Spatial rangeland model

This is a NetLogo replication of Janssen et al. (2002), which was originally implemented in Cormas. The goal of the model is to explore the consequences of non-uniform grazing as a consequence of sheep movement rules compared to the mean-field dynamical model of Anderies et al. (2002).

In the mean-field model, Anderies et al. assessed the conditions under which the system flips from a healthy state to an unproductive shrub state. With the agent-based version we will simulate individual sheep on a spatial lattice, and explore the consequences for different assumptions related to the behavior of sheep, such as herding and the location of water points.

The model describes the interactions between perennial grass, shrubs, fire and commercial stock in a stylized way, based conceptually on the functioning of semi-arid woodlands and shrublands in western New South Wales in Australia. The grass plant consists of the crown, the root system, and the shoots, the above- ground grass portion of the plant. The biomass of grass shoots is denoted by s, and follows a traditional logistic function. The crown promotes growth of the shoots according to the tiller potential $c*a_c$ independent of grass biomass, and through its interaction with above ground biomass via the term c*s. Competition between woody shrubs and grass reduces the grass growth. This is captured by the term $\alpha_{us} * w^{\beta}$, where α_{ws} is a competition coefficient, and where β (>1) leads to a growth reduction effect of woody shrubs that does not kick in until shrubs reach a relatively high density. Grass is removed by grazing pressure via the term $\gamma_g * s$. Finally, grass biomass can be consumed by fire I, which has a general response function of form f().

$$s[t+1]=s[t]+c[t]*(a_c + s[t])*(1 - s[t]-\alpha_{ws} * w^{\beta})-\gamma_g * s[t]-I[t]*f(s;a_s, b_s)$$

The response curve is a monotonically increasing function bounded above by 1; if b > 1, the function is sigmoidal. The parameter a controls the location of the point where f is half its maximum value, and b controls the steepness of the increasing portion. The larger the value of b, the more rapid is the switching.

$$f(k;a,b)=k^b / (a^b + k^b)$$

The crown biomass c grows at rate r_{cs} and dies at a rate 1. The grass growth is dependent on the presence of the crown.

$$c[t+1] = c[t] + r_c * s[t] - c[t]$$

The fire consumption index captures the consequences of fire. A fire will break out when the grass biomass s grows a little beyond a_x. The term δ_I denotes the rate at which the fire begins to die out. The parameter r_I represents the rate of increase of the fire consumption index once sufficient fuel is present.

$$I[t+1]=I[t]+I[t]*r_I *(f(s[t];a_I , b_I)- \delta_I)$$

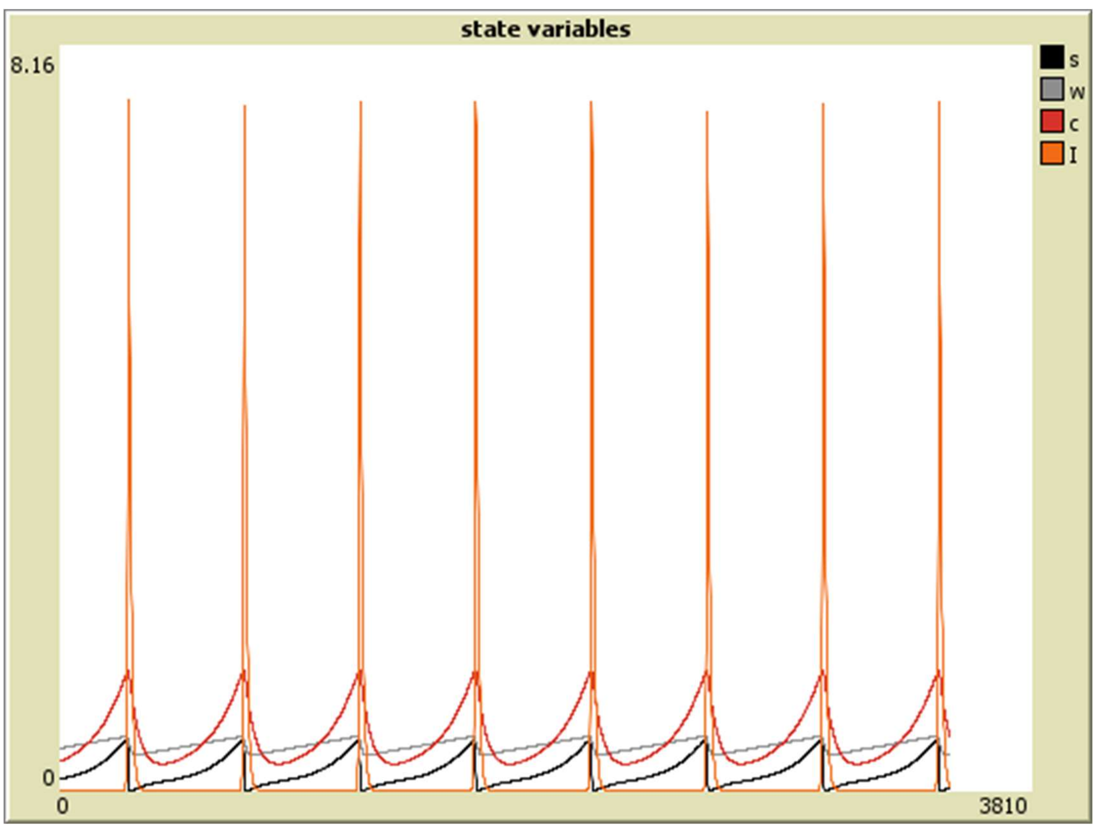
Woody shrubs are simply defined as a logistic growth function, where r_w represents the intrinsic growth rate of shrubs. Furthermore, fire can consume woody shrubs as denoted by the last term of the equation:

$w[t+1] = w[t] + r_w *w[t]*(1-w[t])-\gamma_{Iw} *w[t]*f(I[t];a_w, b_w)$

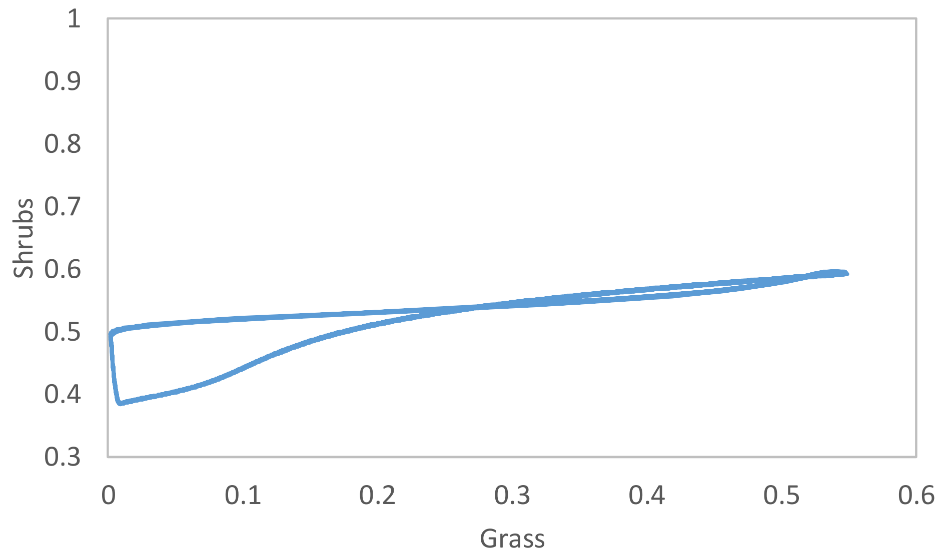
The Table below provides the parameter values used in the model.

Initial values	Ecosystem parameters	Response function parameters
$c_0 = 0.3252$ $s_0 = 0.1262$ $w_0 = 0.4647$ $I_0 = 1E-9$	$r_c = 3$ $r_I = 60$ $r_w = 0.1$ $\delta_I = 0.1$ $a_c = 0.1$ $\alpha_{us} = 0.5$ $\beta = 3$ $\gamma_{Iw} = 1$	$a_s = 0.1$ $a_I = 0.5$ $a_w = 1$ $b_s = 1$ $b_I = 3$ $b_w = 8$

We implemented the model in Netlogo. We consider to model one paddock split up into 100 cells of about 20 ha each. Each cell contain the difference equations described above using a time step of 1/50 year. In the figure below you see the phase diagram for a uniform grazing pressure $\gamma_g = 0.25$. The model follows a stable cycle of about 9-10 years. The grass biomass and the shrub biomass grow until enough fuel is available to start a natural fire. The fire consumes the grass biomass almost completely, and reduces the shrub biomass significantly.



We can use the data from shrubs and grass to depict the figure 8 dynamics of the system.



Now we will introduce agents, representing sheep, who will harvest on individual patches and may move each time step to another patch. We will allocate 300 agents, a typical sheep density for a property. We will explore the model with a number of different possible implementations.

1. The first agent-based version assumes that agents each move to a random neighboring patch in the next step.
2. Instead of moving randomly, we now assume that every time step, the sheep move to the best of the nine patches centered on its current position. Sheep will start to cluster in cells that were considered the best in the local neighborhood last time step.
3. Next we include herding behavior of sheep, assuming that sheep have a greater tendency to occur in larger flocks. Hence sheep are more likely to move to cells with more other sheeps.
4. In this version we include herding with a water point. This indicator takes into account the amount of grass biomass and the relative distance to the water points and the number of sheep in the neighboring cells:

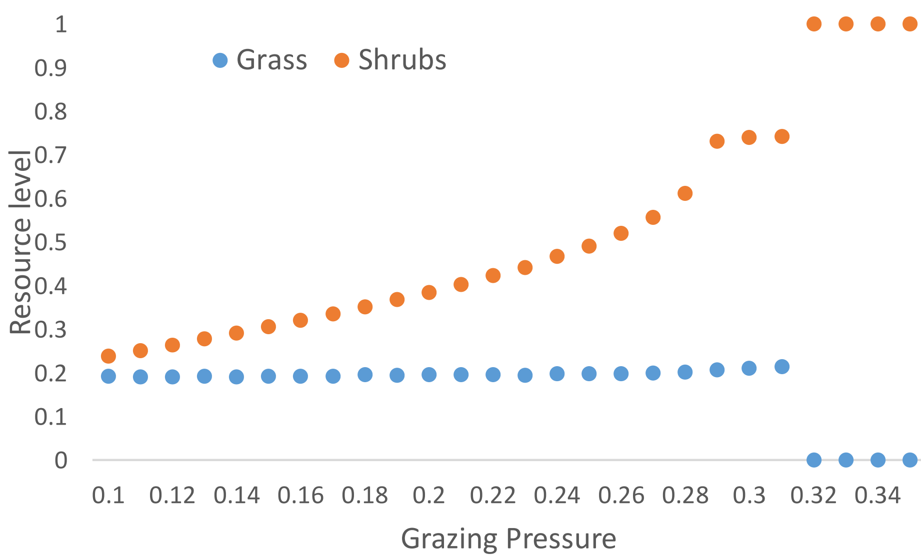
   $att[t] = \exp(-\lambda s[t])*s[t]*d + (1-\exp(-\lambda s[t]))*p[t]$

   and where att is the relative attractiveness, $d \in [0,1]$, the relative location of water point ($d = 1$ is the waterpoint, $d < 1$ means not at the waterpoint. The lower d the further away from the waterpoint). p is the percentage of neighboring cells where other sheep are located. Including herding (with $\lambda = 0.04$) leads to a higher concentration of grazing pressure, and therefore increasing degradation of the paddock for a given grazing pressure. In the results below we assume water point in the center of the paddock.

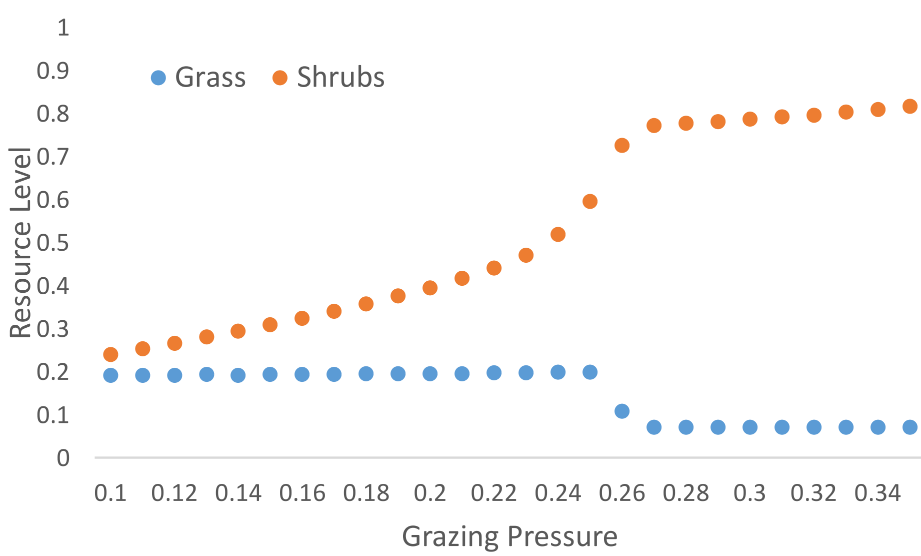
Results

We will explore the model for which grazing pressure the grass will be overharvested. We do this by running the model 60,000 time steps and calculate the mean for the last 10,000 time steps. Due to the stochasticity of the model, we will now run the model 100 times to calculate the metric for each grazing pressure. In the figures below we depict the long term mean values of grass and shrubs.

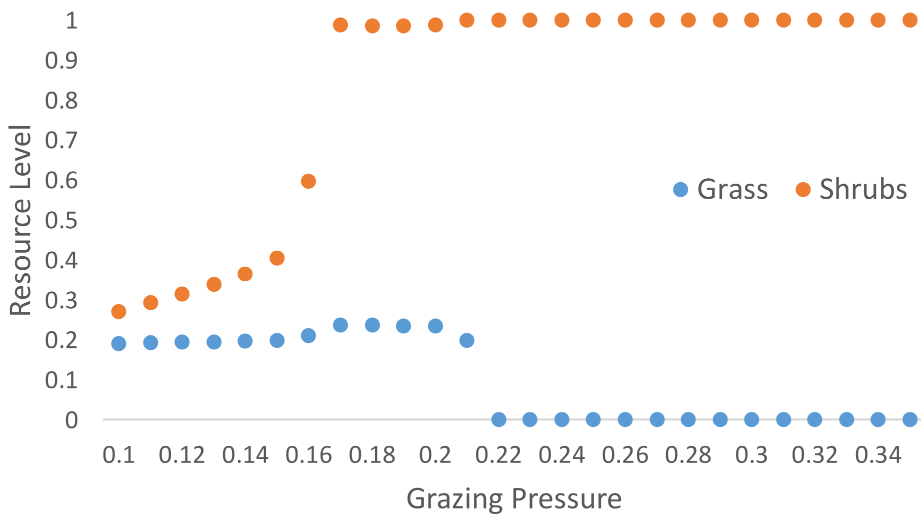
The first figure is the outcome of the mean field model, where there is a bifurcation around grazing equal to 0.32 for which the grass disappears and the system will be dominated by woody shrubs.



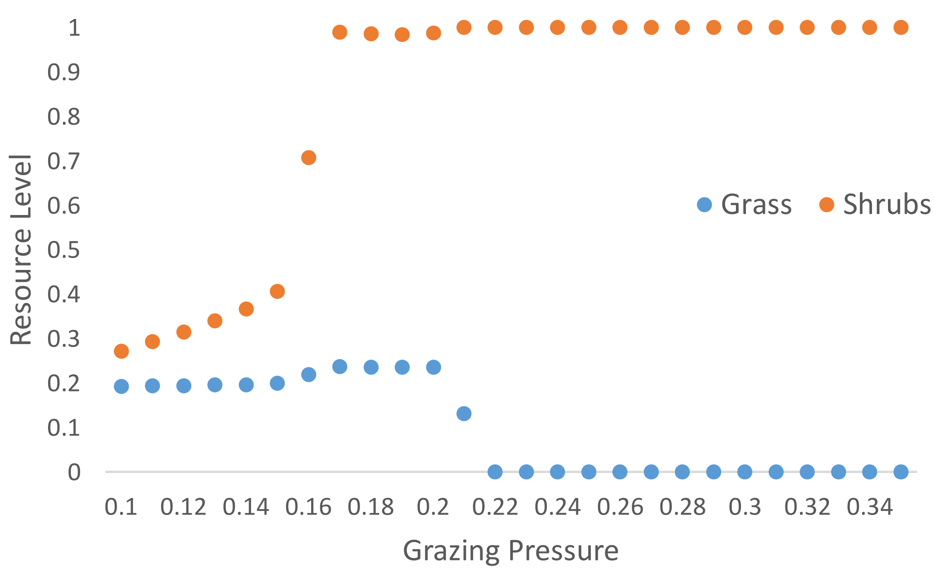
When we assume random movements we see that the grazing pressure leads to a shrub dominated overgrazed landscape with a lower grazing pressure, around 0.26. It does not go as sharply as the deterministic mean-field model due to the stochastic nature of the ABM.



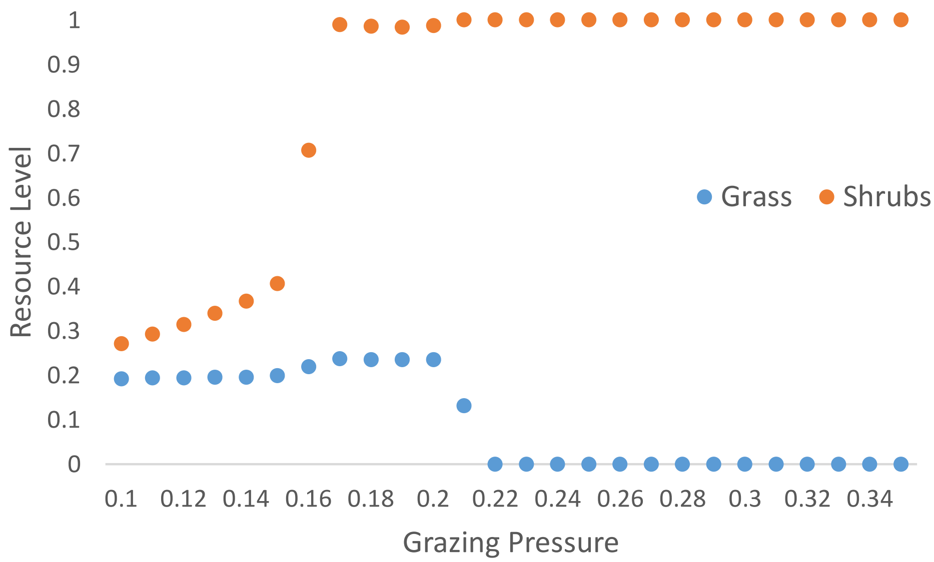
When the agents move to the best neighboring cell the shrubs start to dominate around a grazing pressure of 0.17 and grass disappears with a grazing pressure of 0.22.



Adding herding does not lead to much different results compared to going to the best spots. In both cases we get clustering of grazing pressure that flips the local cell to a shrub dominated overgrazed state.



Adding the water point in the center of the paddock lead to a bit lower grazing pressure for the system to flip into undesirable states.



In all the model shows that behavioral rules of the grazers impact the resilience of the system. Using mean-field equations could underestimate the sensitivity of the system.

References

Anderies, J.M., M.A. Janssen and B.H. Walker (2002) Grazing management, resilience and the dynamics of a fire driven rangeland system, *Ecosystems* 5: 23-44

Janssen, M.A., J.M. Anderies, M. Stafford Smith and B.H. Walker (2002) Implications of spatial heterogeneity of grazing pressure on the resilience of rangelands, in Janssen, M.A. (ed.) *Complexity and Ecosystem Management: The Theory and Practice of Multi-agent Systems*, Edward Elgar Publishers, Cheltenham UK/ Northampton, MA, USA. Pp 103-124.