the effect of communication on the three indicators (see Appendix B). The mean biomass difference between the two treatments with and without communication (M = 9.55, SD = 10.59, N = 45) was

Table 3. Mean Values (and Standard Deviation) for Biomass Variation, Number of Newborns and Total Biomass Harvested After 5 Rounds for Both Scenarios From 45 Gaming Sessions.

Scenario	Resource (biomass variation)	Bird (number of newborns)	Harvest (total biomass units)
No comm.	−49.0% (+− 10.7%)	5.3 (+− 4.1)	81.3 (+− 8.6)
With comm.	−17.1% (+− 30.5%))	10.1 (+− 8.2)	95.7 (+− 12.0)

significantly greater than zero, t(44) = 3.71, two-tail p = 2.82E-07, providing strong evidence that communication is effective in preserving biomass. A 95% C.I. about the biomass preservation is (6.37, 12.74). Similarly, the mean difference in the cumulative number of newborn Birds between the two treatments (M = 4.78, SD = 7.74, N = 45) was significantly greater than zero, t(44) = 4.14, two-tail p = 0.000154, also providing evidence that communication is effective in improving bird reproduction. A 95% C.I. about this improvement is (2.45, 7.10). Finally, the mean difference in the cumulative harvest between the two treatments (M = 14.42, SD = 16.20, N = 45) was again significantly greater than zero, t(44) = 5.97, two-tail p = 3.69E-07, providing strong evidence that communication is effective in improving harvesting. A 95% C.I. about this improvement is (9.56, 19.29).

In three cases (session 5, 36, and 45), all three indicators declined in the second scenario. In session 5, random allocation of the roles led to the *Ranger* being played by two students uncomfortable with publicly expressing themselves in English (not their native language). They did not raise their voice or manage to expose their views to the *Harvesters*. Conversely, in session 45, the two park managers actors were very outspoken, but in total disagreement on the strategy to adopt as one was favoring engagement with the community while the other was pushing for a top-down approach (see Figure 4a). Session 36 was organized with 37 participants, the *Ranger* being controlled by 3 players. *Households* were controlled by groups of 3 to 4 players. This led to a hurly-burly atmosphere and with tight time constraints imposed by the game master, *Rangers* failed to influence *Households* who, in turn, could not come up with a collectively approved strategy.

Balancing Conservation and Development Goals

Figure 10 below shows the trade-off between conservation (Cumulated Newborn *Birds*) and development (Cumulated Harvest) achieved during 45 scenarios with communication.

Nearly half of the sessions ended with a global harvest below 100 (level of community self-sufficiency) and less than 10 newborn birds. The comparison of these results to the average results of the non-communication scenarios (Figure 10: dotted lines; average Cumulated Harvest: 81.31, average Cumulated Newborn *Birds* 5.33) allows us to detail the solution space. None of the sessions did worse than the average

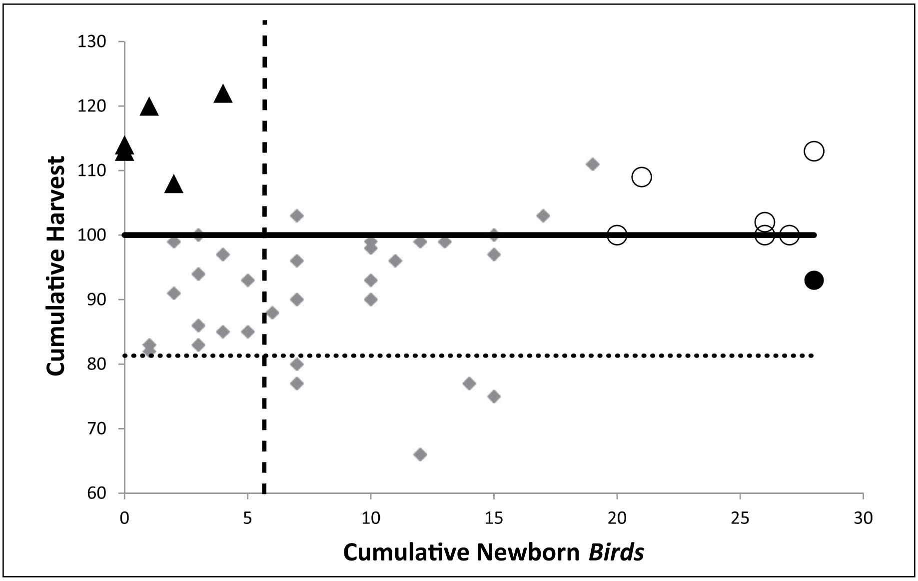

Figure 10. Trade-off between conservation and development - cumulated harvest (Y-axis) versus cumulated number of newborn *Birds* (X-axis) for 45 sessions with communication. Bold line indicates the set collective level of self-sufficiency after 5 rounds (20 *Harvesters* x 1 unit of Biomass x 5 rounds = 100). The average results of all sessions under the non-communication scenario are indicated by dotted lines (81.3 cumulated Harvest and 5.3 newborn *Birds*). All communication sessions have outperformed the average non-communication outcomes in one or both dimensions.

non-communication session. All sessions above the horizontal dotted line outperformed the average non-communication sessions in terms of resource extraction, with 5 sessions managing to maximize harvest at the expense of bird reproduction (Figure 10: black triangles). All sessions to the right of the vertical dotted line outperformed the average non communication scenario in terms of bird reproduction. The most successful sessions achieved 20 newborn birds or more and enough harvest to satisfy the *Harvesters* needs (Figure 10: open circles). One particular session saw the objectives of the *Ranger* prime over those of the *Households* with 28 birds, but only 93 Biomass units extracted (Figure 10: black circle). The proportion of sessions that outperformed non-communication on the development dimension ($f_1 = 0.89$) is significantly higher than the proportion of those that outperformed on the conservation dimension ($f_2 = 0.62$; $z = 3.225$; $p = 0.001$).

Discussion

ReHab has been designed as a teaching tool to allow participants to better understand issues of collective decision-making for environmental management characterized by high levels of uncertainty, multiple stakeholders, conflicting agendas and segmented worldviews. ReHab aims at placing the participants in an active situation, often as an introduction to ecosystem management and modelling courses. This objective imposes restrictions (simplifications) on the game that limit the lessons we can draw from the sessions for direct application in the reality. Another analytical limitation lies in the possibility for players, especially during the second scenario (*with-communication*) to propose new rules such as fines for poachers or the possibility to share resources, or even create new roles such as introducing an NGO with the capacity to negotiate subsidies for conservation. The encouraged flexibility drives potential framing effects in the experimental design (Cookson, 2000). Unlike experimental economics that advocates for neutral framing design, we accept the variability introduced by our flexible framework as a necessary weakness to elicit more creative collective behavioral patterns.

Discussions happening during the debriefing sessions allow participants to draw insight, about four key aspects associated with the management of 'wicked problems' (Balint, Stewart, Desai, & Walters, 2011; Rittel & Webber, 1973): (i) identifying solutions, (ii) learning and sharing knowledge, (iii) nature of the rights and agreements negotiated between players and (iv) the role of monitoring and enforcement.

Identifying Solutions

The distribution of session results in the solution space (Figure 8) suggests the competition between *Households* for *Biomass* was easier to resolve than the competition between *Rangers* and *Households*. However, we need to emphasize that, with the exception of the self-sufficiency target (100 units to sustain 20 *Harvesters* over 5 rounds), no other condition of success was imposed on players. One of the essential elements of the debriefing, and therefore of the collective learning, was to unveil the differences in perceived success conditions – highlighting the fact that not all players are rational maximizers. One of the defining features of wicked problems is that solutions are not right or wrong, but simply more or less acceptable to a variety of stakeholders (Batie, 2008). There is no better illustration of this fact than when *Households* report feeling satisfied with the outcome, despite falling below their self-sufficiency level, on accounts of the good relations between *Households* and *Rangers*.

Learning and Sharing Knowledge

ReHab includes one counter-intuitive process in order to test the ability of players to *read* evidence rather than calling upon general mental statements: the regeneration process of the *Biomass* needs regular harvest to avoid collapse. These rather unusual dynamics are based on a traditional reed harvesting systems in southern Europe, where the plant needs to be harvested to stimulate its regeneration.

Players have access to three sources of knowledge to make sense of the system: first, the empirical knowledge they gather by analyzing results of their actions and those of the other players; they can also share knowledge with other players accessing similar information but having a different empirical knowledge (*Household* to *Household*); finally, they can tap into entirely new perspectives (*Household* to *Ranger*). During the first scenario, players are restricted to the first source of knowledge. Their empirical knowledge can gradually increase as they progress throughout the game and find out the hidden rules. This individual substantive learning process explains only in parts the improved results recorded during the second scenario. Collective learning happens throughout the discussions allowed in the second scenario. However, debriefings at the end of each game session suggest that only in a few cases were the players able to correctly infer all the underlying dynamics of the model.

In many sessions, most players displayed partial or even flawed knowledge of the system. Remarkably enough, players often achieved relatively successful results during the second scenario, despite grossly misleading assumptions about the rules of the game, thanks to a better coordination amongst *Households* and through negotiation with the *Ranger*. And more often than not, the players were able to build a relatively solid collective narrative to justify their decisions based on partial or flawed information. This closely mimics real life management situations, and is relevant to the continual learning and adaptive management principle of landscape approaches (Sayer et al., 2013). Despite uncertainties and knowledge gaps, regardless of the diversity and ambiguity in understandings, improved management of computer-supported role-playing game can be gained through aligning communication frames.

Clarifying Rights and Negotiating Agreements

Communication between players in the second scenario also focused on coordination and negotiation over sharing space (cells) and resources (*Biomass*). That communication fosters improved efficiency and better decision making is a well-established fact in the literature (Isaac & Walker, 1988). It should be noted that the impact of communication in ReHab is probably overestimated as it is impossible to statistically disentangle the influence of individual learning through repetition and collective learning triggered by discussions amongst players. Nevertheless, ReHab allowed us to analyze both the emergence of cooperation amongst *Households* and the initiation of a dialogue between the *Harvesters* and *Rangers*. The tension between these two dimensions of the communication is critical and might be the most influential factor to explain the observed results.

In ReHab, agreements were discussed and proposed by players in all sessions in one form or another. It is important to mention that during the second scenario (with communication), players are allowed to communicate between harvesting periods but decisions made by players are still anonymous. Henceforth, under this configuration ReHab offers an opportunity for free-riders to break the collective rule, testing the trust relationship between *Households*.

In another common-pool-resources game, Janssen, Holahan, Lee, and Ostrom (2010) allow for discussions during the harvesting phase itself and individual decisions are known to everyone. In this case, potential free-riders have to resist peer pressure imposed by other players. A recent evolution of ReHab allows for an option whereby, during the second scenario, players openly interact around a game-board instead of passing their decisions directly to the game master (first scenario). At this time, we do not have enough results to infer statistically significant conclusions yet. Unlike Ostrom, Walker, and Gardner (1992) who chose to dissociate retributive decisions against free-riders from communication opportunities (one following the other), in ReHab punishment can be collectively agreed upon during the discussion phase.

Monitoring and Enforcement

Previous behavioral experiments of commons dilemma have found that people are willing to engage in punishment to get rid of free-riders. Literature suggests that sanctions do increase cooperation and reduce free-riding, at the cost of efficiency, in CPR experiments where exclusion is possible but costly (Ostrom et al., 1992). Unless it is combined with communication, the positive effect of punishment on resource harvesting is not clear. Controlled experimental settings based on computer simulation have been designed to investigate several combinations of sanctioning and communication (Janssen et al., 2010).

In ReHab, as sanctions are not directly implemented in the simulation model and decisions are made anonymously during scenario 2, free-riders appeared in nearly all sessions. This had an impact at two levels: agreements between *Households* to share space (creating *de facto* tenure rights over cells for example), and agreements between *Rangers* and *Households* to respect the protected area. In both cases, players would see (with dismay at times) in the public display that some *Harvesters* had been sent to cells in violation of the agreements, but would not be able to identify the culprits unless they underwent a time-consuming internal investigation.

Compliance was not enforceable unless the players agreed to a social mechanism. In many instances, heated debate, verbal abuse, ostracism and threats of exclusion were observed. These reactions provide a very powerful imprint on players through an emotional experiencing of the difficulties of balancing divergent objectives in environmental management.

Conclusion

The issue addressed with ReHab goes beyond the Tragedy of the Commons and self-governance of CPR. Empirical evidence suggests that appropriators in CPR are able to develop credible commitments without relying on external authorities (Ostrom et al., 1992). The trend of increasing competing claims over land being now noticeable even in isolated rural areas, the interests of non-local stakeholders become drivers for local land-use change and social organizational change. Having to cope with *Rangers* and *Birds, Harvesters* in ReHab face the challenge of self-organization while being put under pressure by an external authority. Playing a session of ReHab allows for promoting co-learning about the tensions between nature conservation and improved rural livelihoods.

With a game featuring two roles with contrasted viewpoints on the same landscape, the opportunity to communicate among participants did not systematically improve the situation, even if this was most often observed. Pre-existing social capital shared by the participants, or underlying cultural norms are likely to be important factors affecting the success of a given session. In the case of ReHab, our objective was not to be able to investigate these aspects by controlling the interactions among participants. In line with the posture of Companion Modelling advocated in Etienne (2011), our position is to remain as open and flexible as possible allowing for new rules or roles to emerge.

Appendix A

Characteristics of the 45 Recorded Sessions.

Session	Date	Location	Setting	Disciplines	Nb participants
1	2008-02	Canberra	Master	Anthropology	7
2	2009-01	Bangkok	Master	Ecology	6
3	2009-05	Bangkok	Training	Multiple	22
4	2009-06	Brisbane	In-site Training	Multiple	6
5	2009-09	Canberra	Master	Anthropology	9
6	2009-10	Montpellier	Master	Geography	6
7	2009-12	Niamey	Workshop	Multiple	7
8	2009-12	Niamey	Workshop	Multiple	6
9	2009-12	Nanterre	Master	Geography	16
10	2010-01	Paris	Master	Ecology	19
11	2010-01	Paris	Master	Ecology	12
12	2010-02	La Réunion	In-site Training	Multiple	9
13	2010-02	La Réunion	In-site Training	Multiple	9
14	2010-09	Canberra	Master	Anthropology	6
15	2010-09	Namur	Workshop	Multiple	20
16	2010-10	Montpellier	Master	Geography	7
17	2010-11	Nanterre	Master	Geography	11
18	2010-11	Montpellier	Master	Geography	22
19	2011-01	Paris	Master	Ecology	10
20	2011-01	Paris	Master	Ecology	12
21	2012-01	Paris	Master	Ecology	18
22	2012-01	Paris	Master	Ecology	13
23	2012-03	Stockholm	In-site Training	Multiple	6
24	2012-09	Montpellier	Training	Multiple	22
25	2012-12	Toulouse	Master	Ecology	16
26	2012-12	Zürich	Master	Multiple	12
27	2013-01	Montpellier	Master	Agronomy	8
28	2013-01	Paris	Master	Ecology	11
29	2013-01	Paris	Master	Ecology	9
30	2013-03	Montpellier	Master	Forestry	14

(continued)

Appendix A. (continued)

Session	Date	Location	Setting	Disciplines	Nb participants
31	2013-10	Montpellier	Training	Multiple	23
32	2013-10	Zürich	Master	Multiple	37
33	2013-11	Nanterre	Master	Geography	22
34	2014-02	Paris	Master	Agronomy	10
35	2014-02	Montpellier	Master	Agronomy	13
36	2014-02	Montpellier	Master	Agronomy	13
37	2014-03	Zürich	Training	Multiple	23
38	2014-05	Harare	Workshop	Multiple	14
39	2014-09	Montpellier	Training	Multiple	20
40	2014-09	Wageningen	Training	Multiple	18
41	2014-12	Toulouse	Master	Ecology	17
42	2015-02	Paris	Master	Agronomy	15
43	2015-02	Paris	Master	Agronomy	12
44	2015-02	Montpellier	Master	Agronomy	11
45	2015-03	Bogor	Workshop	Multiple	21

Appendix B

Results and Statistical Analysis of the 45 Recorded Sessions.

	Biomass			Birds			Harvest		
Sessions	S_1	S_2	S_2-S_1	S_1	S_2	S_2-S_1	S_1	S_2	S_2-S_1
1	16	30	14	0	7	7	99	80	−19
2	16	18	2	11	2	−9	75	108	33
3	17	29	12	4	0	−4	89	114	25
4	15	30	15	0	28	28	91	93	2
5	19	12	−7	5	4	−1	96	85	−11
6	19	23	4	0	7	7	89	96	7
7	10	20	10	5	6	1	77	88	11
8	15	17	2	6	7	1	76	90	14
9	14	33	19	4	21	17	80	109	29
10	18	38	20	6	19	13	89	111	22
11	9	25	16	11	13	2	70	99	29
12	15	20	5	0	10	10	92	90	−2
13	14	35	21	4	4	0	80	122	42
14	17	20	3	2	0	−2	96	113	17
15	15	20	5	6	3	−3	80	94	14
16	16	27	11	11	20	9	74	100	26
17	16	37	21	8	12	4	76	99	23
18	16	18	2	11	10	−1	69	93	24

(continued)

Appendix B. (continued)

	Biomass			Birds			Harvest		
Sessions	S_1	S_2	S_2-S_1	S_1	S_2	S_2-S_1	S_1	S_2	S_2-S_1
19	10	37	27	4	7	3	85	103	18
20	23	37	14	6	26	20	76	100	24
21	11	50	39	10	28	18	77	113	36
22	10	45	35	18	27	9	66	100	34
23	15	28	13	0	15	15	89	100	11
24	15	18	3	3	2	−1	95	91	−4
25	16	20	4	2	1	−1	87	83	−4
26	12	26	14	2	4	2	78	97	19
27	9	26	17	2	2	0	73	99	26
28	14	16	2	13	5	−8	65	93	28
29	16	36	20	11	26	15	74	102	28
30	16	27	11	6	10	4	77	99	22
31	18	17	−1	2	5	3	83	85	2
32	20	16	−4	3	14	11	82	77	−5
33	15	29	14	0	12	12	83	99	16
34	15	20	5	9	11	2	73	96	23
35	14	11	−3	5	7	2	81	77	−4
36	18	13	−5	9	3	−6	92	86	−6
37	17	17	0	2	3	1	87	83	−4
38	22	25	3	7	10	3	78	98	20
39	18	20	2	3	1	−2	79	120	41
40	16	20	4	3	3	0	81	100	19
41	11	38	27	11	17	6	65	103	38
42	12	26	14	3	15	12	79	97	18
43	13	22	9	6	15	9	79	75	−4
44	20	15	−5	4	12	8	83	66	−17
45	16	12	−4	2	1	−1	94	82	−12
Mean			9.55			4.78			14.42
Student t-test			**6.05**			**4.14**			**5.97**

Note. The paired Student t-test was calculated based on the difference *d* between both scenarios.

Authors' Note

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Anne Dray is an hydrologist by training who has specialized in participatory modeling. She is interested in applied research projects dedicated to renewable resources management and

conflict resolution with a strong emphasis on community participation and engagement in order to promote ecological sustainability. She develops and uses dedicated tools to support stakeholders' engagement such as agent-based models and role-playing games.

Pascal Perez received his PhD in Environmental Studies from Montpellier University, France in 1994. He is a specialist of integrative infrastructure modelling, using various computer simulation technologies to explore complex interactions between social and technological components of infrastructure systems. He has a 30-year experience in complex system modelling, first in France, then at the Australian National University and CSIRO. Pascal joined the University of Wollongong in 2011. He currently is the Director of the SMART Infrastructure Facility, University of Wollongong.

Claude Garcia is a tropical ecologist working for CIRAD (French International Centre of Research and Agronomy for Development). Since 2012, he took the lead of the Forest Management and Development Group, in the Department of Earth System Sciences of ETH Zürich (Switzerland). His research aims at understanding tropical landscapes under change. He develops approaches to embrace (i) ecosystem and their processes, (ii) stakeholders and their strategies and (iii) the norms and institutions the latter establish to regulate access to the former. His goal is to balance conservation and development through better public policies bridging disciplines and taking into account local knowledge, constraints and opportunities.