



# **Spatial aspects of grazing in savanna rangelands – a modelling study of vegetation dynamics**

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## **Abstract**

Increasing shrub cover density poses a widespread problem in semiarid savanna rangelands. Recently, vegetation dynamics has been studied with the aid of spatially explicit models, aiming to highlight the response of shrub cover to livestock grazing. Assuming that on a local scale, grazing and trampling act as a disturbance ultimately facilitating local extinction, small scale local variability of grazing intensity might influence density and vegetation cover of forage plants and thus affect shrub cover dynamics. We used a spatially explicit grid based simulation model based on southern Kalahari ecology. Plant life histories were modelled at the level of the three major life forms: perennial grasses and herbs, shrubs, annuals. To study the role of small scale local variability of grazing intensity under various levels of livestock grazing pressure we conducted factorial simulation experiments for two large scale grazing patterns: firstly, assuming homogenous grazing, secondly, assuming a grazing gradient as observed around artificial watering points. Our results confirm the previously reported threshold behavior of shrub encroachment, with threshold levels close to the recommended stocking rates of the study area. Stocking rate threshold levels and rates of shrub encroachment were sensitive to small scale local variability of grazing pressure. For grazing regimes with lower local grazing variability, threshold levels of shrub encroachment shifted towards higher grazing pressures, and at given critical stocking rates, shrub encroachment was slower than for grazing regimes with larger local variability. Equally, for grazing regimes with lower local grazing variability, piosphere formation around boreholes required higher grazing pressures, and was slower at given critical stocking rates than for grazing regimes with larger local variability. We conclude that information on small scale spatial variability of grazing intensity is crucial for correct assessment of the impact of livestock grazing on vegetation dynamics in savanna rangelands.

## **1 Introduction**

For many arid and semiarid rangelands of the world there is evidence of an increasing vegetation cover of woody components.<sup>2,3,5</sup> Generally, livestock



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grazing is considered as the prime causal factor for this development<sup>2,5,24</sup>, although there are also controversial positions.<sup>9,13</sup> Vegetational changes in semiarid communities are slow, with transition times exceeding the usual time horizon of scientific studies. Additionally long term trends may easily be masked by stochastic rainfall fluctuations. Slow response times and high stochasticity make vegetational changes in rangelands a subject well suited for simulation studies.<sup>23</sup>

To date, spatial aspects of livestock grazing have been studied mostly at a larger scale level, e.g. grazing gradients around waterpoints.<sup>1,17</sup> However, the direct plant-animal interaction is essentially a local event taking place at a small spatial scale, generating a spatial variability that has hitherto been largely neglected. There are some empirical studies on smaller scale utilization patterns of free-ranging livestock in semiarid areas of Northern America<sup>16,20</sup>, Australia<sup>14</sup> and South Africa<sup>7,15</sup> thus providing evidence for small scale variability of grazing utilization.

As a consequence of recognizing the local nature of plant interactions, an increasing number of spatially explicit models of plant community dynamics have been published, and recently the impact of grazing has been studied by this approach as well.<sup>10,11</sup> However, so far, the attention for spatial aspects remained mostly focused on the plant community, whereas small scale spatial aspects of grazing behaviour have not been considered. Moreover, in the spatial savanna models published so far, the implications of the necessarily spatial grazing submodels have gone unnoticed and the respective sensitivity of the obtained results has not been studied.

Despite the empirical evidence of small scale non-uniform, non-random but rather patchy utilization patterns by grazing livestock, and the generally high grazing sensitivity of vegetation dynamics in semiarid rangelands, consequences of the former on the latter have not been studied yet. Hence, our study is a first attempt to highlight the consequences of small scale spatial variability of grazing utilization for vegetation dynamics in semiarid rangelands. To this end we conducted simulation experiments with a spatially explicit savanna grazing model for two large scale grazing patterns: firstly, assuming large scale homogeneous grazing, secondly, assuming a grazing gradient as observed around watering points.

## 2 Methods

Our model is tailored to represent a summer rainfall region with 300 to 400 mm mean annual precipitation, characteristic for the drier Kalahari regions utilized for cattle ranging in Botswana<sup>4</sup> and South Africa.<sup>6</sup> In these areas, the shrubs *Acacia mellifera* ssp. *detinens* and *Grewia flava* are prominent representatives of the woody vegetation.<sup>22</sup> The herbaceous layer is dominated by perennial grasses such as *Schmidtia pappophoroides* and *Stipagrostis*

*uniplumis*. In favourable years annual grasses (e.g. *Aristida congesta*) contribute significant fractions to vegetation cover.

## 2.1 Basic Model

Full documentations of the basic model have been published elsewhere.<sup>10,11</sup> Hence, we focus on the modifications introduced in this study and give a summary of the basic model only. We modified a spatially explicit grid-based simulation model with an annual time step employed by Jeltsch et al.<sup>10,11</sup> for studies of shrub cover dynamics in semiarid savanna rangelands in the southern Kalahari. The model depicts three major life form groups, namely perennial grasses and herbs **P**, shrubs **S**, and annuals **A**. The main driving force of vegetation dynamics is soil water availability. Fire and grazing are additional factors modifying vegetation dynamics.

We distinguish two layers of soil water, namely top and sub soil water. Annually available soil water in each layer is computed from daily rainfall data generated with a South African rainfall simulator.<sup>25</sup> Long term mean of annual rainfall is 383 mm.

The modelled area is a rectangular grid of square cells with 5 m edge length each. Possible grid-cell states are: empty, occupied by either life form, or a mixture of any combination. Colonization and mortality are dependent on the amount of available soil moisture, which is subject to resource competition. Colonization is restricted to empty grid-cells. For perennial life forms we distinguish three different classes of grid-cell based potential production levels: low, moderate, and high. For perennial grasses and herbs, production of 800, 1400, and 3000 kg/ha are assumed for the respective levels. Changes in potential production levels are generated by water availability, grazing, and fire.

## 2.2 Grazing Submodel

A grazing event  $e$  is comprised of the selection of a grass cell and the defoliation  $d_e$  of its grass biomass. On an annual basis we can thus define defoliation frequency  $f_a$  as the total number of grazing events in a grid-cell in a given year and defoliation intensity  $d_a$  by cumulating defoliation  $d_e$  over  $f_a$ . We assumed three foraging scenarios generating different frequency distributions of  $f_a$  and  $d_a$  referred to as "high", "medium" and "low" spatial variability. Hence, with a mean patch size identical to the smallest spatial model unit – a grid-cell – three patterns of spatial patchiness are generated.

Total forage required annually,  $F$  [kg ha<sup>-1</sup>], is calculated from stocking rate [ha lsu<sup>-1</sup>] and annual intake per livestock unit [kg lsu<sup>-1</sup>]. With  $B$  [kg ha<sup>-1</sup>] as total grass biomass produced, mean defoliation intensity  $M$  is then given as  $M = F / B$ .

In the scenario of "high" local variability, grass cell selection is independent of the prior grazing history in a given year. For any grazing event,



defoliation intensity  $d_e$  is given by  $d_e = M \cdot b \cdot r$  with  $b$  denominating grass biomass in the selected grid-cell, and an evenly distributed random factor  $r \in [0,2]$ . In the grazing scenario of "medium" local variability,  $r$  is normally distributed around  $M$  with a standard deviation  $s = 0.1$ . To enforce a yet more even utilization pattern of the grass cover, a threshold  $x$  for repeated grid-cell selection is introduced in the grazing scenario for "low" local variability. Unless a fraction  $x = 0.99$  of the total number of grass cells are grazed in a given year, repeated grid-cell selection is excluded. Table 1 summarizes the parameters of the three grazing scenarios.

**Table 1:** Scenarios of small scale variability of grazing utilization; for nomenclature see text.

scenario	$x$	$r$		
		distribution	mean	$s$
high	0	even in $[0,2]$	1	—
medium	0	normal	$M$	0.1
low	0.99	normal	$M$	0.1

Grazing does not affect potential production level of **P**, unless residual biomass is down to the production level of a lower class. In this case, potential production is reduced to the respective class. Perennial grasses are considered extinct, if grazing leaves less than 0.25 kg in a grid-cell.

Computation of the repeated selection thresholds  $x$  of the grazing submodel is adapted to the two large scale grazing patterns studied. For the homogeneous grazing pattern, a global threshold was defined as a fraction of the total number of grass cells in the modelled area. For the borehole pattern, distance specific thresholds were defined as fractions of the number of grass cells in each distance class.

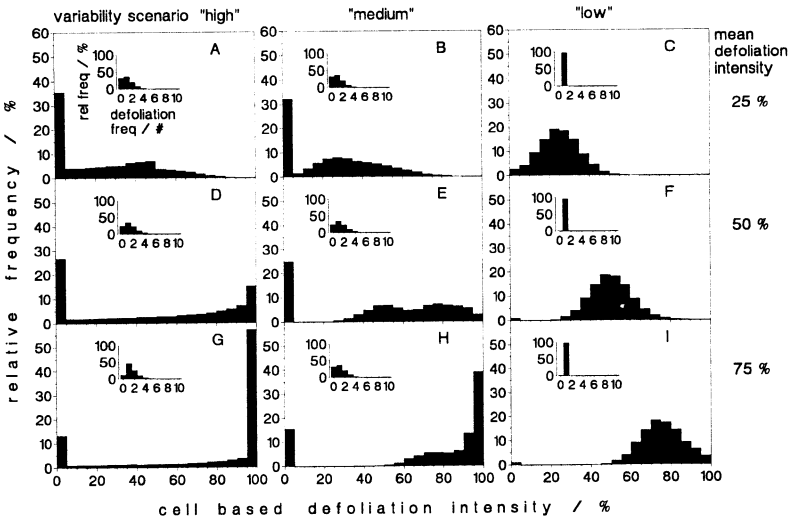
## 2.3 Simulation Experiments

Large scale homogeneous grazing is run on a 200\*100 grid of cells, the grazing gradient on a 640\*100 grid. Initial covers are 70 % **P**, 15 % **S**, and 10 % **A**. For large scale homogeneous grazing, we employed stocking rates from 4 to 30 ha  $lsu^{-1}$ , 4 weather sequences of 50 years each, and 10 simulation runs per factor combination. For the borehole grazing scenario, we present results of single simulation runs. Response variables are shrub covers after 5, 20 and 50 years.

## 3 Results

### 3.1 Grazing Utilization Patterns

To evaluate the implications of the three grazing scenarios, we recorded cell based defoliation frequency  $f_a$  and intensity  $d_a$  for three years with different levels of mean defoliation intensity. Subsequently to grazing, grid-cells were classified in 5%-steps according to their relative level of  $d_a$  (Fig. 1).



**Figure 1:** Frequency distributions of cell based defoliation intensity  $d_a$ . Small scale variability of grazing: A, D, G...high; B, E, H...medium; C, F, I...low. Mean defoliation intensity  $M$ : A, B, C...25%; D, E, F...50%; G, H, I...75%. Insets depict frequency distributions of cell based defoliation frequency  $f_a$ .

In the variability scenarios "high" and "medium", grid-cell selection for grazing is independent of prior grazing history in a given year. Hence, the frequency distribution of grid-cell based defoliation frequency is Poisson-random (Fig. 1 insets, columns "high", "medium"). At a mean biomass reduction of 50 %, approximately 25 % of all grass cells remain ungrazed under high or medium variability (Fig. 1 D, E insets). However, under high grazing variability, 15 % of the grass cells are grouped in the highest defoliation intensity class (Fig. 1 D), whereas under medium variability, no more than 2 % of the grid-cells show such an extremely high defoliation level (Fig. 1 E). Overall, the implementation of the grazing process results in a more or less bimodal distribution of grazing pressure under the high or medium variability scenarios. Whereas some grid-cells remain largely unaffected by grazing, others are subject to very high defoliation intensities.

Under the "low" grazing variability scenario, repeated grid-cell selection for grazing in a given year is excluded as long as less than 99 % of the grass cells have been selected for grazing. In combination with a normally distributed variation in defoliation intensity, this results in a unimodal distribution of grid-cell based grazing intensity (Fig. 1 column "low") with most of the cells selected only once for grazing (insets Fig. 1 column "low"). Even under an

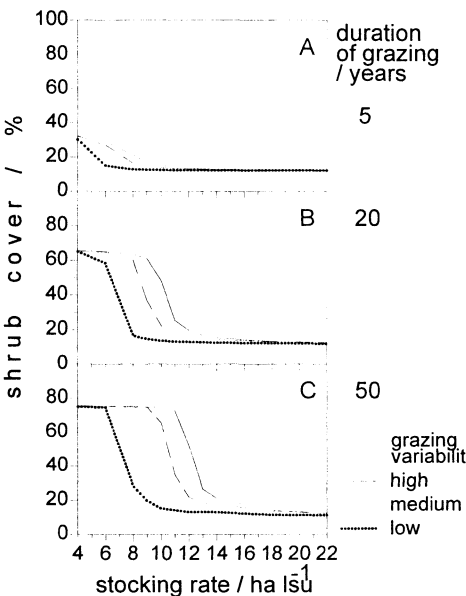
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extremely high mean defoliation intensity of 75%, less than 5 % of the grass cells are in the highest defoliation class (Fig. 1 I).

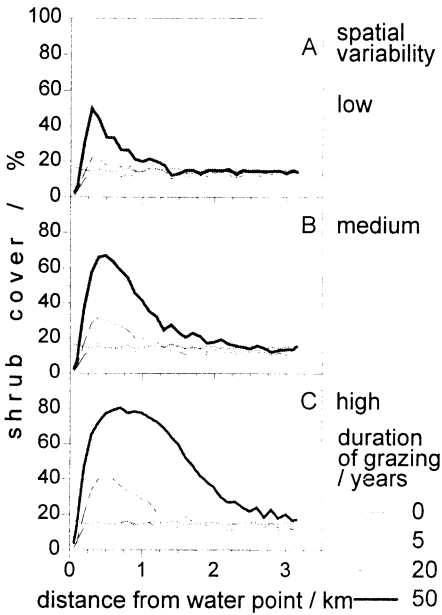
The frequencies of grid-cells with extremely low or extremely high defoliation intensities increase with spatial variability of grazing utilization. Under low variability, grazing pressure is normally distributed over all grass cells, whereas under higher variability, grazing pressure is bimodal with high frequencies of extreme defoliation intensities.

### 3.2 Shrub Cover Dynamics

Under moderate stocking rates, shrub cover remained fairly constant close to the initial level (Fig. 2). However, when stocking rates reached critical levels, shrub cover increased dramatically. This result confirms the previously reported threshold behaviour of shrub encroachment<sup>12</sup>. Under a large scale homogeneous grazing scenario, stocking rate threshold levels and rates of shrub encroachment were sensitive to small scale spatial variability of grazing pressure (Fig. 2). For grazing regimes with lower local grazing variability, threshold levels of shrub encroachment shifted towards higher grazing pressures, and at given critical stocking rates, shrub encroachment was slower than for grazing regimes with larger local variability. After 50 years of grazing, a stocking rate of 12 ha  $lsu^{-1}$  resulted in a shrub cover of ca. 50 % under high spatial variability, whereas under low spatial variability, shrub cover remained at the initial level of 15 % (Fig. 2 C).

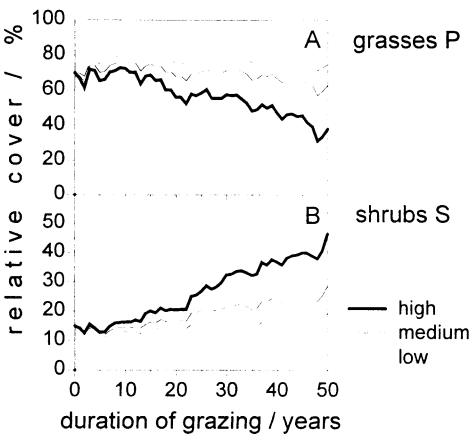


**Figure 2:** Relative shrub cover by stocking rate after 5 (A), 20 (B), and 50 (C) years of large scale homogeneous grazing at 3 different levels of small scale spatial variability of grazing utilization: high, medium, and low.



**Figure 3:** Shrub cover relative to total number of grid-cells in a 100 m wide stripe versus distance from water point at three levels of small scale grazing variability: low (A), medium (B), high (C). Stocking rate: 13 ha  $lsu^{-1}$ .

Under a large scale grazing gradient as observed around watering points, the creation of a zone of increased shrub cover required higher grazing pressures when local grazing variability was lower (undocumented result), and was slower and more limited in spatial extent at given critical stocking rates than for grazing regimes with larger local variability (Fig. 3).



**Figure 4:** Dynamics of shrub (B) and grass (A) cover under a borehole grazing gradient at 3 levels of small scale grazing variability: low, medium, high. Relative cover refers to total area of 640\*100 grid-cells. Stocking rate = 13 ha  $lsu^{-1}$ .

When spatial heterogeneity of grazing utilization occurs at different scales, detrimental effects of grazing are amplified. Whereas 50 years of grazing at a



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stocking rate of 13 ha  $\text{lsu}^{-1}$  under high small scale grazing variability results in an increase of shrub cover to ca. 25 % (Fig. 2 C) when large scale grazing is homogeneous, the overall shrub cover is close to 50 % (Fig. 4) when a large scale grazing gradient is present.

### 4. Discussion

In our modelling study, shrub cover dynamics was highly sensitive to small scale variability of grazing utilization. Scenarios of high small scale heterogeneity of grazing utilization promoted increasing shrub cover due to the increased frequency of patches with extremely high defoliation levels providing vegetation gaps open for shrub colonization. This result is in accordance with the hypothesis that any process increasing heterogeneity of soil resources would ultimately promote increasing shrub cover in semiarid rangelands<sup>21</sup> and parallels the degrading effect of patch-overgrazing reported for grasslands.<sup>7</sup>

Since most empirical studies on small scale grazing aspects<sup>14,19,20</sup> did not quantify the spatial utilization patterns reported, quantitative comparisons of model and field utilization patterns are difficult. However, Fuls<sup>7</sup> provides a map of a "typical patch mosaic" with patch diameters close to the edge length of our grid-cells. Qualitatively, we implemented spatial patchiness of grazing utilization at but one level of mean patch size equal to the smallest spatial model unit. Thus, our study is to be seen as a first step towards a more exhaustive analysis of small scale grazing patterns. Nevertheless, in documenting the high sensitivity of shrub cover dynamics to small scale grazing utilization it uncovers a factor that is implicit in spatial savanna models<sup>10,11,18</sup> but has not been studied so far. Considering the scarcity of empirical knowledge on small scale grazing patterns in savanna rangelands on the one hand, and the high sensitivity of model community dynamics to grazing patterns on the other hand, great care should be taken when results obtained from spatially explicit models are utilized to judge real world stocking rates in savanna rangelands.

Our results support the view that in rangelands prone to increasing cover by woody vegetation, a grazing distribution spatially uniform at the smaller scale level is desirable. However, the cost of managing for spatially homogeneous utilization would usually be prohibitive in areas of low productivity. Hence, patchy grazing utilization might well be inevitable in savanna rangelands, and consequently, management strategies aiming at sustainable land use should account for patchiness. In particular, stocking rates calculated merely from the amount of available biomass and the forage required per livestock unit<sup>6</sup> are underestimating the impact of livestock on community dynamics, since the degrading effects of patch-overgrazing are not accounted for. As our results





showed, this holds all the more, when spatial heterogeneity of grazing utilization is present at more than one spatial scale, e.g. due to a grazing gradient as observed around watering points. Therefore, the provision of additional water sources is a particularly effective means of limiting detrimental grazing effects by promoting a more uniform grazing utilization at the larger scale as advocated by Hart et al.<sup>8</sup>

We conclude that information on small scale spatial aspects of grazing is crucial for correct assessment of the impact of livestock on vegetation dynamics in savanna rangelands and hence for the establishment of management strategies of sustainable land use. Given the present scarcity of such information there is ample scope for both, empirical as well as theoretical studies.

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