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Relevance of rest periods in non-equilibrium rangeland systems - a modelling analysis

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“A simple management principle is that the way in which rangeland is rested is usually more important than the way in which it is utilized”

Snyman, 1998, p. 646

Abstract

The worldwide loss of utilisable rangeland in (semi-) arid areas results in huge economic and social costs. Only adaptive management strategies are able to cope with these systems, which are mainly driven by unpredictable and stochastic rainfall. The aim of the study was to investigate the relevance of rest periods as part of the management scheme in these non-equilibrium rangeland systems. The starting point of the analysis is an approved management system - the Karakul sheep-breeding Gamis-Farm (Namibia). The farmer applies a flexible strategy, which combines short-term adaptation of the stocking rate to the available forage and long-term adaptation by resting a third of the paddocks in years with sufficient rainfall. We developed a simulation model that focuses on the key dynamics of this non-equilibrium system. Beginning with the strategy used by the Gamis-Farm, a set of alternative grazing strategies was defined, all adapted to the available forage but differing in whether and when resting is granted for a part of the pasture. The effectiveness of these strategies was compared according to the long-term productivity of the pasture and the farmer’s livelihood.

Our results reveal ecological settings during which resting is essential for the recovery of the vegetation in a fluctuating environment, as well as those during which it is not. The growth rates of both the vegetation and of the livestock are demonstrated to be highly influential. Rests during wet years are crucial for the regeneration of the pasture. We conclude that even though a non-equilibrium rangeland system is assumed, the application of pure opportunistic strategies - destocking in times of drought and fast post-drought restocking - are not always adequate to maintain the long-term productivity of the pasture. Rest periods are indispensable when vegetation has a low regeneration potential. On an applied level, the study emphasises that improved farming conditions (supplementary feeding, unrestricted options to purchase livestock) may run the risk of ecological as well as economic damages.

Key-words: non-equilibrium system, grazing, opportunistic management, resting, semi-arid, simulation model

1. Introduction

A third of earth's land surface consists of arid or semi-arid regions. The livelihoods of at least one billion people depend on the use of this land (UNCCD, 2004). Hence, the loss of utilisable rangeland carries huge economic and social costs. Adequate management strategies that maintain the long-term productivity of the pasture need to be identified. To do so, a fundamental understanding of the underlying dynamics of the ecosystem is required, which includes taking into account the feedback-mechanisms between vegetation and livestock in a highly fluctuating environment.

Fifteen years ago, a paradigm shift took place with respect to herbivore-vegetation dynamics in (semi-) arid systems. Previously, it was argued that rangeland systems behave as equilibrium systems primarily influenced by biotic factors, with grazing being the main driver of vegetation change. Consequently, degradation (the loss of productive land) was attributed to excessive stocking rates (Lamprey, 1983; Dean and MacDonald, 1994). A relatively low fixed stocking rate was recommended as the appropriate management strategy in order to avoid overuse of the vegetation. In contrast to this, the so-called New Rangeland Science argues that these (semi-) arid systems, characterized by highly unpredictable and variable rainfall, behave as non-equilibrium systems. That means that abiotic factors such as prior rainfall are considered to be the main drivers of the system dynamics, and biotic factors such as grazing to be only of marginal influence (Behnke Jr et al., 1993; Scoones, 1994; Sandford, 1994). It is argued that fixed stocking rates are unsuitable in a variable environment and instead “opportunistic strategies” (Westoby et al., 1989) are favoured. These strategies are characterized by a close adaptation of the stocking rate to the available forage. At the first indication of a pending drought, the animals are destocked and after the drought fast restocking is carried out. These restocking-destocking management strategies, provided they are adapted to the available forage, should be sufficient in maintaining the long-term productivity of the rangelands. By implication additional measures, like rest periods for a part of the pasture, are obsolete and inappropriate for the efficient use of the pasture. For a review and critique of the current paradigms, see Briske et al., 2003) and Cowling, 2000).

The successful Gamis-Farm in Namibia contradicts these recommended strategies. This commercial Karakul sheep-breeding farm closely adapts the number of sheep to the available forage. In addition, part of the pasture is temporarily rested. In the rangeland literature, the danger of degradation in years of drought is emphasized and full stocking (according to available forage) is promoted in wet years (Livingstone, 1991). However, running counter to this intuitive view of relieving the burden on vegetation during dry years, resting on the Gamis Farm is instead carried out in years with sufficient rainfall and not during dry years. In order to assess this strategy, in association with the specific soil, climatic and environmental conditions on this farm, a detailed simulation model was constructed by T. Stephan (Stephan et al., 1996; Stephan et al. 1998a,b, referred to hereafter as the Stephan-Model). This study found that alternative strategies, with less resting, yield a higher short-term profit. However, in the long-term (over some forty years), the strategy used by the Gamis-Farm was found to be superior with respect to the number of sheep.

In contrast to the Stephan-Model, the aim of the present study is to deduce hypotheses for basic principles for livestock-vegetation dynamics under different climatic and environmental conditions. The focus is on the value of resting pastures in a fluctuating environment and the appropriate time of resting (in wet vs. dry years) for maintaining the productive integrity of the ecosystem. We analyse whether pure restocking-destocking management strategies, without resting, are sufficient to maintain long-term productivity of the rangelands. Additionally, we determine whether the ecologically counter-intuitive strategy to rest in wet and not in dry years can be explained. To explore these issues, a simulation model is constructed, not

intended to represent one particular farm but rather biologically plausible relationships in a strongly simplified way.
Two appropriate objective functions are defined for an assessment of the grazing strategies of interest: one with regard to the maintenance of the long-term productivity of the pasture, and a second with regard to the farmer's livelihood. Alternative grazing strategies are compared, all adapted to the available forage but differing in whether and when resting is granted for a part of the pasture.

As a result, a comprehensive understanding of the decisive mechanisms for vegetation and livestock dynamics is reached. Ecological settings are identified under which resting is necessary for the recovery of the vegetation, as well as those during which the vegetation is able to regenerate while under grazing pressure. We hypothesize that the uncriticised application of pure opportunistic strategies - destocking in times of drought and fast post-drought restocking without any resting - are insufficient in non-equilibrium systems. The emergence of unplanned rests is shown to be a crucial factor in determining the appropriate time of resting. We refer here to unintended rest periods for the vegetation, which occur after a crash of livestock numbers following a drought and the subsequent slow recovery of livestock numbers. However, the occurrence of unplanned rests depends strongly on the underlying farming system and the present infrastructure (options of livestock purchase and supplementary feeding). Finally, we can answer the question as to whether and under which circumstances this strategy, successfully used by the Gamis-Farm, can be applied to other farms in semi-arid environments.

2. Methods

2.1. Study site

2.1.1. Ecosystem

The Gamis-Farm is situated 250 km southwest of Windhoek in Namibia (24°05'S 16°30'E) in the district Maltahöhe close to the Naukluft mountains at an altitude of 1250 m. The climate of this arid region is characterised by low annual precipitation (177 mm/y) which is highly variable in space and time. The coefficient of variation is 56 percent (evaluated from annual rain data on the farm during 1979-2001). The vegetation type is classified by Giess, 1998) as dwarf shrub savanna. Dominant shrub species are *Rhigozum trichotomum*, *Catophractes alexandrii*, *Acacia newbrownii* and *Leucosphaera bainesii*. The grass layer is dominated by the perennial grasses *Stipagrostis uniplumis*, *Eragrostis nindensis* and *Triraphis ramosissima*. Detailed information about climatic, edaphic and botanical setting of the study site can be found in Maurer, 1995).

2.1.2. Gamis strategy

Karakul sheep (race Swakara) are bred on an area of 30000 hectares. The primary source of revenue is from the sale of lambskins. Additionally, the wool of the sheep is sold and meat is used for farm consumption (Tombrink, 1999). In good years, up to 3000 sheep are kept on the farm. For forty years, an adaptive management system has tracked the variability in forage. During this time detailed records were kept by the owner, H.A. Breiting. The basis of the system is a rotational grazing system. The pasture land is divided into 98 paddocks. A paddock is grazed for a short period (about 14 days), after which it is rested for a minimum of two months. This system puts high pressure on the vegetation for a short time to prevent selective grazing. Moreover, the farmer has introduced an additional resting. One third of the paddocks is given a rest during the growth period (September - May). Outside this period, all paddocks are grazed. In the literature this strategy is termed rotational resting (Heady, 1970; Stuth and Maraschin, 2000; Heady, 1999; Quirk, 2002). The Gamis-Farm strategy is distinct from simple rotational resting systems in that pasture rests during the whole growth period are granted only in years with sufficient precipitation. In years with insufficient rainfall these pasture rests are reduced or completely omitted. Further measures, such as renting of additional pasture in areas of Namibia with better rainfall, are taken during long periods of drought. Once a year at the end of the rainy season, the farmer decides how many of the lambs will be raised and whether additional land will be rented from farms elsewhere in the country (H.A. Breiting, pers. comm.). For a complete and detailed description of the grazing system, see Stephan et al., 1996, 1998a,b).

The strategy to rest in wet years is economically reasonable, since the income made through lambskin production varies less, compared to rest in dry years or even in each year. Reason: in years with good rain, sufficient forage is available to feed the livestock, even if a part of the pasture is rested, whilst during low rainfall years, the forage of the paddocks that would otherwise be rested is instead additionally available for the livestock. Consequently, the livestock numbers need not be substantially reduced in poor-rain years and therefore fluctuate less over a longer time horizon. This allows this sheep breeding farm to establish a regular supply of high quality furs and to limit unavoidable sale or slaughter of ewes in dry years with insufficient forage.

When considering this strategy from an ecological perspective, the farmer has recognised the importance of rest periods to regenerate the vegetation. However, allowing the rest in wet and not in dry years sounds slightly counter-intuitive. In dry years, when the vegetation has already suffered from drought, it is put under the additional stress of the higher grazing pressure. However, the condition of pasture on the farm is considered good in comparison to the neighbouring farms (Klimm et al., 1994; Maurer, 1995).

2.2. The model

2.2.1. General concept

In semi-arid regions, impacts of inappropriate strategies often become visible only after decades (Briske et al., 2003). Simulation models help to understand the dynamics in these landscapes, since they are able to make forecasts by using current knowledge about ecosystem processes (Wissel et al., 1996; Jeltsch et al., 1997; Weber et al., 2000; Wiegand et al., 1995; Pickup, 1996; Illius and O'Connor, 2000; Beukes et al., 2002).

As we aim at gaining principle understanding of the functioning of rangeland systems and the relevance of resting, we develop a highly abstract, conceptual model that focuses on the essential factors and processes and ignores details. This limits the complexity of the model. In the result, the behaviour of the model and so the principle functioning of rangeland systems can be fully understood.

We developed two relatively simple difference equations for describing the dynamics of a grazed ecosystem (cf. Perrings and Walker, 1997 for another example of a conceptual model for the use of rangelands). The model is time discrete with annual time steps. This time frame is appropriate as there is a single rain season per year, following which the farmer adapts the livestock number to the available forage. Spatial aspects were only implicitly considered and details that were felt to be unimportant for a general understanding were omitted. Therefore, as on the Gamis-Farm, the pasture in the model was divided into paddocks with the dynamics of each paddock modelled separately without explicitly considering the exact position of the paddock. The initial reserve and green biomass for each paddock are assumed to be equal.

In developing this abstract, conceptual model, the main driving processes of the studied system were first identified (Fig. 1). Four principal components drive the dynamics of the vegetation in a semi-arid savanna: (1) plant-available water, (2) plant-available nutrients, (3) fire and (4) grazing (Skarpe, 1992). Natural fires do not occur in this type of ecosystem (H.A. Breiting, pers. comm.). In savanna systems with low rainfall (below 200-300mm), the vegetation is to a greater extent limited by water than nutrients (Snyman and Fouché, 1991; Le Houérou, 1989), and differences in plant-available nutrients resulting from different soil conditions were not explicitly simulated in the model. The importance of the role that nutrients play in vegetation dynamics is not doubted, rather the philosophy of the approach was to include only aspects that are crucial for answering the underlying questions, while other factors were treated only implicitly. Accordingly, of the four components mentioned driving vegetation dynamics, only precipitation and grazing were explicitly included in the model.

- Figure 1 -

The economic viability of alternative strategies was assessed from the number of livestock on the farm. The livestock constitutes the basis of the farmer's existence. On the Gamis-Farm, the farmer earns his living via the revenue from sale of lambskins and sheep wool. The number of livestock on the farm depends on the chosen management strategy; for example, if the farmer embarks on the strategy "resting in wet years", rainfall determines whether some paddocks are rested. In addition, the livestock number is adjusted to the available forage. The surplus of livestock are slaughtered or sold. Hence, in this case, both vegetation and precipitation are key factors in determining the stocking rate.

2.2.2. Vegetation dynamics: Differentiation in green biomass and reserve biomass

The life history of the different vegetation types and their reaction to grazing and browsing is quite diverse (Noy-Meir, 1982). However, initially a single abstract perennial vegetation type was modelled. A central task of the model is to represent the response of the vegetation to precipitation and grazing. The dynamics of the vegetation are not only influenced by the current precipitation but also to large extent by the plant reserves, as determined by the rain history i.e. the precipitation of preceding years (Fig. 2 and O'Connor and Everson, 1998). Hence, two characteristics of the vegetation were differentiated (Stephan et al., 1998a): firstly, the green biomass *G*, describing the photosynthetic organs of the plant and being the part of the plant which serves as forage for the livestock; secondly, the reserve biomass *R* (termed after Noy-Meir, 1982)), describing the non-photosynthetic reserve organs below or above ground. It follows that both rain and grazing history of the vegetation are reflected by the reserve biomass. Stephan et al., 1998a) and Weber et al., 2000) use similar terms for reserve biomass - vital biomass and potential production respectively.

2.2.3. Dynamics of green biomass

The current precipitation has a considerable influence on the production of green biomass (Fig. 2). As mentioned previously, precipitation in arid regions is characterised by a low mean but high spatial and temporal fluctuation. To simulate these properties as a stochastic process, a log-normal distribution of the annual rainfall is effective (Sandford, 1982). It is a right-skewed distribution. Events with low rainfall are frequent, but single high-rainfall-events also occur. Not all water is available for plant growth, due to evotransporation and run-off processes. Hence, in the model, only the portion of precipitation that is available for the plants, indicated by the measure $p(t)$, was incorporated. Obviously, it follows a log-normal distribution as well. The units of the measurement indicate the number of effective rain events per year (on Gamis Farm: events of more than 15mm). For easier handling, a continuous scale is assumed. Intra-annual fluctuations of precipitation, which influence to a high degree the germination and establishment of grasses, were not modelled explicitly to reduce the complexity of the model. Apart from the current precipitation, the available plant reserves strongly influence the formation of new green biomass G. Hence, a multiplicative interrelation between the reserve biomass R and the current precipitation was assumed. The growth dynamics of the green biomass $G_i(t)$ of paddock i in time step t were defined by:

$$G_i(t) = w_{gr} \cdot p(t) \cdot R_i(t), \qquad \text{for} \quad i = 1, \ldots, n \ \text{ and } \ t = 1, \ldots, T, \tag{1}$$

with n denoting the number of paddocks and T the time horizon. The parameter w_{gr} is a conversion parameter, indicating the extent to which the green biomass $G(t)$ responds to the reserve biomass $R_i(t)$ and current plant-available water $p(t)$. The factor w_{gr} is subsequently referred to as the growth rate of green biomass. One unit green biomass corresponds to the amount of biomass consumed per sheep per year. For simplification, it is assumed that even on non-grazed paddocks no green biomass is taken over from one year to the other. The actual amount of remaining green biomass would make up only a very small fraction in arid ecosystems.

- Figure 2 -

2.2.4. Dynamics of the reserve biomass

The generation of new reserve biomass $R(t+1)$ in year t+1 was assumed to be the result of photosynthesis and hence dependent on the available green biomass $G(t)$ in time step t. The extent to which new reserve biomass $R(t+1)$ is accumulated from green biomass $G(t)$ by photosynthesis is described in the growth rate of reserve biomass w_{res} (see equation 2). In the current model, it was assumed that grazing only affects the green biomass $G(t)$ and has no direct influence on reserve biomass $R(t)$ (Fig. 2). So for instance, the effect of animals pulling out entire grass tufts in dry years is ignored. This simplification is justifiable, because the stocking rate S(t) is closely adjusted to the available forage $G(t)$. Nevertheless, grazing has an indirect influence on reserve biomass $R(t+1)$, because less storage may be built up by photosynthesis if the paddock is grazed. In reality, the impact of grazing strongly depends on several factors, for example on the time of grazing during the year. To take into account these aspects a coefficient c was introduced, which expresses the extent to which a grazed paddock can build up new reserve biomass $R(t+1)$ by photosynthesis. This coefficient c is called the “harshness of grazing”, which describes the reduction in vegetation growth under grazing. It is assumed to take values between zero and one. The lower the value of parameter c the less green biomass is available for the production of reserve biomass. The impact of grazing on the regeneration of the vegetation is then high ($R(t+1) = w_{res} \cdot c \cdot G(t)$). By adjusting livestock number to available forage, grazing pressure on paddocks not rested remains constant (cf. 2.2.5.). Hence it is appropriate to assume c to be constant in the model.

Besides the described build-up process of the reserve biomass $R(t+1)$, the decomposition process has to be included. In this model, the reserve biomass $R(t)$ decreases with a constant decomposition rate m describing the use of reserves to maintain the vital functions of the plant. The vegetation dynamics were modelled for each paddock separately and afterwards summarized to determine the state of the pasture and the available forage. For a given paddock i, the annual dynamics of the reserve biomass $R_i(t)$ can be described by:

$$R_i(t+1) = \begin{cases} (1-m)\cdot R_i(t) + w_{res}\cdot c\cdot G_i(t), & \text{if paddock } i \text{ is grazed,} \quad 0 \le c \le 1 \\ (1-m)\cdot R_i(t) + w_{res}\cdot G_i(t), & \text{if paddock } i \text{ rested} \end{cases} \qquad (2)$$

The equation holds for all time steps t, t = 1,…, T, and for all paddocks i, i=1,…, n. T indicates the chosen time horizon in years and n the number of paddocks on the farm, $G_i(t)$ the corresponding green biomass on paddock i, c the harshness of grazing and m the decomposition rate of the vegetation ($0 \le m \le 1$). Equation 1 inserted in equation 2 describes the vegetation dynamics solely dependent on the variable reserve biomass $R_i(t)$.

In order to include density dependence, a corresponding parameter d was introduced. The reserve biomass $R_i(t+1)$ in paddock i in time t+1, depends on the reserve biomass $R_i(t)$ in the previous time period, reduced by a decomposition term and increased by a growth term. The higher d the higher the decomposition and the lower the growth:

$$R_i(t+1) = \begin{cases} R_i(t)\cdot\left[1 - m\cdot(1+d\cdot R_i(t)) + w_{gr}\cdot w_{res}\cdot p(t)\cdot c\cdot(1-d\cdot R_i(t))\right], & \text{if paddock } i \text{ is grazed} \\ R_i(t)\cdot\left[1 - m\cdot(1+d\cdot R_i(t)) + w_{gr}\cdot w_{res}\cdot p(t)\cdot(1-d\cdot R_i(t))\right], & \text{if paddock } i \text{ reste} \end{cases} \qquad (3)$$

This concept of density dependence is a simple linear approach, which differentiates the effect of density regulation for growth and decomposition.

Equation 3 reveals that only the product of the two growth rates of the vegetation, w_{gr} and w_{res}, is crucial for the dynamics. An aggregated parameter, the effective growth rate of vegetation w_{eff} ($w_{eff} = w_{gr} \cdot w_{res}$), was introduced. Since we are not interested to know whether a change in w_{eff} is caused by variation of w_{gr} or w_{res}, this simplification seems feasible.

2.2.5. Stocking rate

A basic assumption of the model is that every year the stocking rate $S(t)$ of the livestock tracks the available forage $G(t)$, or more accurately, the available forage in the paddocks not reserved for resting $G_{avail}(t)$. The surplus of livestock is sold or slaughtered. The dynamics of the flock size are determined by the growth rate of livestock b. Only ewes were included; the number of rams was ignored, because the majority of male lambs are slaughtered just after birth. Purchase of livestock was excluded to maintain the purity of breeding stock. The current stocking rate $S(t)$ is therefore limited by two factors: first by the total available forage not reserved for resting, $G_{avail}(t)$, and secondly, by the internal growth of the livestock flock $((b+1)\cdot S(t-1))$. It was assumed that livestock are sold at the age of seven years, indicated by $S_{old}(t)$. The age of the livestock was recorded within a simulation run. In equation 4, this relationship is formulated:

$$S(t) = Min((b+1)\cdot S(t-1) - S_{old}(t-1), G_{avail}(t)) \qquad (4)$$

Should the sale of the seven-years-old livestock be insufficient to adapt to the available forage, the animals of the preceding younger age class are sold next, until the livestock number is adequately adjusted. If the available forage $G_{avail}(t)$ exceeds the forage needed by the livestock, then the ungrazed paddocks are modelled as rested in year t (without any grazing pressure).

2.2.6. Management strategies

All the management strategies contrasted have in common the previously-described short-term adaptation to the available forage. They differ only as to whether and when additional resting is granted. The following four strategies were investigated: (1) No resting takes place ("without resting"). (2) In each year one third of the paddocks is rested ("always resting"), (3) In wet years one third of the paddocks is rested, whereas in dry years all paddocks are grazed ("resting in wet years"). (4) In dry years one third of the paddocks is rested, whereas in wet years all paddocks are grazed ("resting in dry years").

In order to distinguish between wet and dry years, a threshold had to be defined. For the first step, the median of the rainfall distribution was chosen. Consequently, years above the threshold (so called "wet years") occur equally often as years below the threshold (so called "dry years"). This allows the investigation concerning the appropriate time of resting to be made more easily, since the number of years with resting is the same for both strategies: fifty percent. In the present model, the paddocks with the lowest reserve biomass were always selected for resting first.

2.2.7. Objective functions

Sustainable land use is the criteria by which the different grazing strategies were assessed. The definition of sustainability that is most relevant for this purpose poses a point of discussion. Pickup and Stafford Smith, 1993) include in their definition such activities that maintain the long-term productivity of the vegetation whilst simultaneously providing sufficient financial and non-financial income for manager and employees. We follow this approach, because it reflects our objectives to consider both ecological and economic aspects with equal weight. The variable green biomass $G(t)$ is a poor indicator for the long-term quality for the vegetation. Current precipitation strongly influences available forage and, grazing reduces the current green biomass on the farm. The attribute reserve biomass $R(t)$ on the other hand more effectively reflects the long-term consequences of precipitation and grazing. Hence, this trait was chosen to assess the ecological condition of the farm. Revenue made by the farm is largely from the sale of lambskins and sheep wool. For both the ewes are integral and it was assumed that the income of the farmer is proportional to the number of livestock $S(t)$ kept on the farm. In this simple case, it was assumed that the farmer has no preferences in time. That means that current revenues have the same value as revenues in the future. Consequently, the two objective functions to be maximized are the mean reserve biomass $\overline{R}$, and the mean livestock number $\overline{S}$ where the average is taken over the time horizon T.

2.2.8. Simulation

The interaction of vegetation and grazing was simulated for a time horizon T of 100 years. First, 100 years of vegetation dynamics without grazing were run. This time span was used to minimize the influence of initial conditions of vegetation $R(0)$ on the dynamics. Due to the high level of abstraction, the parameters used in the model were not chosen to reflect exactly the real farm, but for providing a better understanding of underlying dynamics.

To work with a strongly simplified conceptual model, empirical parameter estimations of the ecological parameters, (as for instance for w_{eff} - the effective growth rate for a single abstract perennial vegetation type) are on principle hardly possible. To overcome this deficit, a sensitivity analysis was performed by varying the ecological parameters in plausible ranges and analysing the qualitative behaviour of the model. Default values of growth and decomposition rates of the vegetation were selected in such a way that mean growth rate of vegetation without density dependence and without grazing is slightly increasing ($w_{eff}=1.1$). The rainfall data on the Gamis Farm are used as default parameter values for mean and standard deviation of precipitation.

The default parameter-set is shown in Table 1. Where not mentioned to the contrary, this set is used during the following simulations.

- Table 1-

3. Results

3.1. To rest or not to rest

The first part of the study compares Strategy 1 ("without resting") and Strategy 2 ("always resting") in a fluctuating environment. Since in the underlying simplified model an explicit parameter determination is hardly feasible, in a sensitivity analysis the influence of the ecological parameters on the order of the strategies were investigated.

The effective growth rate of vegetation w_{eff} was found to heavily influence the dynamics. At first, the mean reserve biomass $\overline{R}$ was analysed in relation to w_{eff}, holding the rest of the parameters constant (Fig. 3). As expected, resting results in a higher $\overline{R}$ than not resting, for each value of w_{eff}. However, regarding the mean livestock number $\overline{S}$ three different stages are revealed (Fig. 4a). For low effective growth rate of vegetation w_{eff} (below 0.15), $\overline{S}$ is very low, i.e. the pasture is not capable of supporting livestock, regardless of the chosen strategy. When a high growth rate of the vegetation (w_{eff} above 0.34) is considered, $\overline{S}$ is higher without resting. Resting is dispensable since the recovery capacity is high enough to compensate grazing impacts. However, in an intermediate range of w_{eff}, resting leads to higher values of the economic objective criterion $\overline{S}$ than the strategy without resting. The relative difference between the adaptive Strategy 2 ("always resting") and the adaptive Strategy 1 ("without resting") is calculated by:

$$\frac{\bar{S}^{Strategy\,2} - \bar{S}^{Strategy\,1}}{\bar{S}^{Strategy\,1}}. \qquad (5)$$

With an effective growth rate of vegetation w_{eff} =0.2, about 25 percent more livestock can be supported by the farm when applying the strategy with resting (770 livestock) in comparison to the strategy without resting (616 livestock) (Fig. 4b). This difference is of high economic importance.

In the sensitivity analysis it was shown that an increase in *E(p)* (decrease in *m*) has the same effect as an increase in w_{eff}. The same holds to a certain extent by reducing the effect of density dependence, modelled by parameter *d*.

- Figure 3 –
- Figure 4a,b -

Beside the effective growth rate of vegetation w_{eff}, a second parameter turned out to be crucial: the harshness of grazing *c* represents the extent to which grazing influences the regeneration of the vegetation. Analyses not presented here, indicated that a variation of parameter *c* shifts the threshold in Fig. 4a, above which the strategy without resting becomes superior. In detail: Increasing *c* above 0.5 (low impact of grazing) shifts the threshold in Fig. 4a to the left. This implies that even at a lower value of w_{eff} the strategy without resting becomes superior. In contrast, dropping *c* below 0.5 (high impact of grazing) moves the threshold to the right. Hence, the strategy without resting becomes superior only for a higher value of w_{eff}. However, the qualitative behaviour of the dynamics does not change as the parameter *c*, the harshness of grazing, is varied.

3.2. Why resting in wet years?

The farmer on the Gamis-Farm applies a more sophisticated strategy than simply resting a third of the paddocks; instead he permits the rests only in years with sufficient rainfall. The simulation model was used to analyse the state of the vegetation under the two strategies “resting in wet years” and “resting in dry years”. The growth rate of livestock *b* was set at first to an extreme value of 3. This unrealistic parameter 3 lambs per sheep stands actually for the possibility to adapt livestock number without restriction to available biomass (equivalent to purchase). Surprisingly, regardless of the effective growth rate w_{eff}, the strategy to rest in wet years maintains the reserve biomass $\overline{R}$ at a higher level, compared to the strategy to rest in dry years (Fig. 5a). A small calculation, demonstrated in the following, explains the result. To make it simpler, the effect of density dependence *d* in equation 3 is ignored (*d*=0). Let us assume, a dry year, *t*=1, is followed by a wet year, *t*=2 ($p(1)<p(2)$). Applying resting in dry years, the first year *t*=1 is rested. In the second case, resting takes place in the second year. After two years, starting from the same initial reserve biomass *R*(0), the reserve biomass applying “resting in dry years” ($R^{dry}{}_{2}$) and “resting in wet years” ($R^{wet}{}_{2}$), respectively, can be expressed by:

$$R_{dry}(2) = ((1-m) + w_{eff} \cdot c \cdot p(2)) \cdot R_{dry}(1) \quad \text{with} \quad R_{dry}(1) = ((1-m) + w_{eff} \cdot p(1)) \cdot R(0) \tag{6}$$

$$R_{wet}(2) = ((1-m) + w_{eff} \cdot p(2)) \cdot R_{wet}(1) \quad \text{with} \quad R_{wet}(1) = ((1-m) + w_{eff} \cdot p(1) \cdot c) \cdot R(0) \tag{7}$$

After insertion of $R_{dry}(1)$ in $R_{dry}(2)$ and of $R_{wet}(1)$ in $R_{wet}(2)$, the difference $R_{wet}(2)$- $R_{dry}(2)$ is calculated. Since

$$R_{wet}(2) - R_{dry}(2) = (1-m) \cdot w_{eff} \cdot (1-c) \cdot R(0) \cdot (p(2) - p(1)) \tag{8}$$

it follows $R_{wet}(2) - R_{dry}(2) \geq 0$ since $0 \leq m \leq 1$, $0 \leq c \leq 1$, $R(0)>0$, $w_{eff}>0$ and $p(1)<p(2)$. Consequently $R_{wet}(2) \geq R_{dry}(2)$. This result holds too if the wet year appears first ($p(1)> p(2)$).

With respect to the mean livestock number $\overline{S}$, three different ranges of effective growth rate w_{eff} occurred, similar to the preceding analysis comparing the livestock number under resting and without resting (without figure). For a low effective growth rate w_{eff}, no livestock can be supported regardless of the chosen strategy. For high w_{eff}, the vegetation is able to buffer the impacts of grazing. Consequently, vegetation is not a limiting factor. Therefore, those of both strategies ("resting in wet years" and "resting in dry years") has to be selected, for which more livestock is held. This is "resting in dry years" - completely utilising the available forage during the highly productive wet years. However, in an intermediate range, "resting in wet years" leads to higher mean livestock number $\overline{S}$ than "resting in dry years".

- Figure 5a,b -

Apart from the growth rate of the vegetation w_{eff}, the reproductive rate of the livestock b strongly influences the dynamics. Setting b=0.8, resulted in the previously superior strategy of "resting in wet years" with respect to mean reserve biomass $\overline{R}$, to no longer be so, for all w_{eff} (Fig. 5b). This result stimulated a systematic investigation of the influence of the growth rate of the livestock b on the objective functions. The effective growth rate of vegetation w_{eff} was held at an intermediate level (w_{eff} =0.22). It appears that a critical value of the growth rate of livestock (b=1.1) exists above which "resting in wet years" is superior to "resting in dry years" with respect to mean reserve biomass $\overline{R}$ (Fig. 6). Below this threshold, the opposite is true.

- Figure 6, Figure 7 -

The mean livestock number $\overline{S}$ was determined for different growth rates of livestock *b* (Fig. 7). Regarding the "resting in dry years" strategy, the livestock number is higher when *b* is low than when *b* is high. The reason for this trend is that the condition of the pasture is crucial for $\overline{S}$. The same effect is apparent when both strategies are compared. For each value of *b*, a strategy is superior with respect to $\overline{S}$, whenever it is also superior with respect to the mean reserve biomass $\overline{R}$ (in case of *b* low: "resting in dry years", in case of *b* high: "resting in wet years").

4. Discussion and conclusion

4.1. Resting – relevant for non-equilibrium systems

This study contributes to the theoretical debate of the appropriateness of opportunistic strategies versus planned measures in human utilised (semi-) arid ecosystems. In the current literature, the recommendation for non-equilibrium systems is to adjust livestock numbers closely to available forage (Behnke Jr and Kerven, 1994). This is considered the most appropriate strategy to prevent degradation in a highly fluctuating environment. However, the analysis presented here supports the idea that there are no universally applicable grazing strategies, because particular context-specific conditions have to be taken into account (Scoones, 1994). It is shown that measures targeted for the long term, such as resting a part of the pasture, may also be relevant in non-equilibriums systems (in contrast to a statement made by Oba et al., 2000)). Admittedly, when vegetation is assumed to have a high reproductive potential (high effective growth rate of vegetation w_{eff} and small harshness of grazing (*c* high)), resting seems to be not necessary from an ecological point of view and is economically counter-productive. Nevertheless, under certain conditions (low effective growth rate of vegetation w_{eff} and high harshness of grazing (*c* low)), we hypothesis that grazing has a high impact and this strategy of "seizing opportunities when and where they existed" (Scoones, 1994, p. 9) does not allow the vegetation to recover sufficiently. Rest seems to be in need. In this case, our results indicate that resting accelerates improvements in range condition and allows a higher total stocking rate within a certain time period (Quirk, 2002).

4.2. The appropriate time of resting

The investigation of the appropriate time of resting (during wet years or dry years) with respect to the ecological and economic objective criterion (mean reserve biomass $\overline{R}$ and mean livestock number $\overline{S}$) has shown that no universally superior strategy exists. Two parameters of the system, the effective growth rate of vegetation w_{eff} and the growth rate of livestock b, are the key factors. Tables 2 and 3 represent the results of the qualitative influence of these two parameters. For each combination of the two parameters, the reason for the superiority of one of the two strategies will be carefully analysed in the following paragraphs.

4.2.1. Ecological objective criterion – mean reserve biomass

Assuming the growth rate of livestock b to be low (Table 2, column 1): After a drought and subsequent reduced livestock number, the available green biomass $G_{avail}(t)$ exceeds the required forage. Hence some paddocks are not used and effectively (unplanned) rested. These unplanned rests occur to a higher degree under "resting in dry years", as during the years of drought the stock numbers are reduced for two reasons: insufficient forage and the rule to rest a third of the paddocks. This "breath" for the vegetation in post-drought years leads to a better overall condition of the pasture. Therefore, in this case, "resting in dry years" is favourable with respect to the mean reserve biomass $\overline{R}$ (Table 2: r1/c1, r2/c1). For a further discussion of unplanned rests see below.

Assuming the growth rate of livestock *b* to be high (Table 2, column 2): After a drought, the increase in the livestock number is fast. Unplanned rests for the vegetation do not occur, regardless of the chosen grazing strategy. Consequently, both strategies have the same frequencies of resting (only planned resting) but differ in the time of resting. Counter to intuitive thinking that the vegetation has to be spared in years of drought, the model results reveal that the granting of rests during wet years is crucial for the regeneration of the pasture. In dry years, the vegetation barely benefits from resting. There is too little water available to build up new reserve biomass by photosynthesis. Hence, grazing in dry years seems to have little impact on vegetation (Sullivan and Rohde, 2002). In contrary, when resting is allowed in a wet year, the vegetation is able to exploit the higher amount of precipitation in photosynthesis to build up new reserve biomass. To summarize, the simultaneous incidence of a high amount of available water and resting is hypothesized to be crucial for vegetation regeneration.

This issue has seldom been explicitly investigated in the rangeland literature. Although Danckwerts and Stuart-Hill (1988) emphasise the importance of resting in post-drought years "to facilitate rapid recovery after a drought" (Danckwerts and Stuart-Hill, 1988, p. 218), they do not acknowledge the value of resting in wet years in general. More frequent investigations have been made into a similar aspect. Resting during the wet season of a year enables flowering, seed production, and biomass production (see Oba et al., 2000).

4.2.2. Economic objective criterion – mean livestock number

When assessing the economic objective criterion one has to bear in mind, which one of the two growth rates is low, and therefore limiting the dynamics (Table 3):

w_{eff} low (row 1): Here the livestock production is limited by the low regeneration potential of the reserve biomass $\overline{R}$. Hence, a strategy needs to be chosen that will allow higher mean livestock numbers $\overline{S}$, by being superior with regard to $\overline{R}$ (cf. Table 2) - in the case of low growth of livestock *b* "resting in dry years", in the case of high *b* "resting in wet years".

w_{eff} high, but *b* low (Table 3: r2/ c1): The low regeneration potential of the livestock is limiting. Management needs to focus on maintaining the minimal number of livestock as high as possible. Consequently, the strategy that encourages the smallest reduction of livestock numbers in dry years is superior. "Resting in wet years" is preferential, because in this case rested paddocks are disposable for forage in dry years.

No limiting parameters (w_{eff} high, *b* high) (Table 3: r2/ c2): The farmer chooses those strategies which enable the highest amount of livestock to be supported on the farm. The pasture should not be rested in a wet year but rather fully grazed with "resting in dry years" being more effective. Obviously, the best strategy would be to never rest.

The question arises as to the range of the parameters used for the Gamis-Farm (Tables 2 and 3). Considering the underlying arid climate, the effective growth rate of vegetation w_{eff} can be classified as low. However, long-term establishment is possible. Hence, resting is an essential part of the system. With b=0.8 (or 0.4 when considering only the females) the growth rate of the livestock on the farm is low. According to Tables 2 and 3 "resting in dry years" should be applied. This contradicts the strategy applied on the farm. However, the inclusion of additional drought-coping measures, like renting of pasture, changes the result. Renting leads to comparably high livestock pressure on the vegetation, evident in the first year following drought, and non-planned rests do not occur. Consequently, the Gamis-Farm is classified to have low vegetation growth but relatively high livestock growth and Tables 2 and 3 indicate “resting in wet years” to be an effective strategy.

- Table 2, Table 3 -

Thus, the farmer on the Gamis-Farm applies a flexible strategy, combining short-term adaptation of the stocking rate with measures targeted for the long term such as resting a third of the paddocks in years with sufficient rainfall. This strategy is able to maintain a more constant income when compared to an opportunistic strategy without resting. Hence, the negative consequences of highly unpredictable and variable environments can be avoided or lessened. These include transaction costs resulting from low livestock prices in times of drought in contrast to higher values in post-drought times (Campbell et al., 2000; Toulmin, 1994), as well as reduced transport availability and restricted livestock-markets.

It remains to be established, how large a farm needs to be for a part of the pasture to be rested, whilst sustaining a viable livelihood - a problem that applies particularly to communally-owned land in Africa.

The study has shown that not only economic measures seem to be able to buffer environmental variability (contrary to Behnke Jr and Kerven, 1994), but also the vegetation itself. Our results give hints to doubt the general assumption of Sandford, 1982), p. 67, that “nor overgrazing or undergrazing in one year affect, favourably or adversely, productivity… in subsequent years”. Maurer, 1995), referring to the study site Gamis-Farm, confirms that deficits of precipitation may be buffered by biomass reserves of preceding years. Here unplanned rests play a significant role.

4.3. Rest periods – the role of the farming system

Whether resting is carried out by planned or unplanned measures depends on the farming system. On commercial farms, this repose is obtained primarily through planned rotational resting. If subsistence farming is carried out, a differentiation has to be made between (a) application of de- and restocking strategies (by sale and purchase) tracking the climate and (b) climate induced die-off and slow recovery of the livestock for herders with limited access to livestock markets. In the second case, without the purchase of livestock, the regeneration of the reserve biomass is stimulated in post-drought years because of the slow increase of livestock. These non-planned rests are of high importance, as shown in the present study.

In the literature, however, the distinct ecological consequences of the two strategies are very rarely explicitly considered (although cf. Toulmin, 1994 and Briske et al., 2003). Both strategies ((a) de- and restocking and (b) die-off and slow recovery) are referred to as “opportunistic” (Behnke Jr et al., 1993; Sandford, 1982; Bartels et al., 1993). Sandford, 1994), p.175, terms the “de- and restocking strategy” even “efficient opportunism” without mentioning any ecological consequences. Toulmin, 1994) in contrast highlights the pros and cons of slow recovery of livestock numbers resulting from the second strategy. She mentions the need for a given time period for recovery from drought for certain ecosystems, yet acknowledges the social implications of the “waste of grazing resources“, if there is a prolonged absence of grazing. In particular, if farmers change from die-off and slow recovery of livestock to the “de- and restocking strategy”, for instance as a result of improved access to livestock markets, they need to be aware of the effects of discontinuing un-planned rests. The long-term consequences for the condition of the vegetation and for the number of livestock that can be held on the farm, must be explicitly considered. It stands to reason that this issue should also be kept in mind by political decisions makers.

Similar consequences occur when supplementary feeding is carried out (Illius and O'Connor, 1999). This measure has been prescribed by the New Rangeland Science as being suitable to cope with droughts (Scoones, 1994; Toulmin, 1994). However, the ecological consequences are not considered. Under this strategy, the stocking rate is held at a high level in dry years. Consequently, the vegetation receives no respite in post-drought years by non-planned resting. The blind support of supplementary feeding is therefore questionable. Only Briske et al., 2003) stresses the adverse impact of supplemental feeding and other management options on vegetation dynamics.

Final remark: this conceptual model depicts and examines a highly simplified representation of the real Gamis Farm. The model was shown to be suitable to deliver simple and plausible explanations for farmer’s behaviour observed on the Gamis Farm. Its application to concrete management support for other farms is limited due to high degree of abstraction. However, conceptual simplifications are essential for range management (Stafford Smith, 1996). By focusing only on the main characteristics of the dynamics, and through systematic analysis, valuable insights for basic principles regarding the value of resting in a fluctuating environment could be made. In taking this approach, a contribution to the present discussion surrounding the existing paradigms in rangeland science has been made.

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Table 1: Default parameter set of the simulation

Parameter	Abbreviation	Default value	Range for sensitivity analysis
Mean of precipitation	$E(p)$	1.2	0-2
Standard deviation of precipitation	$\sigma(p)$	0.7	-
Effective growth rate of vegetation	w_{eff}	0.22	0-0.4
Decomposition rate of reserve biomass	m	0.15	0.1-0.3
Growth rate of livestock	b	0.8	0-4
Initial total cover of reserve biomass	$R(0)$	4000	1000-8000
Harshness of grazing	c	0.5	0-1
Density dependence of reserve biomass	d	1/8000	1/15000 – 1/4000
Number of paddocks	n	60	-
Number of simulations	s	1000	-
Time horizon in years	T	100	-

Table 2: Efficiency of strategy „resting in wet years“ (wet) versus “resting in dry years“ (dry) with respect to mean reserve biomass $\overline{R}$

Objective: mean reserve biomass		
Growth rate livestock / Growth rate vegetation	low	high
low	dry	wet
high	dry	wet

Table 3: Efficiency of strategy „resting in wet years“ (wet) vs. “resting in dry years“ (dry) with respect to mean livestock number $\overline{S}$

Objective: mean livestock number		
Growth rate livestock / Growth rate vegetation	low	high
low	dry (reason: unplanned rests occur)	wet (reason: resting in rainy years more efficient for re-generation of vegetation)
high	wet (reason: decline of live-stock number in dry years is less)	dry (reason: higher stocking in rainy years is possible)

Figure legends:

Fig. 1: Schematic representation of the system and its components. Livestock and vegetation are closely connected. Precipitation affects biomass production and chosen grazing strategy.

Fig. 2: Model concept for vegetation dynamics: An idealised vegetation type is represented by two characteristics: green biomass and reserve biomass (for further details it is referred to the text). Livestock number is cut with respect to available green biomass. Grazing is assumed to directly influence green biomass only.

Fig. 3: Mean reserve biomass $\overline{R}$ over 100 years versus effective growth rate of vegetation w_{eff}, compared for the adaptive strategy with resting and the adaptive strategy without resting.

Fig. 4: (a) Mean livestock number $\overline{S}$ over 100 years versus effective growth rate of vegetation w_{eff}, compared for the adaptive strategy with resting and the adaptive strategy without resting. (b) Results of (a) represented as the relative difference in mean livestock number $\overline{S}$ (denoted in percent) resulting from the strategies - with and without resting.

Fig. 5: Mean reserve biomass $\overline{R}$ versus effective growth rate of vegetation w_{eff} comparing "resting in wet years" and "resting in dry years", (a) growth rate of livestock b=3, (b) growth rate of livestock b=0.8.

Fig. 6: (a) Mean reserve biomass $\overline{R}$ and (b) mean livestock number $\overline{S}$ for different growth rates of livestock b comparing "resting in wet years" and "resting in dry years", number of simulations s=4000.