Model description

Rangelands are the semi-arid regions of the world that are too dry for reliable crop cultivation and hence used for livestock production of one form or another. The vegetation is characteristically a mixture of grasses, shrubs and trees, ranging from pure grasslands to the woodland savannas of the subhumid tropics. Depending on the kind of rangeland, the welfare of the pastoralists who live in them is based on grazing animals (cattle and sheep), mixed feeders (browsers and grazers like camels and goats) or a combination of both. Fire has been an integral part of the environment of rangelands, and the net effect has been to maintain rangelands in more open, grassy states than would be achieved in the absence of fire. Fire is not a disturbance in most rangelands; fire suppression is a disturbance.

The model described is based on Janssen et al. (2000; 2002; 2004), and Anderies et al. (2002). 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 terms z_{max} and q_z. We assume that there is a maximum number of sheep per unit area the pastoralist will allow, z_{max}. The pastoralist uses a control variable, q_z, which defines the shrub density beyond which the pastoralist will reduce grazing pressure. If q_z is high pastoralists reduce grazing pressure at a higher level of shrub density. Finally, grass biomass can be consumed by fire I, which has a general response function of form f().

$$s[t+1]=s[t]+c[t]*(a_c + s[t])*(1 - s[t]-\alpha_{ws} * w^{\beta})- z_{max} *(1-f(w[t],q_z,b_{zmax}) * f(s[t], 0.1,1) - I[t]*f(s;a_s, b_s)$$

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:

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

With no manager or sheep, fires will die out naturally when the fuel load is consumed. With increasing numbers of sheep on the property, the pastoralist must suppress fire to provide feed for the stock and maintain wool production. If z increases, the pastoralist would increase δ_I from its minimum value of λ up to a maximum of 1. The control variable q_δ defines a threshold stocking rate at which the pastoralist begins to suppresses fire, and b_δ defines the sharpness of the pastoralists response as this threshold is approached. As such we define δ_I as

$$\delta_I[t]=\lambda-(1-\lambda)*f(z[t],q_\delta,b_\delta)$$

Building on Janssen et al. (2004) we define the profit of a pastoralist as a function of wool production, the cost of mustering sheep, adjustment costs associated with changes in grazing pressure, and lost revenue when grass during a fire. The first two elements are driven indirectly by grass and shrub dynamics in the system. The second two are direct consequences of management action and are thus related to the choice of control parameters.

Wool production is assumed to be a function of the number of sheep and their nutritional status as measured by grass offtake. When grass biomass is low, offtake will be low and the animals will be malnourished. This will cause wool production to go down. In the semi-arid region of Australia supplementary feeding is not economically feasible. When shoot biomass is high, offtake will be high, sheep will be well nourished, and sheep numbers will be the primary determinant of wool production, and wool production varies with z: Costs associated with shrubs are related to mustering—locating and gathering animals on several occasions per season. The more shrubs, the more difficult and costly it is to muster the animals. The cost per animal associated with shrubs does not increase significantly until shrub density is quite high. A first-order approximation to capture this fact is a quadratic representation. This yields a cost per unit of grazing pressure of Cw^2 .

The cost of adjusting the sheep density (moving sheep on or off the property), C_a; is directly related to the derivative of the sheep density. Assuming a constant movement cost per sheep (agistment costs), we assume that changes in the stock level are due entirely to management actions. This, of course, is not completely accurate. However, given that managers decide when to mate their ewes and rams, when to buy, sell, and move their stock, one can assume that these adjustments are stronger determinants of the stock dynamics than natural population dynamics.

Now we can define the profit function $\pi[t]$ in time step t as

$$\pi[t]=z*(f(s[t],0.1,1) - C_w * w[t]^2) - C_a * |\Delta z|$$

What is the best management policy for the rangeland system? We can formulate this as an optimization problem where a pastoralist maximize the accumulation of discounted profits given z_{max} , q_z and q_δ being the control variables. We can solve this problem in Netlogo using the genetic algorithm from the behavior search tool of Netlogo. When we use an annual discount rate of 2%, we that the optimal values of the control parameters are 0.324 for z_{max}, 0.582 for q_z and 0.347 for q_δ. This leads to a 3 year cycle of the system in which the stocking is adjusted between 0.33 and 0.36, and the grass biomass is kept at a high level due to fire suppression. In Figure 2 we see that the stocking rate declines when the biomass of shrubs is increasing. But because the control strategy keeps the shrub level contained, the stocking rates are varying not that much either.

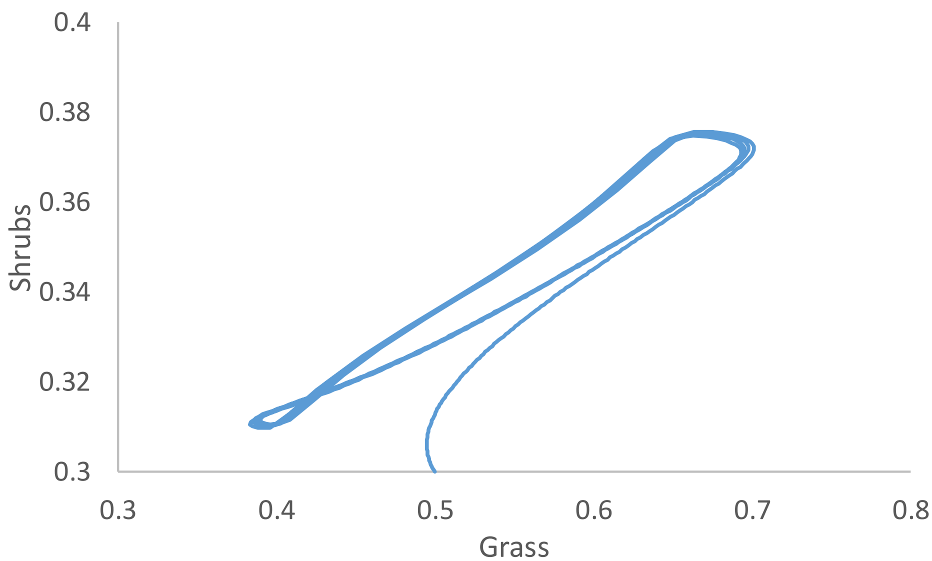

Figure 1: The optimal strategy depicted in a phase plane of grass and shrub levels.

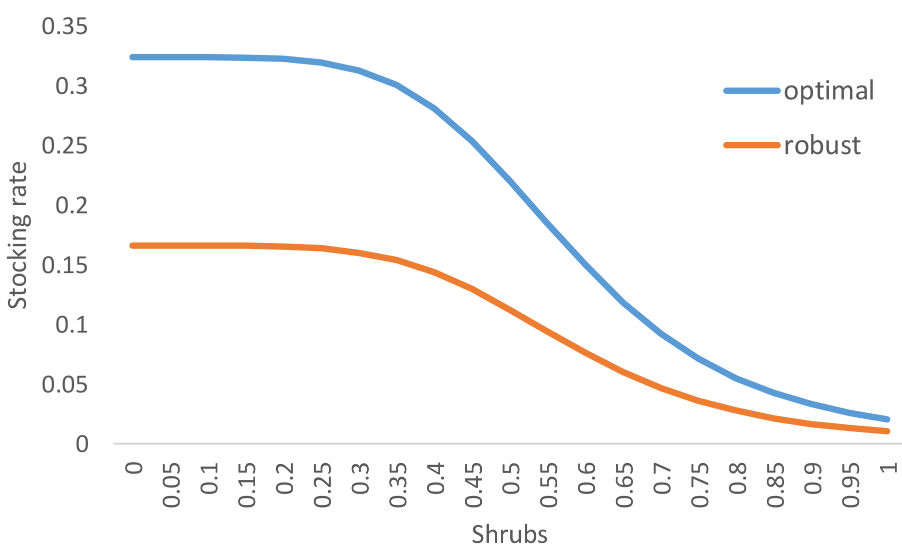

Figure 2: The control strategy for stocking levels as a function of shrub biomass. The optimal strategy is the outcome of the optimization without stochastic events. The robust solution is the outcome of the optimization with stochastic rainfall events.

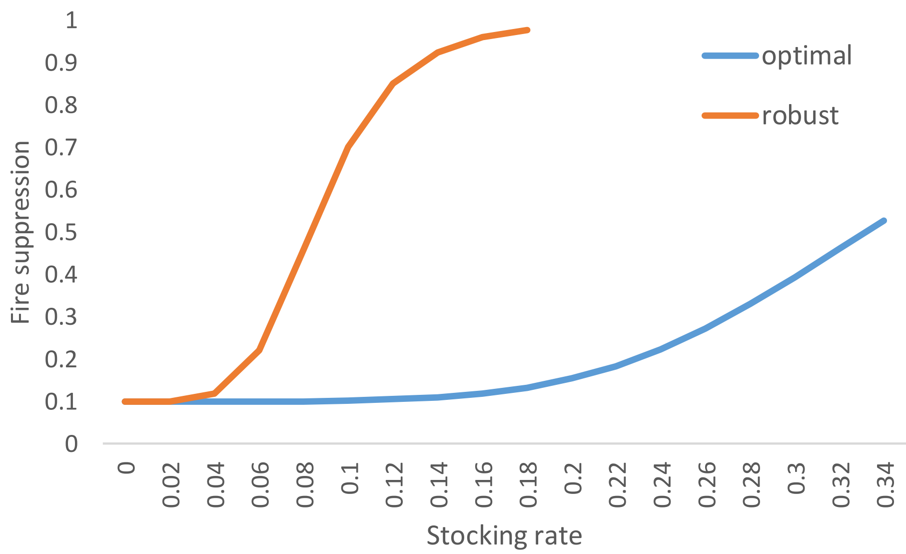

Figure 3: The control strategy for fire suppression levels as a function of stocking rate. The optimal strategy is the outcome of the optimization without stochastic events. The robust solution is the outcome of the optimization with stochastic rainfall events.

We now include rainfall variability into the model. Variability in rainfall patterns increases the vulnerability of the system to grazing pressure. In wet years, the shrub growth is faster. This, combined with heavy grazing pressure which reduces the accumulation of shoot-biomass will increase the chance that the system will fall into the stability domain dominated by shrubs. In this case more caution is needed to manage shrubs when rainfall is variable. A rainfall is defined which will affect growth rates of crowns, shoots and shrubs, and follows a lognormal distribution with mean 1 and variance 0.28:

$r_f = \exp(n(-0.125,0.5))$

When we use a genetic algorithm to find an optimal solution, we calculate the value of the objective function as the mean of 100 runs with different rainfall patterns. The resulting optimal solution can therefore be considered as a robust solution leading to on average a high mean value of accumulated discounted profits for diverse rainfall patterns. The maximum stocking level is halved (z_{max} =0.166 and q_z=0.58), and fire suppression is much higher at lower stocking levels (q_δ=0.087).

References

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