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MARCHI: A serious game for participatory governance of ecosystem services in multiple-use protected areas

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A B S T R A C T

The management of multiple-use reserves is challenging due to trade-offs between the conservation of natural capital, the provision of different ecosystem services (ES) and the capture of its benefits, as well as a poor governance. In this context, the potential of serious games for simultaneous training of decision-makers and informing researchers is of special interest. Here we present MARCHI, a serious computer game inspired by a MAB Biosphere Reserve from Argentina, through which we evaluated player's preferences for investing annual budgets in different management instruments, and player's ability to feedback their investing decisions on the outcomes from previous games. The main objective for MARCHI players is to maximize the sustainable capture of benefits from natural capital under unpredictable changes in the rate of natural capital loss. Different social actors played the game in their simulated role of members of a management committee. Each game comprises 15 consecutive runs, and each run is an opportunity for players to allocate limited annual funds to Monitoring and Prospective, Control, Payment for ES (PES), Access to ES, and Land Use Planning. MARCHI was able to induce significant and relevant changes of initial preferences for conventional conservation instruments (Control) towards instruments that are little known and practically not applied in the country, such as the PES, or still poorly prioritized in the context of protected natural areas like the access to the ES. Mean Learning Index, an indicator of players ability to improve their game scores along successive games, was positive and significantly different from zero (18.29% ± SE = 4.46%). Final players' performance was not related to their allocation of time to reviewing tutorials, but to their time spent with a review screen after each game. This study illustrates the utility of serious games as a research-action tool for the participatory governance of ES.

1. Introduction

While important progress has been achieved in the ecosystem services (ES) framework or approach (ESApp) in providing knowledge and tools to assist land use decisions and policy design, it is likely still below academic expectations (Brunet et al. 2018; Mandle et al. 2021; Nahuelhual et al. 2021; Stevenson et al., 2021; Stevenson et al., 2022). Nowadays, nature's conservation and supply of sustainable benefits from natural capital do not seem immediately constrained by the available scientific knowledge on processes leading to ES supply, but by

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effective institutions and instruments for mainstreaming the ESApp into the governance of socio-ecological systems (Mastrángelo et al. 2019; Posner et al., 2016; Simoncini et al. 2019; Weyland et al. 2019).

1.1. Challenges for the management of multiple-use protected areas

After the dubious effectiveness of top-down attempts to implement the ESApp, often due to low social legitimacy, there is growing evidence that ESApp implementation is benefited by stakeholders' engagement through participatory governance processes (Newig and Fritsch 2009). However, such processes are not free of their own drawbacks and pitfalls (Berbés-Blázquez et al., 2016; Verburg et al. 2016). The management of multiple-use protected areas through the ESApp represents a challenge for finding solutions to the trade-offs between different ES and conflicts between social actors with different preferences, interests and/or values, particularly under uncertainty scenarios. This is especially true for Biosphere Reserves of the MAB Programme where an attempt is made to harmonize conservation and sustainable development (Coetzer et al. 2014; Schliep and Stoll-Kleemann 2010; Stoll-Kleemann et al., 2010).

Participatory governance may be especially critical for multiple-use protected areas due to trade-offs between the provision of different ES types, social conflicts originating from their demand, limitations for simultaneously financing the conservation of natural capital and the sustainable capture of their benefits. By analyzing the performance of the world network of MAB Biosphere Reserves, Schultz et al. (2011) found that the success of these kinds of projects mostly depends on the participation level of local users or inhabitants. In addition to asymmetric participation of stakeholders in decision-making and poor training in system thinking, top-down proposals usually fail to implement the ESApp (Nguyen and Bosch, 2013).

The exclusion of stakeholders in decision making responds to various barriers to collaboration and informed participation. Successful cases of participatory governance of natural resources and ES are based on their ability to improve the engagement of stakeholders, the dialogue between knowledge systems, the reduction of power asymmetries, and access to the benefits derived from natural capital (Laterra et al. 2019; Lynam et al. 2007; Oldekop et al. 2016). The legitimacy and effectiveness of these processes requires overcoming miscommunication, lack of basic training and knowledge (Hogl et al. 2012; Opdam et al. 2016; Spyra et al. 2019; Ward et al. 2018). This is particularly true for Latin American countries, where the ESApp and the participatory governance usually constitutes a discourse waiting for its effective mainstreaming in land use policies (De la Mora – De la Mora, 2022; Weyland et al. 2019).

1.2. Serious games as a participatory governance tool

Fostering participatory governance of multiple-use protected areas or other types of socio-ecological systems has been intended through different approaches and tools, like participatory mapping of ES (García-Nieto et al. 2019), conceptual modeling (Etienne et al., 2011) and decision support systems (DSS) (Grêt-Regamey et al. 2017; Acosta and Corral, 2017). More recently, participation of stakeholders is being explored by highly interactive tools, mostly in digital format, through the use of playful strategies like gamified applications and serious or simulation games (Bakhanova et al. 2020; Edwards et al., 2019; Forrest et al., 2022; Medema et al. 2016).

"Gamified" applications consist of incorporating particular game elements to motivate users to complete tasks or reach specific goals within non-game contexts (Antwi et al., 2017; Aubert & Lienert 2019). On the other hand, the "serious" or simulation games are designed to teach users a specific skill or knowledge by integrating most of the main design elements of games (e.g. stories, rules, choices, challenges achievement, performance feedback, rewards, scores). More precisely, serious games allow for rule based interaction, where players learn by exploring the consequences of their decisions and modifying them via specifically designed feedback loops (Mayer 2009). In these games, players access both cognitive and psychological dimensions of learning, by relaxing prejudices and enabling experimentation and creativity in a safe and low-risk environment. In contrast with DSS, serious games do not focus on immediate and usually black-box solutions to the most frequent or realistic conditions, but on users' engagement, understanding and learning to improve decision making in the long run upon broad decision scenarios or challenges.

Games designed as research tools are usually aimed to assess choices or preferences of stakeholders by different natural assets and landscape design (Merlet et al. 2018; Speelman et al. 2014; Verutes and Rosenthal 2014). The integration of process-based simulation models into serious games to support land-use policy makers and planners is still uncommon (Maaß 2021). To our knowledge, the potential of serious games to promote learning and training about the combination of different management instruments, like monitoring and prospective, payment for ES (PES), and land use planning (LUP) for the provision of ES and their benefits, has yet poorly explored. In the context of this paper, prospective studies (also known as foresight or futures studies) refers to the ability to anticipate and plan for potential changes in land use based on dynamics of external drivers and local stakeholder preferences (Bell, 2017; Hallberg-Sramek et al., 2023; Patrouilleau, 2022).

Serious games provide a range of advantages for training, research, and intervention in governance matters. These include reducing real-world constraints like knowledge disparities, economic costs, and limited time frames and scenarios. However, this approach also has its own challenges, including gaining stakeholder involvement, overcoming low initial trust, overcoming high power asymmetries, providing sufficient facilitation and debriefing, ensuring learning retention in the long run, and linking learning with decision objectives (Edwards 2023; Flood et al. 2018).

1.3. MARCHI overview, objectives and hypotheses

Here we present the design and application of MARCHI, a serious game strongly embedded into the ESApp, with the double purpose of exploring (i) the preferences of different social actors for different management instruments of a multiple use area, that is, the ability to prioritize one option over another, given a set of alternatives (instruments) based on individual judgment on their relative utility, and (ii) how these preferences may be changed by learning, in response to the combination of tutorials and multiple instances of feedback between player decisions and game outcomes. MARCHI is inspired by the Mar Chiquita Biosphere Reserve (Buenos Aires, Argentina) (Appendix B). Through their simulated role of members of a reserve management committee, players are asked to allocate a limited annual budget into five different management instruments with the aim of maximizing the sustainable capture of benefits from natural capital. MARCHI confronts the players with different planning and management strategies, ES and benefit indicators, monitoring, reassessment of their decisions and empowering them through the learning process. The management instruments available to players (i.e. monitoring and prospective, control of conservation regulations, PES, mechanisms for the access to natural capital benefits, and LUP), are some of the most important ESApp instruments. Reassessment is represented in MARCHI by specific instances for the evaluation and feedback of the games by the players throughout their successive games.

ES concept and its distinctive instruments (i.e. evaluation and assessment of ES, PES, other compensation mechanisms) are little known, highly questioned by different social actors, scarcely institutionalized, and rarely adopted in Mar Chiquita Reserve (Batista et al. 2019). Poor governance processes were recently reported by other authors (Renzi et al. 2022). Instead, there is some level of investment to provide and maintain access to benefits from natural capital, to control the regulations on biodiversity conservation and land use (hereafter control of regulations or just control), through the implementation of a management plan (including land use planning), the maintenance of a park ranger corp and an interpretation center. As part of independent research, populations of some species are also monitored and there are some prospective studies on land uses within the basin, but there is no monitoring of threats or state indicators (e.g. water quality), nor there is a technical team in charge of processing this type of information and producing appropriate management recommendations.

The usefulness of MARCHI as a cognitive and experiential learning tool (Bakhanova et al. 2020; Kolb 1984) is explored through the analysis of multiple successive games, with unpredictable (surprising) changes in system pressures, played by different social actors linked to the reserve, and through a survey about user's experience. In order to improve their game scores, players must find appropriate management strategies by changing their budget allocation to the five management instruments available (monitoring and prospective, control of regulations, PES, access to benefits from ES, and LUP). We hypothesize that players are able to learn about the suitability of different management instruments for different scenarios along successive games (H1), and predict that: H1.P1) initial preferences in favor of control of regulations, the most conventional and installed conservation instrument, over PES, the less accepted and not well understood conservation instrument in Argentina, decrease from the earliest to the latest repetitions of the game; H1.P2) the preference for instruments aimed at providing access to the benefits derived from natural capital (Access), increases through the successive repetitions of the game; H1.P3) the adjustments induced in the investment to PES, through the experience and skills acquired in successive games, are amplified in the face of unexpected increases in the rate of loss of natural capital; H1.P4) same as H1.P3 for Access instead of PES, and H1.P5) the design of the game, along with the design and use of its tutorials, does not allow for any eventual advantages for researchers as compared to non-researcher players.

In addition, we examined whether mean player's decisions was at least partly influenced by a simple trial-and-error approach, in opposition to mindful and well-informed decisions upon a meaningful learning environment (H2) (Westera 2022). By assuming that a non-reflexive playing strategy is mostly driven by the relative sensitivity of the game scores to random player's decisions (Fig. F.1), we expected significant relationships between the levels of exploration of the different management instruments by the players and the sensitivity of the simulation model to the variation of these instruments (H2.P1).

While here we evaluate MARCHI as a research tool, it is worth noting that the ultimate purpose of MARCHI and/or its derivatives is to contribute to participatory governance of social-ecological systems. However, evaluating the utility of serious games as intervention (Rodela et al. 2019), that is to trigger and facilitate socio-ecological changes (e.g. social learning, practices or instruments replacing), is a long-term process that is beyond the scope of this article.

2. Methods

MARCHI was designed as a learning and research object based on a simulated decision-making upon a participatory context, by exposing users to management scenarios, spatial and time scales, as well as system complexity, that go beyond their usual perception. It is a single-user, non-competitive game whose design and evaluation included both participatory (conceptual modeling, problematization, debriefing) and non-participatory procedures (knowledge integration, model formalization, and gamification). Hypotheses were addressed through four main steps (game design, participation, data collection, and data analysis). In addition to an informal postgame debriefing, an evaluation of users ́ experience was explored through a semi-structured survey.

MARCHI was inspired by the Mar Chiquita Biosphere Reserve, which provided a necessary realism for the engagement of the local participants in both preparatory (participatory conceptual modeling, Appendix A) and evaluative instances. Even so, the game warns players that this is not a tool for prediction or management of that system. For a description of the system represented by MARCHI, see section 2.1.3 (Knowledge support, within Game design).

2.1. Game design

2.1.1. Overview

MARCHI was developed using STELLA Architect ® 3.1, both for the knowledge integration phase in the supporting simulation model, and the model-user interface containing the user guides, tutorials, and the game console. While former STELLA versions have been widely applied as dynamic model builder, the Architect versions also allow for model gamification, communication and online sharing. Preliminary versions of the model-user interface were iteratively adjusted from opinions and comments made by a total of nine volunteers (six students and three non-professional citizens). Final versions of the supporting simulation model and the game can be accessed and played online from computer, tablet or smartphone devices, in Spanish, from https://exchange.iseesystems.com/public/pedrolaterra/marchi-163/index.html#page1, and can be downloaded from: https://exchange.iseesystems.com/profile/4908.

The game begins with a presentation of the general problem in text format with illustrations, and then continues with a questionnaire aimed at defining the player's profile. After answering this questionnaire, the player accesses the conceptual foundations, objectives and rules of the game, which are offered in text and video format, as described below.

2.1.2. Goals and main trade-offs

The ultimate goal of the players is to maximize the capture of ES benefits, while minimizing the loss of natural capital, in the medium term (15 years). It requires a balanced investment of limited financial resources to conservation of natural assets and ES supply (i.e. control of regulations and PES) vs. access mechanisms for the capture of their benefits.

2.1.3. Knowledge support

The game is based on a simulation model that integrates two sources of information. On the one hand, a conceptual model of the functioning of the Mar Chiquita Biosphere Reserve was obtained from three multi-stakeholder, participatory workshops, where the lagoon was identified as the main natural asset of the reserve, as well as the opportunities and threats associated with their ecological "health" (Appendix A). On the other hand, the knowledge and scientific information available on the factors and drivers that affect the water quality of the Mar Chiquita lagoon (and comparable systems) and the capture of its benefits were gathered, including published information as well as authors ́ educated guesses when that information was not available (Appendix B).

The simulation model is based on the ESApp, integrating sub-models on the dynamics of i) natural capital, ii) ES and their benefits, iii) land use changes, and iv) management strategies. Part of the feedback between these models depends on the decisions that players make through a virtual console. The main aspects of each sub-model are described below and a detailed description of the model can be found in Appendix C.

Natural capital. This sub-model assumes that the bundle of benefits depends directly on the quality of the lagoon's water, which can present different levels of degradation. We used concentration of phosphorus (P) as a proxy of water degradation and loss of ES supply. In turn, the P concentration depends on the P load in the main tributaries of the lagoon. Most of the catchment basin is made up of agricultural production systems (annual crops and livestock) outside the reserve, and the P carried by the tributaries depends largely on the balance between land cover of crop fields and cattle ranching. Annual crops represent a high source of P from their fertilizers, and cattle ranching is mostly based on direct grazing on semi-natural grasslands that are scarcely or not fertilized. In contrast, wetlands and riparian vegetation strips are able to filter P and thus play an important role in protecting the water quality of the lagoon.

Ecosystem services and their benefits. The main output of the model consists of the bundle of benefits generated from the ES supplied by the Mar Chiquita lagoon. These benefits are expressed as a relative index (dimensionless) that represents the fraction of the bundle of ES (e.g. sport fishing, commercial fishing, water sports, camping, flora and fauna observation) that are captured by different beneficiaries through different fishing activities, recreation and, indirectly, through the provision of services to these beneficiaries (fishing guides, boat rentals, jobs in tourism and conservation, hotels, construction and maintenance, among other economic activities). The final ecosystem service that supports this set of benefits is the regulation of the water quality of the lagoon. Despite that nutrient retention occurs in sediments and vegetation of shallow lagoons, for the sake of simplicity the model assumes that water quality only depends on: a) P exported by runoff from crop fields to the drainage system, b) retention of P loaded in runoff within strips of riparian vegetation, and c) the retention of P that reached into riparian wetlands of the tributary streams of the lagoon (Appendix B).

Land use changes. This sub-model defines the annual rate of P export to the streams that drain into the lagoon, which depends on the area of the main cover and land use types in the basin: a) native grasslands, riverine wetlands (hereafter just wetlands), and riparian vegetation under direct grazing, and b) fields of annual crops. These areas vary from play to play (one play = one annual run), according to two alternative scenarios of the annual rate of conversion of less modified ecosystems (native grasslands, wetlands and riparian vegetation) to annual crops (hereafter, agriculturization rate, Manuel-Navarrete et al. 2009): i) a slow and uniform agriculturization rate, by default during 92% of the annual runs, and ii) the doubling of that rate in a deterministic way but not anticipated by the players (surprise events), during three consecutive years (5th, 6th and 7th years or plays) within four independent games (the 3rd, 4th, 6th and 10th games). We included surprise events based on our hypothesis about their effect on instrument adoption, which meets one of the requirements of socio-ecological systems. Additionally, these surprise scenarios were created to improve learning outcomes by increasing motivation and engagement (Wouters et al. 2017).

Management strategies. The reserve management strategy is decided by the players and consists of the allocation of funds among five instruments that compete for funding from the same annual budget: a) Monitoring and Prospective, b) Control of regulations, c) PES, d) Access to the benefits of ES, and e) Land Use Planning (LUP). Investing in Monitoring and Prospective gives players the advantage of early warnings about natural capital stocks, environmental services, and benefit flows, as well as potential land use changes. This data is generated by a virtual technical team that periodically evaluates environmental indicators and examines trends and scenarios on land use changes. Control represents different actions to limit agriculturization rate (i.e. the expansion of agriculture on grasslands, strips of riparian vegetation and wetlands) following current legislation. The allocation of the budget to PES represents a financial compensation to farmers who agree to conserve native and cultivated grasslands, strips of riparian vegetation and wetlands within their properties. By charging an entrance fee, PES is the only instrument capable of increasing the funds available to finance conservation actions. By default, it is assumed that the Control, PES and Access actions have a very low level of efficiency to achieve their goals, but that efficiency increases when informed by previous LUP studies and followed by Monitoring and Prospective activities.

2.1.4. Learning objectives

The supporting simulation model and the rules of the game were designed to ensure that the final score of each player depends on their ability to understand and apply a series of basic learning objectives, which can be synthesized as follows:

a. The objectives of multiple-use protected areas are not limited to the conservation of biodiversity and other forms of natural capital, but also include the sustainable provision of benefits from that capital.
b. Neglecting access to ES can be just as detrimental to reserve objectives as neglecting the conservation of natural capital.
c. The natural capital that sustains the ES of the reserve is not necessarily constrained to the spatial limits of that reserve.
d. Natural capital can only be partially protected by management actions under the control of decision makers. There are external factors (drivers) that require continuous adjustments in management strategies.
e. The level of pressure exerted by these drivers can vary unpredictably, but signs of change can be early warned to players by allocating resources to finance Monitoring and Prospective tasks.
f. Investment in the development and implementation of economic compensation mechanisms for private owners can promote levels of conservation that are complementary or even higher than those obtained through regulation and control mechanisms.
g. Both actions for the conservation of natural capital and those aimed at improving access to ES improve their effectiveness when they are in prioritized areas based on LUP.

The incorporation of these learning objectives to player's decisions is not only induced through the game tutorials, but also through a) messages (pop-ups) with warnings and recommendations to the players that appear during the game depending on the state of the represented system, simulating decisions support from a technical team, and b) a synthesis of the decisions made by the players and their outcomes, throughout the 15 runs that make up each game. The progressive incorporation of the basic principles of the game into the decisions of the players should improve the scores of their games and, consequently, their final scores (both visible to each player). In each play (one year), players can modify the parameters that define their management strategy (Fig. 1).

2.1.5. Command board and feedback systems

Each player was asked to repeat the game 10 times consecutively, that is, within the same work session. These repetitions were designed to assess the game's ability to foster learning through self-reflection on the moves, as well as to generate enthusiasm and drive for the players to complete game repetitions, based on their perceived self-efficacy (Bandura, 1994). Each player's score is defined by the average service capture over the 10 consecutive games.

Having gone through the instructions and questionnaire, players can access a virtual console or command board. Here, they can allocate the budget among the management instruments before each annual play, taking into account messages from the virtual technical team (depending on the prior allocation of funds to Monitoring and Prospective), as well as the trajectory of the ES supply, ES benefits, and annual crop coverage (all as percentages of the initial value).

In order to promote learning by doing, the game offers players three feedback instances. First instance follows each one year running and consists in a score displayed after each run within the command board, where players can see their numerical scores, play after play, classified as low, medium and high scores with different colors within the display (Fig. 2). Second, a menu of 13 different pop-up messages within the command board, simulating recommendations from the technical team in face of player decisions as well as the conditions of the reserve and its watershed (Appendix D). Third feedback instance takes place at the end of each game (after 15 successive plays), when the command board automatically goes to a graphical synthesis of the decisions made by the player and the consequent trajectories of natural capital, ES and benefits (hereafter, game Review Screen) (Appendix E).

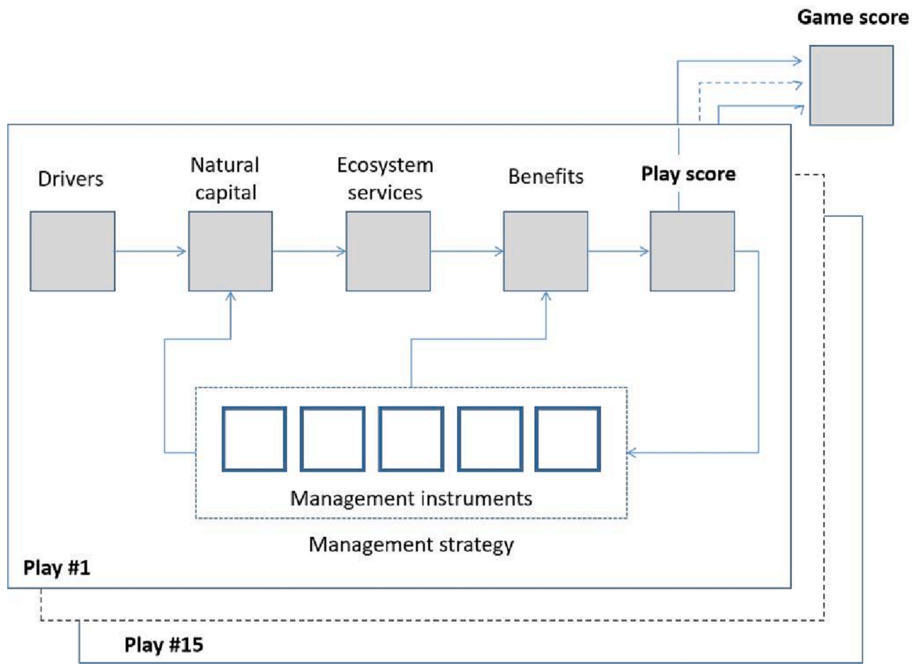

Fig. 1. General flow chart of the mathematical model behind MARCHI. In each run or play, the player defines the management strategy, which partly defines the conservation of natural capital and the access to benefits from ES. Every play corresponds to one year and one game is completed after 15 runs. The game score results from the cumulative play scores, and the player's final score results from the average of 10 subsequent games.

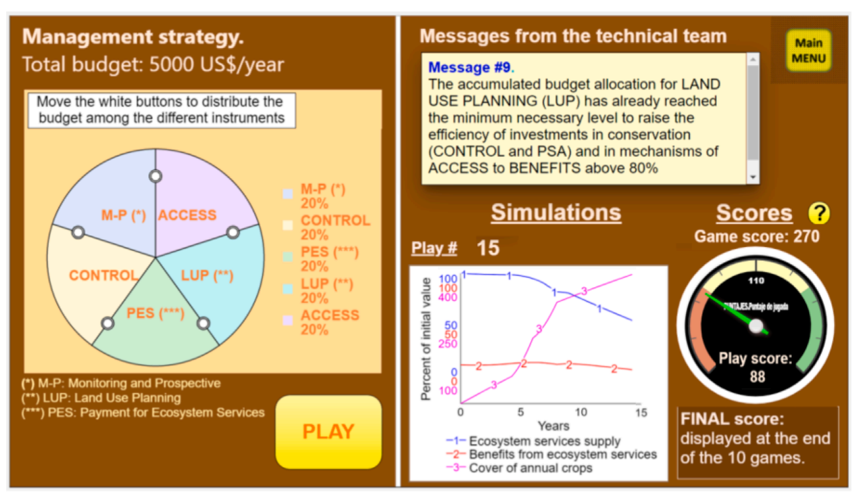

Fig. 2. MARCHI's command board with budget distribution among management instruments (left), messages from a virtual technical team (top right), trajectories of main variable states (bottom center), and partial scores (bottom right).

2.2. Participation and data collection

Data was obtained by means of online plays on the website of the Isee Systems ExchangeTM service. It was then collected from players who responded to two types of calls. The first of them was carried out by email invitation to a list of 215 selected from the author's personal contacts, including researchers and other social actors linked to biodiversity conservation and ecosystem management in Argentina. The second call consisted of personalized and social media invitations to social actors from the Mar Chiquita Biosphere Reserve, previously identified during the above mentioned workshops (Appendix A). A small reward was offered for each of the three best scores, which consisted of books on ecology and biodiversity.

The game was accessed by a total of 38 respondents from both calls during October and November 2021, 30 of them scientific researchers and the remaining 8, corresponding to other types of social actors linked to the reserve (park rangers, neighborhood association officers, social communicators, etc.). Researchers played remotely while the other social actors participated in a workshop held at the Interpretation Center of the Mar Chiquita Biosphere Reserve in November 2021. Facilitators helped and encouraged them to make their game decisions individually and independently. The analysis of the results was carried out with data collected from the 24 players who completed the series of 10 games (17 researchers and 7 representatives of the other social actors).

2.3. Data analysis

2.3.1. Learning

While serious games may promote cognitive, skill-based as well as attitudinal learning outcomes, our evaluation of learning by playing was limited to the first two types, assuming that a better understanding about the ESApp, their management instruments, and the tradeoffs among different decisions involved in the sustainable capture of ES benefits, can be reflected by the progression of game scores obtained by each player throughout the series of 10 games. In order to estimate this progression of the player's initial level of knowledge independently, a Learning Index (LI) was calculated as the relative increase in the scores of the last games with respect to the scores obtained in the first games, as follows:

$$LI = 100*\frac{ASC_2 - ASC_1}{ASC_1} \quad (2)$$

where ASC_1 is the averaged score for the first five games set, and ASC_2 is the averaged score for the second five games set. Although a learning process cannot be ruled out within the first five games, in order to account for the ability of players to incorporate surprising changes in the external conditions of the system into their decisions, this index compares two game sets with the same frequency of surprise changes in the rate of agriculturization. Due to the limited number of responses received, testing the suitability of MARCHI to induce learning of its principles and comparing the learning capability between the two player profiles was performed using a resampling procedure based on 10,000 bootstrap samples (with replacement) to generate the median effect size and 90% and 95% confidence intervals. The same procedure was carried out to analyze the player's final scores.

Instrument preferences. Budget allocation to the different instruments was statistically analyzed using a repeated measures analysis of variance (ANOVA), and predictions were tested through planned comparisons. To facilitate interpretation of results, the high dimension of the original experimental design (2 Profile levels × 10 Game levels × 15 Play levels × 5 Instrument levels = 1500 levels) was reduced to 40 levels by selecting four Games levels (two early games and two late games), two Play levels (early and middle years) and the five Instruments levels (Monitoring and Prospective, Control, PES, Access and LUP) as within-subjects factors, and two Profile levels (researchers vs. other social actors) as between-groups factor. One game with a slow agriculturization scenario and another game with a suddenly fast agriculturization scenario were selected within both the early and the late game sets. While early selected years represented a period of low agriculturization rate in all games, middle selected years represented a period of fast and sudden agriculture expansion in only two games (one in each game set).

2.3.2. Sensitivity analysis and instrument exploration

Variance-based sensitivity analysis has been adopted because it has been found to be more effective than conventional sensitivity analyses in complex non-linear models (Jadun et al. 2017; Veihe and Quinton, 2000) like the MARCHI case. This type of analysis takes into account the variance of the results for representing the model's output changes in response to continuous changes in its inputs. This is in contrast to conventional sensitivity analyses, which involve arbitrarily and discretely increasing and decreasing individual input variables and parameters. The coefficient of variation of the model outputs (scores) was used instead of the variance to identify which types of instruments are most influential in determining those outputs, regardless of their influence on the mean scores. The instrument-specific sensitivity of the model was estimated as the coefficient of variation of the game scores (CV_s) obtained from an STELLA® built-in sensitivity analysis, where the percentage of assignment to the instrument varied sequentially along 100 runs of the model within the range 1–100%, using a random uniform distribution and distributing the remaining budget equally among the remaining instruments (Fig. F.1).

In addition, the level of exploration of management instruments by players was characterized by the mean coefficient of variation of the investment in each type of instrument (CV_i), separately calculated for two game sets (first five games vs. second five games). The effects of player profile, game set and instrument type on CV_i was statistically analyzed using a repeated measures analysis of variance (ANOVA).

Trial-and-error influence on players' strategies, as expected according to H2.P1, was tested by examining the relationships between CV_s and CV_i, by assuming that purely trial-and-error strategy of budget investment for instruments with low sensitivity (low CV_s) leads to lower exploration levels (low CV_i) than for instruments with high sensitivity (Fig. F.2). The relationship between each instrument-specific CV_i and the instrument-specific CV_s of the model was preliminarily examined in a scatter plot and no further statistical analysis was necessary.

2.4. Users' experience

Evaluation of users' experience included the answering rate to playing invitation, completion rate of the 10 asked games, a non-intrusive assessment of users' interaction with the system based on time-on-pages collected and provided by the online game host (https://www.iseesystems.com), as well as the answers to a post-game questionnaire and informal debriefing groups during the play-time. The link to an online anonymous questionnaire was sent to each gamer, that is any invited person who played at least part of one game (N = 32). Detailed questionnaire is shown in the Appendix G, and since only 8 responses were received, analysis was basically descriptive and qualitative.

3. Results

3.1. Preferences for management instruments

Neither player's profile nor instrument types showed simple main-effects on budget allocation, but double and triple interactions between instrument types with Games and/or Play factors were significant or highly significant (Table 1). Results suggest that researchers and non-researcher players did not have enough differences in knowledge and skills before the game to affect their performance, or MARCHI design plus the tutorials were able to provide a similar basis for scientific and non-scientific players, so prediction H1.P5 could not be rejected. Therefore, significant Instrument × Game and Instrument × Game × Play interactions, respectively (Table 2), and planned contrasts (Table 3) agreed with H1.P1, H1.P2, and H1.P3 predictions, but not with H1.P4 prediction.

Table 1
P-values for different sources of variation of budget allocation to management of the modeled reserve, according to a series of repeated measures ANOVA applied to simulations collected data, with two player Profile levels (researchers vs. other social actors) as between-groups factor, and four Game levels (two early games and two late games), two Play levels (early and middle years) and the five Instruments levels (Monitoring and Prospective, Control of regulations, PES, Access and LUP) as within-subjects factors. Bold numbers highlight significant p-values ($p \leq 0,05$). References: PES: Payment for Ecosystem Services; LUP: Land use planning.

Sources of variation	d.f.	F	p
Profile (P)	1	0.490	0.492
Game (G)	3	0.490	0.691
G * P	3	0.490	0.691
Play (Pl)	1	0.490	0.492
Pl * P	1	0.490	0.492
Instruments (I)	4	1.750	0.147
I * P	4	1.340	0.263
G * Pl	3	0.490	0.691
G * Pl * P	3	0.490	0.691
G * I	**12**	**2.800**	**0.001**
G * I * P	12	0.990	0.458
Pl * I	**4**	**3.410**	**0.012**
Pl * I * P	4	0.300	0.876
G * Pl * I	**12**	**3.180**	**<0.0001**
G * Pl * I * P	12	0.970	0.474

Table 2
Contrasts performed for testing the four predictions (P1, P2, P3, P4) from the first hypothesis (H1). Contrasts including Profile factor are omitted because of their lack of significance in ANOVA. Sc. indicates scenarios (1: default slow agriculturization rate; 2: surprisingly high agriculturization rate). Bold numbers highlight significant p-values ($p \leq 0,05$). References: PES: Payment for Ecosystem Services; LUP: Land use planning.

Sources of variation	Levels		Contrasts			
			H1.P1	H1.P2	H1.P3	H1. P4
Profile	1	Researchers	1	1	1	1
	2	Others	1	1	1	1
Game	1	(2nd) Sc. 1	1	1	1	1
	2	(3th) Sc. 2	1	1	−1	−1
	3	(9th) Sc. 1	−1	−1	1	1
	4	(10th) Sc. 2	−1	−1	−1	−1
Year	1	(1st)	1	1	1	1
	2	(5th)	1	1	−1	−1
Instrument	1	Monit.	0	1	1	1
	2	Control	1	1	1	1
	3	PES	−1	1	−4	1
	4	Access	0	−4	1	−4
	5	LUP	0	1	1	1
Sum of sq.			**1516.33**	**1431.26**	**346.98**	51.42
d.f.			**22**	**22**	**22**	22
F			**6.05**	**7.93**	**6.39**	0.80
p			**0.022**	**0.010**	**0.019**	0.380

Table 3
Spearman ranks correlations of game scores with learning index, time spent by players in the review screen, reading the introduction plus the written tutorial, watching the video tutorial and the total run time. Numbers in bold indicate significant correlations for p<=0,05.

	Learning Index	Review Screen	Introduction + text tutorial	Video tutorial	Total run time
Learning index	–	−0.23	−0.14	−0.25	0.01
Scores from 1st games set	**−0.43**	**0.56**	−0.06	0.07	0.01
Scores from 2nd games set	**0.79**	0.06	−0.10	−0.18	0.23
Final scores	0.21	**0.45**	−0.35	−0.07	−0.13

According to H1, players showed changes in their preferences for different management instruments that reflect an effective learning process about their relative suitability. As posed in H1.P1 prediction, and in accordance with the model assumption of a higher return on investing in PES than in Control instruments, Control to PES investment ratio was higher in the earlier (2nd and 3rd) than in the latest (9th and 10th) games (Fig. 3). Furthermore, the higher average investment in Control than in PES observed in the 2nd game was reversed in the 3rd game, and investment differences between both instruments became more pronounced in the last two games. Moreover, in agreement with H1.P3, the adjustments induced in the investment to PES were amplified in the face of surprising increases in the rate of loss of natural capital under high rate of agriculturization scenarios. Investment to Access instrument was higher during the latest than during the early games as posed in the H1.P2 prediction, but no significant investing adjustment was shown for this instrument in response to surprises in agriculturization rate (H1.P4) (Table 2, Fig. 3).

In addition to the predictions tested, Fig. 3 shows the variation of other instruments that are worth commenting on below. First, the low average investment in Monitoring and Prospective after the 3rd game is striking, despite its importance in guiding decision-making. Rapid learning of the recommendations during the first game may have led to the incorrect conclusion that subsequent games did not require such investment, without taking into account the warnings from the game's presentation and tutorials that different games could bring surprises. Secondly, after the first game, there was a sharp drop in the investment in LUP between the 1st and 5th games. This reflects the virtual teaḿs recommendations to use the instrument early on, as its effect on the efficiency of conservation and access instruments will saturate after a certain level of investment and remain throughout the game. Finally, investment to Access increased during the year with a high agriculturization rate, despite a prioritization of conservation instruments (Control and PES) could be expected. However, sensitivity analysis suggests that by the final Game, players were able to find that for this model an intermediate to high investment to Access was the best general decision (Fig. 3), independently of theoretical considerations.

3.2. *Learning*

Players did not differ in the Learning Index according to their profile, either using parametric or bootstrap confidence intervals. The Learning Index ranged between −28.85 and 192.35, with a positive mean value significantly different from zero ($18.29 \pm SE = 4.46$). This general trend was mainly explained by increasing late scores, since only the mean play score of two last games under the low and stable scenario of agriculturization rate resulted significantly higher than the rest (Fig. 4).

According to correlation analysis, the Learning Index was not significantly influenced by different indicators of players' total investment of time playing the game or part of that time spent in its different components, like the tutorials and the Review Screen (Table 3). The correlation between the Learning Index and scores from the first and second games, as demonstrated by eq. [1], not only reflects a mathematical dependence. It also indicates that players with high performance in the first game set had limited chances to demonstrate a high Learning Index. This can explain why time spent by players in the Review Screen was significantly related to scores from the first games set and final scores but not to the Learning Index.

3.3. *Instruments exploration*

Within the simulation model underlying MARCHI, the reserve management instruments show different patterns of sensitivity (Fig. E.2). Allocation of the budget to Monitoring and Prospective showed a negative influence on the game scores, declining almost linearly until an abrupt change in slope at high budget share values. This response corresponded to the highest sensitivity (CV_i) compared to the rest of the instruments. Game scores also varied inversely with the conservation actions (Control and PES), although PES stood out by showing the lowest sensitivity of all the instruments. The budget allocation to LUP displayed a maximum game score response at relatively low allocation values and an intermediate sensitivity. In comparison, the budget allocation to Access revealed a maximum game score response at intermediate allocation values with an intermediate sensitivity. Additionally, it had a higher mean score than the rest of the other instruments.

In disagreement with H2.P1, players' instrument exploration did not differ significantly between game sets, and it was not related to model sensitivity (Fig. 5). Land use planning was the most explored instrument by the players within the two sets of games, while the exploration of the rest of the instruments did not show differences between them.

3.4. *Users' experience*

The response rate for the first call was low (14%) and the completion rate of those who responded to the first or the second call (the portion of invites who accessed the game and completed the 10 asked games) was 63%. Except for one case, all the players who resigned before completing the 10 games corresponded to remote players. In the face-to-face

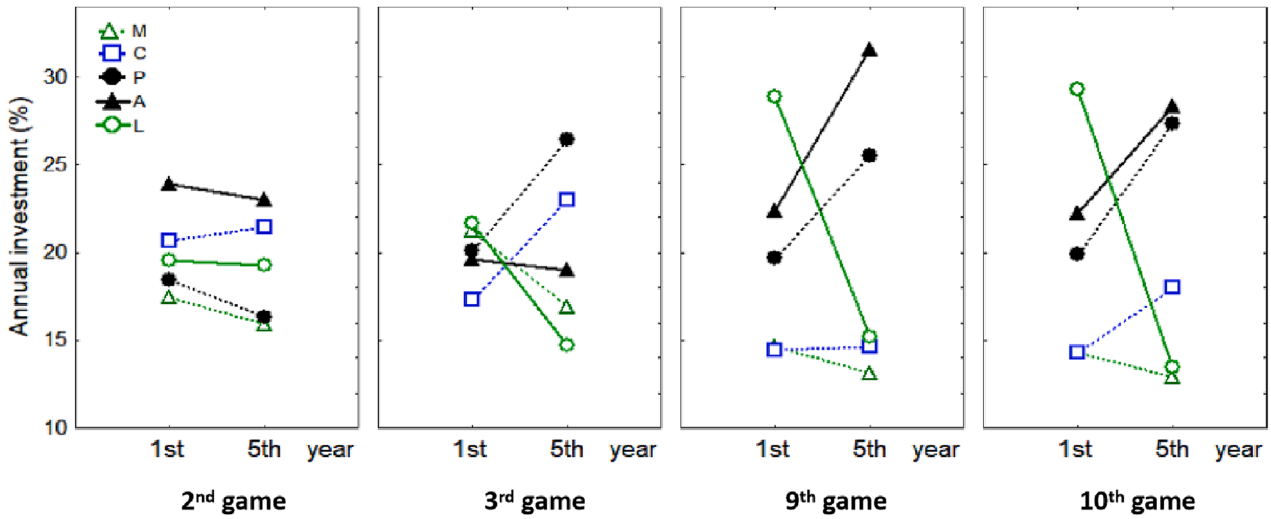

Fig. 3. Weighted means after repeated measurements ANOVA of budget allocation (investment) in different management instruments (M: Monitoring and Prospective, C: Control of regulations, P: Payment for Ecosystem Services, A: Access to benefits from ecosystem services; L: Land Use Planning), for two scenarios, the default slow agriculturization rate (2nd and 9th games) and high agriculturization rate (3rd and 10th games), and two selected years (1st and 5th years) within games.

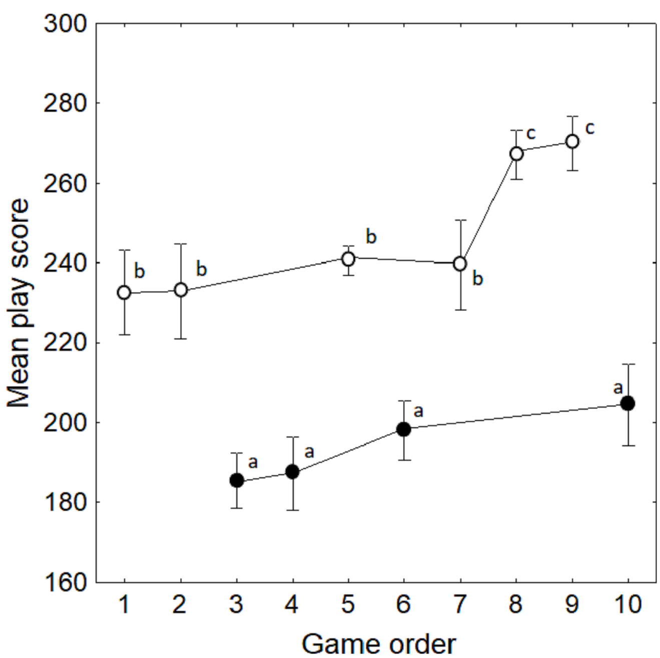

Fig. 4. Mean play scores by game along the 10 games sequence. White and black filled points indicate games with low-stable or surprisingly high scenarios of natural capital loss, respectively. N = 24; whiskers represent two standard errors. Different letters mean significant differences (p<=0,05) according to a post-hoc Tukey test.

workshop, the players showed a high level of interest, concentration and interaction with the facilitators and with each other (authors' *pers. observation*). There were no expressions or attitudes of abandonment, or questions about the instructions or the realism of the game, except for the only player who did not complete the 10 games, who expressed to the facilitators his decision to always prioritize the conservation of species and ecosystems, despite having understood the instructions of the game, due to a matter of personal conviction.

No significant differences were observed between profiles of the 24 players who completed the 10 games in the time spent across the 10-game series, nor in the average time spent watching tutorials. The mean total time assigned was 59.96 min (range = 26.62–122.22, SE = 5.60). The average time assigned exclusively to the game (without the introductions or tutorials) was 40.44 min (range = 13.59–92.60, SE = 4.32). Mean time allocation to the Review Screen did not vary between profiles, ranging 0.00–8.01 min with a mean value of 0.52 min (SE = 0.34). Final scores did not differ between player's profiles, and varied between 310.33 and 444.43, with a mean value of 381.59 (SE = 7.18).

The post-game survey was answered by 8 players out of 32 who started the game. Five of those players strongly agreed with the statement "I have read or watched the MARCHI tutorials and instructions carefully", and the remaining three players disagreed with it. Six of the eight players fully agreed with the statement that "MARCHI has helped me to better understand the consequences of different management strategies for a multi-purpose reserve" and only the two remaining players disagreed. Seven of those eight players agreed or totally agreed with the statement that "I found MARCHI useful as inspiration to apply simulation games to other problems of interest to me", while the remaining player disagreed with that statement. Five of the eight players strongly agreed with the statement that "In general, I found the fundamentals and instructions of MARCHI understandable and useful", while the remaining three players disagreed. In general, the open comments received in the questionnaire reflect a positive evaluation of the game. In three of the answers, it was suggested that some of the game components were too long and capable of inducing fatigue, with effects on the concentration in the game.

4. Discussion

Our results illustrate the suitability of serious games for learning and better understanding of stakeholders' decisions in a particular socio-ecological context, and suggest some cues for improving users̕engagement and learning outputs. Formerly posed hypotheses and predictions are discussed below, with particular attention to the capability of a serious game to induce changes in players' preferences on the management instruments of a multiple-use area, along four main items: preferences, game exploration, learning, and users' experience.

4.1. Preferences for management instruments

One of the most frequently cited barriers to effective stakeholders' collaboration is constituted by adherence to apparently opposed

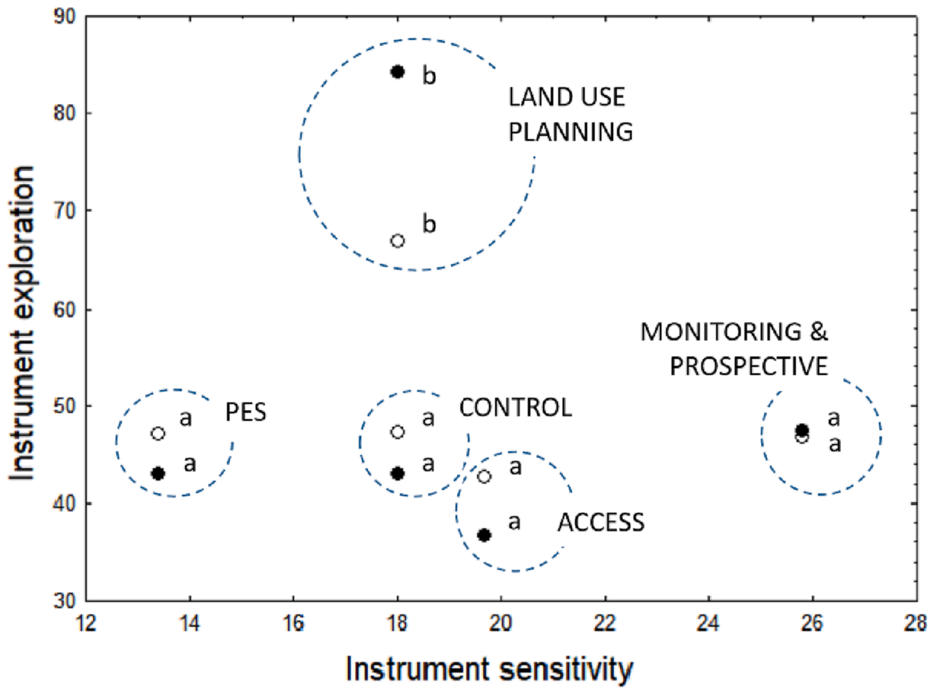

Fig. 5. Relationships between the mean Players' exploration levels of the different management instruments in different game sets (○: first games set, ●: second games set) and model sensitivity for these instruments (instrument sensitivity). Players' exploration levels are represented by mean coefficients of variation (%) of their budget allocation to instruments and model sensitivity is represented by coefficients of variation (%) of final game scores upon random variation in that budget allocation (see Figs. E.1 and E.2). Encircled markers correspond to the same instrument. Different letters indicate statistically significant differences ($p < 0.05$). PES: Payment for Ecosystem Services.

paradigms. That is the case of conservation oriented by the intrinsic value of biodiversity vs. by ES, and management oriented by regulation and control mechanisms vs. its complementation through compensation mechanisms PES (Muradian et al., 2013; Van Hecken et al. 2015). MARCHI demonstrated the ability to reveal the initial preferences of the players around different management instruments, as well as to induce non-random changes in those strategies. Observed influences from the provided feedback opportunities (e.g. correlations with time spent on the review screen) on players scores showed that changes induced in the players' strategies were, at least partly, the result of a learning process. In general, results support the ability of this tool to create a virtual environment where the participants were able to cope with some barriers for the integration of ESApp instruments reported for Argentina (Batista et al. 2019). Thus, initial preferences for conventional conservation instruments (Control) were effectively balanced by PES, which are barely known and applied in a very incipient way within the country, as well as the progressive investment in Access instruments for the capture of benefits from natural capital.

4.2. Learning

Our results support the potential utility of serious games as learning tools aimed at policy- and decision-makers for improving the conceptual and instrumental application of the ESApp to complex scenarios, real or inspired by real cases. Learning was basically expressed as changes in the relative preferences for the different management instruments of the reserve, and in their consequences on the capture of benefits of ES accumulated in the long-term. More significantly, this evidence suggests that the players' decision-making was guided by the basic principles incorporated into the game and by feedback on decisions based on outcomes in a low-risk experimental environment.

Assuming individual game scores as proxies of understanding, it follows that MARCHI was able to significantly improve the players' understanding about how different management instruments can be combined, for the long-term capture of benefits from nature in particular scenarios. Positive average learning partly reflects MARCHI efficacy for increasing players' preferences by Access to capture of benefits and PES, two key ESApp instruments and main components of the MARCHÍs principles.

On the other hand, Learning Index showed a poor capacity for explaining individual variation in final scores, probably because of a ceiling effect, which consists in the lack of detectable learning of highly skilled or knowledgeable players before the intervention (Koedel and Betts 2010; van Beek et al. 2022), because the achievement of very high scores in the first games set. Therefore, the observed influence of time spent in the Review Screen on individual variation in final (accumulated) scores was at least partly explained by mean scores in the first but not in the second game set, indicating that disposition to or capacity for analysis of consequences of previous decisions was the key factor explaining players' success, overriding any direct influence of player's profile, and time spent playing or looking tutorials.

Results also provided evidence on the influence of the number of repetitions necessary for significant learning of the average players. Despite the variations between players, the mean average final scores only improved after seven replays of the game, and only for the low and stable agriculturization rate scenario. This implies that the utility of MARCHI, as well as other comparable serious games, could be underestimated after an insufficient number of repetitions, and that players' learning was impaired by the surprising scenarios. It is noteworthy that, due to our interest in exploring the system's properties that are revealed over the medium to long term (e.g. resilience to surprises, sustainability), we have tested observable learning by comparing games over a 15-year period, rather than the more immediate learning observable by comparing plays within the same game over a one-year period. This differentiates our study from other learning assessments we have reviewed, while preventing us from making comparisons regarding the importance of the number of repetitions to learning.

The lack of observed links of the Learning Index and the final score with the time allocated to the introductory pages of the game, nor with the tutorials in text or video format, does not allow us to rule out the usefulness of these tutorials on learning opportunities, due to the lack of control over prior knowledge. In fact, players' answers to the survey showed a variable assessment of the usefulness of these tutorials for making the most of the game.

Since learning outcomes not only depend on their content but also on how game characteristics affect behavior and attitudes, different relationships between learning outcomes and gameś attributes have been explored (Landers 2014; Wilson et al. 2010). While some of those attributes, like fantasy and mystery, are clearly undesirable for the engagement to serious games, others like representation, adaptation, assessment, challenge, conflict, control and interaction play complementary roles for enabling learning outcomes. The influence of these attributes in learning outcomes from MARCHI were not objectively evaluated; however, some cues were observed from the interaction with players and instructors as well as from the answers to open questionnaires. For example, the low representation level (i.e. the physical and psychological similarity between a game and the environment it represents), *a priori* not so important for a socio-ecological system game compared to, for example, a flight simulator, may have precluded a direct perception of results for players less acquainted with graphs. An iterative adaptation of game complexity to players' proficiency may improve their learning outcomes (Van Oostendorp et al. 2014) and should be considered in future versions of MARCHI and similar serious games. Motivation for learning with MARCHI was not based on challenges, in terms of difficulty and improbability of obtaining goals. However, conflicts in terms of budget allocation to alternative combinations of management instruments, and the consequent trade-offs between conservation of natural capital vs. capture of ES benefits under unpredictable scenarios, challenged the players to maximize the capture of ES benefits in the long-term.

4.3. Game exploration and users' experience

Our results did not provide evidence for any relationship between the relative exploration level of management instruments and model sensitivity to them, as expected according to a significant influence of a trial-and-error approach on player strategies. The trial-and-error approach to serious games is not necessarily an undesirable strategy for learning objectives, but rather may reflect a free exploration of the system in search of creative solutions. However, in contexts such as the one provided by MARCHI, where it is intended to promote the application of new knowledge to produce rational decisions from reflective feedback, a predominance of trial-and-error may indicate a certain inability of the game to achieve its objectives. Some authors warn about the tendency to act before thinking in serious games (Westera 2016), and overly complex games can discourage reflective behavior and promote essentially non-rational trial-and-error strategies (Grana 2022).

Assessment opportunities, which were provided in MARCHI through different tutorial formats, as well as plenty of feedback between decisions, intermediate and final system outputs and scores, showed mixed relevance. Time spent on the Review Screen seems a good proxy of players' relative effort for educating their decisions on the basis of past games and becomes the best observed predictor of userś performance according to its correlation with early and final game scores.

Even though the duration of the game was within 1–2 h, which is considered appropriate to promote engagement and avoid fatigue of play-learner (Loh & Sheng 2015), the previous questionnaire and tutorial sessions greatly expanded that time, so most of users finally showed symptoms of fatigue. This could not only have had a negative impact on the performance of these players, but also made it inadvisable to carry out the planned debriefing. This experience suggests the convenience of paying more attention to the duration of the game and the related sessions.

4.4. MARCHI's limitations and opportunities

The effectiveness of serious games hinges on recognizing and addressing key factors affecting learning outputs, as previously discussed for different contexts (Barreteau et al. 2021; Ravyse et al. 2017). The capability of MARCHI to promote learning would be susceptible to improvements in at least three major aspects: a) realism and engagement, b) call success and duration of the learning process, c) post-game surveys and debriefings.

Although there is agreement on the importance of game realism in the learning outputs, its optimal level depends to a large extent on the type of intended learning (cognitive, normative, relational), learning subject (e.g. training on surgery skills, training on decision making in natural resource management contexts), the player profile (e.g. age, education level), as well as on the type of realism under consideration (e.g. perceptual, systemic). The level of realism of a serious game can affect its usefulness through different mechanisms. It is generally recognized that if the system representation is too narrow or abstract and disconnected from the player's real-world experiences and interests, players may not perceive it as relevant to their learning goals and may lose interest and motivation to learn. On the other hand, the excessive information and complexity of system representation may hinder the player's learning outputs by overloading different cognitive mechanisms (Aubert et al. 2018; Thorpe et al. 2019; Wouters et al. 2008).

Since perceptual realism mediated by animation and sound features were assumed of low importance for the expected cognitive learning and the profile of MARCHI's players, design effort was directed to system realism, through a process-based representation of most of the links between management decisions and ES (Appendixes B and C). This effort ran into two important limits in the available knowledge on functional relationships between the phosphorus content in the water column of the lagoon, the flow of different ES, and the capture of the ES flows into benefits. We faced these limitations by adopting ecological production functions (Paruelo et al. 2019; Tallis & Polasky 2009), consisting in a threshold model representing P dependent eutrophication risks for similar ecosystems, and hyperbolic ES flow to benefit capture relationships. These assumptions clearly jeopardize a forecast utility as might be expected from a predictive model or a DSS, but since they do not violate conceptual or systemic realism, we cannot foresee any significant consequences on MARCHI learning processes. In contrast with the ecological processes, the social dimension of MARCHI's was poorly represented, offering multiple opportunities for improvement in future modules or versions of the game. For example, farmers' enrollment rate into PES programs was assumed as a constant portion of those eligible according to available funds, land use and farm position into the landscape, without considering any other psycho-social factor affecting the process (Giaccio et al. 2020).

Despite obtaining enough data to test the proposed hypothesis, the low response rate highlights the difficulty of engaging the participation of the main social actors, including local government, farmers and the hotel industry. In addition to an unknown influence from the COVID-19 pandemic and lock-down, the low participation level may be explained by a still insufficient coverage of the problem in the local and national mass media, a small social commitment, and/or the absence of other incentives for potential players' participation. Therefore, learning processes involving all the key stakeholders and distributed over multiple gaming sessions over time, typical in formal educational contexts, seems very difficult to sustain unless more effective social commitment and other attraction mechanisms are implemented.

Our post-game questionnaire was valuable in mobilizing players' reflection on their experience and obtaining information about their perception of the learning process, so the need to implement these queries immediately after finishing the game and increase the response rate becomes evident. Along with questionnaires, observations, interviews, and data recording, debriefings is one of the most common methods of evaluating learning outcomes from serious gaming experiences (den Haan and van der Voort 2018). While our evaluation basically relied on data logging for the assessment of cognitive learning, the inclusion of well planned debriefings on what happened during the game could also elicit the normative (e.g. changes in participant beliefs) and relational dimensions (e.g. changes participant reflections and social networks) of learning (Baird et al. 2014; Crookall 2014).

4.5. Conclusions and final remarks

In the context of common barriers in Latin America for the sustainable use of nature for local well-being, tests for H1 suggest that a playful tool like MARCHI can foster stakeholder's learning about the advantages of combining poorly adopted ESSApp instruments (PSA and Access to SE), with more conventional conservation instruments (monitoring, command and control and LUP).

Despite the barriers observed in Argentina for the implementation of the ESApp, our work illustrates that under a playful and learning environment it is possible to promote the progressive and successful application of its most neglected instruments by stakeholders. In addition, tests for H2 suggest that the significant learning effect shown for the average of players did not result from simple trial-and-error behavior, from mindful and well-informed decisions upon a meaningful learning environment.These results encourage the application of serious games like MARCHI for educational, research as well as intervention purposes, and extends their use for testing preferences for ES and values (Costanza et al., 2014), to preferences for management instruments and consequent investing strategies.

The potential contribution of serious games in supporting socio-ecological governance processes cannot be fully revealed by exposing a group of stakeholders to an individual experiential learning event, informally connected to the demand for solutions. However, lessons learned regarding the design of the game and its auxiliary material, as well as the evaluation and explanation of the levels of learning achieved by the players represent a first step towards the exploration of other forms of collaborative and participatory gaming, of proven efficacy to foster motivation and engagement for more effective long-term effects.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

We have shared a link within the manuscript to a downloadable version of the game's interface and its supporting simulation model. Players' survey data is available upon request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2023.101549.

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