TRUE GRASP: Actors visualize and explore hidden limitations of an apparent win-win land management strategy in a MAB Reserve

Marco Braasch[a1], Luis García-Barrios[a2], Sergio Cortina-Villar[a3], Elisabeth Huber-Sannwald[b4] and Neptalí Ramírez-Marcial[a5]

[a] El Colegio de la Frontera Sur (ECOSUR), Carretera Panamericana y Periférico Sur s/n Barrio María Auxiliadora, 29290 San Cristóbal de Las Casas, Chiapas, Mexico. Tel: +52 967 674 9000.

[b] Instituto Potosino de Investigación Científica y Tecnológica, A.C. (IPICYT), Camino a la Presa San José 2055, Col. Lomas 4ta Sección, 78216 San Luis Potosí, SLP, Mexico. Tel: +52 444 834 2000

[1] marcobraasch@gmail.com (corresponding author) Tel: +52 967 674 9000 ext. 1427

[2] luis.garciabarrios@gmail.com

[5] scortina@ecosur.mx

[4] ehs@ipicyt.edu.mx

[5] nramirezm@ecosur.mx

Highlights

Participatory multi-actor approach towards decision making

Agent-based modeling for long-term rural land use planning

Short-term benefits vs. long-term undesired regime shifts, how can we manage trade-offs?

Abstract

Win-win solutions might be short-lived. Government permission for smallholder farmers to extract and sell resin from a pine savanna biosphere-reserve in Mexico has settled a long dispute among different stakeholders in the short-term, however forest production and conservation beyond 20 years are compromised due to low pine recruitment caused by competition with exotic grasses. Grass control practiced by farmers through grazing and fire has previously been discouraged by conservation authorities, which inadvertently limits long-term pine conservation and use. We describe the participatory design, rationale and simulation attributes of an educational, interactive, agent-based model that explores suites of management options and their economic and ecological outputs. We present and analyze the outcomes of four simulation workshops, where farmers and external-actors better grasped the complex ecological interactions involved in conserving and using pines in grazed pine savanna with exotic grasses, and discuss these findings with a long-term vision and tradeoff analysis approach.

Keywords:

Agent-based model, cattle in forests, decision making, forest management tradeoffs, participatory modeling, smallholder farmers

Software availability

The agent-based model TRUE GRASP is available (with restricted access during the review process of this paper) online at CoMSES Net / OpenABM, following this link:

https://www.comses.net/codebase-release/6d4a0b9e-3105-47f1-989d-7d7c5c62643c/download/

True Grasp, was developed in NetLogo language, program version 5.2.1. Developers of True Grasp are Marco Braasch (marcobraasch@gmail.com) and Luis Garcia-Barrios (luis.garciabarrios@gmail.com)

1. Introduction

The Man and the Biosphere Reserve (MABR) Program is a worldwide program formally implemented in the 1970s as a space for accomplishing both paradigmatic rural development and protection of nature (UNESCO, 1996). In Mexico, this program incorporated many territories occupied by smallholder farmers within a new model of conservation by decree to improve the social and economic well-being of populations. It was supposed to promote economic, social and environmental policies to allow families, long-established in these territories to sustain decent livelihoods by creating or supporting agroforestry or silvopastoral landscapes in buffer zones of MABR, serving as high quality matrices for conservation (Bouamrane et al., 2016; Cruz-Morales, 2014; Martín-López et al., 2011). Achieving this goal has been at best problematic from the very beginning (Castri, 1976); reasons range from stark conflict among actors related to possession or control over land, to poor understanding and agreement over the effects of land management strategies on ecosystems and smallholder farmers' livelihoods (Adams, 2004; Cruz-Morales, 2014; García-Barrios and González-Espinosa, 2017; Ma et al., 2009; Wittmer et al., 2006).

In this context, win-win land management solutions in MABs are desirable but unusual. When pathways are reasonably accepted by most or all parties, they may represent progress in some dimensions (Plummer et al., 2017) but will likely generate new issues and tradeoffs elsewhere, something to be expected in any complex social-ecological system (Agrawal and Ostrom, 2001; DeFries et al., 2007; Martín-López et al., 2011). More importantly, some emerging issues might work directly against the previously agreed-upon solution, yet this might not be easily perceived or detected, because their consequences are mid and/or long-term (Allen and Gunderson, 2011). These emerging issues commonly become invisible, get ignored or postponed for better times (swept under the carpet) by resource-stricken actors accustomed to jointly muddle through so-called wicked problems (Allen et al., 2011; Sierra-Huelsz et al., 2017). This sometimes unavoidable mishap may have dire consequences, when actors are dealing with changes in land cover, land use and/or livelihoods close to tipping points, as the situation becomes extremely sensitive to miscalculations, unconsidered indirect interactions and short-term pragmatism (Carpenter and Gunderson, 2001; Huber-Sannwald et al., 2012; Ribeiro Palacios et al., 2013).

In La Sepultura MABR, Chiapas, Mexico, created in 1995, anthropogenic pine savannas surround highly valued montane forest core zones as part of the buffer zone (CONANP, 2013). Prior to that year, modest pine lumber extraction and extensive cattle grazing were part of people's livelihood and intentional or accidental burning of the savanna understory was common (Guevara-Hernández et al., 2013; Navarro et al., 2017). Then, as a conservation strategy, the National Commission of Natural Protected Areas (CONANP according to its Spanish acronym) prohibited fire use, tree extraction, and livestock production in the pine savannas. However, these top-down decisions affected smallholder farmers' livelihoods and ignited a decade-long conflict between communities and CONANP (Cruz-Morales, 2014). Farmers saw no reason to protect pine trees on their land other than to avoid monetary sanctions or jail because of illegal extraction (Guevara-Hernández et al., 2013). In 2012, all parties' interests finally converged in a joint project to extract turpentine resin from adult pine trees to be sold to the AlEn del Norte Corporation. Under these new perspectives, the imposed land management strategies now made more sense to smallholder farmers, at least for a 20-year time span ahead during which current adult pine trees would yield a marketable oily product. Yet, a hidden contradiction remained: in most pine stands, small native grasses and herbs have long been outcompeted by tall exotic grasses; in the absence of fire and grazing, they can be a significant obstacle for recruiting future generations of productive adult pine trees (Braasch et al., 2017). By targeting this attractive short-term win-win solution (i.e. protecting the pines and extracting resin), actors in this partnership are paying little attention to the long-term effects or do not reach consensus over strategies to deal with them. Insights from smallholder farmers and plant ecology suggest livestock grazing could create opportunities for pine recruitment but may also cause trampling damage or mortality of saplings (Archer et al., 2017; Braasch et al., 2017; Van Langevelde et al., 2003; Werner, 2005).

Interactive agent-based simulation models (ABM) and socioecological board-games have emerged within different social learning frameworks, e.g. the Companion Modelling approach methodology (ComMod; Etienne et al., 2014) has useful participatory education tools such as role playing games (RPG) that facilitate communication and reflection among those involved in resource management, and promote a common knowledge ground from where to build effective management and governance (Le Page et al., 2010; Etienne et al., 2011; Garcia-Barrios et al., 2017, 2015, 2011). Some of these frameworks and tools have allowed smallholder farmers and other actors to simulate and jointly explore land use and management options in rural small-holder territories (Barnaud et al., 2013; Berthet et al., 2016; Etienne, 2014; Villamor and van Noordwijk, 2011) and more specifically in those contiguous or within MABR (Bouamrane et al., 2016; Perrotton et al., 2017).

ABMs are currently used in many fields of scientific research, education and policy making as extremely powerful tools to better grasp complex processes; an ever-growing model library is currently available (Rollins et al., 2014). Many social, educational and technical challenges associated with ABM remain, spanning from their proper development to their use as multi-actor social learning tools within rural settings (Barnaud et al. 2013; Becu et al. 2007; García-Barrios et al. 2017). Le Page and Perrotton (2017) fruitfully discuss the different objectives and tradeoffs involved in abstract, stylized and realistic agent-based models, and stress that the requirements and purposes of social learning should guide the choice, construction and use of these simulation models in multi-actor, land-stewardship processes.

Since 2007, the second author (LGB) has been leading participatory multidisciplinary research in La Sepultura MABR, with special emphasis in the social and ecological consequences of land use innovations meant to reconcile livelihoods and conservation (García-Barrios and González-Espinosa 2017; Valencia et al., 2015, 2014; Zabala et al., 2017). In this process, a number of agent-based models (Speelman et al., 2014a, b; Speelman and García-Barrios, 2010) and socio-ecological board games (Garcia-Barrios et al., 2017, 2015, 2011) have been developed. For this study, starting in 2014, we were welcomed by actors to follow and support the resin production project and we engaged in participatory research comprising field transects, forest inventories, ecological experiments, farmer surveys, agent-based modelling, and scenario simulation workshops to address the following questions: Do actors consider the pine savanna and resin (turpentine) extraction a short- or long-term livelihood and conservation option? Is pine recruitment actually lower where exotic grass is dominant? Is low pine recruitment a critical issue for the resin project, and for which actors? What management options for controlling exotic grass are preferred by different types of actors? What are potential short and long-term tradeoffs of these management options?

We described in detail the anthropogenic origin of the pine savanna (Braasch et al. 2017); we showed that current pine population structure and low recruitment due to dense exotic grass cover cannot support long-term resin production. Furthermore, we presented experimental evidence that cattle grazing in the savanna may have both positive and negative effects on recruitment. Here, we describe and discuss the development and use of an interactive agent-based model with farmers and other actors, to help address the above questions.

The objectives of this paper are to (a) describe the interactive, stylized agent-based model TRUE GRASP (Tree Recruitment Under Exotic GRASs in the Pine-savanna) and its background, rationale and main attributes; (b) present and discuss the outcomes of four TRUE GRASP simulation workshops held separately and jointly with smallholder farmers and external actors to address in a stylized, qualitative way the questions listed above and to support social learning of all parties involved, including ourselves.

2 Methods

2.1 Study area

The study was carried out in the pine savanna under *ejido* tenure (a mixture of private and communal land) belonging to the rural towns of California and Tres Picos, located in the buffer zone of La Sepultura Biosphere Reserve (SBR) in Chiapas, Mexico (16°16'40" - 16°12'40"N and 93°37'10" - 93°32'55"W; **Fig. 1**).

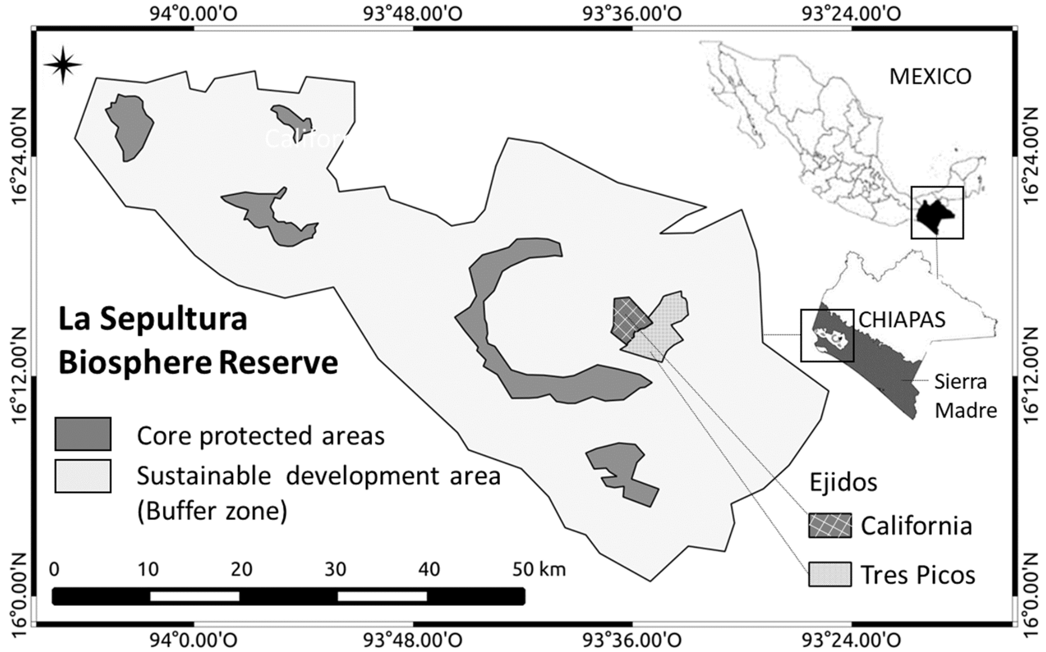


Fig. 1 La Sepultura Biosphere Reserve in the Sierra Madre mountain range of Chiapas, Mexico with the protected core areas and buffer zone and the location of the two *ejidos* California and Tres Picos, where this study was carried out.

The topography of the area is highly irregular with steep slopes. Dominant soils are Regosols and Cambisols over granitic rock. The tropical climate is seasonally dry. Annual mean temperature ranges between 25 and 28 °C. Average annual precipitation reaches 2003 ± 484 mm (30-year average; CONAGUA, 2015). The pine savanna is located between 900 and 1100 m above sea level. Both communities were established during the 1970s by landless people (Cruz-Morales 2014). Since the settlement, cattle raising together with maize and bean production for self-supply and regional markets have formed part of the smallholders' livelihoods (Cruz-Morales 2014), but livestock became even more important in the late 90s, when maize prices plummeted in 1995 as a result of NAFTA (García-Barrios et al., 2009; García-Barrios and González-Espinosa, 2017). In the same year, the federal government designated a buffer zone in the SBR. Currently, the people grow mainly maize and beans for self-supply. For monetary income, they raise livestock, grow organic coffee, and more recently, extract resin from *Pinus oocarpa* Schiede ex Schltdl. Of their total land area, pine savanna is particularly important for production, as cattle raising plus resin represents a significant share of their income. In both communities, pine savanna extends close to the forest frontier in one of the core protected areas of the SBR, which consists of a highly biodiverse montane cloud forest ecosystem (CONANP, 2013). In the pine savanna, the most abundant exotic grass species are *Melinis minutiflora* P. Beauv. ("Gordura grass") and *Hyparrhenia rufa* D.A. Reid ("Jaragua grass"), which were introduced to Mexico in the late 19th century for livestock production (Parsons, 1972). *Pinus oocarpa* dominates the pine savanna tree stratum (Braasch et al., 2017).

2.2 Extensive surveys with resin producers, main topics and analyses

The most relevant actors related to pine savanna management are the local families (roughly 74 % of them are involved), the conservation authority (CONANP), and the national corporation that buys the turpentine (AlEn del Norte). Secondary actors are the national forestry department (CONAFOR), an environmental conservation and development NGO (Pronatura), and public research institutes (ECOSUR and Universidad Autónoma de Chapingo). The authors of this paper have sustained frequent interactions with all actors during the past three years, both in the field and in organized meetings. From these interactions, it became apparent that within and among these groups of actors there are different and sometimes conflicting views on the level and importance of pine recruitment in the savanna, and on the existence of ecological and economic tradeoffs associated with exotic grass management options. With the aid of questionnaires, maps, photos, drawings and field visits in 2016, we interviewed 52 local people involved in turpentine extraction (men and women of different age groups from both communities) to further clarify their activities; land use interests; expectations about resin extraction as a short or long-term livelihood option; knowledge on ecological factors affecting pine recruitment; tradeoffs involved in each exotic grass control measure (controlled fire, weeding, grazing); and preferred control option. Surveys were analyzed with descriptive statistics and results were used to build TRUE GRASP and design farmer and multi-actor workshops. Farmers were involved in the modelling process: Most resin producers participated in defining its general purpose; fifty-two discussed with researchers the relevant processes involved and provided empirical data, which were later stylized by researchers as model parameters; ten farmers tested the user-interface and validated the model's qualitative behavior and outcomes in a pre-workshop meeting. All along they showed interest in research oriented towards exploring management options for recruitment. The day they attended the single actor workshop, farmers were invited to actively work all day and thus received six USD covering a local daily salary.

2.3. The TRUE GRASP agent-based model

2.3.1. Virtual world and components

In this section, we provide a short summary of how TRUE GRASP was designed and describe its components. For more detail see the Overview, Design concepts, and Details (ODD) protocol in Supplementary data (Appendix A), where we followed the updated ODD protocol by Grimm et al. (2010) and Müller et al. (2013).

TRUE GRASP is an agent-based model created with NetLogo v.5.2.1 (Wilensky, 1999). It allows users (farmers and other actors) to set management parameters, run the simulation, observe the trajectory of relevant variables, and repeatedly reset the simulation and its parameters to stir specific trajectories towards desired ecological and productive outcomes with acceptable tradeoffs. The entire landscape of the virtual world has an extension of 81 x 129 patches (10449 cells), which represents 4-hectare of land divided into two equal parts, pine savanna and open pasture, representing typical landscapes in the SBR (**Fig. 2**). The total size of the NetLogo "World" was selected to contain a realistic initial population of 50 adult pine trees per ha of savanna, while allowing space for all other user interface features (buttons, sliders, switches, plots, monitors etc.). Each patch covered 3.8 square meters, an arbitrary but convenient size to reconcile the different spatial scales of the modeled agents and their movements (grass, fire, farmer, cattle, pine dispersion). It is worth noting that these agents' movements are highly stylized; we deliberately avoided dubbing them with complex dispersion and search behaviors. We chose the rabbit-grass-weed algorithm (Wilenski, 2001) to produce a semi-random walk for cattle; the mushroom hunter model algorithm (Railsback and Grimm, 2012) for farmers searching pines, and Moore neighborhood colonization for grass and fire. The general assumption in this stylized approach is that – for the current purpose of the model - the intensity and consequences of interactions among all these agents reasonably and sufficiently depend on their local and global densities (albeit in nonlinear ways).

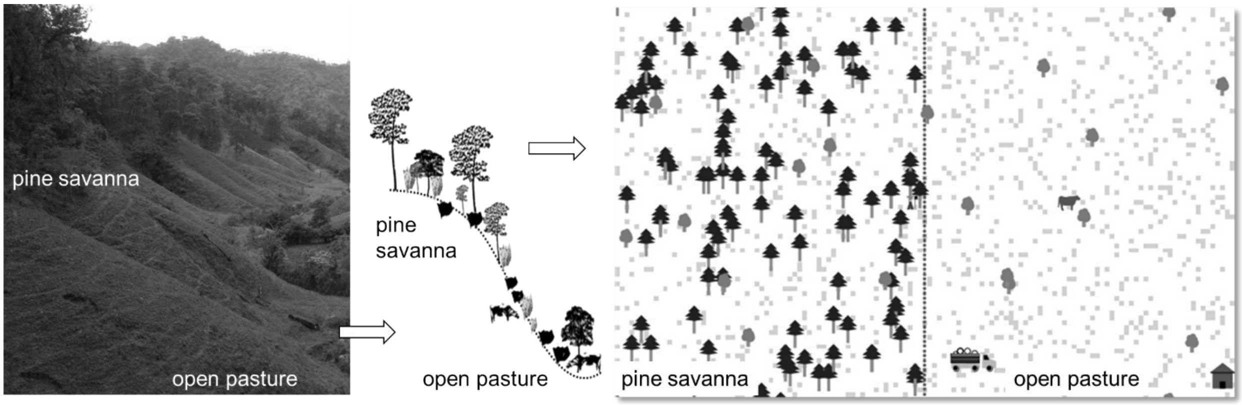


Fig. 2 Design of the virtual world of the agent-based model TRUE GRASP based on a mountainous landscape in La Sepultura Biosphere Reserve, Chiapas, Mexico, representing 2 ha pine savanna and 2 ha of open pasture.

The pine savanna is a forest stand with an open canopy and initially contains 100 mature pine trees in two ha land. The forest understory cells (patches in NetLogo language) can be covered by the following agents representing different vegetation cover types: (1) pine seedling; (2) pine sapling; (3) exotic tall grass cell, that impedes seed germination and seedling establishment; (4) short grass cell, short-statured native grass or recently burned forest floor or exotic grass kept short by cattle grazing with all these cell occupations allowing pine seedling establishment; (5) pine needle litter or shade near adult pine trees not allowing seed germination or seedling establishment (see Supplementary data A; Fig. 2). Other agents are resin producer, cow and fire. The user embodies and assists the virtual resin producer in defining cattle load and the frequency of cattle rotation, use of fire, and manual weeding. The most relevant outputs (reported annually and cumulatively) are the number of pine seedling/saplings, mature productive resin trees, resin barrels and calves. Each iteration (time step) in the model represents one day. A thirty-year simulation with an Intel-Core i5 processor takes between 5 and 10 minutes. Several decades (50 – 100 years) of simulation can transform the pine savanna into an open pasture land if no recruitment takes place, or into a closed pine forest without grass in the understory, if tree recovery and growth is high; intermediate states are also possible. Although half of the virtual world is open pasture land, potential pine recruitment can also proceed there, albeit at a low pace.

<ins>Pine lifecycle in the savanna:</ins> each adult pine produces seeds every year; they are randomly distributed within a radius of 15 cells. A seed only germinates in short grass cells. Daily seedling

growth rate is reduced as a function of surrounding exotic tall grass cells within its Moore neighborhood, which slows down the process by which the sapling becomes a young tree and is free from this competitive effect. Seedlings and saplings adjacent to trees older than 10 years die by a self-thinning process. Young trees can resist cattle trampling and fire once they reach the age of 3 and 9 years, respectively. Thus, a successfully established tree needs to have found space for germination and survive all risks (fire, trampling, competition of exotic grasses, and self-thinning by other pines) during its lifecycle. With intermediate exotic grass competition, an established new pine can be tapped for resin by the age of 25 years. An average individual pine's resin production lasts between 10 and 20 years depending on tapping intensity. In the real world, a tree face is tapped for five years, by moving the resin tapping face upwards to a maximum height of 2.5 m each year before a new tapping face is initiated at the other side of the tree. Tree diameter in the study area permits between 2 to 4 faces on a single tree (see Supplementary data A. Fig. 7).

By the age of 45 years, an adult tree will have exhausted its resin production and thus can be felled for lumber. Otherwise, it dies naturally at the age of around 140 years (**Fig 3**). We do not incorporate the probability of death due to bark beetles, because they are not an appreciable factor in the area.

<u>Short grass, browsed, or burnt cells:</u> they refer to all cells on the forest floor not occupied by adult pine trees, pine-needle litter, or tall exotic grass, which can be colonized by a pine seedling under appropriate environmental (seasonal) conditions.

<u>Exotic tall grass cells:</u> preclude pine recruitment and provide fuel for fire and fodder for cows. If in following iterations the exotic tall grass cell is covered by pine needle litter or shade, grazed by cattle or burnt, it becomes a short grass cell, which again can become an exotic tall grass cell if tall grass later recovers.

<u>Pine needle litter/shade:</u> Exotic tall grass and short grass cells within a five-cell radius around an adult pine tree transit gradually into litter/shade cells, and do not allow seedling establishment. Only fire, manual cleaning or litter decomposition transforms the cell back to a short grass cell. Full pine leaf litter decomposition occurs two years after an old tree has died naturally or has been felled, allowing grass growth.

<u>Cow:</u> It moves in a semi-random walk within the assigned space: pasture land, savanna, or both with or without rotation. If a cow crosses over a susceptible seedling (aged < 3 years), it tramples and kills the seedling. The cow starts with an initial energy (weight) of 1000 units. Energy is lost each time-step (day) due to movement, and energy increases only with consumption of an exotic tall grass cells. If the cow encounters insufficient exotic tall grass cells, its energy eventually falls to zero and the cow dies. If availability of exotic tall grass cells is high and the cow reaches more than 1650 units (reproductive weight), it conserves 1000 units for itself and devotes the rest to produce a calf. Each cow is calibrated to produce no more than one calf per year (see also section 2.3.3). Calves do not consume grass, as they are sold and thereby removed from the virtual world.

<u>Resin producer:</u> Five family members (farmers) move in the savanna, searching for pines. If a farmer encounters a resin-producing tree, he taps it and harvests the resin. The farmer is initially endowed with 100 energy units, which he spends walking. Harvested resin first compensates for this energy loss (kg of resin converts into money, which covers his labor costs) and any resin surplus accumulates in the farmer's resin container. If the energy level reaches zero, the farmer quits being a resin producer. If there is a surplus of resin in the farmer's resin container (400 units [40 kg]), the harvested resin is stored in 200 kg barrels for sale and thus leaves the system. In this simulation, the resin producer is always in the savanna and moves forward one cell per time-step (day) in search of resinous trees. Although obviously unrealistic, this stylized tree search dynamic is parameterized so that the average weekly harvest of this family in the two-hectare virtual pine stand resembles average yield per week in the study area. If a farmer moves over an exotic tall grass cell, his movement is delayed, compared to a short grass cell free of obstacles and also spends more energy that decreases his net resin accumulation slightly.

2.3.2 Management practices to control exotic grasses and pine needle litter

Exotic grasses and pine needle litter both influence pine seedling establishment. The model considers the following management practices to overcome this constraint. The user can select among:

<u>Manual weeding and cleaning:</u> the farmer in the model converts by cutting manually exotic tall grass cells and cleaning pine needle litter within a 4-cell radius of a resinous tree into short grass cells. This accelerates the farmer's forward movement and opens space for seedling establishment,

but also reduces the farmer's energy level due to the invested labor, which ultimately affects his net resin harvest.

Fire: It is simulated following the simple fire percolation model from NetLogo 5.2.1 model library (Wilensky, 1997). Fire always starts in the center cell of the virtual world and spreads with each time-step from a burning cell to any of the eight surrounding cells (Moore neighborhood) that contain fuel (exotic tall grass cells and/or pine needle litter). Fire converts these cells to burnt (short grass) cells. If fire reaches a cell covered by fuel and containing a susceptible pine tree, the latter dies. Fire can occur spontaneously each year with low probability (4 %). It can also be used as a management practice by the user, at any moment or with a fixed periodicity. In the current version of TRUE GRASP, fire is not required for pine seed germination.

Cattle stocking and rotation frequency*:* The model user chooses a certain number of cows (between zero and eight) and decides whether they occupy only the pasture land, the savanna, or both. In the second case (pasture land and savanna), cows can perambulate freely or rotate between fenced paddocks with a user-defined frequency.

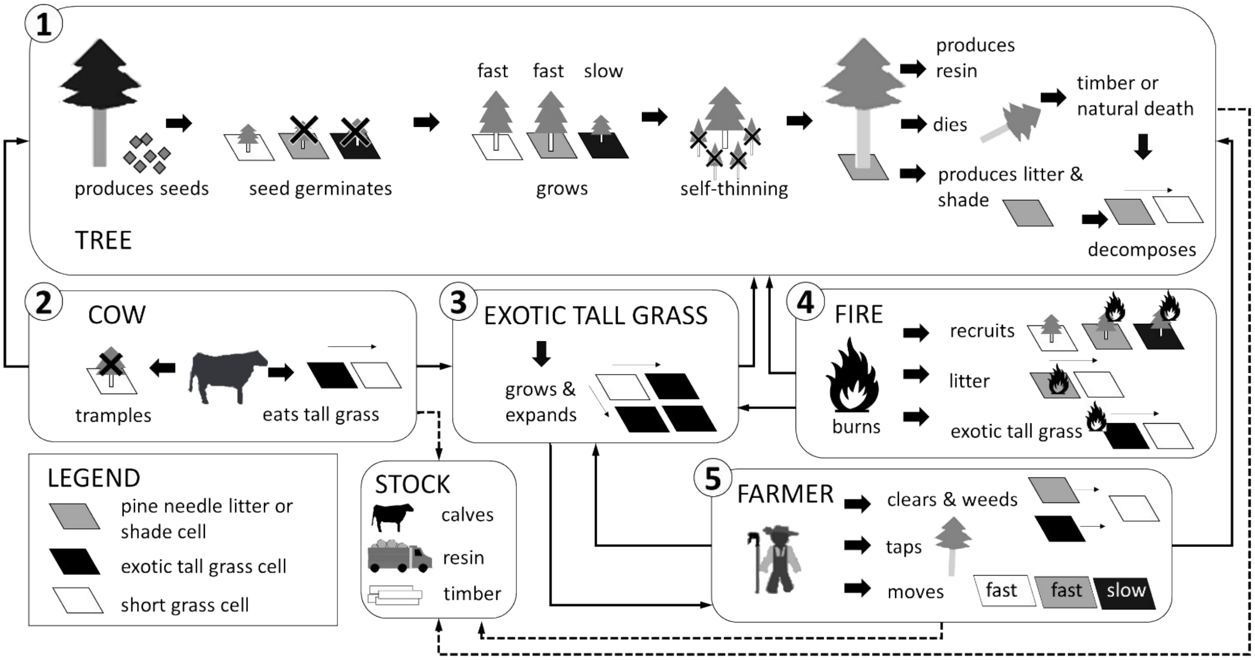


Fig. 3 Schematic diagram of TRUE GRASP agents, processes and links between the sub-models (continuous lines) and outputs (dashed lines): 1) tree, 2) cattle, 3) exotic tall grass, 4) fire and 5) farmer.

2.3.3 Model parameterization and calibration

In **Appendix B,** we present a non-exhaustive but comprehensive multivariate sensitivity analysis of TRUE GRASP responses to a relevant set of parameters. Here we highlight some important aspects of the model's rationale. TRUE GRASP stylizes ecological and economic processes, and produces outputs that do not mimic the exact quantities to be expected in real-world situations (and which are still largely unknown and highly variable). It is not predictive in that sense, but its time series reproduce fairly well the short- and mid-term qualitative system behavior described by local and external actors in response to their proposed management practices in the pine savanna. Moreover, it produces reasonably well long-term scenarios that seem plausible to users.

A central purpose of the model is to allow users to explore individual and combined effects and tradeoffs of different options (fire, weeding and cattle grazing) of controlling exotic grasses in the pine savanna. Cattle grazing is currently the most contentious option and the best studied in the area, so it is better specified in the model than the other options. Actual grazing strategies in these and surrounding communities (cattle stocks, rotation rates, etc.) are context-dependent and therefore highly variable. In the SBR, smallholder farmers' cattle herds are composed of 5 to 20 animals and are rotated adaptively in their land between open pasture, savanna, or boththeir combination. Farmer's rule of thumb for an annual average stock which allows the production of 0.8-1.0 calf per cow per year, and that does not produce a steady long-term decline of grass cover in open pasture, is one cow per hectare of open pasture. However, detailed surveys and analysis prior to this study (Rosabal-Ayan, 2015; Valdivieso-Pérez et al. 2012; and in García-Barrios et al. unpublished database) showed that for rangelands combining open pastures and savannas, an appropriate stocking density is 0.5 cow per ha. Therefore, we selected and coupled parameters for cow reproduction and exotic grass recovery rate so that (a) a cow would produce 1.0 calf per year in 2 ha of open pasture and 0.8 calf in the combination of 1 ha of savanna and 1 ha of open pasture, and (b) a cow browsing 2 ha of open pasture would keep grass cover at an equilibrium value near 80%. Thus, more than 1 cow per 2 ha increases the percentage of short grass cells for pine recruitment at the expense of calf production, while a lower cattle load could significantly reduce space for pine recruitment with little or no gain in calf production. **Fig 4a-c** show these variables' trajectories and sensitivity analyses for different cattle stocks. **Appendix B** provides further details and sensitivity analyses for a broader set of outputs. Fire was modeled rather crudely using a simple percolation model (Wilensky, 1997), which was parameterized such that pine recruits are sensitive to burning during the first nine years of establishment, thereby allowing reasonable recruitment under a low fire frequency regime. Weeding was parameterized to reflect the fact that it ceases to be cost-effective, when used too frequently and/or as the sole grass management practice.

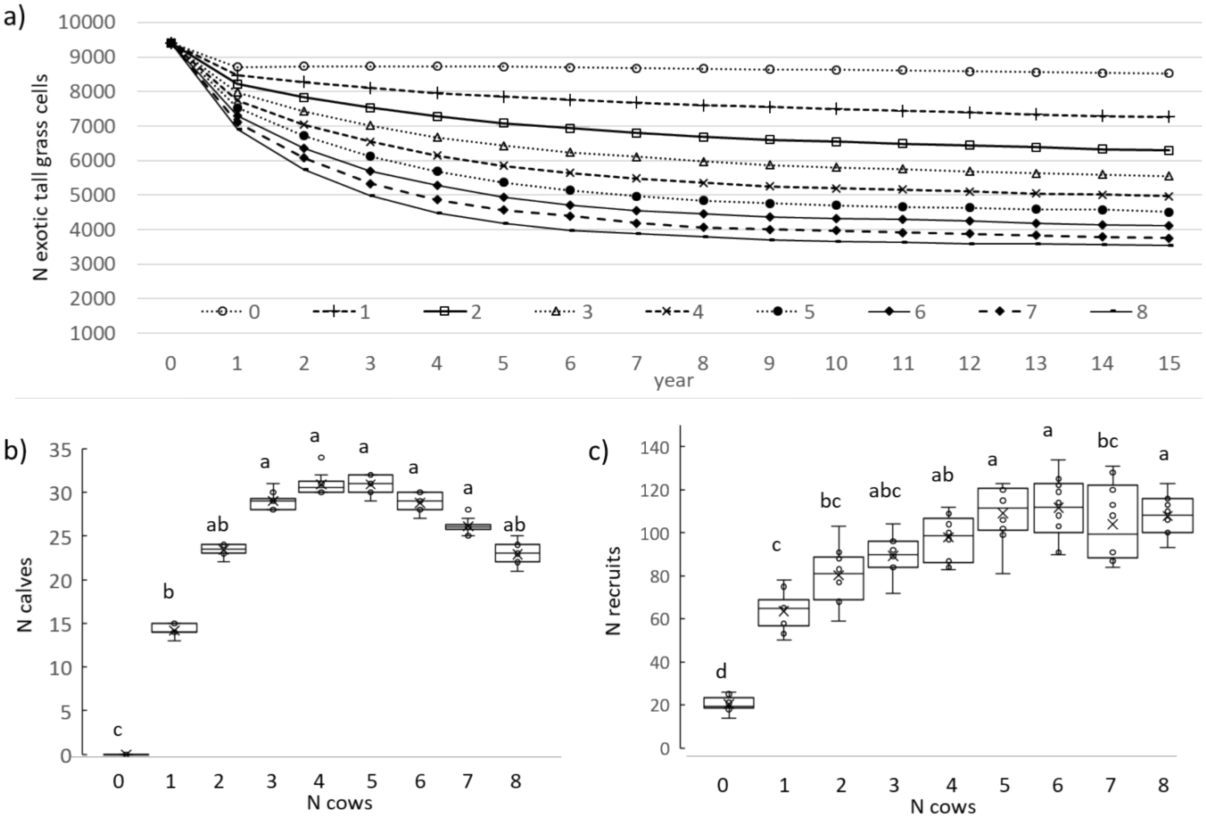


Fig. 4 a) 15-years time series with cattle stocking density of 0 to 8 cows per 4 hectares of rangeland. Each data point represents the average of 10 model runs (replicates) by the end of each year. Simulations begin with 90% of space occupied by exotic tall grass cells. See also Supplementary data B; Fig 2a-h. b) 15-year sensitivity analysis with ten model runs with livestock stocks of 0 to 8 cows for cumulative calve production. c) Cumulative pine sapling production as a function of livestock number between 0 and 8 cows. Letters over Box-Whisker plots that share one or more letter label do not differ significantly according to the Tukey HSD multiple mean comparisons test (*a* = 0.05).

2.4 Single and Multi-actor Workshops

2.4.1 Preliminary surveys

Before starting each of three single-actor workshops with smallholder farmers of California, Tres Picos and external actors, participants were asked to (a) determine knowledge on factors affecting pine recruitment and potential tradeoffs associated with preferred management practice to control exotic tall grass cover; and (b) explain the type and consequences of emerging interactions (direct or inverse) with the help of a resin production system diagram, to make aware of tradeoffs when including e.g. cows or fire and identify the preferred effects of these components.

2.4.2 Single actor workshops

Three four-hour workshops were held separately with 10 participants from California, 7 participants from Tres Picos and 5 external actors respectively, on March 27 to 29, 2017. Two participants and one trained facilitator from the researcher/students team sat at each computer. Workshops included the following sessions:

1. Welcome, ice breaking dynamics, and sharing workshop purpose

2. Presentation of an illustrated talk, leading participants from real images of the savanna landscape with its vegetation, livestock and human components to their *in-silico* representation in a NetLogo World. This was accompanied by brief simulations of the behavior of each NetLogo agent and patch.

3. Demonstration of a 15 and 30-years simulation, carried out by the first author, showed how a pine and native grass savanna (without cows) allow pine recruitment and natural development towards a closed pine forest, with its accumulated saplings, productive trees and resin production.

4. Based on the same initial spatial state, a 15 and 30-years simulation, led by the first author and executed by participants with the help of facilitators, showed the consequences on pine recruitment when substituting native grass with exotic grass considering the previous simulation setting (see 3). Each participant was asked to write down his predictions on how outputs would change qualitatively (increase, remain, decrease) and then compare them with the actual simulation outcomes.

5. Eight 15-years simulation scenarios led by the first author and executed by participants and facilitators, showed both the consequences on recruitment and other outcomes of (a) burning the savanna; (b) weeding tall grass and (c) allowing cattle grazing in the whole grassland-savanna

area. Scenario 1 starts with a full ground cover of native grasses leading to a closed pine stand with abundant recruits and no exotic grass. Scenario 2 substitutes native for exotic grass and it is headed in the long run (>50 yr) to an open grassland. Scenarios 3, 4, and 5 add to scenario 2 a fire event every year, in years 1-4-8-12, and in years 1 and 12, respectively; only the last of these fire regimes creates a window for saplings to escape size-related vulnerability to fire and therefore increases recruitment. Scenarios 6 and 7 consider scenario 2 but include manual weeding around pine trees every year and in years 1 and 15, respectively. Scenario 8 also starts with scenario 2 but with 6 cows grazing freely the open pasture and pine savanna (the whole NetLogo world).

6. In both farmer and external actors workshops during a thirty-minute period, pairs of participants were asked to select a set of parameters (available on the user interface) to achieve five non-trivial output goals simultaneously pre-established by researchers by year ten. These ecological-economical goals were: 40 recruits, 20 resin barrels, 18 calves, less than 25% trampled saplings, and more than 50% tall grass cover. This goal-oriented approach was chosen to increase participant's familiarity with the interface and for them to experience the many potential interconnected tradeoffs involved.

7. The "two brothers exercise": seven pairs of smallholder farmers were teamed up such that in real life one team member actually having pines and cattle, while the other one having only pines. They were told: suppose you are two young brothers A and B, whose father wishes to inherit a small herd of cattle and four hectares of land (two as pine savanna and two as open pasture). Your father says: "I am inheriting the whole property to both of you; A will own any present and future pine tree on the whole property, and B any present and future cattle and grass. It is up to you how you will manage the whole property together." To make a livelihood, by year ten A must meet 18 resin barrels, 45 recruits, trampling less than 30 % and a non-negative weeding subsidy; B must meet 20 calves, and grass cover not less than 50 %. Reaching both sets of goals was possible but non-trivial and the process could drift towards one participant's interests at the expense of the other's. Participants had 30 minutes per team to select and explore parameter sets and run simulations to reach together their respective goals.

8. A thirty-minute collective reflection on the workshop experiences concluded the single actor workshop.

2.4.3 Multi-actor joint workshop

Participants were six smallholder farmers from the *ejidos* California and Tres Picos (3 representatives from each village), three CONANP officers, two representatives from the NGO Pronatura, and the regional officer of AlEn del Norte. All 12 participants had been acquainted previously as neighbors and/or partners or observers of the resin business. After a brief reminder presentation of the model operation, each farmer was paired with an external actor to explore and reach the following three goals in a single attempt with one fifteen-year simulation: optimize sapling number, resin and calve production. The five teams were free to define their own sets of management parameters for this one-shot experiment, except for the number of cattle, which was fixed to five by researchers; an excessive and suboptimal stock would make participants confront stronger tradeoffs among outputs. The exercise was presented as a contest to see which team would achieve the best result.

Immediately after the simulation contest and reflection over the outcomes, we conducted a collective and public exercise for all actors to explore hypothetical pine savanna management choices along a decision tree, where questions were revealed to them step by step. Binomial decisions were: Is resin production a long-term project (> 50 years)? Should saplings be recruited naturally or nursed and planted? Should the main exotic grass control strategy be based on cattle stock management or grass weeding and scorching? Are such interventions collective or private decisions and endeavors? Should they be subsidized?

3 Results

3.1 Farmer interviews to explore local ecological knowledge

The majority of interviewees were males older than 40, active in resin extraction and with four to five primary activities (resin, maize, beans, coffee and livestock). Fifty-three percent of resin producers in California and Tres Picos owned livestock at that time. Most considered that the livelihood-importance of resin and coffee would grow, while maize and livestock would remain stationary. Older farmers were well aware of how the current landscape came about through selective logging and land clearing for crop and cattle production (for more detail see Braasch et al., 2017). Fifty percent envisioned local landscapes in the next ten to twenty years to consist of a semi-closed pine-oak forest combining resin, cattle and firewood production; 23% chose a closed pine forest dominated by *Pinus oocarpa* to increase resin production, and 19% decided for a mixture of several land use types (pasture land, open pine-oak forest and closed pine-oak forest) but separated in space. A few included also oak forest (6%) for firewood production.

Regarding strategies by smallholder farmers to maintain pine stands, all interviewees said “do not cut pine trees”; two-thirds “do not burn”, only two fifths “recruit saplings” and only one in twenty “reforestation with nursery pine trees”. Eighty percent considered that natural pine recruitment was appropriate at the whole *ejido* level, while 58% considered it was reasonably high in their own pine stands. Only half of the interviewees were aware that *P. oocarpa* trees need to reach 25-40 years of age before they produce resin in this area.

Considering pine recruitment, thirty-five percent of the interviewees considered it requires bare soil, while 19% mentioned grazing and very few included post-fire conditions, such as fertile soil and a seed shedding pine tree nearby. More than one third did not have an answer to the question on regeneration niche. When asked about obstacles to recruitment (**Fig. 5a**), two-thirds considered ungrazed exotic grass and pine leaf litter accumulation, while only one fifth included also trampling of saplings by cows. Regarding cattle effects on forest floor (**Fig. 5b**), almost all interviewees mentioned “grazing lowers fire risk and grass competition for saplings”; three fourths “cattle browse and trample”; one third “trampling prepares the soil for pine germination”; 5% “cattle causes soil erosion”, and 10% “no effect”.

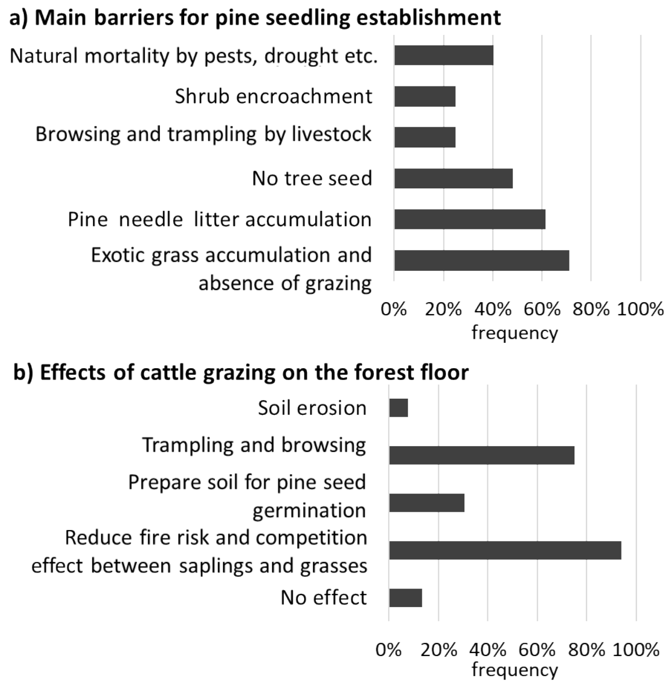


Fig. 5 a) Main barriers for pine seedling establishment, and b) effects of cattle grazing on the forest floor identified by 52 small-holder farmers of the *ejidos* California and Tres Picos, La Sepultura Biosphere Reserve, Chiapas, Mexico. X-axis represents frequency with which the variable was mentioned.

Overall, responses showed that many farmers have a broad and precise knowledge of landscape history, resin production requirements, pine life cycle and regeneration niche, factors affecting pine recruitment, and tradeoffs of cattle grazing in pine savannas for sapling establishment and growth. When considering all interviewees, knowledge and opinions were diverse, incomplete and in some cases contradictory (e.g., some farmers mentioned the positive effect of fire, "…fire is needed to stimulate tree recruitment…" but at the same time they said that they do not use it, because it is bad as it causes wildfires). Contrasting opinions occur most likely due to differences in age, activities, and livelihood-related preferences and opportunities. The rich yet incomplete ecological knowledge of smallholder farmers and the diversity of their interests regarding savanna management were useful both to guide the design and parameterization of the ABM and to further value the pertinence of facilitating farmer workshops on this matter.

3.2 Agent-based model capabilities

TRUE GRASP proved capable to qualitatively reproduce three different long-term scenarios of interest to the smallholder farmers for resin extraction and calf production. These were (**Table 1**): A) a baseline scenario (previous to exotic grass invasion) represented by closed pine stands with native grass/pine needle litter understory and abundant pine recruitment; B) open exotic grassland as a consequence of lack of pine recruitment; and C) exotic grass cover with moderate cattle load (two cows in four ha) and pine savanna with both high recruitment and high calf production (a win-win situation). Resin producers and other actors considered each of these scenarios relevant, and graphically (**Fig. 6**) and conceptually credible. Each scenario proved to be robust under a range of ecological and management conditions, and sensitive to threshold values of a single or several parameters potentially causing regime shifts between some of these scenarios.

Table 1. Means (± standard error) for the main economic and ecological outputs after 30-year simulations, considering the initial simulation condition compared to A) native grass understory without management, B) exotic grass understory without management and C) exotic grass cover with moderate cattle load (two cows). Each of the scenarios had 20 replicates.

Scenario	Resin trees (#)	Recruits (#)	Resin barrels (#)	Trampling (%)	Calves (#)	Timber (#)	Exotic tall grass (%)	Short grass (%)	Litter or shade (%)
Initial condition	100	-	-	-	-	-	90	10	0
A)	263 ± 5.3	464 ± 5.8	77 ± 0.9	0	-	57 ± 1.2	-	55 ± 0.4	45 ± 0.4
B)	24 ± 1.1	23 ± 1.2	32 ±0.2	0	-	2 ± 2.0	82 ± 0.2	2.4 ± 0.1	16 ± 0.2
C)	53 ± 2.1	108 ± 2.9	36 ± 0.4	23 ± 1	42 ± 0.3	52 ± 1.2	58 ± 0.4	24 ± 0.2	18 ± 0.4

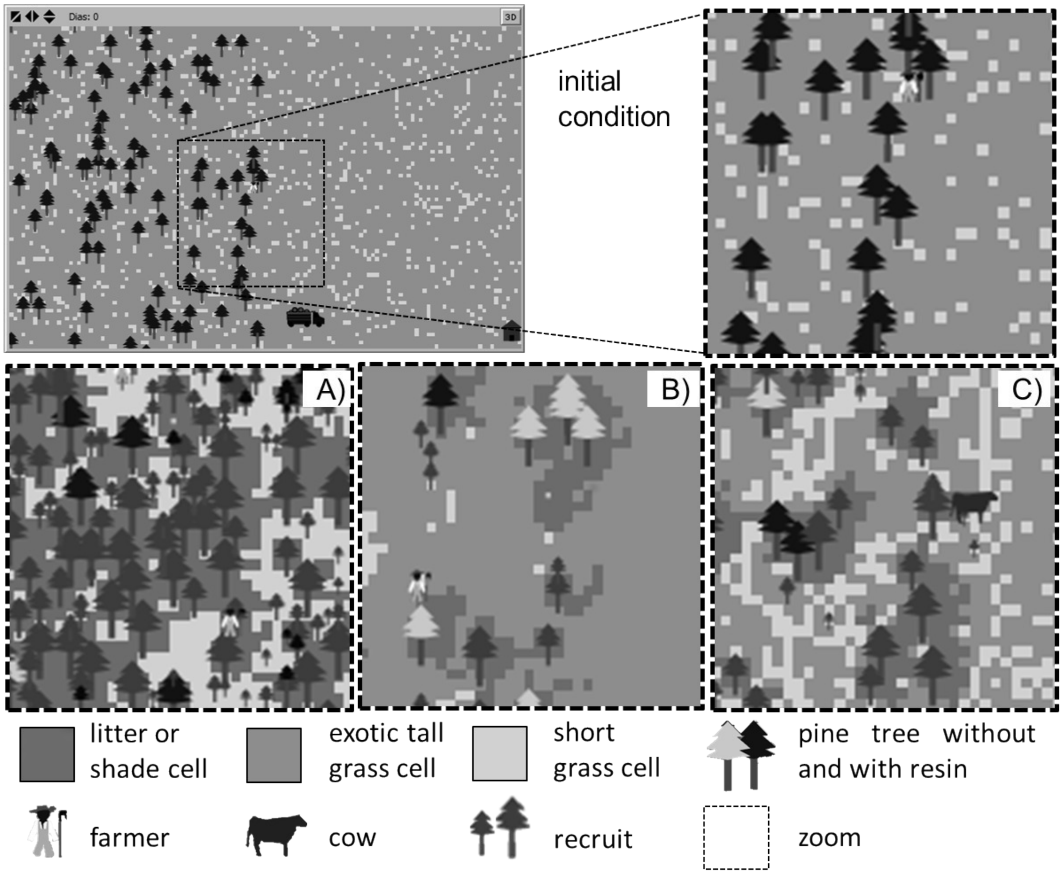


Fig. 6 Possible long-term (30-year) scenarios for the pine savanna in the La Sepultura Biosphere Reserve, modeled with TRUE GRASP. Above: initial condition for all simulations, bellow: A) native grass understory without management, B) exotic grass understory without management and C) exotic grass cover with moderate cattle load (two cows). (Appendix B Figure 4 provides a color image for better interpretation).

3.3 ABM-supported scenario exploration workshops

Seventeen persons in total participated in two farmer workshops in 2017, with the same proportion of farmers owning cattle (53%) as in the 52 interviews held in 2016. Five persons participated in an external actor workshop and 12 in a multi-actor workshop.

3.3.1 Pre-agent-based model surveys and tests

Pre-ABM interviews and exercises revealed that: (a) All actors got high scores when identifying the sign of direct interactions among pine savanna silvopastoral components in **Fig 7**; yet positive effects of cattle and fire on pine recruitment were more frequently missed, the former more by external agents and the latter more by farmers. In consequence, the same trend was observed when actors identified tradeoffs associated with cattle presence and with fire use. (b) After the fire and cattle tradeoffs were identified by actors or pointed out by facilitators, 60% of farmers and only 20% of externals saw more benefit than damage in cattle. Regarding controlled fire tradeoffs, the opposite occurred: all externals and only one elder farmer (an *ejido* founder) saw more benefits and would apply fire to control exotic grasses.

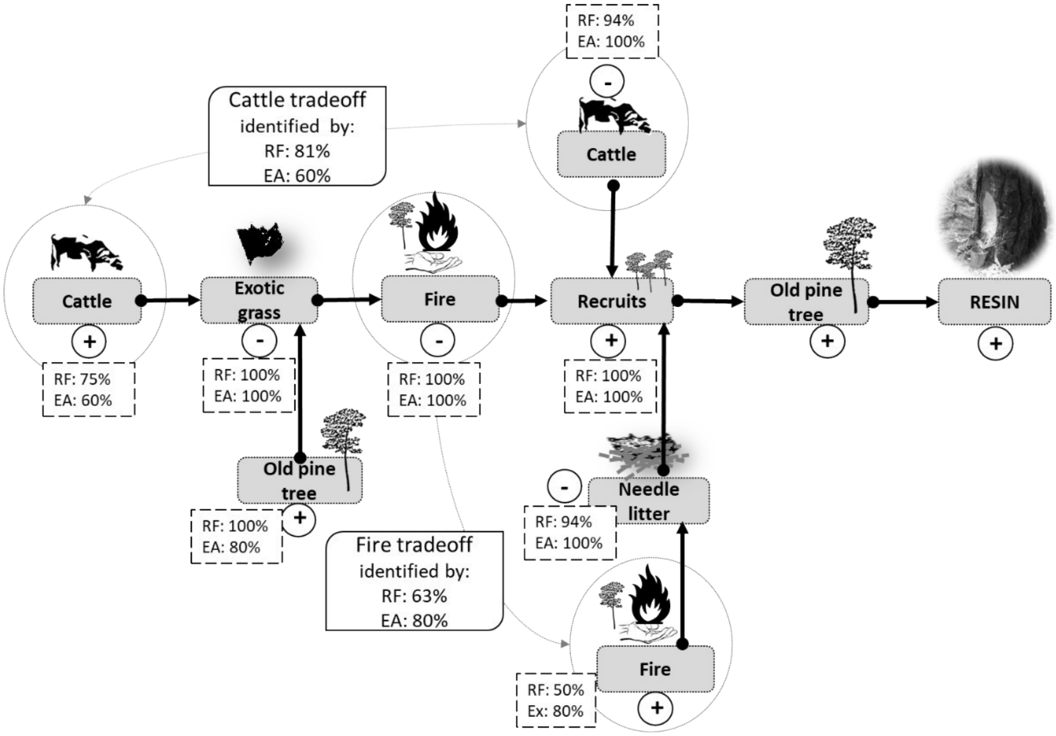


Fig. 7 Interaction diagram of the resin production system. Black solid lines represent interactions between variables. A filled circle indicates cause and an arrowhead indicates effect. Signs indicate if the variable must increase (+) or decrease (-) to ultimately increase resin production. Cattle are in two causal relationships, which need to have different signs to increase resin. The same happens with fire. For example, fire increase reduces needle litter, which increases recruits, which increases pine trees, which increases resin. Dashed line boxes are percentage of correct scores for each interaction, by resin farmers (RF) and external actors (EA). Gray circles and arrows show tradeoffs between positive and negative effects of livestock and fire in this system. The corresponding tradeoff boxes show how many farmers or externals identified the cattle tradeoff: trampling and biomass reduction, and the fire tradeoff: sapling burning and pine leaf litter burning.

3.3.2 Smallholder farmers´ and externals´ understanding and validation of the agent-based model

Figure 8a shows the ABM outcomes for recruits under eight mid-term scenarios (15-years) presented to participants for them to explore on the computer (see also Supplementary data, Appendix B, Fig. 3 and 4). The figure shows that recruitment is very high under scenario 1, and collapses in 2. Compared to scenario 2, recruitment increases slightly with a 12-year fire regime but increases more with yearly weeding instead of fire, albeit with very high labor costs. When using cattle instead of weeding, recruitment is only slightly lower, but produces additionally around 30 calves.

Participants were presented these eight scenarios sequentially and were asked to predict prior to each simulation, if recruitment would be higher or lower. The simulation of the native grass cover was compared with the initial condition; exotic grass cover simulation was compared with the output of the native grass scenario, while the predictions for fire, weeding and cattle management were compared to the exotic grass cover scenario. **Figure 8b** shows almost all farmers predicted qualitative outcomes correctly in each case, and only a few underestimated the damage caused by yearly or four-year interval fires. In the course of these simulations, participants started to become aware of other outputs as well (resin and calf production, grass cover) and the nonlinearities and tradeoffs associated with the modeled situations. Through these predictive exercises, farmers (a) learned the user interface and got used to interact with it; (b) developed confidence in the tool to later explore qualitatively ranges and combinations of management options and their tradeoffs, and (c) learned to understand the importance of discussing mid and long-term effects of management rather than short-sighted snapshots of immediate effects.

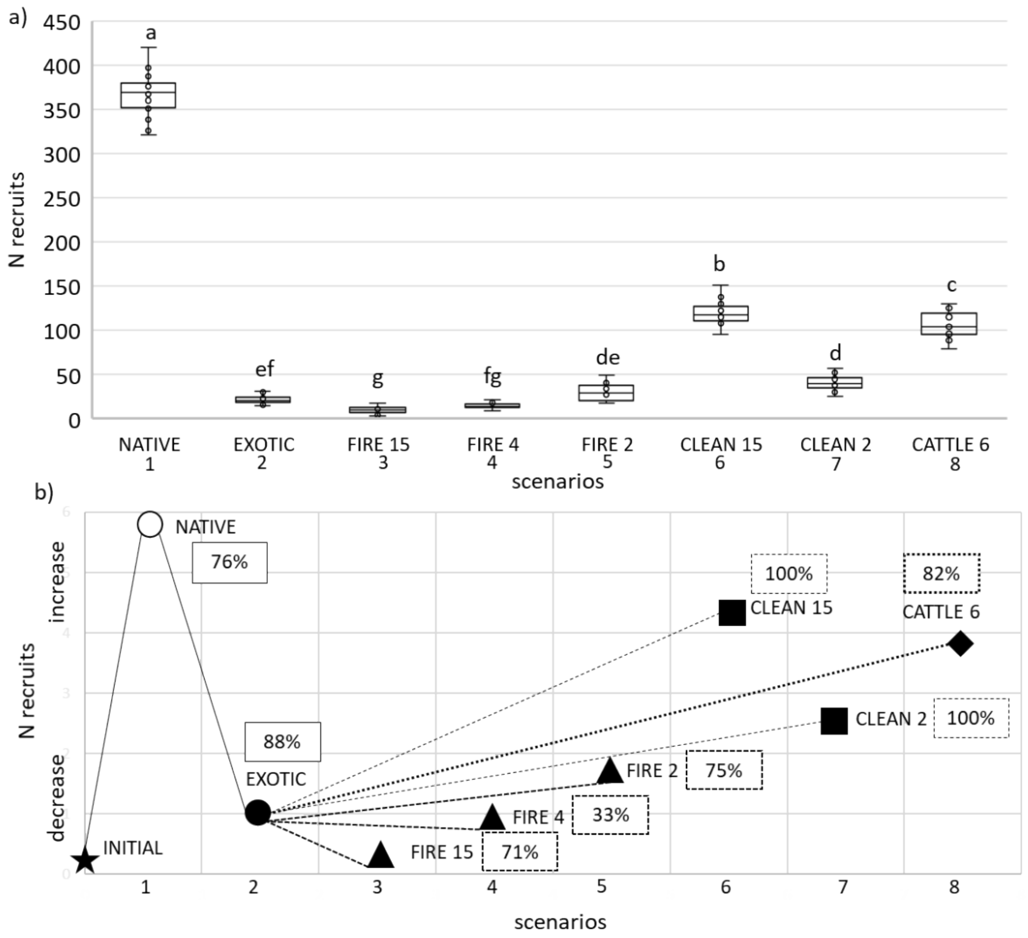


Fig. 8 a) Output of a sensitivity analysis for eight mid-term (15-years) simulations for alive recruits; 1) NATIVE grass cover without management; 2) EXOTIC grass cover without management; 3, 4, 5) FIRE (the number indicates frequency of burnings during 15 years simulation); 6, 7) CLEAN (the number indicates frequency of weeding during 15 years simulation; and 8) CATTLE, extensive grazing with six cows. Each scenario was run 20 times. Letters over Box-Whisker plots that share one or more equal letter label do not differ significantly according to the Tukey HSD multiple mean comparisons test (*a* = 0.05). b) Percentage (boxes) of farmers that correctly predicted an increase or decrease in pine recruitment before they ran each of the 15-years simulations. For example, 33% correctly predicted that recruits in the exotic grass with four years with fire (scenario 4) should decrease compared to exotic grass with no fire (scenario 2); 75% predicted an increase with only two years with fire (scenario 5).

Between the simulation of scenario 2 (exotic grass dominates) and the simulations with fire, weeding, and grazing scenarios, participants were asked to list their options to deal with the low recruitment associated with unmanaged exotic grass. Around 50% of the farmers mentioned weeding and planting saplings, 24% excluding cattle from pine stands, and 25% using cattle grazing to control grass; very few mentioned controlled fire **(Fig 9)**. In contrast, all external actors mentioned fire as an option and cattle grazing only as the second choice. Weeding and planting saplings were no real options for externals, because of high labor costs.

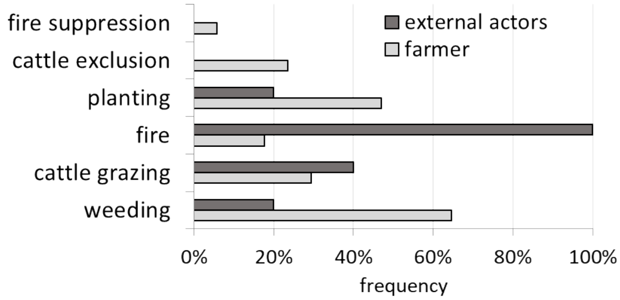


Fig. 9 Possible management strategies to control exotic tall grass cover fostering pine recruitment, mentioned by farmers and external actors after the simulation of scenario 2, shown in Figure 8.

3.3.3 Smallholder farmers´ and externals´ management parameter explorations in search for pre-established ecological and economic goals

In the first goal-oriented exercise, 33% of farmer teams met three goals, 44% met four, and only 22% met all. External actors did better, 25% met four and the rest met five goals. Both groups' success frequency was very similar for recruits, barrels and calves; the difference lied in farmer's lower success due to trampling and very low grass cover, because on average, they stocked more cattle per land unit. Examples of selected management strategies and their multivariable output are presented for farmers (**Fig. 10a**) and externals (**Fig. 10b**). In both cases, the most successful model outputs combined moderate weeding with the rotation of medium (2-4 animals/ha) cattle loads.

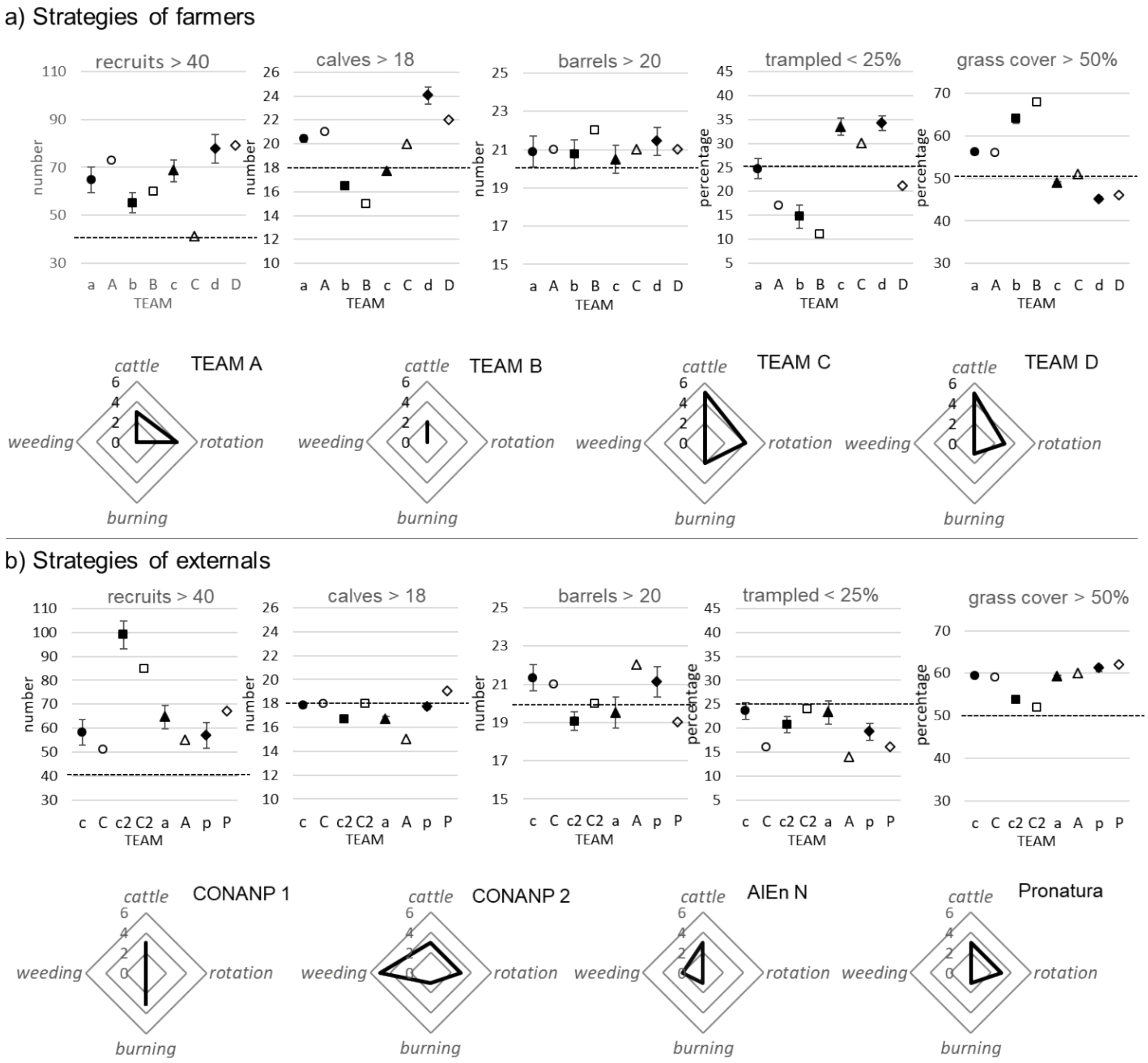


Fig. 10 Multivariable outputs for the economic and ecological goals for a 10-years simulation by a) farmers and b) external actors. Dashed line within each graph shows the upper pre-set limit for each goal. Capital letters on x-axis and unfilled markers are the economic and ecological results from workshop participants. Lower case letters on x-axis and filled markers with error bars (confidence interval 95%) are the means of a sensitivity analysis (20 replicates) using the same management strategies selected by different participant groups shown as heading of the radar charts; above: number of cattle, right: number of rotations each year, below: number of burnings, and left: number of weeding events during a 10-years simulation.

All available management practices affect exotic grass cover directly, and this eventually affects indirectly all simulation outputs. Where cattle were included, the teams had to figure out how to deal with the direct and indirect effects of grazing in order to strike a balance between the positive and negative effects of cows on recruitment and to reach the pre-defined calf and recruit scores. **Fig. 11** shows examples of different search strategies.

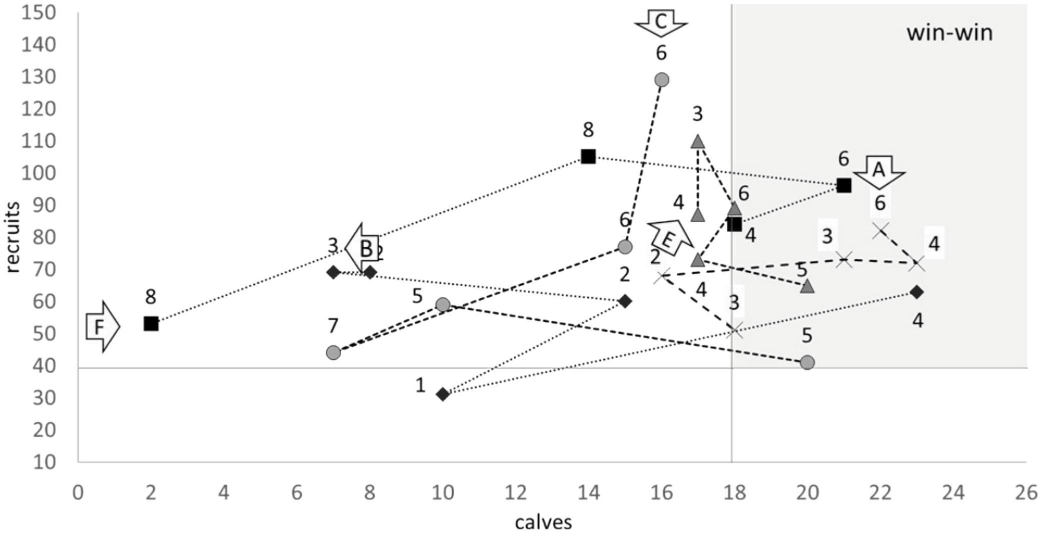


Fig. 11 Examples of farmers search path to achieve scores for calf and recruit production after a 10-years simulation, balancing the negative and positive effects of livestock grazing. Lines represent the pathway of a team, starting at the arrow (team name A-F), each marker states an attempt, and the number above the marker indicates the initial number of cows. The second quadrant (grey box) is the area were both recruit and calf production goals are met. Because of a fixed time limit for the exercise, not all teams reached five attempts.

More generally, **Fig. 12a-d** shows as grey clouds the relations (and nonlinear tradeoffs) between some of the model's output sets, produced by 3240 parameter combinations available to participants, for fire frequency (0, 1, 2, 3, 5 and 10 burnings), weeding frequency (0, 2, 3, 5 and 10 weedings), cattle loads (0 to 8 cows), and rotation frequency (0, 1, 2, 3, 4, 6 and 12 per year). In these ten-years scenarios, reduction in exotic grass is associated to broad and nonlinear sets of responses for both recruits and calves (**Fig 12a, b**), produced by a myriad of ways, how management options can be combined; this, in turn, defines a relation between recruit and calf sets that on average turns from synergistic to antagonistic (**Fig 12c**). Superimposed on these clouds are black dots representing the actual (x,y) ordered pairs of outputs achieved by participants in all their attempts to reach the established goals. The latter outputs show that most participants did not explore parameters in a veil of ignorance and at random, but found their way in this multivariate and nonlinear search space towards the model's win-win scenarios for cattle production, pine stand persistence, and long-term resin production. Both regressions in each graph are showing the same trends. For the regression between resin barrels and exotic grass cover **(Fig. 12d)** R^2 value (polynomial regression) is low, because in ten years there is yet no correlation between this set and the effect of recruitment on barrels is yet to come (see also Supplementary data, Appendix B, Fig. 5 and 6).

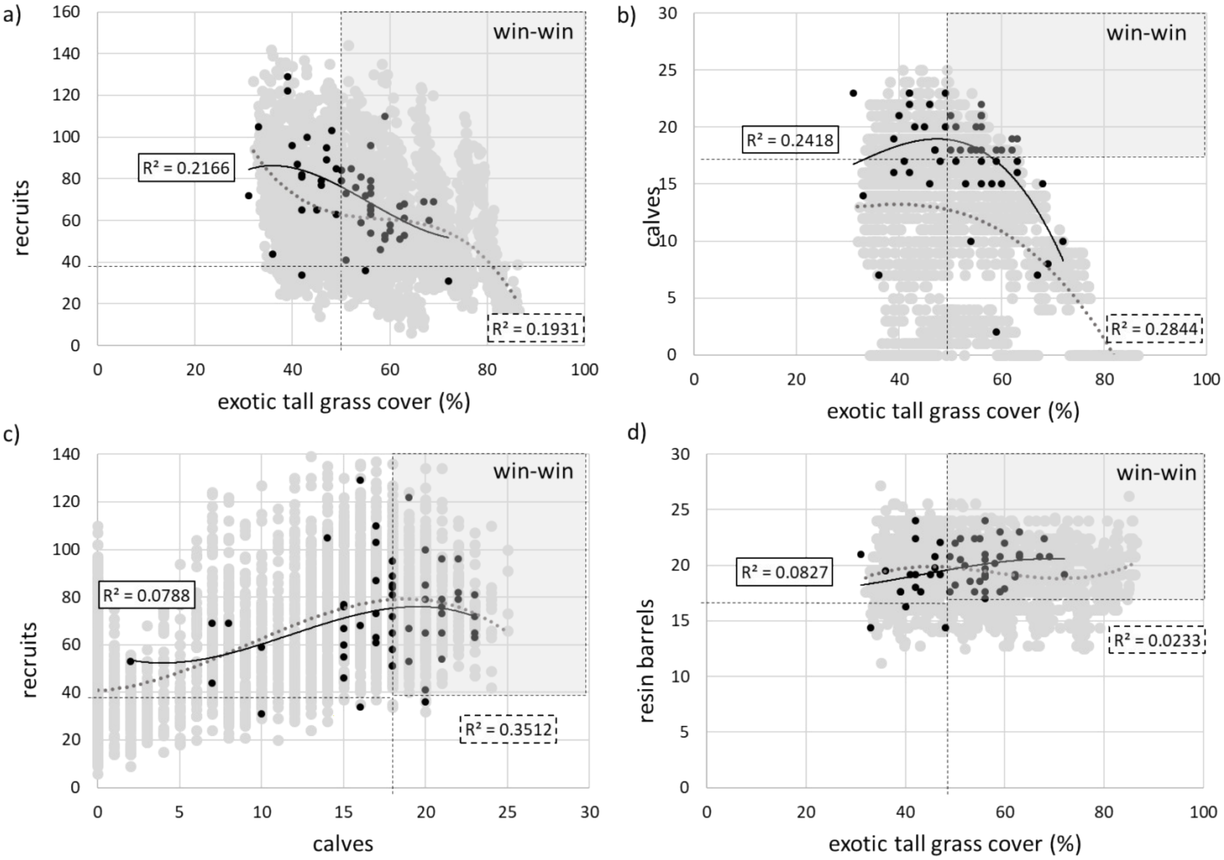


Fig 12. Regression examples of some ecological and economic outputs for 10-years simulations with different management strategy combinations. Gray dots, dotted lines and regression coefficient on the right side (R^2) are the result of 3240 possible combinations (runs; for more detail see Supplementary data B, Fig. 5), Black dots, black line and R^2 on the left side of the graphs are the results of the output variables from workshop participants.

3.3.4 The "two-brothers" exercise

In the “two brothers exercise”, two out of seven teams met both brothers’ goals (calf vs. resin/recruit productions). They arrived at proper cattle loads combined with rotation and moderate fire or manual weeding (but not both), which rendered productive and cost-effective levels of exotic grass. The other five teams also arrived at 3 or 4 cows but did not meet all goals. Three penalized their income from resins due to high weeding costs; two penalized their calf production by excessively reducing grass availability by weeding and burning. In the one-actor exercise, team members had only common goals and therefore clear reasons to collaborate and deal with tradeoffs together. In this brothers exercise, they had individual goals, and there was room for transforming tradeoff management into conflict and dominance of one brother’s goals and interest over the other. Yet, search spaces of the two-brother exercise did not differ with the first exercise nor compared to the regression trend of the sensitivity analysis (**Fig. 13**). We observed collaboration to try and meet both participant’s goals although again few teams actually met them.

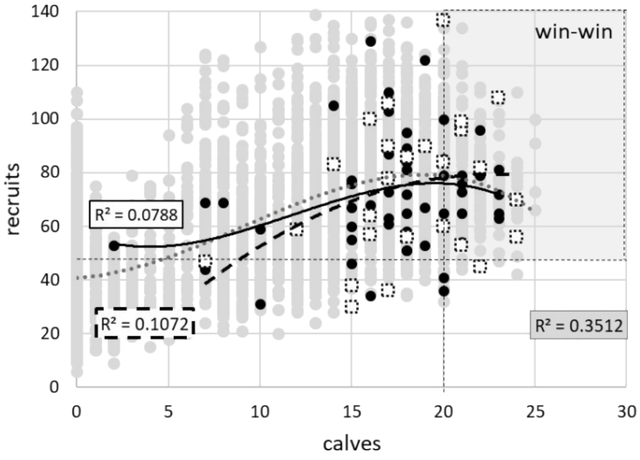


Fig. 13. Calves and recruit’s joint outputs resulting from the combination of management options explored through (a) a full sensitivity analysis with 3240 runs of possible combinations (gray dots, gray dotted line, R^2 in grey box), (b) simulations done by all teams during the first exercise (black dots, black line, R^2 in white box), and (c) simulations done by all teams during the two brothers exercise (white dots with dashed line, black dashed line, R^2 in white dashed box).

3.3.5 Reflection meetings

Both groups of farmers considered the simulation exercises increased their awareness of the long-term effects of any current management strategy on resin production and forest cover in the pine savanna, and on the consequences of not paying sufficient attention to recruitment. They also said they became more clearly aware of the cattle tradeoff and the need to handle cattle load properly. One farmer summarized it as “I am used to putting any number of cows in my pine stand without much thought and take them out when the grass becomes too short, but with no consideration for pine saplings; now I know managing stocking size can make a difference”. Farmers did not express concern for the fact that most teams did not meet all goals set by researchers in either of the free exercises; rather, they highlighted the many tradeoffs involved in such challenging multi-goal searches. Interestingly some farmers valued specifically TRUE GRASP as a tool with which they could experience the connectedness of many inputs and outputs through their joint responses. Some also mentioned that they could see very clearly what were the preferences of their team-mates and other participants, when faced with management choices and output tradeoffs. Many farmers stated that the ABM sufficiently captures what goes on in the pine savanna and that trying to meet goals really made them get involved; that they had fun and paid attention to the behavior of the many factors involved, and therefore learned much more than by sleeping over a long tedious power-point. External actors valued tradeoff analysis, but some were concerned with the model not being sufficiently realistic (e.g. not having slope effects, soil erosion) nor being quantitatively predictive (e.g. exactly how many saplings would be produced in real life, and management cost-effectiveness).

3.3.6 Multi-actor joint ABM exploration

During the last workshop, all multi-actor teams used a suite of different options (with different frequency) rather than focusing on a single one (**Fig. 14**). Interestingly, when trying to define a winning team, all concluded that it was not possible nor reasonable as some were ahead in some variables, while behind in others, an experience which made the concept of tradeoff even clearer to participants. Recruitment-wise, a winner team did stand out; the farmer said about their scores: “these resin tanks are our present, these recruits are our future, and these few calves are the tradeoff for taking the future into account”.

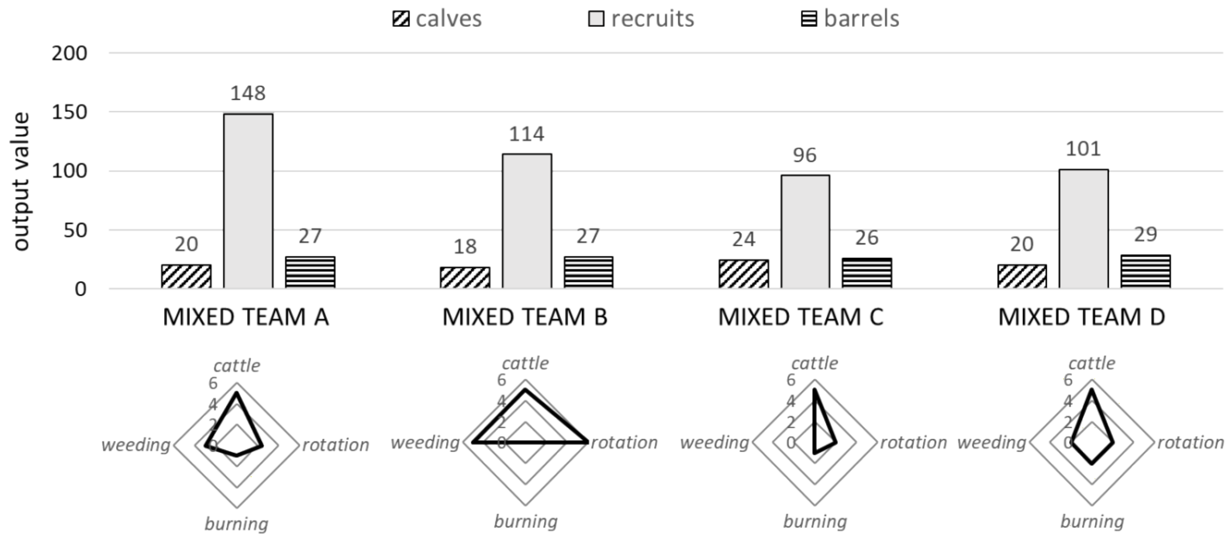


Fig. 14 Examples of the multi-actor exploration of selected management strategies (radar chart) for cattle loads, rotation frequency, number of burnings and weeding events and their multivariable outputs (bar charts) for the number of recruits, calves and resin barrel production after a 15-years simulation. Teams (x-axis below bar chart) were mixed groups of farmers and external actors.

3.3.7 Multi-actor meeting to discuss decision tree

Immediately after the simulation contest, we conducted an exercise for actors to make hypothetical management choices along a decision tree, revealed to them step by step (**Fig. 15**). All chose resin production as a long-term project (> 50 years). The most consolidated production partners (*ejido* California and AlEn Co.) preferred tree stand regeneration with pine nurseries and sapling planting, something they sustained since the pre-simulation interviews (**Fig 9**), while all others preferred assisted natural recruitment. Both *ejidos* preferred exotic grass control around sapling by cattle and suppress fire, while the NGO and AlEn Co. preferred weeding and controlled ground-burning. Some, but not all participants changed their points of view along the process, and particularly after the collective exercise. CONANP had strongly advocated concentrating cattle in intensive land use areas and keeping them out of the savanna; it now accepts it is sound and less costly to control exotic grass with a combination of cattle grazing and controlled fire (and occasionally other methods). The AlEn officer initially stated that cattle were the cause of exotic grass invasion; during the simulations he acknowledged the capacity of cattle to control these grasses and favor recruitment; during the decision-making exercise, he again dismissed cattle presence in the pine savanna. AlEn Co. considered that proper management of pine stands (and associated monetary costs) to promote new trees should be each farmer's endeavor. The *ejidos* preferred to request government subsidies for such practices through a resin producer organization, while CONANP and the NGO did not favor subsidy requests.

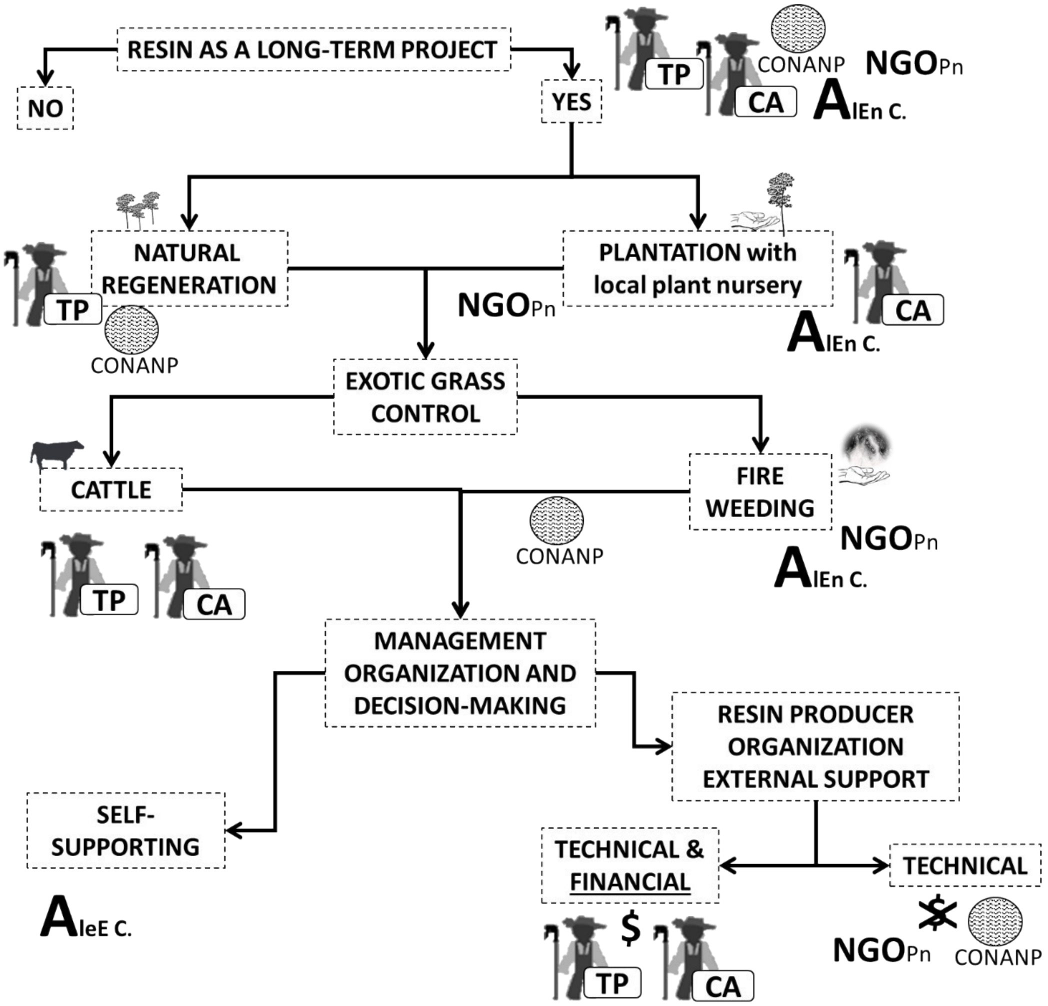


Fig. 15. Result of the decision tree exercise in the multi-actor workshop, participants were local resin and cattle farmers from the *ejidos* Tres Picos (TP) and Califonia (CA), resin buyer AlEn C., CONANP, and a regional conservation NGO Pronatura. Note, if an actor has no clear position to a question he was placed between both answers (e.g. exotic grass control in case of CONANP).

4 Discussion and Conclusion

Peasant populations established at tropical and subtropical forest frontiers have secularly developed silvo-pastoral practices, livelihoods and landscapes in their territories (García-Barrios and González-Espinosa 2017; Koning, 2014; Sloan, 2007; Van Vliet et al., 2012; Walker et al., 2002). Many of their multiple-use forested areas have recently been claimed by other actors and declared MABR. The few new opportunities and the many constraints to silvopastoral use and management dictated by external actors have frequently led to all types and levels of conflict, and lack of success for all parties (Bernard et al., 2014; Bouamrane et al., 2016; Cortina-Villar et al., 2012; Ma et al., 2009; Martín-López et al., 2011). In consequence, actors in some cases have slowly acknowledged the need to engage in collective learning and deliberation to better understand and negotiate their interests. Socio-ecological researchers have shown interest in these processes and are active in helping to develop and deploy strategies, methods and tools to support learning, negotiation and decision making (Berthet et al., 2016; Etienne et al., 2011; Kok, 2009; Mathevet et al., 2011; Tenza et al., 2017; Villamor et al., 2014; Voinov and Bousquet, 2010; Wittmer et al., 2006). These multi-actor efforts are riddled with theoretical and practical challenges related to the different values, knowledge frameworks, interests and power relations of those involved (Galafassi et al., 2017; Huntington, 2000; Tenza et al., 2017). A number of participatory decision-making frameworks have been developed to deal with these challenges (for a review, see Lynam et al. 2007). Additionally, land under silvopastoral use exhibits complex non-linear social and ecological interactions that confer both obvious and subtle tradeoffs, which not only have short-term consequences, but can lead to long-term undesired shifts in vegetation regime, and to local production and livelihood collapse (Allen and Gunderson, 2011; Carpenter and Gunderson, 2001; Filatova et al., 2016; Filatova and Polhill, 2012). ABMs and RPGs are instruments well suited to capture and explore in stylized and dynamical form these complex silvopastoral behaviors (An, 2012; Becu et al., 2008; Bousquet et al., 2002; Etienne, 2014; Filatova et al., 2016, 2013; Parker et al., 2003; Villamor and van Noordwijk, 2011; Voinov and Bousquet, 2010). A small but growing suite of rangeland and silvopastoral tools have been developed: SYLVOPAST (Etienne, 2003), SIERRA SPRINGS (García-Barrios et al., 2011, 2015), ABM/RPG grazing tool for herders and foresters (Dumrongrojwatthana et al., 2011), RANGELAND RUMMY (Farrie et al., 2014), SEQUIA BASALTO (Bommel et al., 2014), GRAZING GAME (Villamor and Badmos, 2015), FORAGE RUMMY (Martin, 2015), and KULAYIJANA (Perrotton et al., 2017). They differ in their specific purposes, complexity, precision and realism and in actors' involvement in the various stages of development. Creating an ABM-supported RPG that represents the dynamics of silvopastoral land subject to a suite of management options and actors' interests is in itself a very elaborate process that involves dealing with many design tradeoffs and difficult choices regarding realism, precision and generality. We and others have previously found that smallholder farmers - in some but not all senses - are initially in disadvantage relative to other actors when learning, using and interpreting these complex tools, but that the gap can be closed (Garcia-Barrios et al., 2017). Thus, we consider that design decisions should be led by making sure that smallholder farmers can engage, trust the qualitative outcomes, enjoy the virtual immersion in complex behaviors, and contribute to the collective learning experience (Galafassi et al., 2017; Garcia-Barrios et al., 2017; 2015; 2011; Le Page and Perrotton, 2017; Perrotton et al., 2017).

The tool described in this paper allows exploring management options and assessing their consequences in the short- (10-15 years) and mid- (16-50 years) term. Each combination of options is investigated independently. The tool is therefore currently suitable to explore individual management options at the farm level or to represent landscape effects, assuming that a collective agreement for centralized management exists. Yet the ABM would need to be further developed in order to capture more complex social behaviors, where defection and free riding may exist, and where individual agents are making concurrent decisions accounting for what the others may decide at the same time. The consequences on the landscape could differ significantly from centralized management. Such a model (which could be built in NetLogo´s Hubnet platform) would offer a group of 5-6 participants the possibility to re-adjust their individual management options at each step during a simulation run. This would allow going further than the "two-brothers" experiment into co-managing renewable resources. In short, there is ample space for further developing the model.

We will now briefly discuss the most relevant findings derived from pre-modelling interviews, model building, pre-workshop quizzes, interactive simulation workshops and group deliberations.

Pre-modelling interviews

Most smallholder farmers stated that (a) resin as an income option will grow in the future and that they are willing to conserve the pine-oak savanna; (b) sapling establishment requires bare soil, and is reduced by dense exotic grass cover, pine-leaf litter accumulation and sapling trampling by cows; (c) grazing is one of several possible means for pine recruitment, very few mentioned fire management to burn the grass. This recent fire taboo (or silence) stems from previous conflict with CONANP over traditional fire use in the area (Braasch et al., 2017; Guevara-Hernández et al., 2013; Navarro et al., 2017). Smallholder farmers strongly depend on their ecological knowledge but also incorporate information from external actors (Soto-Pinto et al., 2007; Valencia et al., 2015). There is no unique truth, processes change continuously and unpredictably and therefore knowledge is never complete. Participatory approaches can help navigate such complexity by combining farmer and academic knowledge, and developing together new insights (Allen and Gunderson, 2011; Dawoe et al., 2012; García-Barrios et al. 2017; Vandermeer and Perfecto 2013).

Model development and validity

Structuring and parameterizing TRUE GRASP based on quantitative and qualitative knowledge provided by farmers, field research and literature was successful. This simulation framework exhibits sufficient internal validity, because - as shown by a thorough sensitivity analysis - (a) it reproduces qualitatively the different long-term scenarios of interest for pine recruitment (closed pine forest, open grassland and pine savanna); (b) it produces qualitative scenarios that are robust under various combinations of management practices (cattle, rotation, weeding, fire), but may shift when ecological thresholds are crossed; (c) it exhibits interesting and credible nonlinear responses to each practice's range of possible values as well as credible nonlinear tradeoffs among practices and among desired outputs; (d) it clearly captures the fact that similar output syndromes (sets of relevant output values) can be achieved with different management combinations. As reported by An (2012), ABM are increasingly used to simulate the complexity of SES, because they can deal with heterogeneity, featuring feedbacks, nonlinearities and adaptation. They provide several advantages over other models when dealing with land cover change, regime shifts and tradeoffs (Filatova et al., 2016; Miyasaka et al., 2017; Parker et al., 2003).

Pre-simulation Quizzes

TRUE GRASP directly exposes users to nonlinear, non-trivial tradeoffs when using different management practices. Such tradeoffs became apparent to all actors only after having solved the quizzes. Smallholder farmers were more interested in managing cattle tradeoffs, while external actors in managing fire tradeoffs, again manifesting their respective biases and preference taboos. It is ironic, considering that a few years ago smallholder farmers used fire liberally and externals prohibited it. As described in Galafassi et al. (2017), these outputs can be explained in three ways; a) tradeoffs are often invisible, because of a lack of systemic understanding; b) tradeoffs are perceived differently by different actors; different people see gains and losses differently; and c) tradeoffs are often hidden or ignored, when taboos are involved (Daw et al., 2015; Schoemaker and Tetlock, 2012).

Learning, trusting and using TRUE GRASP

All actors found the long-term qualitative forest cover scenarios relevant and credible, appreciated this long-term approach to management choices, and increasingly trusted the tool for qualitatively exploring ranges and combinations of management options and their tradeoffs. Most users correctly predicted the qualitative forest cover scenarios, discovered and dealt with tradeoffs, and found their way towards the goals for cattle production, pine stand persistence, and resin production pre-established by researchers as training exercises. As mentioned earlier, TRUE GRASP behaviors and outputs are only qualitatively predictive. Sun et al. (2016) called these kinds of qualitative models simple ABMs, and Le Page and Perrotton (2017) call them stylized, referring to the model structure as compared to quantitative, data-hungry prediction models. Generic, stylized qualitative models are highly recommended for participative approaches to foster deliberation and decision making (Edmonds and Moss, 2004; Le Page and Perrotton, 2017; Sun et al., 2016; Tenza et al., 2017; Voinov and Bousquet, 2010), especially when dealing with tradeoffs, hard choices between ecological and social benefits, individual and community benefits, and among actors who bear different costs and benefits (Lazos-Chavero et al., 2016). Interestingly, the reserve management team expected an ABM with more realism and prediction of operational quantities, while farmers expressed they were content with experiencing and becoming more aware of interactions, tradeoffs, and indirect effects. Thus, the tension between favoring generality, realism, and precision (Levins, 1966) and between building theoretical, stylized or realistic ABMs (Le Page and Perrotton, 2017) is probably unavoidable in multi-actor settings.

During these exercises, team members with common goals had clear reasons to collaborate. In the “two brothers” exercise performed by farmers, there was room for transforming tradeoff management into conflict and dominance of one brother’s goals and interests over the other, yet this did not occur. This has at least two explanations or their combination: users would actually collaborate in real life in an effort to balance the tradeoffs in a fair way, as found by García-Barrios et al. (2015), where users enjoyed exploring the possibility of such collaboration in a safe environment, with no significant cost in their real-life relations, as found by Berthet et al., (2016).

User´s evaluation of TRUE GRASP

Most actors said that the exercises had increased their awareness of (a) the long-term resin production and forest cover effects, (b) the consequences of low pine recruitment, (c) the usefulness of cattle and/or fire to increase pine recruitment, and (d) the many tradeoffs involved. They said that TRUE GRASP really made them get involved in dealing with the relevant issues, have fun and pay attention to the behavior of the many factors involved and their interactions. The capacity of the TRUE GRASP workshops to produce collective socio-ecological learning is in line with other ABM and RPG rural workshops (Berthet et al., 2016; Garcia-Barrios et al., 2017, 2015, 2011; Patel et al., 2007; Perrotton et al., 2017; Speelman et al., 2014a, 2014b; Villamor et al., 2014; Villamor and van Noordwijk, 2011).

Multi-actor exercises and deliberation

Exploration and negotiation among actors ran smoothly and collaboratively (although subtle dominance by external actors was frequently expressed by hoarding the computer mouse and output sheet). These actors have been interacting and negotiating different issues for the past 20 years and the exercise reflected in a playful way both collaboration and unspoken conflict of their past relationships. One principle of RPG described by the ComMod group, but also by other authors (Etienne, 2014; Lynam et al., 2007; Villamor and van Noordwijk, 2011) is the capacity to cross boundaries among actors belonging to different worlds, while being interested in the same resource and to promote a dialog in a fair and balanced multi-actor space.

Fostering the dialog in MABR is essential, because actors would be able to present, discuss and better understand one another's perspectives and needs (Bouamrane et al., 2016). However, it is also important to provide a space for social and collective learning among actors, to solve problems, conflicts and to negotiate agreements (Patel et al., 2007).

While in the TRUE GRASP exercise, participants were more open to combine contrasting management practices, during the decision tree exercise they privileged their previously expressed real-life preferences, while stating they remained open to further discussion. This is not surprising as ABM/RPG workshops should not be expected to produce effects totally aligned with the model's stylized propositions, nor to do so immediately and in a one-shot experience. Yet, we are certain that the simulation exercise leveled the ground for a more honest discussion and for understanding other actors' statements and choices during this last exercise. As mentioned by Bodin (2017), participatory approaches are sometimes unable to deliver immediate and expected concrete results, or create the illusion of results in the form of symbolic outcomes such as aggregated wish lists, where conflicts of interest are left untouched. The creation of a socially and ecologically sustainable management plan implies a fair and balanced designed arena, for productive discussions and negotiations between the smallholder farmers and external actors (Etienne, 2014; Perrotton et al., 2017). However, this calls for the commitment of researchers and all actors to social learning that truly involves smallholder farmers and provides tools that do not overwhelm them (Galafassi et al., 2017; Garcia-Barrios et al., 2017).

Acknowledgements

We thank the *ejido* members of California and Tres Picos in the La Sepultura Biosphere Reserve, and all external actors; CONANP, Pronatura, AlEn de Norte, for their participation in the workshop and the Biosphere staff in California for supporting research logistics. This work was supported by ECOSUR's M&T Family Agriculture Project and the Rufford Foundation [17207-1]. MB thanks CONACYT for a PhD scholarship [375409 − 250287]. We gratefully acknowledge Yanus Dechnik-Vásquez, Alan Heinze-Yothers and Alejandra Hernández-Guzmán who participated as facilitators during the workshop and helped in logistics. We thank the three anonymous reviewers for their comments, which greatly improved the clarity of the text.

Cited literature

Adams, W.M., 2004. Biodiversity Conservation and the Eradication of Poverty. Science 306, 1146–1149. doi:10.1126/science.1097920

Agrawal, A., and Ostrom, E. 2001. Collective action, property rights and decentralisation in resource use in India and Nepal. Politics and Society 29(4):485–514. http://dx.doi.org/https://doi. org/10.1177/0032329201029004002

Allen, C.R., Fontaine, J.J., Pope, K.L., Garmestani, A.S., 2011. Adaptive management for a turbulent future. J. Environ. Manage. 92, 1339–1345.

Allen, C.R., Gunderson, L.H., 2011. Pathology and failure in the design and implementation of adaptive management. J. Environ. Manage. 92, 1379–1384. doi:10.1016/j.jenvman.2010.10.063

An, L., 2012. Modeling human decisions in coupled human and natural systems: Review of agent-based models. Ecol. Model., Modeling Human Decisions 229, 25–36. doi:10.1016/j.ecolmodel.2011.07.010

Archer, S.R., Andersen, E.M., Predick, K.I., Schwinning, S., Steidl, R.J., Woods, S.R., 2017. Woody Plant Encroachment: Causes and Consequences, in: Rangeland Systems, Springer Series on Environmental Management. Springer, Cham, pp. 25–84. doi:10.1007/978-3-319-46709-2_2

Barnaud, C., Le Page, C., Dumrongrojwatthana, P., Trébuil, G., 2013. Spatial representations are not neutral: Lessons from a participatory agent-based modelling process in a land-use conflict. Environ. Model. Softw. 45, 150–159. doi:10.1016/j.envsoft.2011.11.016

Becu, N., Neef, A., Schreinemachers, P., Sangkapitux, C., 2008. Participatory computer simulation to support collective decision-making: Potential and limits of stakeholder involvement. Land Use Policy 25, 498–509. https://doi.org/10.1016/j.landusepol.2007.11.002

Bernard, F., van Noordwijk, M., Luedeling, E., Villamor, G.B., Sileshi, G.W., Namirembe, S., 2014. Social actors and unsustainability of agriculture. Curr. Opin. Environ. Sustain. 6, 155–161. doi:10.1016/j.cosust.2014.01.002

Berthet, E.T., Barnaud, C., Girard, N., Labatut, J., Martin, G., 2016. How to foster agroecological innovations? A comparison of participatory design methods. J. Environ. Plan. Manag. 59, 280–301.

Bodin, Ö., 2017. Collaborative environmental governance: Achieving collective action in social-ecological systems. Science 357, eaan1114. doi:10.1126/science.aan1114

Bommel, P., Dieguez, F., Bartaburu, D., Duarte, E., Montes, E., Pereira Machín, M., Corral, J., Lucena, C.J.P. de, Morales Grosskopf, H., 2014. A Further Step Towards Participatory Modelling. Fostering Stakeholder Involvement in Designing Models by Using Executable UML. J. Artif. Soc. Soc. Simul. 17, 6.

Bouamrane, M., Spierenburg, M., Agrawal, A., Boureima, A., Cormier-Salem, M.-C., Etienne, M., Le Page, C., Levrel, H., Mathevet, R., 2016. Stakeholder engagement and biodiversity conservation challenges in social-ecological systems: some insights from biosphere reserves in western Africa and France. Ecol. Soc. 21. doi:10.5751/ES-08812-210425

Bousquet, F., Barreteau, O., D'Aquino, P., Etienne, M., Boissau, S., Aubert, S., Le Page, C., Babin, D., Castella, J. C. (2002). Multi-agent systems and role games: collective learning processes for ecosystem management. In M. A. Janssen (Ed.), Complexity and ecosystem management. The theory and practice of multi-agent systems (pp. 248–285): Edward Elgar Publishing.

Braasch, M., García-Barrios, L., Ramírez-Marcial, N., Huber-Sannwald, E., Cortina-Villar, S., 2017. Can cattle grazing substitute fire for maintaining appreciated pine savannas at the frontier of a montane forest biosphere-reserve? Agric. Ecosyst. Environ. 250, 59–71. doi:10.1016/j.agee.2017.08.033

Carpenter, S.R., Gunderson, L.H., 2001. Coping with Collapse: Ecological and Social Dynamics in Ecosystem Management Like flight simulators that train would-be aviators, simple models can be used to evoke people's adaptive, forward-thinking behavior, aimed in this instance at sustainability of human–natural systems. BioScience 51, 451–457.

Castri, F. di, 1976. International, interdisciplinary research in ecology: Some problems of organization and execution. The case of the man and the biosphere (MAB) programme. Hum. Ecol. 4, 235–246. doi:10.1007/BF01534288

CONAGUA [Comisión Nacional del Agua], 2015. http://www.cna.gob.mx.

CONANP [Comisión Nacional de Áreas Naturales Protegidas], 2013. Modificación del Programa de Manejo de la Reserva de la Biosfera La Sepultura. CONANP, México, D.F., México. [In Spanish.].

Cortina-Villar, S., Plascencia-Vargas, H., Vaca, R., Schroth, G., Zepeda, Y., Soto-Pinto, L., Nahed-Toral, J., 2012. Resolving the Conflict Between Ecosystem Protection and Land Use in Protected Areas of the Sierra Madre de Chiapas, Mexico. Environ. Manage. 49, 649–662. doi:10.1007/s00267-011-9799-9

Cruz-Morales, J., 2014. Construcción de territorios ambientales mediante procesos de aprendizaje social. El caso de la Cuenca Alta del Río El Tablón, Reserva de la Biosfera La Sepultura, Chiapas, México. Universidad Autónoma Metropolitana, Mexico, D.F., Mexico. [In Spanish.].

Daw, T.M., Coulthard, S., Cheung, W.W., Brown, K., Abunge, C., Galafassi, D., Peterson, G.D., McClanahan, T.R., Omukoto, J.O., Munyi, L., 2015. Evaluating taboo trade-offs in ecosystems services and human well-being. Proc. Natl. Acad. Sci. 112, 6949–6954.

Dawoe, E., Quashie-Sam, J., E. Isaac, M., Oppong, S., 2012. Exploring farmers' local knowledge and perceptions of soil fertility and management in the Ashanti Region of Ghana. doi:10.1016/j.geoderma.2012.02.015

DeFries, R., Hansen, A., Turner, B.L., Reid, R., Liu, J., 2007. Land use change around protected areas: management to balance human needs and ecological function. Ecol. Appl. 17, 1031–1038. doi:10.1890/05-1111

Dumrongrojwatthana, P., Page, C.L., Gajaseni, N., Trébuil, G., 2011. Co-constructing an agent-based model to mediate land use conflict between herders and foresters in northern Thailand. J. Land Use Sci. 6, 101–120. https://doi.org/10.1080/1747423X.2011.558596

Edmonds, B., and Moss, S. 2004. From KISS to KIDS–an 'anti-simplistic' modelling approach. In International workshop on multi-agent systems and agent-based simulation (pp. 130-144). Springer, Berlin, Heidelberg.

Etienne, M. 2003. SYLVOPAST: a multiple target role-playing game to assess negotiation processes in sylvopastoral management planning. Journal of Artificial Societies and Social Simulation 6(2).

Etienne, M. (Ed.), 2014. Companion Modelling. Springer Netherlands, Dordrecht. doi:10.1007/978-94-017-8557-0

Etienne, M., Du Toit, D., Pollard, S., 2011. ARDI: A Co-construction Method for Participatory Modeling in Natural Resources Management. Ecol. Soc. 16. doi:10.5751/ES-03748-160144

Farrie, B., Jouven, M., Launay, F., Moreau, jean-christophe, Moulin, C.-H., Piquet, M., Taverne, M., Tchakérian, E., Thénard, V., Martin, G., 2014. Rangeland Rummy – A board game to support adaptive management of rangeland-based livestock systems. doi:10.1016/j.jenvman.2014.08.018

Filatova, T., Polhill, G., 2012. Shocks in coupled socio-ecological systems: what are they and how can we model them?

Filatova, T., Polhill, J.G., van Ewijk, S., 2016. Regime shifts in coupled socio-environmental systems: Review of modelling challenges and approaches. Environ. Model. Softw. 75, 333–347. doi:10.1016/j.envsoft.2015.04.003

Filatova, T., Verburg, P.H., Parker, D.C., Stannard, C.A., 2013. Spatial agent-based models for socio-ecological systems: Challenges and prospects. Environ. Model. Softw. 45, 1–7. doi:10.1016/j.envsoft.2013.03.017

Galafassi, D., Daw, T.M., Munyi, L., Brown, K., Barnaud, C., Fazey, I., 2017. Learning about social-ecological trade-offs. Ecol. Soc. 22. doi:10.5751/ES-08920-220102

Garcia-Barrios, L., Cruz-Morales, J., Vandermeer, J., Perfecto, I., 2017. The Azteca Chess experience: learning how to share concepts of ecological complexity with small coffee farmers. Ecol. & Soc. 22(2) 37. doi:10.5751/ES-09184-220237

García-Barrios, L., Galván-Miyoshi, Y.M., Valdivieso-Pérez, I.A., Masera, O.R., Bocco, G., Vandermeer, J., 2009. Neotropical Forest Conservation, Agricultural Intensification, and Rural Out-migration: The Mexican Experience. BioScience 59, 863–873. doi:10.1525/bio.2009.59.10.8

García-Barrios, L., García-Barrios, R., Cruz-Morales, J., Smith, J.A., 2015. When death approaches: reverting or exploiting emergent inequity in a complex land-use table-board game. Ecol. Soc. 20. doi:10.5751/ES-07372-200213

García-Barrios, L., García-Barrios, R., Waterman, A., Cruz-Morales, J., 2011. Social dilemmas and individual/group coordination strategies in a complex rural land-use game. Int. J. Commons 5.

García-Barrios, L., González-Espinosa, M., 2017. Investigación ecológica participativa como apoyo de procesos de manejo y restauración forestal, agroforestal y silvopastoril en territorios campesinos. Experiencias recientes y retos en la sierra Madre de Chiapas, México. Rev. Mex. Biodivers. 88 (Suppl.):129-140. https://doi.org/10.1016/j.rmb.2016.10.022

Grimm, V., Berger, U., DeAngelis, D.L., Polhill, J.G., Giske, J., Railsback, S.F., 2010. The ODD protocol: a review and first update. Ecol. Model. 221, 2760–2768.

Guevara-Hernández, F., Gómez-Castro, H., Medina-Sansón, L., Rodríguez-Larramendi, L.A., Mendoza-Nazar, P., McCune, N.M., Tejeda-Cruz, N.M., Pinto-, Ruiz, R., 2013. Traditional fire use, governance and social dynamics in a Biosphere Reserve of Chiapas Mexico. Pensee J. 11, 110–125.

Huber-Sannwald, E., Ribeiro Palacios, M., Arredondo Moreno, J.T., Braasch, M., Martinez Pena, R.M., de Alba Verduzco, J.G., Monzalvo Santos, K., 2012. Navigating challenges and opportunities of land degradation and sustainable livelihood development in dryland social-ecological systems: a case study from Mexico. Philos. Trans. R. Soc. B Biol. Sci. 367, 3158–3177. doi:10.1098/rstb.2011.0349

Huntington, H.P., 2000. Using Traditional Ecological Knowledge in Science: Methods and Applications. Ecol. Appl. 10, 1270–1274. doi:10.1890/1051-0761(2000)010[1270:UTEKIS]2.0.CO;2

Kok, K., 2009. The potential of Fuzzy Cognitive Maps for semi-quantitative scenario development, with an example from Brazil. Glob. Environ. Change 19, 122–133. doi:10.1016/j.gloenvcha.2008.08.003

Koning, J. de, 2014. Unpredictable Outcomes in Forestry—Governance Institutions in Practice. Soc. Nat. Resour. 27, 358–371. doi:10.1080/08941920.2013.861557

Lazos-Chavero, E., Zinda, J., Bennett-Curry, A., Balvanera, P., Bloomfield, G., Lindell, C., Negra, C., 2016. Stakeholders and tropical reforestation: challenges, trade-offs, and strategies in dynamic environments. Biotropica 48, 900–914. doi:10.1111/btp.12391

Le Page, C., Becu, N., Bommel, P., Bousquet, F., 2010. Participatory Agent-Based Simulation for Renewable Resource Management: The Role of the Cormas Simulation Platform to Nurture a Community of Practice. J. Artif. Soc. Soc. Simul. 15, 10.

Le Page C., Perrotton A. (2017) KILT: A Modelling Approach Based on Participatory Agent-Based Simulation of Stylized Socio-Ecosystems to Stimulate Social Learning with Local Stakeholders, in: Autonomous Agents and Multiagent Systems, Lecture Notes in Computer Science. Presented at the International Conference on Autonomous Agents and Multiagent Systems, Springer, Cham, pp. 31–44. https://doi.org/10.1007/978-3-319-71679-4_3

Levins, R.: 1966, 'The Strategy of Model Building in Population Biology'. In: E. Sober (ed.): Conceptual Issues in Evolutionary Biology. Cambridge, MA: MIT Press, first edition, pp. 18–27.

Lynam, T., de Jong, W., Sheil, D., Kusumanto, T., Evans, K., 2007. A Review of Tools for Incorporating Community Knowledge, Preferences, and Values into Decision Making in Natural Resources Management. Ecol. Soc. 12. doi:10.5751/ES-01987-120105

Ma, Z., Li, B., Li, W., Han, N., Chen, J., Watkinson, A.R., 2009. Conflicts between biodiversity conservation and development in a biosphere reserve. J. Appl. Ecol. 46, 527–535. doi:10.1111/j.1365-2664.2008.01528.x

Martin, G., 2015. A conceptual framework to support adaptation of farming systems ? Development and application with Forage Rummy. Agric. Syst. 132, 52–61. doi:10.1016/j.agsy.2014.08.013

Martín-López, B., García-Llorente, M., Palomo, I., Montes, C., 2011. The conservation against development paradigm in protected areas: Valuation of ecosystem services in the Doñana social–ecological system (southwestern Spain). Ecol. Econ. 70, 1481–1491. doi:10.1016/j.ecolecon.2011.03.009

Mathevet, R., Etienne, M., Lynam, T., Calvet, C., 2011. Water management in the Camargue Biosphere Reserve: insights from comparative mental models analysis. Ecol. Soc. 16.

Miyasaka, T., Le, Q.B., Okuro, T., Zhao, X., Takeuchi, K., 2017. Agent-based modeling of complex social–ecological feedback loops to assess multi-dimensional trade-offs in dryland ecosystem services. Landsc. Ecol. 32, 707–727. doi:10.1007/s10980-017-0495-x

Müller, B., Bohn, F., Dreßler, G., Groeneveld, J., Klassert, C., Martin, R., Schlüter, M., Schulze, J., Weise, H., Schwarz, N., 2013. Describing human decisions in agent-based models – ODD + D, an extension of the ODD protocol. Environ. Model. Softw. 48, 37–48. doi:10.1016/j.envsoft.2013.06.003

Navarro, A.G., Barrios, L.E.G., Vázquez, M.P., Rosset, P., 2017. De la supresión al manejo del fuego en la Reserva de la Biosfera La Sepultura, Chiapas: perspectivas campesinas. Región Soc. 29. doi:10.22198/rys.2017.70.a329

Parker, D.C., Manson, S.M., Janssen, M.A., Hoffmann, M.J., Deadman, P., 2003. Multi-agent systems for the simulation of land-use and land-cover change: A review. Ann. Assoc. Am. Geogr. 93, 314–337.

Parsons, J.J., 1972. Spread of african pasture grasses to the american tropics. J. Range Manag. 25, 12. http://dx.doi.org/10.2307/3896654.

Patel, M., Kok, K., Rothman, D.S., 2007. Participatory scenario construction in land use analysis: An insight into the experiences created by stakeholder involvement in the Northern Mediterranean. Land Use Policy 24, 546–561. doi:10.1016/j.landusepol.2006.02.005

Perrotton, A., de Garine-Wichatitsky, M., Valls-Fox, H., Le Page, C., 2017. My cattle and your park: codesigning a role-playing game with rural communities to promote multistakeholder dialogue at the edge of protected areas. Ecol. Soc. 22. doi:10.5751/ES-08962-220135

Plummer, R., Baird, J., Dzyundzyak, A., Armitage, D., Bodin, Ö., Schultz, L., 2017. Is Adaptive Co-management Delivering? Examining Relationships Between Collaboration, Learning and Outcomes in UNESCO Biosphere Reserves. Ecol. Econ. 140, 79–88. https://doi.org/10.1016/j.ecolecon.2017.04.028

Railsback, S.F., Grimm, V., 2012. Agent-Based and Individual-Based Modeling: A Practical Introduction. Princeton University Press.

Ribeiro Palacios, M., Huber-Sannwald, E., García Barrios, L., Peña de Paz, F., Carrera Hernández, J., Galindo Mendoza, M. de G., 2013. Landscape diversity in a rural territory: Emerging land use mosaics coupled to livelihood diversification. Land Use Policy 30, 814–824. doi:10.1016/j.landusepol.2012.06.007

Rollins, N.D., Barton, C.M., Bergin, S., Janssen, M.A., Lee, A., 2014. A Computational Model Library for publishing model documentation and code. Environ. Model. Softw. 61, 59–64. https://doi.org/10.1016/j.envsoft.2014.06.022

Rosabal Ayan L. 2015. Vulnerabilidad e impacto de las estrategias campesinas de alimento del ganado durante el estiaje en la CART-REBISE, Chiapas. TESIS de Maestría en Ciencias en Recursos Naturales y Desarrollo Rural, ECOSUR San Cristóbal de las Casas. [In Spanish.].

Schoemaker, P. J., & Tetlock, P. E. (2012). Taboo scenarios: How to think about the unthinkable. California management review, 54(2), 5-24. doi:10.1525/cmr.2012.54.2.5

Sierra-Huelsz, J.A., Kainer, K.A., Keys, E., Colli-Balam, S.S., 2017. Three stories under the same hut: Market preferences and forest governance drive the evolution of tourism construction materials. For. Policy Econ. 78, 151–161. doi:10.1016/j.forpol.2017.01.022

Sloan, S., 2007. Fewer People May Not Mean More Forest for Latin American Forest Frontiers. Biotropica 39, 443–446. doi:10.1111/j.1744-7429.2007.00288.x

Soto-Pinto, L., Villalvazo-López, V., Jiménez-Ferrer, G., Ramírez-Marcial, N., Montoya, G., Sinclair, F.L., 2007. The role of local knowledge in determining shade composition of multistrata coffee systems in Chiapas, Mexico. Biodivers. Conserv. 16, 419–436. doi:10.1007/s10531-005-5436-3

Speelman, E.N., García-Barrios, L.E., 2010. Agrodiversity v.2: An educational simulation tool to address some challenges for sustaining functional agrodiversity in agro-ecosystems. Ecol. Model. 221, 911–918. doi:10.1016/j.ecolmodel.2009.12.007

Speelman, E.N., García-Barrios, L.E., Groot, J.C.J., Tittonell, P., 2014a. Gaming for smallholder participation in the design of more sustainable agricultural landscapes. Agric. Syst. 126, 62–75. doi:10.1016/j.agsy.2013.09.002

Speelman, E.N., Groot, J.C.J., García-Barrios, L.E., Kok, K., van Keulen, H., Tittonell, P., 2014b. From coping to adaptation to economic and institutional change – Trajectories of change in land-use management and social organization in a Biosphere Reserve community, Mexico. Land Use Policy 41, 31–44. doi:10.1016/j.landusepol.2014.04.014

Sun, Z., Lorscheid, I., Millington, J.D., Lauf, S., Magliocca, N.R., Groeneveld, J., Balbi, S., Nolzen, H., Müller, B., Schulze, J., Buchmann, C.M., 2016. Simple or complicated agent-based models? A complicated issue. Environ. Model. Softw. 86, 56–67. doi:10.1016/j.envsoft.2016.09.006

Tenza, A., Pérez, I., Martínez-Fernández, J., Giménez, A., 2017. Understanding the decline and resilience loss of a long-lived social-ecological system: insights from system dynamics. Ecol. Soc. 22. doi:10.5751/ES-09176-220215

UNESCO. (1996) Biosphere Reserves: The Seville Strategy and the Statutory Framework of the World Network. United Nations Educational, Scientific and Cultural Organization, Paris, France.

Valdivieso-Pérez, I.A., García-Barrios, L.E., Álvarez-Solís, D., Nahed-Toral, J., 2012. De maizales a potreros: cambio en la calidad del suelo. Terra Latinoam. 30:363-374.

Valencia, V., García-Barrios, L., West, P., Sterling, E.J., Naeem, S., 2014. The role of coffee agroforestry in the conservation of tree diversity and community composition of native forests in a Biosphere Reserve. Agric. Ecosyst. Environ. 189, 154–163. doi:10.1016/j.agee.2014.03.024

Valencia, V., West, P., Sterling, E.J., García-Barrios, L., Naeem, S., 2015. The use of farmers' knowledge in coffee agroforestry management: implications for the conservation of tree biodiversity. Ecosphere 6, 1–17.

Vandermeer, J., Perfecto, I., 2013. Complex Traditions: Intersecting Theoretical Frameworks in Agroecological Research. Agroecol. Sustain. Food Syst. 37, 76–89. doi:10.1080/10440046.2012.717904

Van Langevelde, F., Van De Vijver, C.A., Kumar, L., Van De Koppel, J., De Ridder, N., Van Andel, J., Skidmore, A.K., Hearne, J.W., Stroosnijder, L., Bond, W.J., others, 2003. Effects of fire and herbivory on the stability of savanna ecosystems. Ecology 84, 337–350.

Van Vliet, N., Mertz, O., Heinimann, A., Langanke, T., Pascual, U., Schmook, B., Adams, C., Schmidt-Vogt, D., Messerli, P., Leisz, S., others, 2012. Trends, drivers and impacts of changes in swidden cultivation in tropical forest-agriculture frontiers: a global assessment. Glob. Environ. Change 22, 418–429.

Villamor, G.B., Badmos, B.K., 2015. Grazing game: a learning tool for adaptive management in response to climate variability in semiarid areas of Ghana. Ecol. Soc. 21. doi:10.5751/ES-08139-210139

Villamor, G.B., Palomo, I., Santiago, C.A.L., Oteros-Rozas, E., Hill, J., 2014. Assessing stakeholders' perceptions and values towards social-ecological systems using participatory methods. Ecol. Process. 3, 22.

Villamor, G.B., van Noordwijk, M., 2011. Social Role-Play Games Vs Individual Perceptions of Conservation and PES Agreements for Maintaining Rubber Agroforests in Jambi (Sumatra), Indonesia. Ecol. Soc. 16. doi:10.5751/ES-04339-160327

Voinov, A., Bousquet, F., 2010. Modelling with stakeholders? Environ. Model. Softw. 25, 1268–1281. doi:10.1016/j.envsoft.2010.03.007

Walker, R., Perz, S., Caldas, M., Silva, L.G.T., 2002. Land use and land cover change in forest frontiers: The role of household life cycles. Int. Reg. Sci. Rev. 25, 169–199.

Werner, P.A., 2005. Impact of feral water buffalo and fire on growth and survival of mature savanna trees: An experimental field study in Kakadu National Park, northern Australia. Austral Ecol. 30, 625–647. doi:10.1111/j.1442-9993.2005.01491.x

Wilensky, U. (1997). NetLogo Fire model. http://ccl.northwestern.edu/netlogo/models/Fire. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.

Wilensky, U. (1999). NetLogo. http://ccl.northwestern.edu/netlogo/. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.

Wilensky, U. (2001). NetLogo Rabbits Grass Weeds model. http://ccl.northwestern.edu/netlogo/models/RabbitsGrassWeeds. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.

Wittmer, H., Rauschmayer, F., Klauer, B., 2006. How to select instruments for the resolution of environmental conflicts? Land Use Policy 23, 1–9. doi:10.1016/j.landusepol.2004.09.003

Zabala, A., Pascual, U., García-Barrios, L., 2017. Payments for Pioneers? Revisiting the Role of External Rewards for Sustainable Innovation under Heterogeneous Motivations. Ecological Economics 135, 234–245. doi:10.1016/j.ecolecon.2017.01.011

Appendix A

Supplementary data

TRUE GRASP: Actors visualize and explore hidden limitations of an apparent win-win land management strategy in a MAB Reserve

Marco Braasch (marcobraasch@gmail.com), Luis García-Barrios (luis.garciabarrios@gmail.com),
Neptali Ramírez-Marcial (nramirezm@ecosur.mx), Elisabeth Huber-Sannwald (ehs@ipicyt.edu.mx), and
Sergio Cortina-Villar (scortina@ecosur.mx)

TRUE GRASP: Overview, Design concepts, and Details (ODD)

The following description of the TRUE GRASP model follows the updated ODD (Overview, Design, and Details) protocol by Grimm et al. (2010). Some sections of the description were adapted to address socio-ecological contexts involving a human decision making process, as recommended by Müller et al. (2013).

1. Overview

1.1 Purpose

TRUE GRASP (Tree Recruitment Under Exotic GRAsses in a Savanna-Pineland) is a socio-ecological agent-based model (ABM) and role playing game (RPG) for smallholder farmers and other stakeholders involved in rural landscape planning. This model, which simulates economic and ecological tradeoffs and can be used in participatory decision-making processes, addresses long-term consequences of current land use practices - such as changes in land cover and regime shifts, and identifies tipping points and thresholds.

Design of TRUE GRASP is based on 3 years of socio-ecological fieldwork in a human-induced pine savanna in La Sepultura Biosphere Reserve (SBR) in the Mexican state of Chiapas. In this savanna, farmers harvest resin from *Pinus oocarpa*, which is used to produce turpentine and other products. However, long term persistence of this activity is jeopardized by low tree recruitment due to exotic tall grass cover in the forest understory (see Braasch et al., 2017). The TRUE GRASP model provides the user with different management strategies for controlling exotic grass cover and avoiding possible regime shifts, which in the case of the SBR would jeopardize resin harvesting.

1.2 Entities, state, variables, and scales

The virtual world of the model consists of 81 x 129 cells, which together represent a 4-hectare plot of land; each plot in the model consists of 2 hectares of open pasture and 2 hectares of pine savanna, representing typical landscapes in the SBR (Fig. 1).

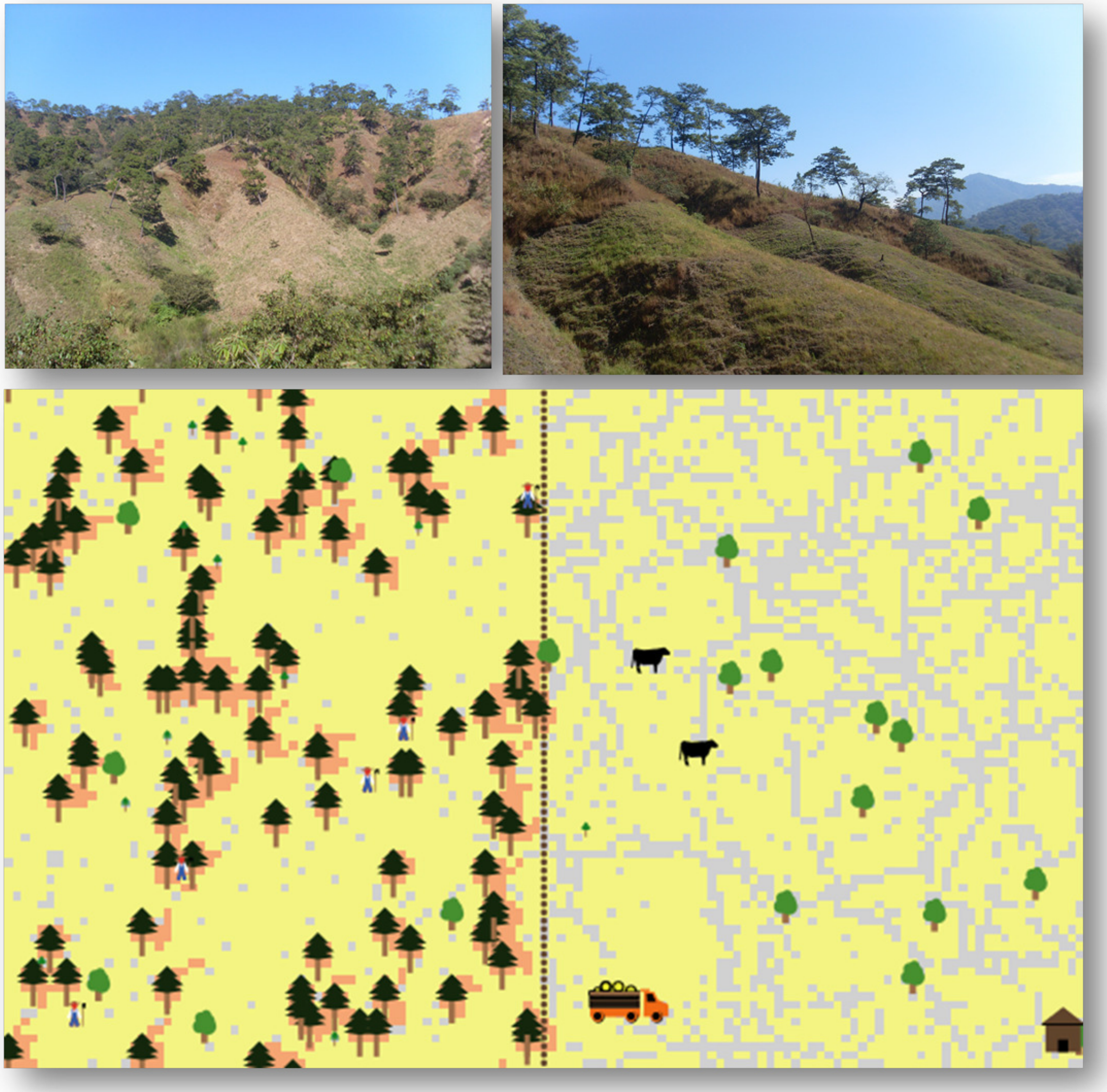
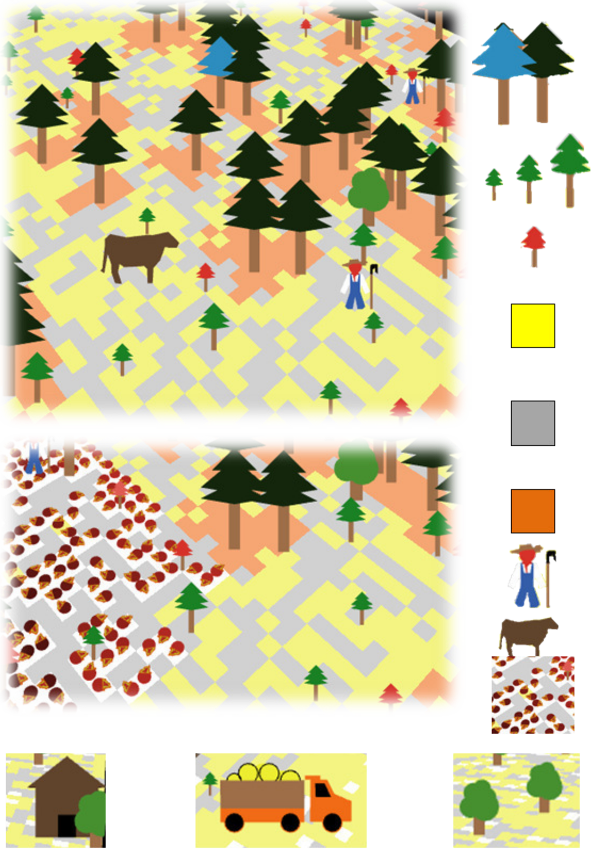


Fig. 1 Design of the virtual world based on a mountainous landscape in La Sepultura Biosphere Reserve, Chiapas, Mexico, representing 2 ha pine savanna and 2 ha open pasture.

The savanna of the virtual world contains 100 adult pine trees, whose geographical position is defined in the model. Mature trees produce resin, shade, leaf litter, and seeds. Seeds germinate and resulting recruits pass through four stages (seedling, sapling, juvenile, and adult) which vary by age and size. Farmers in the model collect resin from adult trees, and deposit it in their resin container. Each tree in the model has a defined amount of resin, which decreases upon tapping. This is represented by the tree´s resin tank. If a tree´s resin tank is empty, the tree may be used for timber production. If the user does not select timber production as a management practice, as long as the tree is not cut down, it survives until 140 years. Understory vegetation consists of: a) Short grass cells (native grass cover, bare soil, browsed or burnt exotic grasses– all of which are inedible to cattle), b) exotic tall grass cells, and c) areas of pine needle litter which are impacted by the shade of adult trees. The geographic location of these cells is specified by their coordinates (Fig. 2). Within the virtual pine savanna, five farmers move in a semi-random walk in search of adult pine trees for resin tapping and harvesting, using the "Mushroom Hunter" model algorithm by Railsback and Grimm, (2012). The amount of resin a farmer harvests is recorded in his resin container, which represents his energy. This amount increases as resin is harvested and decreases as the farmer moves and energy is lost. If a farmer's energy reaches zero, the farmer "dies" - that is, he stops harvesting resin. When a farmer´s resin container becomes full, the resin is stored in 200 kg barrels for sale. Farmers´ movement is recorded using geographical coordinates. Cows also move in a semi-random walk in the virtual world, using the "Rabbits Grass Weeds" model algorithm by Wilensky, (2001). They eat grass and their movement is also specified via coordinates. As they roam, they use up energy, and as they eat grass, they gain energy. If a cow has a surplus of energy at the end of the year, it reproduces one calf. If energy reaches zero, the cow dies. Another element in the system is fire, which may be manually induced or occur randomly with a 4 % annual probability. Fires are shown in red to denote flames and brown to denote embers, following the "Fire Percolation" model by Wilensky (1997). Fire converts exotic tall grass cells and leaf litter (both of which are considered to be fuel) into short grass (burnt) cells. If a recruit (< 9 yr.) grows in a "fuel" cell, it dies.

The principal external controls of the model, which are set by the user, are cattle load (number of cows), cattle management strategy (taking into account only one or both sites), frequency of rotation, manual weeding, and controlled burning.

One iteration (time step) represents one day in the virtual world. The user defines which of three scenarios the model will simulate: short-term (<10-years), mid-term (10-30 years), or long-term (>50 years). The eastern and western borders of the virtual toroid world are impermeable, while those to the north and south are permeable. If a mobile agent (farmer, cow, fire, or seed) crosses a border, it re-enters on the opposing border of the virtual world in the same vegetation category (from savanna to savanna, or from pasture to pasture). In order for the model to appear more realistic - especially to rural farmers, it includes oak trees, a resin-transporting truck, and a cattle-shed, which have no effect on any of the agents and are not involved in any processes (Fig. 2).



Agent	Description	Variables
Pine tree	adult with resin (dark green)	age, location, amount of resin, size
	adult without resin (blue)	
	recruit: seedling, sapling, juvenile tree (light green)	
	dead recruit (red)	location
Exotic tall grass	exotic tall grass (yellow)	location
Short grass	includes bare soil, native grass, burnt or browsed exotic short grass (grey)	location
Pine needle litter/shade cell	around a mature tree (brown)	location
Farmer	family of 5 resin tappers	location, energy (resin level)
Cattle	cow	location, weight
Fire	fire (red)	location, color
	embers (dark brown)	
Oak tree	for esthetic purposes only	location
Truck		location
Cattle shed		location

Fig. 2 Left: three-dimensional view of the TRUE GRASP model, showing all agents involved. Right: description of agents and their controlling variables.

1.3 Process overview and scheduling

Fig. 3 presents an overview of all interactions among agents and processes involved in the model during simulation. Before beginning the simulation, the user chooses among a set of management strategies for controlling exotic grass cover; these strategies vary by initial cattle load and management system, rotation, weeding, and burning frequency. After actualization, the model loads pine trees, vegetation cover, cows, and resin-tapping farmers. Upon running the model, several sub-models and processes operate sequential:

a) Mature trees produce shade, litter, resin, seeds, and wood, and later die.
b) Young trees become established and grow, and older trees eliminate some seedlings, thereby regulating their density through a self- thinning process.
c) Exotic tall grass cover expands and regrows after burning or being consumed by cows.
d) Leaf litter accumulates around mature trees, and when a tree dies and leaf litter below it decomposes, these cells are converted into short grass cells.
e) Famers move, seek resinous trees, tap them, and harvest resin; if the user selects weeding, farmers weed around mature resinous trees.
f) Cows move to seek fodder, eat grass, trample recruits under age 3, and reproduce.
g) Fire burns grass, leaf litter, and recruits under age 9, if they become established in a “fuel” cell.

In the model, each ecological process is cyclical, as in the real world. Tree growth, weeding, and resin tapping are simulated in a daily time step; rotation and resin selling are simulated monthly; and seed production, calf reproduction, and burning are simulated annually. All agents interact directly or indirectly with other agents and with the environment. These interactions establish a system of feedback mechanisms in which the state of the agent, its variables, and their quantity continually change. The model records resin barrels, timber, and calves as stocks leaving the system (Fig. 3). The procedures mentioned above are described in detail below in the section on sub-models.

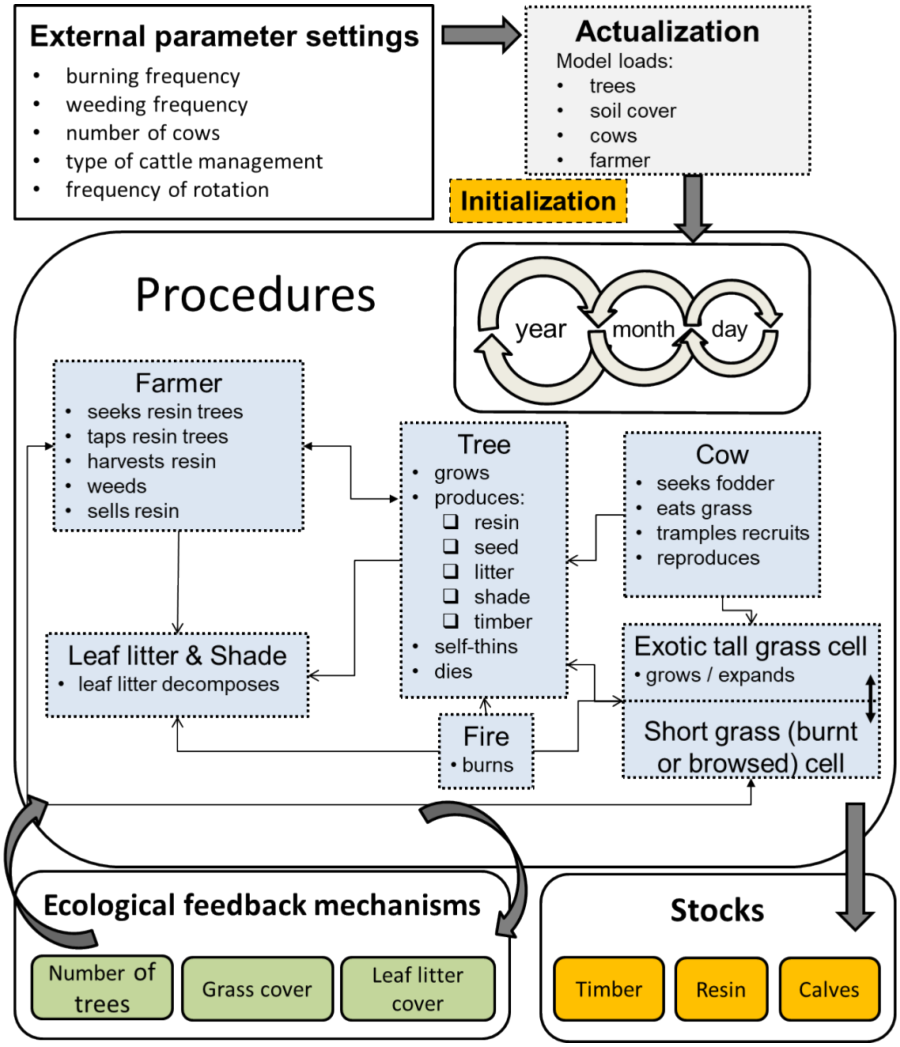


Fig. 3. Flowchart of the principal processes involved in the model. Direct interactions between agents are denoted with arrows.

2. Design concepts

TRUE GRASP was created for educational purposes, rural land use planning, and as a participatory research tool. One purpose of this model is to allow actors to explore the individual and combined effects - as well as tradeoffs - of three methods of controlling exotic grasses in pine savannas: fire, weeding, and grazing cattle.

Design of the model, selection of agents, definition of variables, and parameterization were based on a 3-year participatory socio-ecological study (2014 to 2016) in the *ejidos* (mix of private and collectively-owned land holdings) California and Tres Picos in La Sepultura Biosphere Reserve, in Chiapas, Mexico. The objective of the study was to identify processes affecting natural recruitment of the resinous pine *P. oocarpa.* Two principal impediments to natural regeneration were identified: a) presence of two highly competitive exotic grasses (*Melinis minutiflora* and *Hyparrhenia rufa*), and b) a 20-year history of fire suppression as a strategy for conserving the biosphere reserve´s forest. We then tested the hypothesis that controlled extensive cattle grazing favors tree regeneration and reduces risk of fire, thereby contributing to maintaining the ecologically unstable - but socially desirable - structure of the pine savanna system, in which exotic grasses are dominant (see Braasch et al., 2017). Use of cattle to promote tree regeneration was mentioned by local smallholder farmers, and has been described in the literature as a disturbance-based method of maintaining a balance between tree cover and grass cover in savanna ecosystems (Coppock et al., 2017; Fuhlendorf et al., 2009; Limb et al., 2011; Murphy and Bowman, 2012; Van Langevelde et al., 2003). Herbivory reduces competition of grass with trees, thereby favoring tree recruitment and growth (Werner, 2005). However, cattle must be carefully managed as they have a strongly negative effect on recruits due to trampling and browsing (Braasch et al., 2017).

Decision-making: The farmer agents in TRUE GRASP set off very simple environmental feedback processes. They are not autonomous, as they are controlled by decisions made by real human participants. TRUE GRASP lies somewhere between a very stylized ABM and a very elaborate RPG. Upon playing the game, users learn through feedback provided by the model´s variables. In order to improve the outcome, the results are analyzed, adjustments are made in management, and the simulation is repeated. New initial conditions for the following model run are set also based on real life experience, desired landscape cover, and land use interests (livestock production, resin extraction, timber, and conservation).

Emergence: Depending on the management strategy selected (grazing, weeding, and controlled burning - or a combination of these), various ecological processes emerge which affect long-term land cover. In the long term, the structure of the savanna may persist, or the system may transition to alternate regimes such as closed pine forest or open pasture, directly impacting future land use and farmers' livelihoods.

Adaptation: Agents in the model react to changing conditions. For example: a) If resinous trees are scare and resin production declines, farmers abandon the activity and leave the system; b) Lack of grass cover due to overgrazing affects the annual calf production rate, and in the long term, adult cows die: and c) The amount of fuel available determines how many recruits die as a result of fire and regulates tree species´ population growth.

Uncertainty: The TRUE GRASP model provides the user with a set of problematic or uncertain conditions: a) When controlled burning is not used as a management strategy, annual risk of a human-induced or natural forest fire is 4%; b) Whether or not a recruit under age 9 is burned depends on the amount of fuel and the connectivity among fuel cells at the moment of burning, which is not predictable; and c) The short-term economic benefit as a result of present management may be counteracted by a regime shift in the long run as a result of the management strategy selected; however, at the start of the simulation, some long term tradeoffs are often not visible or are ignored by the user.

Collectives: A single exotic tall grass cell inhibits seed germination, but the set of these exotic tall grass cells also has an effect on recruits. Recruits growth rate is inhibited in proportion to the number of surrounding exotic tall grass cells. A continuous soil cover of fuel consisting of exotic tall grass cells and pine needle litter also affects fire expansion and mortality of recruits. Also, if tree density increases, leaf litter and shade produced by mature trees form a continuous soil cover that suppresses regrowth of exotic grass as well as establishment of seedlings.

Prediction: The model contains a set of output variables that may be used to predict - for example - number of recruits, future tree density, grass cover for calf production, and number of trees available for long term resin production.

Learning: TRUE GRASP fosters collective social learning, as it is an RPG. When the game is played, the model effectively creates feedback loops between the virtual and real worlds. As the user learns by doing, he or she may repeatedly explore different combinations of management strategies to control the highly competitive exotic grass cover and discover the tradeoffs of each management strategy.

Observations: In order to observe and analyze tradeoffs, the model provides monitors and graphs showing the most relevant economic and ecological output variables: number of resin-producing trees and recruits (live, trampled, burned, and self-thinned); exotic tall grass, short grass (burnt or browsed), and litter and shade cells; and stock for producing calves, resin, and wood.

Interactions: Continual direct and indirect interaction of most agents results in a set of tradeoffs. For example, with respect to the interaction of cows, recruits, grass cover, and fire, fire and cattle trampling have a direct negative effect on recruits, while grazing has an indirect positive effect, reducing highly competitive exotic grass cover and thereby favoring seedling establishment and growth. This reduction in continuous fuel cover also reduces spatial expansion of fire.

Stochasticity: Many of the processes in the model are cyclical, such as seed and litter production. However, number and distribution of seeds is random. Furthermore, if controlled fires are not carried out, annual risk of fire is 4 %.

3. Details

3.1 Implementation details

The model was implemented using the NetLogo platform, version 5.2.1. (Wilensky, 1999), available upon request by e-mail to the first or second author of this paper. Development of the model consisted of four phases: a) design and parameterization based on a three-year long socio-ecological study, b) 12 scholars testing the model in order to evaluate ecological processes, c) 10 smallholder farmers playing the game separately to evaluate ease of comprehension and visually improve the model to facilitate use, and finally d) a total of 10 students, foresters, and scholars testing the model and playing the game in order to define game rules for later use in a participatory multi-actor workshop. After each phase, a variety of sensitivity analyses were conducted, and the model´s visual design and source code were modified based on users' recommendations.

3.2 Initialization

The initial condition of the model represents the start of the resin tapping activity in the savanna. The model, which shows ecological conditions similar to those in La Sepultura Biosphere Reserve, simulates possible future land-cover changes in a daily time step. Each time the model is run, it begins with 100 mature resinous trees, in similar densities as in the real world. The trees, which range in age from 80 to 130 years, are always located in the same positions; initial resin volume is constant for all trees. Understory vegetation cover is set at a proportion of 90 % exotic tall grass cells to 10% short grass (burnt or browsed) cells. Both vegetation types are randomly distributed in the virtual world. Leaf litter and shade cells are not present initially, but begin to appear as soon as the model begins to be run. The number of resin tappers is five for all runs, representing a family of five. Number of cows, livestock management strategy, rotation, frequency of burning, and frequency of weeding are chosen by the user.

3.3 Input Data

No input data were used.

3.4 Sub-models

This section provides details of all sub-models and procedures listed in Fig. 3, organized into five models: a) pine tree life cycle sub-model, including shade and litter production, b) cow sub-model, c) grass growth sub-model, including exotic tall grass and short grass (burnt or browsed) cells, d) fire sub-model, and e) resin tapper sub-model.

3.4.1 Pine tree life cycle sub-model

Each pine tree over the age of 15 annually produces 6 seeds, which are randomly distributed within a 15-cell radius. A seedling may only become established in a short grass (burnt or browsed) cell; litter, shade, and exotic tall grass cells inhibit germination (Fig. 4). During its first 3 years, a tree is susceptible to trampling by cattle. Recruits that die from trampling, fire, or clearing change in color from green to red, and after two years disappear from the virtual world. In order to simulate the ecological effect of decreased growth rate over time due to increased competition by surrounding trees, until age 6 growth rate continually decreases in proportion to the number of surrounding exotic tall grass cells. If a tree less than 9 years old in an exotic tall grass or leaf litter cell - which serve as fuel – is exposed to fire, it will be destroyed. Recruits within a three-cell radius of trees over age 10 die through a self-thinning process. If tree has survived all risks and has reached 10 ecological years (the time required for a tree in an exotic tall grass region to grow the size of a tree that does not face competition), it begins to produce shade and leaf litter. Once pine trees reach the age of 20, they produce resin for 10 to 20 years. If a tree´s resin tank is empty, the color of the tree changes from green to blue, and it can be used for timber. Each year, 10 % of all trees without resin are automatically harvested. When the user does not choose wood production and a tree reaches the age of 140, it dies naturally and leaves the system; it is assumed that the farmer makes use of it. When a tree dies naturally or is used for timber, shade disappears immediately and litter decomposes the following two years, converting the forest floor to short grass cells.

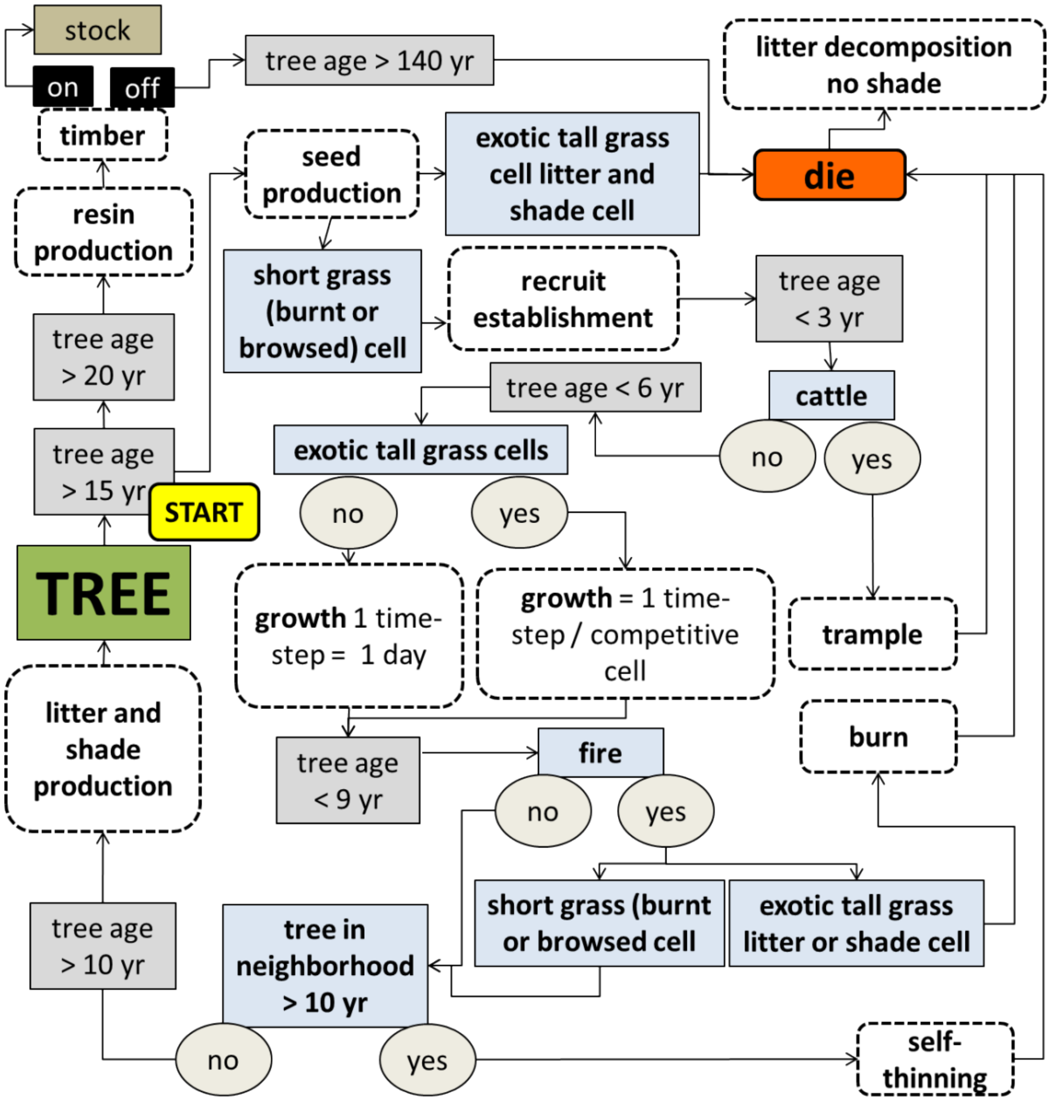


Fig. 4. Flowchart for the pine tree life cycle. The chart is read beginning with the yellow "start" box

3.4.2 Cow sub-model

The cow and exotic grass growth sub-model is a modified version of the "Rabbits Grass Weeds" model from the NetLogo library, developed by Wilensky, (2001). We broadened and otherwise modified the source code of this model to adapt it to our purposes.

Cattle move randomly within the assigned space: pasture land, savanna, or both - with or without rotation. Upon coming into contact with a susceptible seedling, the cow tramples it and the seedling dies. Each cow has an initial energy level (weight) of 1000 units. Energy is lost each time-step due to movement, and energy increases with consumption of fodder - exotic tall grass. If energy is reduced to zero due to lack of availability of fodder, the cow dies. If sufficient fodder is available and energy surpasses 1650 units - the minimum weight necessary for reproduction, the cow conserves 1000 units for its own maintenance and devotes the surplus (reproductive weight - 1000 units) to producing a calf. Each cow is calibrated to produce no more than one calf per year. Calves do not consume grass, as they are sold and thereby extracted from the virtual world (Fig. 5a).

3.4.3 Grass growth sub-model exotic tall grass and short grass cells

Shade and pine needle litter accumulation suppress exotic tall grass cover and may replace these cells. Exotic tall grass cover may be converted into short grass cells through consumption by cows, burning, or weeding. Short grass (burnt or browsed) cells may be colonized by pine seedlings, but these cells always contain short inedible exotic grass, or at least the established roots of these grasses that have potential to sprout. Over time, a short grass cell may once again be converted into an exotic tall grass cell if it has not been occupied by shade or leaf litter (Fig. 5b).

3.4.4 Fire sub-model

The fire sub-model is a modified version of the “Fire Percolation” model by Wilensky (1997). Spontaneous occurrence of fire has a low probability (4 %). Fire can also be chosen when desired by the user as a management technique, at an established frequency. Fire begins in the center cell of the virtual world, and spreads with each time-step from a burning cell to all (eight) surrounding cells (Moore-neighborhood) covered by fuel (exotic tall grass cells and/or pine needle litter). Fire converts these cells to short grass cells, and any susceptible recruit that has become established in such a cell dies. Mature trees, cattle, and farmers are not directly affected by fire (Fig. 5c).

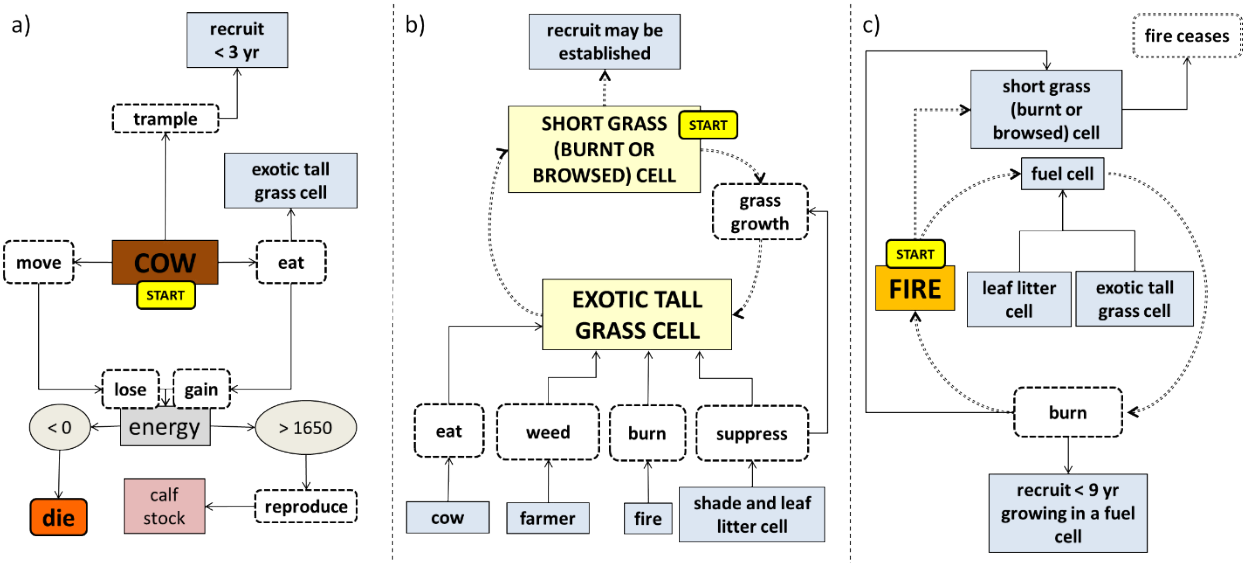


Fig. 5 Flowcharts for: a) cow sub-model, b) grass growth sub-model, and c) fire sub-model. The chart is read beginning with the yellow "start" box.

3.4.5 Resin tapper sub-model

Each of the five farmers begins with an initial energy level (resin) of 100 units. Farmers move in a semi-random walk throughout the pine savanna in search of resinous trees (Mushroom Hunter model Railsback and Grimm, 2012).. Upon reaching a mature tree (> 20 years) with resin, the farmer taps it and harvests a set amount of resin (15 units). Energy is lost by moving, and gained by harvesting resin. If the energy level reaches zero, the farmer leaves the savanna. If there is a surplus of resin (400 units), harvested resin is accumulated in barrels for sale and leaves the system. The amount of resin sold monthly per tree in the virtual world is similar to that of the real world (40 kg), which is an average of what one family is able to produce on 2 hectares of land containing 100 mature trees. Each farmer moves forward one cell per time-step, walking through short grass (burnt or browsed) cells or leaf litter. If the farmer crosses exotic tall grass cells, he moves 3 times slower, affecting his resin-harvesting efficiency. If the user activates weeding, the farmer in the model converts exotic tall grass cells and leaf litter within a 4-cell radius of a resinous tree into short grass cells. This accelerates the farmer´s forward movement and opens the space for seedling establishment, but also reduces the farmer´s energy level due to labor invested (Fig. 6).

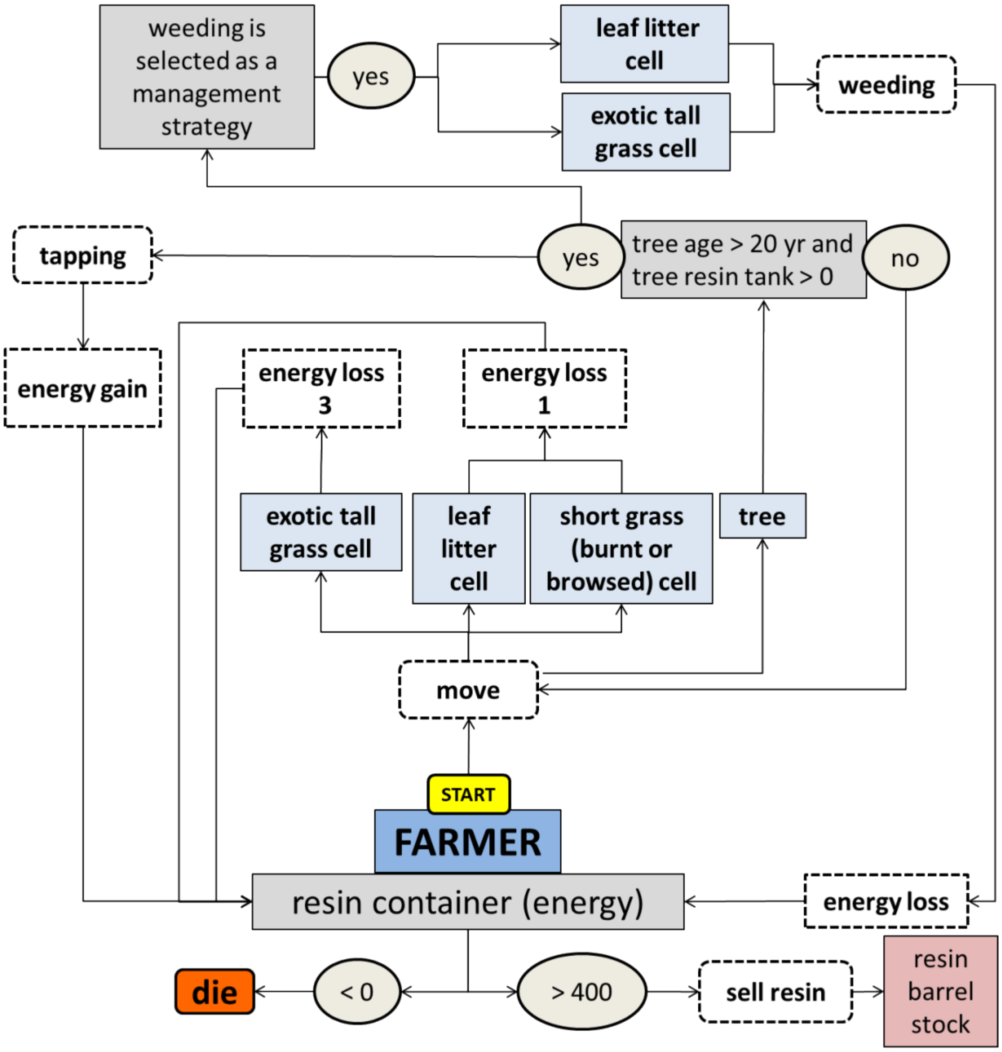


Fig. 6. Flowchart for the resin tapper sub-model. Note that energy refers to the farmer´s resin container, which is converted into money that allows the farmer to continue to work. Resin not needed by the farmer for proper working energy accumulates in barrels for sale and leaves the system. The chart is read beginning with the yellow "start" box.

Fig. 7 Example of tapped resin pines (Pinus oocarpa) in the pine savana. In the real world, bark and wood is scratched away on a weekly basis in order to maintain resin flow into the cup. Each year the cup is moved 50 cm upwards leaving the previous year's. Each face is tapped for 5 years, after which a new tapping face is made on another side of the tree or a new tree is found.

References

Braasch, M., García-Barrios, L., Ramírez-Marcial, N., Huber-Sannwald, E., Cortina-Villar, S., 2017. Can cattle grazing substitute fire for maintaining appreciated pine savannas at the frontier of a montane forest biosphere-reserve? Agric. Ecosyst. Environ. 250, 59–71. doi:10.1016/j.agee.2017.08.033

Coppock, D.L., Fernández-Giménez, M., Hiernaux, P., Huber-Sannwald, E., Schloeder, C., Valdivia, C., Arredondo, J.T., Jacobs, M., Turin, C., Turner, M., 2017. Rangeland Systems in Developing Nations: Conceptual Advances and Societal Implications, in: Briske, D.D. (Ed.), Rangeland Systems: Processes, Management and Challenges. Springer International Publishing, Cham, pp. 569–641. doi:10.1007/978-3-319-46709-2_17

Fuhlendorf, S.D., Engle, D.M., Kerby, J., Hamilton, R., 2009. Pyric Herbivory: Rewilding Landscapes through the Recoupling of Fire and Grazing. Conserv. Biol. 23, 588–598. doi:10.1111/j.1523-1739.2008.01139.x

Grimm, V., Berger, U., DeAngelis, D.L., Polhill, J.G., Giske, J., Railsback, S.F., 2010. The ODD protocol: a review and first update. Ecol. Model. 221, 2760–2768.

Limb, R.F., Fuhlendorf, S.D., Engle, D.M., Weir, J.R., Elmore, R.D., Bidwell, T.G., 2011. Pyric–herbivory and cattle performance in grassland ecosystems. Rangel. Ecol. Manag. 64, 659–663.

Müller, B., Bohn, F., Dreßler, G., Groeneveld, J., Klassert, C., Martin, R., Schlüter, M., Schulze, J., Weise, H., Schwarz, N., 2013. Describing human decisions in agent-based models – ODD + D, an extension of the ODD protocol. Environ. Model. Softw. 48, 37–48. doi:10.1016/j.envsoft.2013.06.003

Murphy, B.P., Bowman, D.M.J.S., 2012. What controls the distribution of tropical forest and savanna? Ecol. Lett. 15, 748–758. doi:10.1111/j.1461-0248.2012.01771.x

Railsback, S.F., Grimm, V., 2012. Agent-Based and Individual-Based Modeling: A Practical Introduction. Princeton University Press.

Van Langevelde, F., Van De Vijver, C.A., Kumar, L., Van De Koppel, J., De Ridder, N., Van Andel, J., Skidmore, A.K., Hearne, J.W., Stroosnijder, L., Bond, W.J., others, 2003. Effects of fire and herbivory on the stability of savanna ecosystems. Ecology 84, 337–350.

Werner, P.A., 2005. Impact of feral water buffalo and fire on growth and survival of mature savanna trees: An experimental field study in Kakadu National Park, northern Australia. Austral Ecol. 30, 625–647. doi:10.1111/j.1442-9993.2005.01491.x

Wilensky, U. (1997). NetLogo Fire model. http://ccl.northwestern.edu/netlogo/models/Fire. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.

Wilensky, U. (1999). NetLogo. http://ccl.northwestern.edu/netlogo/. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.

Wilensky, U. (2001). NetLogo Rabbits Grass Weeds model. http://ccl.northwestern.edu/netlogo/models/RabbitsGrassWeeds. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.

Appendix B

Supplementary data

TRUE GRASP: Actors visualize and explore hidden limitations of an apparent win-win land management strategy in a MAB Reserve

Marco Braasch (marcobraasch@gmail.com), Luis García-Barrios (luis.garciabarrios@gmail.com),
Neptali Ramírez-Marcial (nramirezm@ecosur.mx), Elisabeth Huber-Sannwald (ehs@ipicyt.edu.mx), and
Sergio Cortina-Villar (scortina@ecosur.mx)

Sensitivity analisis

Below we present a non-exhaustive though comprehensive multivariate sensitivity analysis of TRUE GRASP´S responses to a set of parameters selected to manage a pine savanna. Also we present a broad spectrum of possible ecological and economic outputs for exercises carried out in a workshop as described in the results section in the main text.

Table 1. List of all agents involved in the model, including processes that affect them and output variables

AGENT	**PROCESS**	**EFFECT**	**OUTPUT VARIABLE (quantity)**
ADULT PINE TREE	produces shade and pine leaf litter	pine leaf litter accumulates around tree	pine needle litter and shade cells
	produces seeds	seeds disperse	recruits
	produces resin	resin tapper is attracted	resin
	produces wood	tree dies	timber
	dies	litter decomposes	short grass (burnt or browsed) cells
YOUNG PINE TREE	grows	other seedlings are suppressed (self-thinning)	recruits
	reaches maturity	resin is produced	resin
			recruits
EXOTIC TALL GRASS CELL	grows /expands	tree recruitment is suppressed	recruits
		tree growth is suppressed	recruits
		resin tapper´s movement is reduced	resin (farmers energy)
		cattle weight increases due to grass consumption	calves
	fuel accumulates and burns	recruits die	recruits
		these cells are converted to short grass (burnt) cells	short grass cells
SHORT GRASS (burnt or browsed) CELL	provides open space for seeds	trees may be established	recruits
	no fuel accumulation	recruits survive burning	recruits
LEAF LITTER and SHADE CELL	accumulates around mature trees	exotic tall grass and short grass cells are converted into leaf litter and shade cells	leaf litter and shade cells
		tree recruitment is suppressed	recruits
	fuel accumulates	recruits burn	recruits
COW	moves	cow spends energy	calves
			cows
	tramples	recruits die	recruits
	eats exotic tall grass	cow gains energy	calves
		exotic tall grass cells decrease	short grass cells
RESIN TAPPER (FARMER)	moves	farmer spends energy	resin (farmers energy)
	taps/harvests	farmer gains energy	resin (farmers energy)
	weeds	leaf litter and exotic tall grass cells are converted into short grass cells	recruits
			short grass cells
		farmer spends energy	resin (farmers energy)
FIRE	burns	fuel cells are converted into short grass (burnt) cells	recruits
		recruits are burned	recruits
		resin tapper moves faster	resin (farmers energy)
		fodder decreases	calves

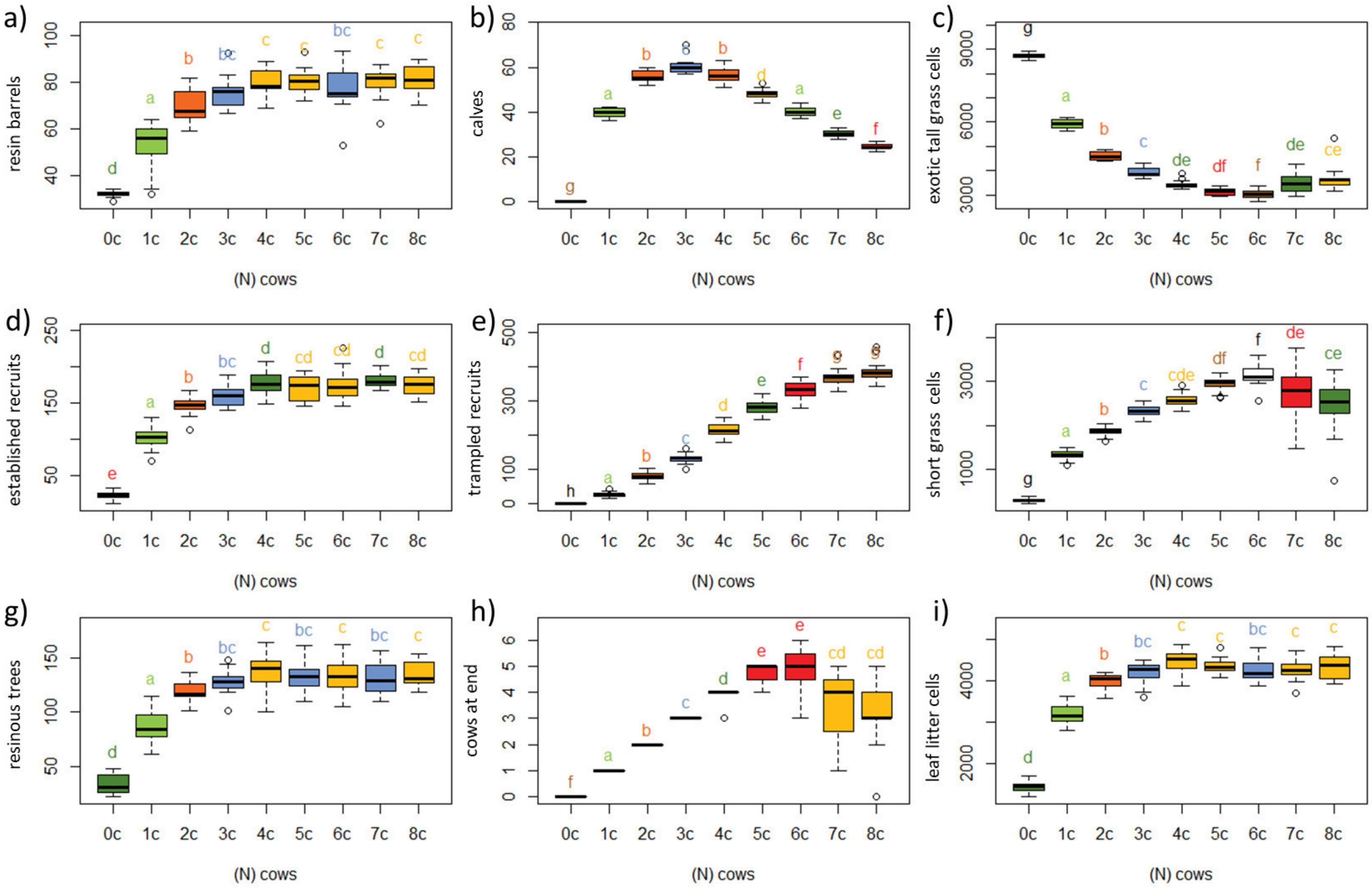


Fig.1 Long-term (50 year) sensitivity analyses for simulations of different cattle loads (0-8 cows) on 4 ha of land (including pine savanna and open pasture) without rotation. Fire and weeding frequency was set at zero. Each cattle load scenario was run 15 times. Graphs show those economic and ecological output variables which are most relevant to these scenarios: a) resin barrels, b) calves, c) exotic tall grass cells, d) number of established living recruits, e) number of total trampled recruits, f) short grasss (burnt or browsed) cells, g) productive resin trees, h) cows at end when simulation was finished, and i) pine needle litter and shade cells. While the majority of the output data increase with higher livestock loads, beyond a 4-cow threshold output stagnates or decreases. Values decrease due to the effect of over-grazing. The model has the capacity of self-regulation less fodder (c) results in less calf production, the cow does not attain the necessary weight for reproduction (b) and in the long run cows are reduced, they die due to scarcity of grass (h). Letters over Box-Whisker plots that share one or more letter label do not differ significantly according to the Tukey HSD multiple mean comparisons test (a = 0.05).

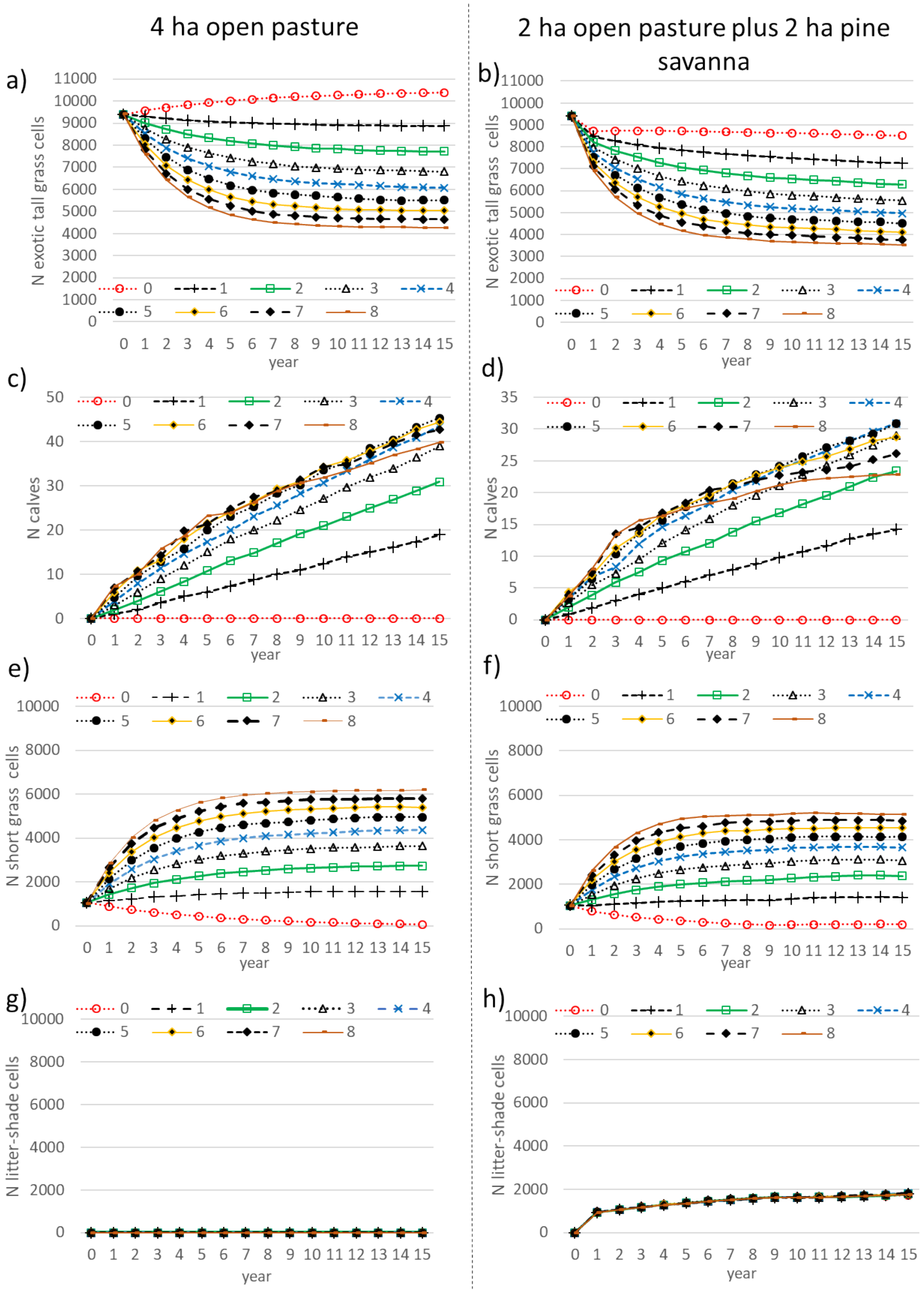

4 ha open pasture
2 ha open pasture plus 2 ha pine savanna
a)
N exotic tall grass cells
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
year
0
1
2
3
4
5
6
7
8
b)
c)
N calves
50
40
30
20
10
0
d)
35
30
25
20
15
10
5
e)
N short grass cells
10000
8000
6000
4000
2000
0
f)
g)
N litter-shade cells
h)

Fig. 2. 15-year time series with cattle loads from 0 to 8 (colored lines). Each data point represents the average of 10 repetitions. As described in the main text, in the ABM, we selected and coupled parameters for cow reproduction and exotic grass recovery rate (i.e. transition from short grass to exotic tall grass cell) so that 2 cows would produce (i) 1.0 calves per cow per year in 4 has of open pasture and 0.8 calves in the combination of savanna and open pasture, and (ii) no less than 20% of short grass cells for potential pine recruitment. Under such optimal conditions, in 15 years two cows produced 30 calves, see green line (c). When pine trees were included in the virtual world (2 ha savanna plus 2 ha open pasture), calf production was reduced to 24 calves (d). Figure e) number of short grass cells for 4-hectare open pasture and f) for the mixted range land. Pine needle litter and shade accumulation in 4 ha open pasture land g) and h) for the mixed rangeland 2 ha savanna and 2 ha open pasture.

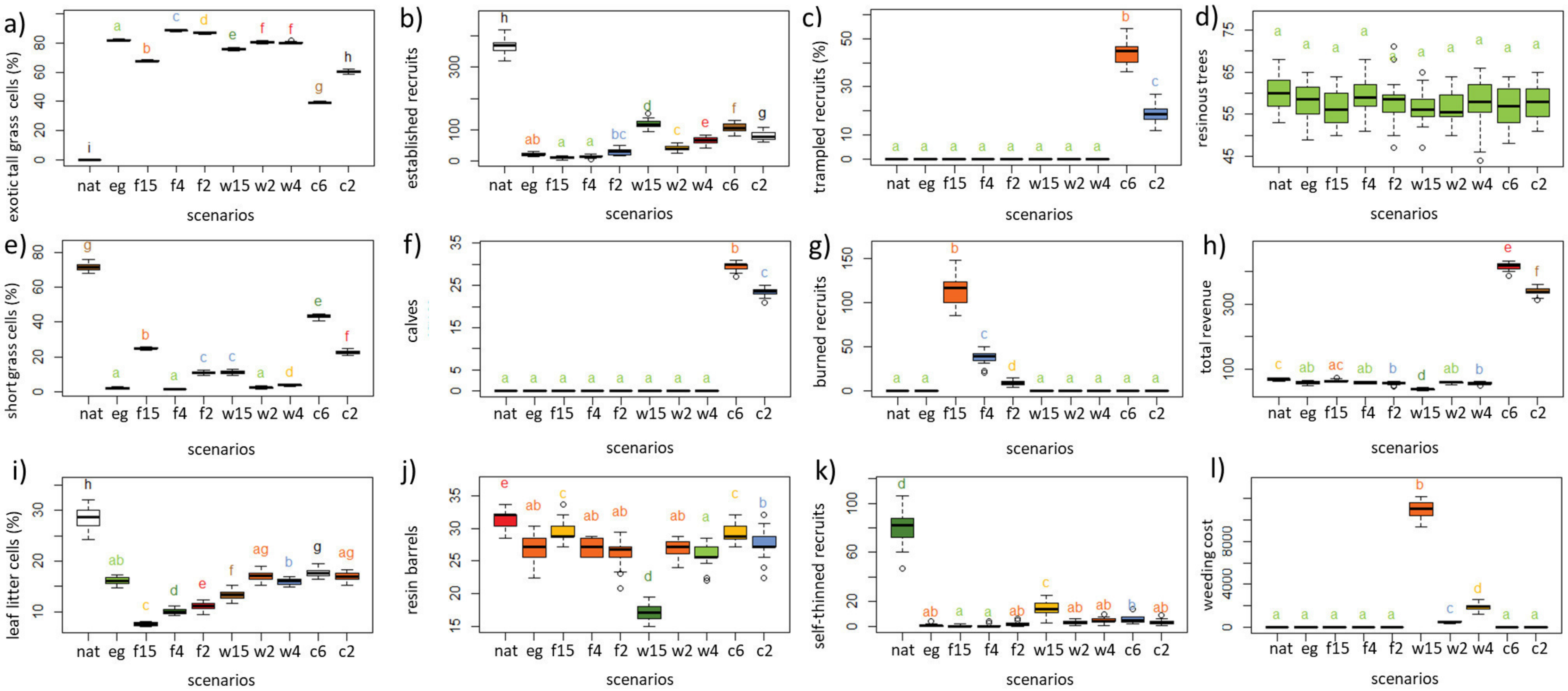


Fig. 3 The above data displays a broad spectrum of output data for the prediction exercise described in the results section 3.3.2. of the main text: a) percentage of exotic tall grass cells, b) number of established recruits, c) percentage of trampled recruits, d) number of resinous trees, e) percentage of short grass (burnt or browsed) cells, f) calf production, g) number of burned recruits, h) total monetary revenue, i) percentage of leaf litter cells, j) number of resin barrels, k) number of recruits that died due to self-thinning, and l) labor cost of weeding. This sensitivity analysis was run 15 years for 10 scenarios: nat = natural grass cover without management, eg = exotic tall grass cover without management, f + # = number of burnings used to control exotic grass during the 15-year simulation, w + # = number of weeding events used to control exotic grass during the 15-year simulation, and c + # = cattle load with six and two cows, respectively. Each scenario was run 20 times. Scenarios w4 (4 weeding events to control exotic grass cover) and c2 (grazing with 2 cows) were not run in the workshop and therefore are not mentioned in the main text, but are included here to more precisely compare high and low weeding frequency and high and moderate cattle loads Letters over Box-Whisker plots that share one or more letter label do not differ significantly according to the Tukey HSD multiple mean comparisons test (a = 0.05).

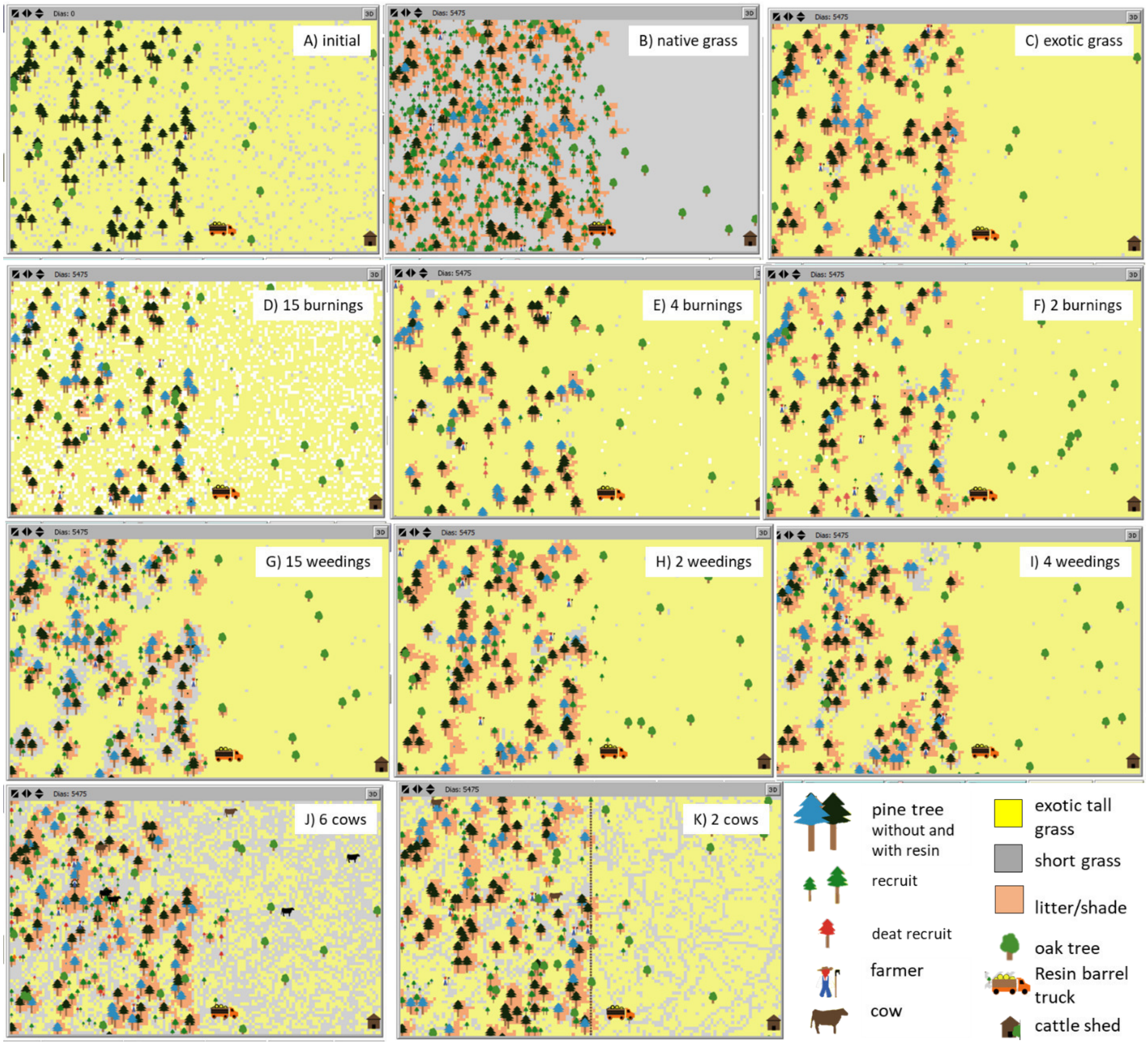


Fig. 4 Screen shots of 10 scenarios after a 15-year simulation described in figure 3 of this document and in section 3.3.3 of the main text. A = initial condition for all further scenarios: B = native grass cover without management, C = exotic grass cover without management, D = 15 burnings to control exotic grass cover during the 15-year simulation, E = 4 burnings to control exotic grass, F = 2 burnings to control exotic grass, G = annual weeding, H = 2 weeding events over 15 years, I = 4 weeding events over 15 years, J = 6 cows, and K = 2 cows to control exotic grass. Land cover change is not yet clearly visible in these 15-year simulations. These screen shots show similar results as those obtained by workshop participants after a 15-year simulation. During the workshop, screen shots of 30, 50 and 100-year simulations were also displayed to demonstrate possible regime shifts.

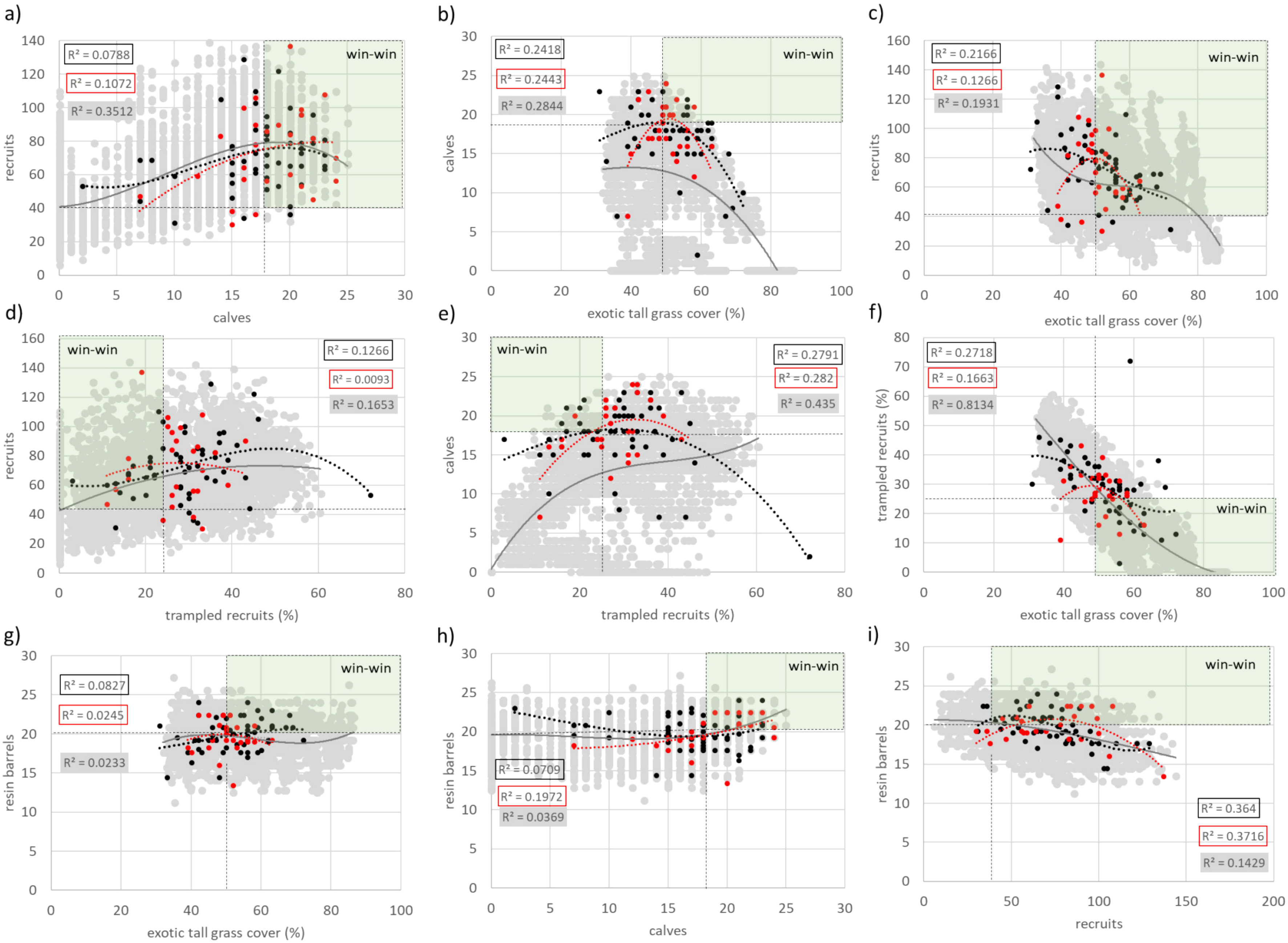

a)
R² = 0.0788
R² = 0.1072
R² = 0.3512
win-win
recruits
calves
b)
R² = 0.2418
R² = 0.2443
R² = 0.2844
win-win
calves
exotic tall grass cover (%)
c)
R² = 0.2166
R² = 0.1266
R² = 0.1931
win-win
recruits
exotic tall grass cover (%)
d)
win-win
R² = 0.1266
R² = 0.0093
R² = 0.1653
recruits
trampled recruits (%)
e)
win-win
R² = 0.2791
R² = 0.282
R² = 0.435
calves
trampled recruits (%)
f)
R² = 0.2718
R² = 0.1663
R² = 0.8134
win-win
trampled recruits (%)
exotic tall grass cover (%)
g)
R² = 0.0827
R² = 0.0245
R² = 0.0233
win-win
resin barrels
exotic tall grass cover (%)
h)
win-win
R² = 0.0709
R² = 0.1972
R² = 0.0369
resin barrels
calves
i)
win-win
R² = 0.364
R² = 0.3716
R² = 0.1429
resin barrels
recruits

Fig. 5 Regressions of some ecological and economic outputs for 10-year simulations using different combinations of management strategies. Grey dots and lines, and grey boxes with regression coefficients (*R^2*; polynomial regression), are the result of 3240 possible combinations (runs) for frequency of fire (0, 1, 2, 3, 5, or 10 burnings), weeding frequency (0, 2, 3, 5, or 10 weeding events), cattle load (0 to 8 cows), and frequency of rotation (0, 1, 2, 3, 4, 6, or 12 per year). Black dots and dotted lines, and regression coefficients in boxes with black borders, are the result of the output variables from simulation by workshop participants, as described in section 3.3.3 of the main text. Red dots and lines, and the regression coefficients in boxes with red borders, are the result of the "brother exercise" described in section 3.3.4 of the main text. Quadrants with grey backgrounds represent the win-win area for each possible combination of two variables in the exercise described in section 3.3.3 of the main text: a) established recruits and calf production, b) calf production and exotic tall grass cover, c) recruits and exotic tall grass cover, d) established recruits and percentage of trampled recruits, e) calf production and percentage of trampled recruits, f) percentage of trampled recruits and exotic tall grass cover, g) resin barrels and exotic tall grass cover, h) resin barrels and calf production, and i) resin barrels and established recruits. For the "two brother" exercise, in section 3.3.4 in the main text, goals were slightly different than for the exercise in section 3.3.3 in the main text. For the regression between resin barrels and exotic grass cover, and for that between recruits and calf production, the R^2 value is low because after ten years no correlation exists given that recruitment has not yet had an effect on barrels.

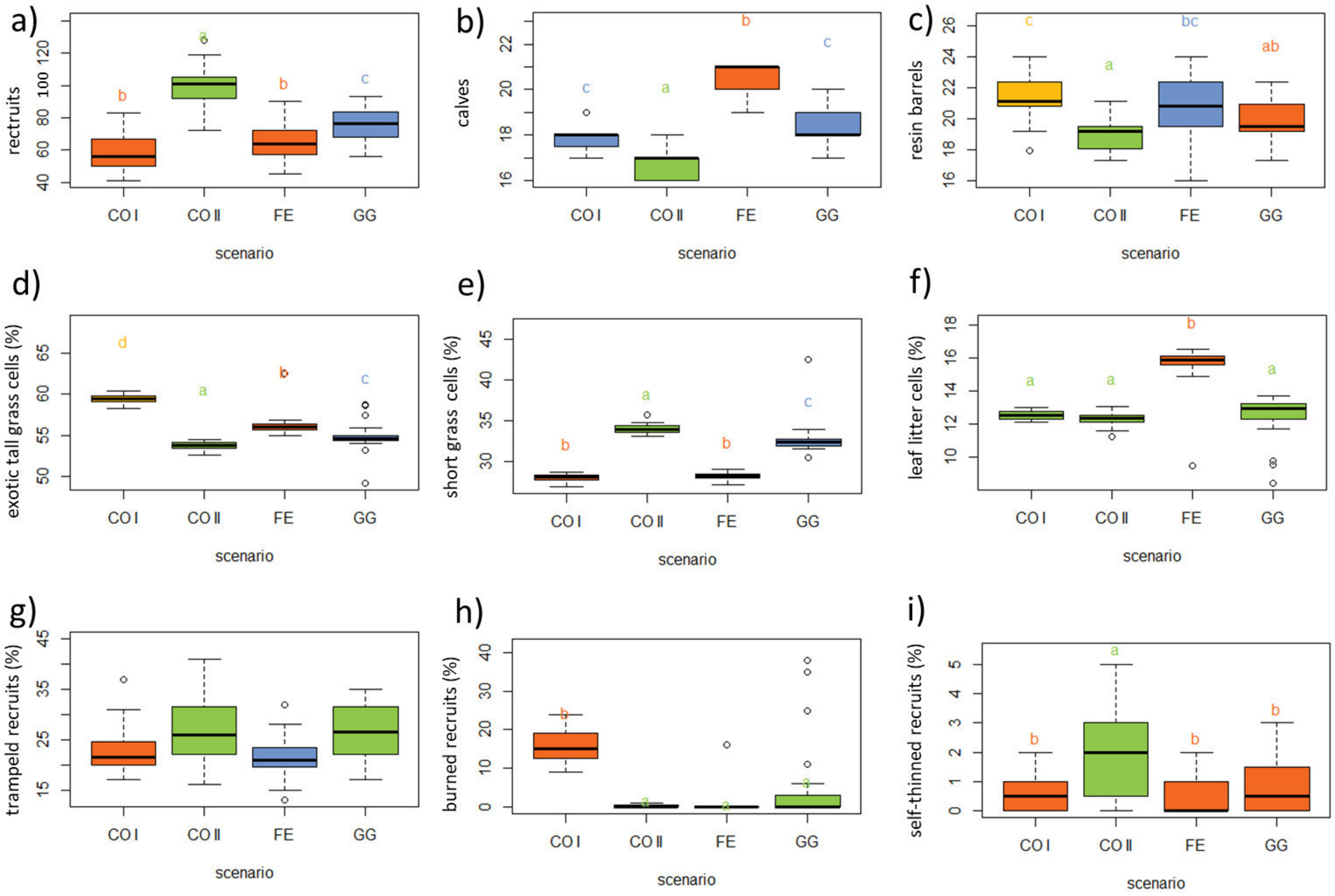


Fig. 6 Results of a sensitivity analysis for different combinations of management strategies to control exotic grass cover in a pine savanna. In this analysis, cattle load was constant (3 cows) for all four scenarios. Resulting variations are the effect of possible combinations for rotation, weeding, and frequency of fire. Scenario COI consists of 3 cows, no rotation (cattle use both sites), and no weeding or fire. Scenario COII consists of 3 cows, rotation every 4 months, one burning, and 5 weeding events. Scenario FE consists of 3 cows, rotation every 3 months, and no burning or weeding. Scenario GG consists of 3 cows, rotation every 2 months, 4 weeding events, and no burning. These management strategies are examples chosen by workshop participants, as described in section 3.3.3 and Fig. 11 in the main text. Each scenario was run 20 times. While cattle greatly controlled exotic grass cover, the other management strategies – alone or combined - also influenced output data. Letters over Box-Whisker plots that share one or more letter label do not differ significantly according to the Tukey HSD multiple mean comparisons test (a = 0.05).

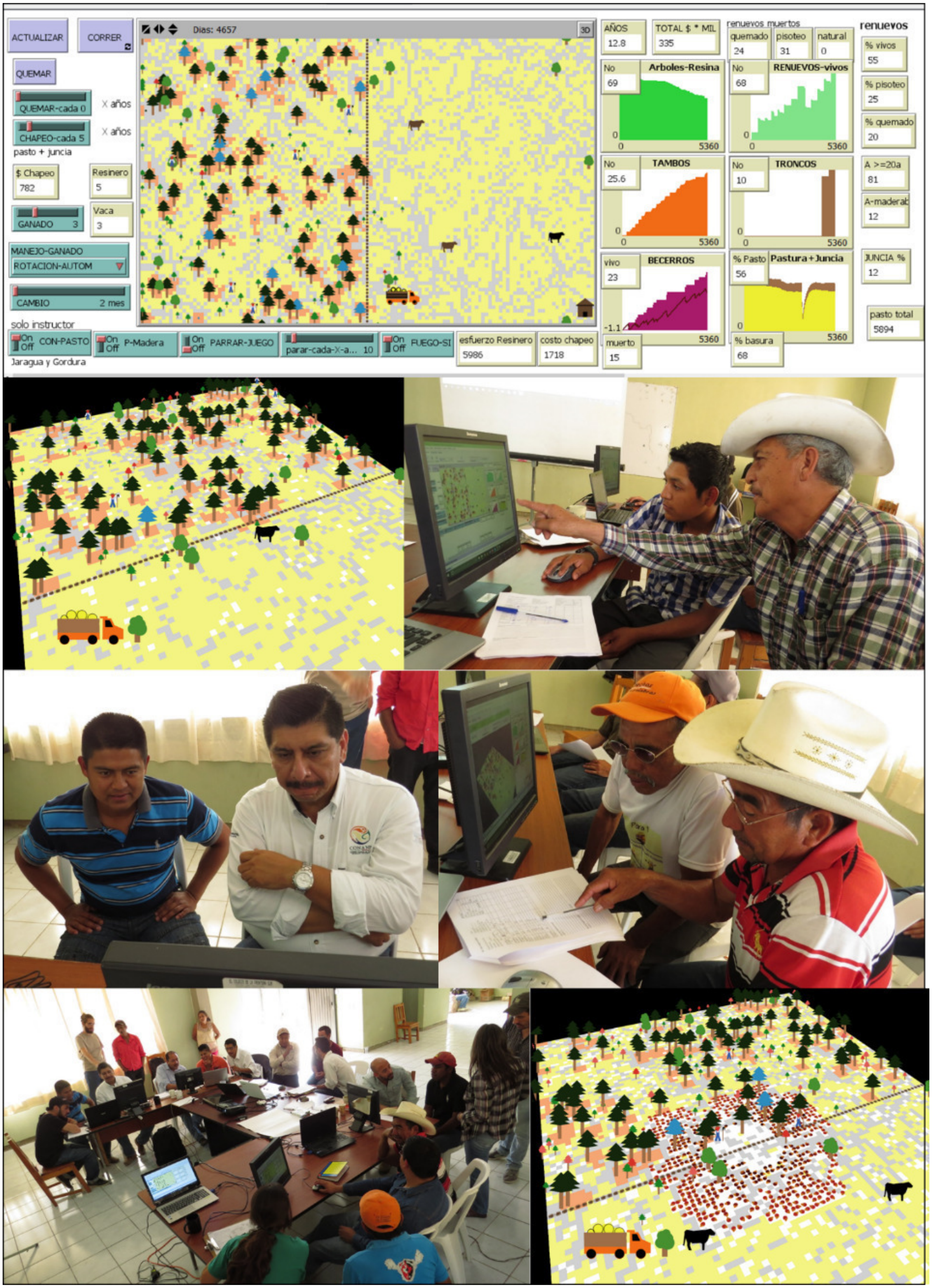


Fig. 7. Smallholder farmers and external actors playing TRUE GRASP during a workshop held March 27-29, 2017 in La Sepultura Biosphere Reserve, in Chiapas, Mexico