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

TRUE GRASP: (Tree Recruitment Under Exotic GRAsses in a Savanna-Pineland), 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).

If you mention this model in a publication, we ask that you include the citations below:

Braasch, M., García-Barrios, L., Cortina-Villar, S., Huber-Sannwald, E., Ramírez-Marcial, N. 2018 (in Press). TRUE GRASP: Actors visualize and explore hidden limitations of an apparent win-win land management strategy in a MAB Reserve. Environmental Modelling & Software, 2018.

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).

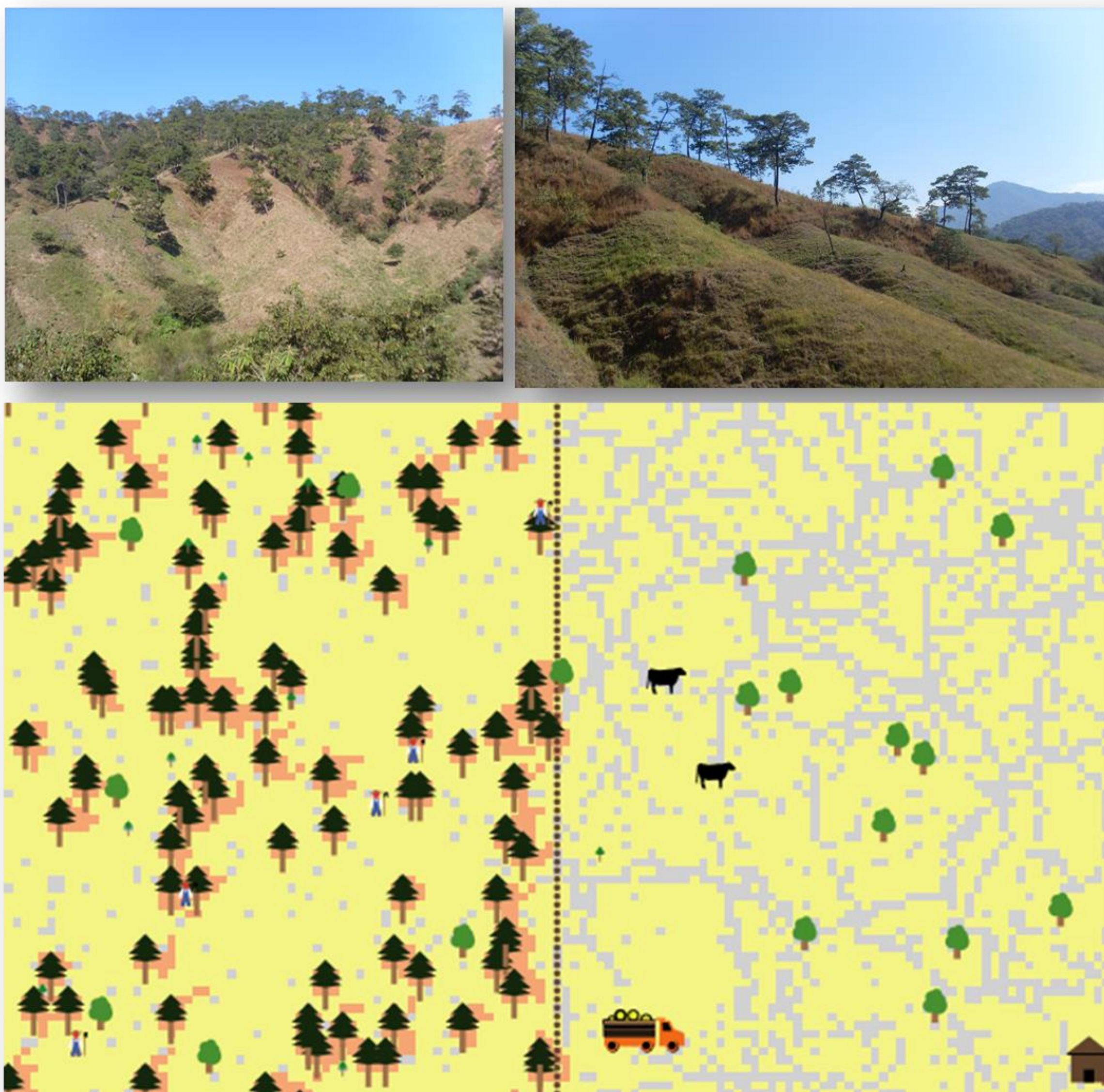
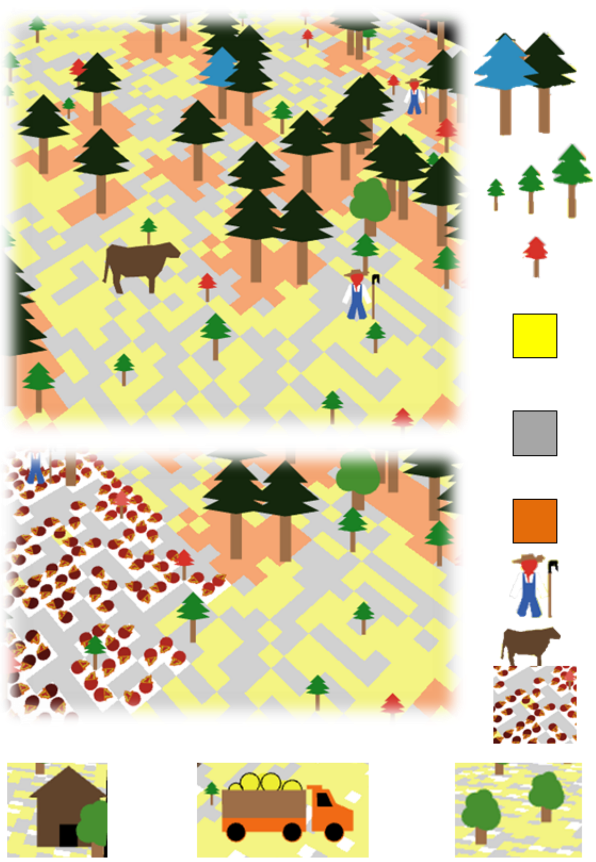


Fig. 1 Design of the virtual world based on a mountainous landscape in La Sepultura Biosphere Reserve, Chiapas, Mexico, representing 2 ha pine savanna and 2 ha open pasture.

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.

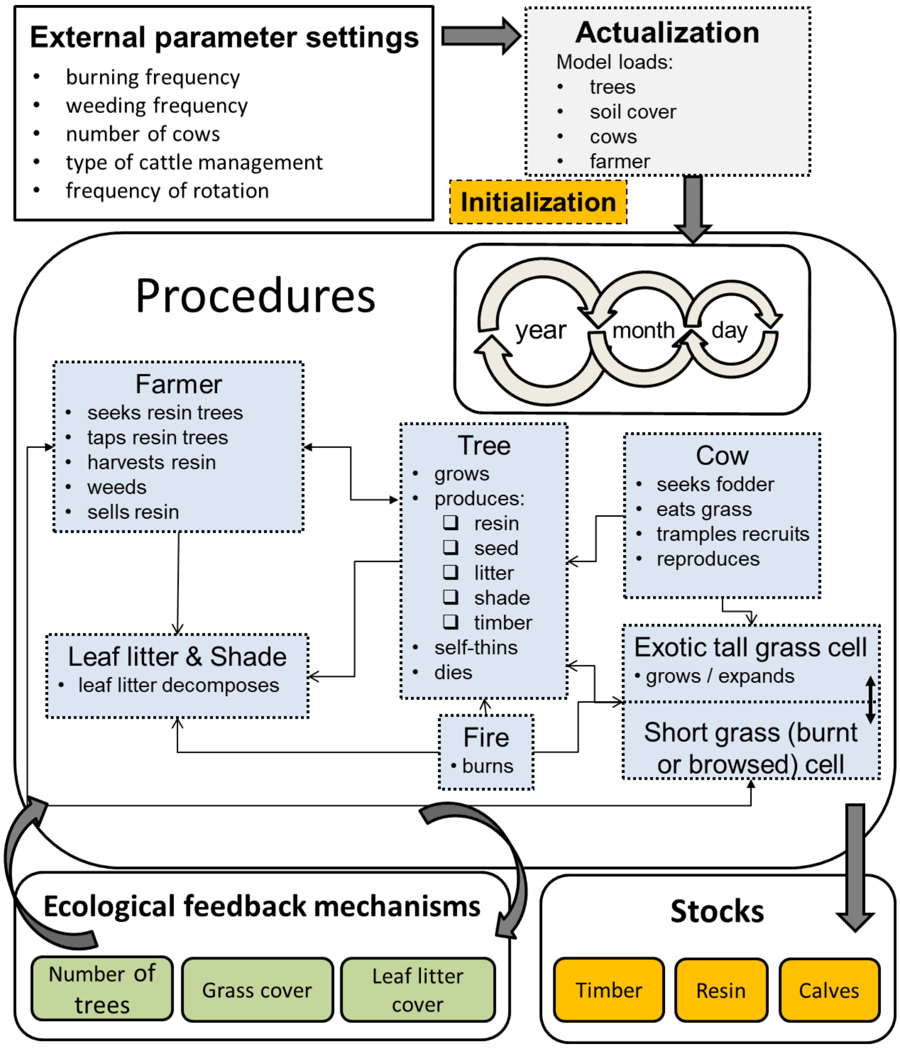


Fig. 3. Flowchart of the principal processes involved in the model. Direct interactions between agents are denoted with arrows.

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.

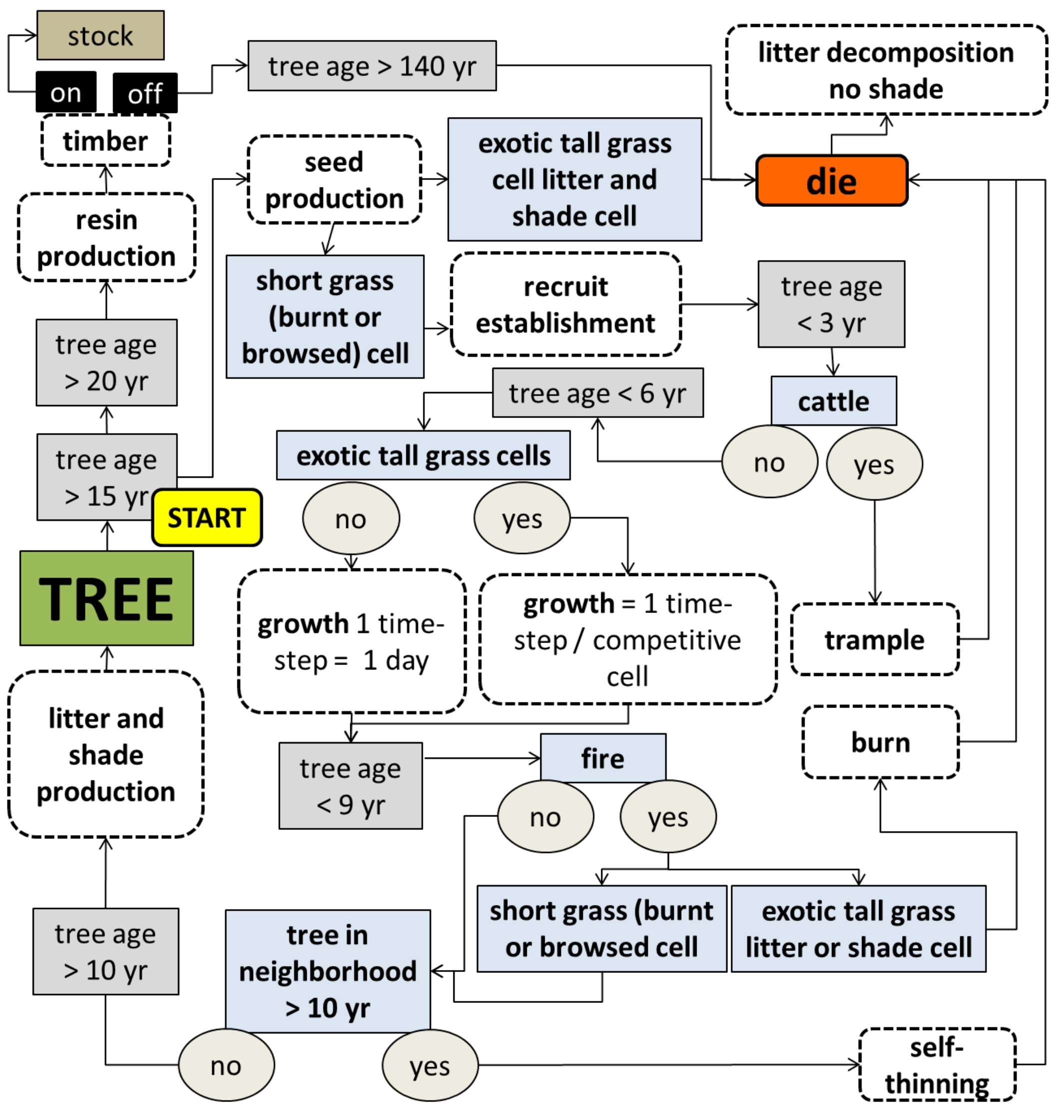


Fig. 4. Flowchart for the pine tree life cycle. The chart is read beginning with the yellow "start" box

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).

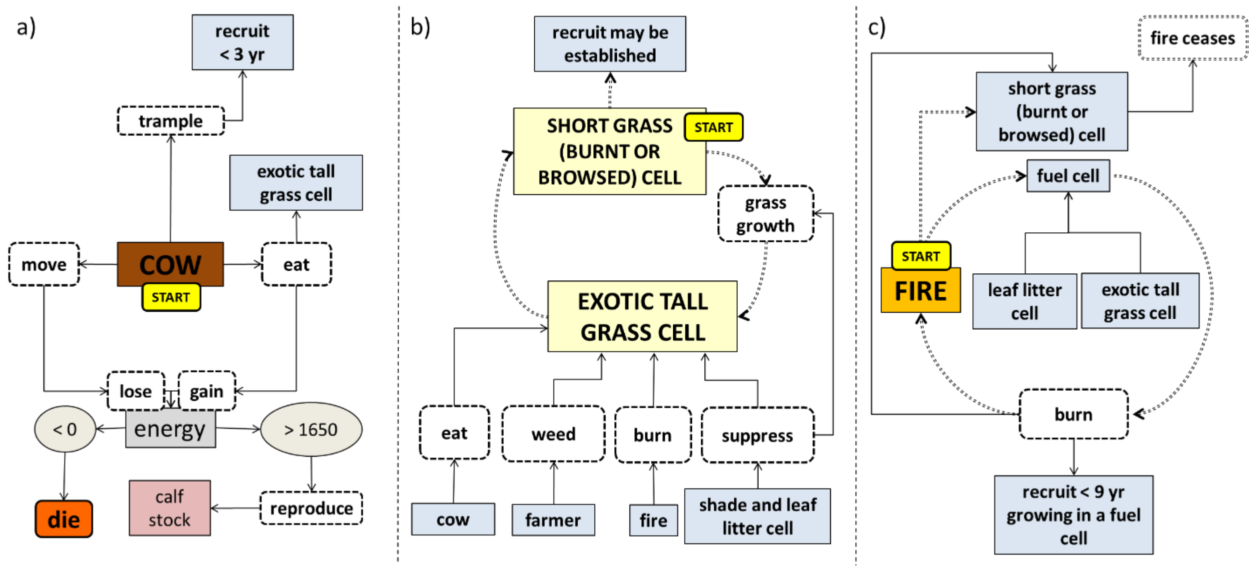


Fig. 5 Flowcharts for: a) cow sub-model, b) grass growth sub-model, and c) fire sub-model. The chart is read beginning with the yellow "start" box.

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).

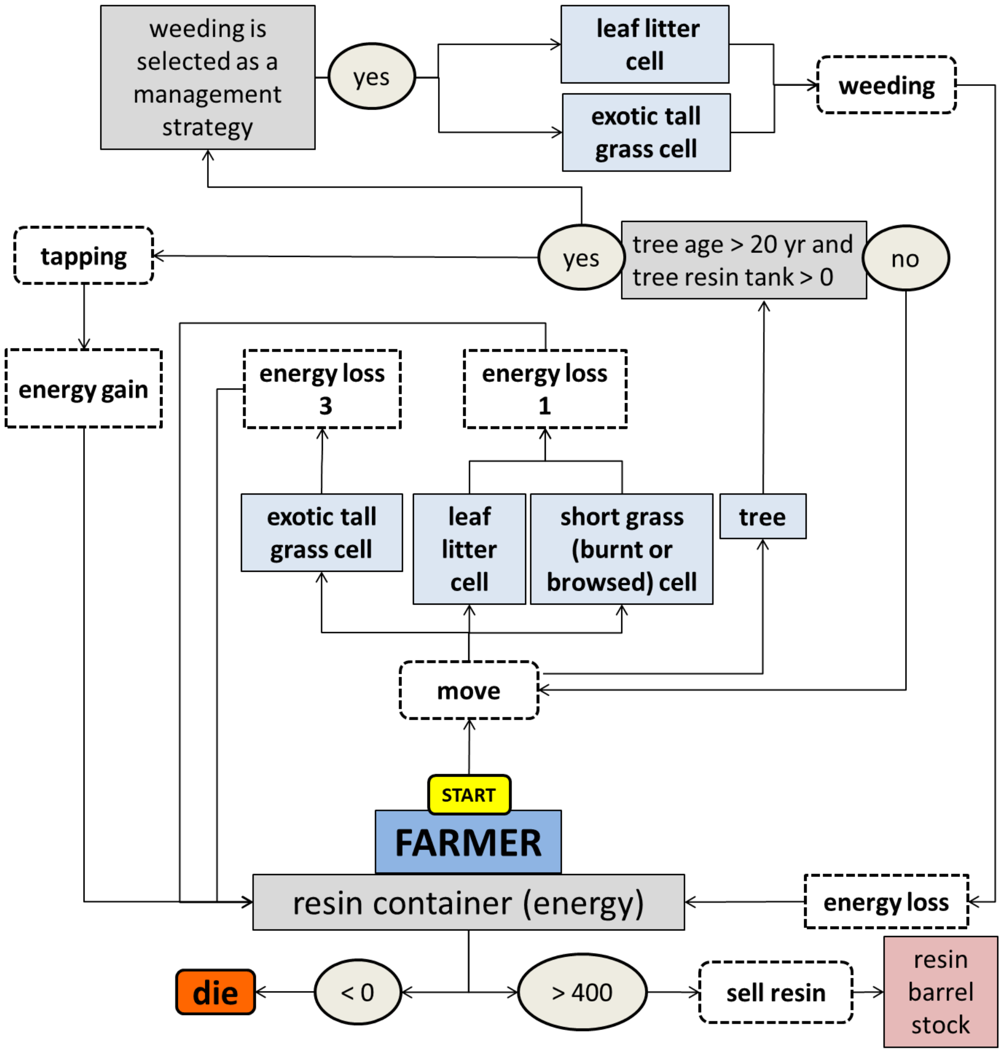


Fig. 6. Flowchart for the resin tapper sub-model. Note that energy refers to the farmer´s resin container, which is converted into money that allows the farmer to continue to work. Resin not needed by the farmer for proper working energy accumulates in barrels for sale and leaves the system. The chart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

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