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LEARNING FROM LOCAL KNOWLEDGE: MODELING THE PASTORAL-NOMADIC RANGE MANAGEMENT OF THE HIMBA, NAMIBIA

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Abstract. It is widely accepted that successful grazing management strategies in semiarid ecosystems need to be adapted to the highly temporal and spatially heterogeneous forage production. Nevertheless, a full understanding of the key factors and processes for sustainable adaptive management has yet to be reached. The investigation of existing, successful range management systems by simulation models may help to derive general understanding and basic principles.

The semi-nomadic Himba in northern Namibia applied a sophisticated management system until the mid-1990s which combined season-dependent pasture use (resulting in rainy-season pastures and dry-season pastures), preservation of reserves for drought and sanctions for rule breaking. A stochastic ecological simulation model has been developed here which represents the main aspects of this management system. With this model we analyze (1) which components of the traditional Himba strategy are essential for sustainability and (2) what happens to the state of the rangeland system under socioeconomic changes.

This study shows that temporally and spatially heterogeneous pasture use yields higher productivity and quality of a pasture area than the pressure of homogeneous permanent grazing. Two aspects are of importance: (1) intra-annual heterogeneous use (resting of the dry-season pastures during the rainy season) and (2) interannual heterogeneous use (spatial extension of grazing in years of drought). This management system leads to an effective build-up and use of a buffer in the system: the reserve biomass (the non-photosynthetic reserve organs of the plants), an indicator for grazing and management history.

Analyzing purchase as one form of socioeconomic change, we demonstrate that easier market access to purchase livestock may lead to a decline in vegetation quality. However, cattle production increases as long as rest periods on parts of the pasture during the rainy season are granted.

Methodologically, we emphasize that simulation models offer an excellent framework for analyzing and depicting basic principles in sustainable range management derived from local knowledge. They provide the opportunity of testing whether these basic principles are also valid under different ecological and socioeconomic settings.

Key words: indigeneous people; livestock grazing; non-equilibrium system; pastoralism; rangeland degradation; reserves for drought; resting strategy; semiarid savanna; simulation model; spatial and temporal heterogeneity; traditional ecological knowledge.

Introduction

The livelihood of a vast majority of people in (semi-)arid regions depends on livestock farming. Hence, the loss of productive land poses an existential problem in these regions.

The mechanisms of land degradation are still being controversially discussed. An equilibrium view dominated until the beginning of the 1990s. It was assumed that rangeland systems reach an equilibrium state primarily determined by biotic factors, with grazing being the main driving force for vegetation change (Lamprey 1983, Dean and MacDonald 1994). Since the mid-1990s, highly variable and unpredictable rainfall was seen to be the major driving force at least in "arid" rangelands with a rainfall variability higher than 30%. Thus variability in abiotic conditions would be the key determinant, and biotic factors such as grazing pressure would have only marginal influence on vegetation dynamics (Westoby et al. 1989, Behnke et al. 1993, Sandford 1994, Scoones 1994).

This non-equilibrium concept has been vividly discussed by ecologists over the past years (Cowling 2000). One of its main tenets, i.e., that herbivores have minimal impact on vegetation or production, was questioned (Sander et al. 1998, Illius and O'Connor 1999). It is argued that strong equilibrial forces may act over a limited part of the system. For example, "key resources" such as dry-season ranges, where water is also available during dry seasons, enables heavier use of wet-season ranges. As a consequence, animal numbers and available

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fodder on wet-season ranges may become uncoupled, especially during droughts. Recent attempts which consider both biotic and abiotic factors to be essential for vegetation dynamics on different temporal and spatial scales appear to be the most promising (Illius and O'Connor 1999, 2000, Fuhlendorf and Engle 2001, Briske et al. 2003, Vetter 2005). However, a full understanding of the underlying key aspects and processes for sustainable range management has not yet been reached and hence the debate continues (cf. Fynn and O'Connor 2000, Sullivan and Rohde 2002).

These shortcomings can be overcome by analyzing successful range management systems in semiarid ecosystems. For instance, pastoral nomads in different parts of the world have developed sophisticated strategies adapted to the temporal and spatial heterogeneity of fodder production (Galaty and Johnson 1990, Fratkin 1997, Bollig and Schulte 1999, Niamir-Fuller 2000). Only a few studies emphasize the merit of analyzing this local knowledge with respect to range management (e.g., Fernandez-Gimenez 2000, Griffin 2002). It consists of biophysical observations, skills, technologies as well as norms and institutions (Fernandez-Gimenez 2000). The transfer of local knowledge to global scientific knowledge may help to find basic principles. These principles could be, under certain conditions, applicable to other range management systems with different ecological and economic settings.

In this study, the range management system of a Himba community in Namibia is taken as the starting point for the analysis of a "good practice" example. Up to the mid-1990s, the Himba herders had maintained a successful land use system. It was based on joint management of the communal goods "pasture" and "water" and included a season-dependent pasture use and the preservation of reserves for drought. Rule breaking was sanctioned within a community (Bollig 1997, Schulte 2002*a*). Before Namibia's independence in 1990, they were subsistence herders because livestock trade was prohibited under colonial rule (Bollig 1998). Like most of the transhumant management systems in general (Niamir-Fuller and Turner 1999) the political and socioeconomic circumstances for the Himba people have recently changed. Their management system is affected by numerous changes due to internal and external factors that interact with each other (population and livestock growth, increasing installation of boreholes for water, installation of infrastructure permitting sale and purchase of livestock, changing institutions). Today, it is crucial to understand (1) which components of the traditional management system of the Himba are essential for sustainable land use and (2) what happens to the state of the rangeland system under socioeconomic changes. Concerning the second question, we focus here on the economic and ecological consequences of a easier market access and consequently the Himba's increased interest in purchasing livestock. To answer these questions, a thorough understanding of the dynamics and of the crucial features of a successful land management system is needed, and a transfer of these features to other range management systems should render meaningful results.

Simulation models offer a promising approach to tackle these questions. They are most often the only possibility to investigate the long-term dynamics of range management systems in arid ecosystems, because their impact becomes visible only after decades (Wissel et al. 1996, Jeltsch et al. 2001). In numerous studies, the spatially and temporally heterogeneous response of vegetation dynamics to grazing and precipitation is investigated with the aid of modeling (Pickup 1996, Wiegand and Milton 1996, Jeltsch et al. 1997, Illius et al. 1998, Janssen et al. 2000, Weber et al. 2000, Adler et al. 2001, van de Koppel et al. 2002, Pütz 2005, Müller et al. 2007). However the few modeling studies of mobile management systems of pastoral nomads are mainly focused on socioeconomic issues (Rouchier et al. 2001, Kuper et al. 2003, Thornton et al. 2003, 2006, Milner-Gulland et al. 2006) and not on the impact on vegetation (as exception Coughenour 1992, Illius and O'Connor 2000, Galvin et al. 2006). Recently some studies have used simulation models to study the effects of changes in management actions of pastoralists on the ecosystem. Boone et al. (2002) investigate alternative management options, as improved veterinary health and use of prior excluded areas, on a multiple-use area utilized by the Maasai in Tanzania. In Boone (2005) a simulation model is applied to quantify the effects of land subdivision and sedentarization on vegetation traits in South Africa and Kenya. Retzer and Reudenbach (2005) developed a dynamic model simulating forage competition between rodents and livestock in the Mongolian South Gobi, explicitly including herders' migration strategies.

In the current study, a spatially implicit ecological model is used to investigate the range management system of one settlement of Himba herders including its pastures. The long-term impact of the grazing regime under stochastic rainfall on the two primary sources of fodder annual and perennial grasses is investigated.

First, we give an introduction to the ecosystem and management system of the Himba. Secondly we present the spatially implicit model with its model rules. We then analyze the consequences of the traditional grazing strategy on vegetation and livestock dynamics over the long term. Following, the traditional strategy is compared (1) to alternative strategies where parts of the traditional one have been altered and (2) to strategies including purchase of livestock. Using global sensitivity analysis, we investigate whether our results hold true for different ecological and economic conditions.

Methods

Study area

The northern Kunene Region (former Kaokoland) is situated in the northwestern part of Namibia and covers an area of about 50 000 km^2. Mean annual precipitation

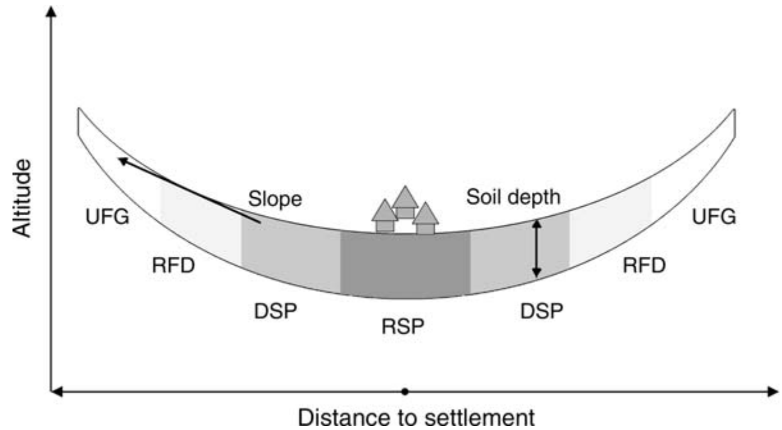

FIG. 1. Schematic characterization of pasture types in the northern Kunene Region of Namibia including distance to settlement, altitude, slope, and soil depth of pasture types RSP (rainy-season pasture), DSP (dry-season pasture), RFD (reserves for drought), and UFG (area unsuitable for grazing). The shading indicates the intensity of pasture use (dark, heavy use; white, no use). Note that this sketch does not give accurate, to-scale values for any of the four traits or for the area covered by pasture.

ranges between 50 mm/yr in the far west and 380 mm/yr in the east. The study site in the northern Kunene Region (around Omuramba North) receives about 280 mm/yr and has rainfall variability higher than 30% (Schulte 2002*b*). The rainy season starts in November/December and lasts until March/April (Sander and Becker 2002). The geomorphology of this landscape is quite heterogeneous due to small-scale differences in topography and geology. The vegetation can be characterized as savanna woodland or, more precisely, as Mopane savanna (cf. Giess 1998). This vegetation type has a closed herbaceous layer and an open woody layer with cover values between 2% and 15%, dominated by the species *Colophospermum mopane* (Schulte 2002*b*). The colonial encapsulation (Bollig 1997) until 1990 forced the Himba to employ subsistence living without permission to trade livestock.

Since probably the 18th century, the land has been grazed by large herds of domestic livestock (Bollig and Vogelsang 2002), while evidence of early pastoral foraging dates back some 2000 years (Vogelsang 2002). Until now, semi-nomadic Himba herders have earned their living by keeping cattle and small stock.

The Himba people have always applied a mobile management system adapted to highly unpredictable rainfall and patchy resource distribution. However, due to changing internal and external conditions their grazing regimes seem to always have a limited lifespan. The following strategy was applied from the sixties to the mid-1990s. The grazing regime comprised of a season-dependent use of the pasture. During the rainy season, the pastures (RSP) around the households (onganda) were grazed. These areas were often characterized by deep soils since households were situated near ephemeral rivers (Fig. 1). During the dry season, only lactating animals were kept in the neighborhood. The main part of the herd was moved to cattle camps situated in dry-season pastures (DSP) at a distance of at least 2 km to the households. These areas were characterized by permanent water sources such as boreholes, in comparison to temporal water sources in the rainy-season pastures (Behnke 1999). Because the dry-season pastures were situated further away from the ephemeral rivers, they were mainly characterized by shallow soils (Sander and Becker 2002, Schulte 2002*b*). During the rainy season, these areas were not allowed to be grazed by livestock. At the onset of the dry season, herdsmen from different households made arrangements in order to move to neighboring cattle camps at the same time. In this fashion, negative impact from trampling could be minimized. To cope with years of very low rainfall and fodder production, reserves for drought (RFD) were held back. These areas were difficult to access and/or had a greater distance to the water sources. Herdsmen were only allowed to use these pastures under emergency conditions in times of drought. For a more detailed description of this complex management system, refer to Bollig (2002) and Behnke (1999). We refer to this as the "traditional strategy."

The deep soils on rainy-season pastures maintained a higher productivity than the shallow soils on dry-season pastures or on reserves for drought (cf. Schulte 2002*a*). Due to the heavy impact of grazing throughout the year, rainy-season pastures were dominated exclusively by annual grasses and herbs (of partly low grazing value). Dry-season pastures were mainly covered by annual grasses such as *Schmidtia kalahariensis*. The resting of these areas during the rainy season avoided early disturbance during the growing period of the grasses. However, intensive grazing has changed natural species composition and abundance. Without livestock grazing, a dominance of perennial grasses, mainly *Stipagrostis uniplumis*, was shown by the grazing exclosures on both rainy and dry-season pastures (Schulte 2002*b*). Today, perennial grasses have cover values generally lower than 5% (Schulte 2002*b*). In contrast, the human impact was

TABLE 1. The full set of state variables in the model.

Measure	Description	Variable	Units
Precipitation	amount per year	$r(t)$	four classes
Habitat	soil type of cell i	st_i	three types (deep, shallow, unsuitable)
Vegetation			
Grass layer (1): fodder production	green biomass per cell i	$b_i^{\mathrm{per}}(t), b_i^{\mathrm{ann}}(t)$	Mg/ha
Grass layer (2): reserve biomass of perennial grasses	perennial ground cover per cell i	$c_i(t)$	four classes (%)
Grass layer (3): status of soil seed bank	depletion level of soil seed bank per cell i	$\mathrm{sb}_i^{\mathrm{per}}(t)$, $\mathrm{sb}_i^{\mathrm{ann}}(t)$	$0, 1, \ldots, \mathrm{sl}_{\mathrm{per}}$ $0, 1, \ldots, \mathrm{sl}_{\mathrm{ann}}$
Pasture (four types)	available biomass for livestock; required biomass for livestock	$b_{\mathrm{av}}^{\mathrm{past}}(t), b_{\mathrm{req}}^{\mathrm{past}}(t)$	Mg
Management	traditional strategy, alternative strategy	T, A1, A2, A3	four types
Management	purchase	oP, P1, P2	three types
Livestock	number of animals, number of purchased animals	$n(t)$, $n_{\mathrm{purch}}(t)$	number, in TLU

Note: Abbreviations are TLU, tropical livestock unit; $\mathrm{sl}_{\mathrm{ann}}$ and $\mathrm{sl}_{\mathrm{per}}$, longevity of the annual/perennial seed bank.

less detectable on reserves for drought. The proportion of perennial grasses was higher, unless it was inhibited by a soil that is too shallow. Bush encroachment in the heavily used pastures did not take place, because shrub and tree density was limited by woodcutting and browsing by small livestock.

Recently the system has changed, because of internal and external forces. For instance, forced resettlement by the South African government to the Omuhonga Basin in the 1970s (cf. Bollig 1997) led to severe signs of degradation in this region (Sander et al. 1998, Welle 2003). The population and livestock numbers increased as a result of an improved health system and an ongoing installation of new boreholes. Hence reserves for drought were not maintained. On former dry-season pastures new households were established, because of new income possibilities from tourist camps situated nearby. Arrangements between herdsmen become less binding.

Further changes in the management regime will result from the ongoing installation of infrastructure for the sale of livestock. Although the Himba could, to a certain extent, purchase livestock previously, it will become increasingly more interesting in the future due to the improved possibilities for selling livestock.

Model

The model description follows the ODD protocol for describing individual respectively agent-based models (Grimm and Railsback 2005, Grimm et al. 2006). The first three elements of the description provide an overview and the remaining elements give details on the model structure.

Purpose.—The model was developed to analyze the ecological and economic implications of the traditional range management practiced by the pastoral-nomadic Himba. In particular, we ask which components of the traditional management regime are essential for sustainability and should be maintained under changing socioeconomic circumstances.

Structure and scales.—The model is based on central rules of the traditional range management and on the consequences of cattle grazing for pasture productivity. The area modeled is the pasture utilized by the user group of the village Omuramba in the northwestern Kunene Region with an area of 40 × 40 km. Other households, existing in the area, are not modeled separately. The area under investigation is represented by a grid of 6400 cells with a cell size of 25 ha.

A habitat cell is characterized by its soil type and vegetation state (Table 1). Three soil types are distinguished: (1) deep soil, (2) shallow soil, and (3) unsuitable soil. To describe the vegetation state, two functional components of the grass layer are differentiated: first, annual grasses and forbs, and second, perennial grasses. Both annual and perennial grasses are characterized by the amount of palatable "green biomass" produced within a particular vegetation period, which serves as forage for livestock. The perennials are additionally characterized by their reserve biomass (termed after Noy-Meir 1982). This characteristic is measured via the ground cover of perennial grasses and represents vegetation vitality and, hence, the rain and grazing management history (O'Connor 1991). Finally, both plant functional types have a status of the soil seed bank for each grid cell.

The livestock is modeled as a herd which is characterized by its size. The grazing management strategy maintained during the whole modeled time span is indicated by two components: (1) the time of pasture use (all year round; only in dry season; no use) and (2) to which extent purchase of livestock is allowed.

Pastures are characterized by a fixed proportion of habitat cells with the same soil type. In this spatially implicit model, the location of the cell on the grid is not considered. In each cell of a pasture, the same grazing strategy is applied. Four pasture types are differentiated: rainy-season pasture (RSP), dry-season pasture (DSP), reserve for drought (RFD), and area unsuitable for

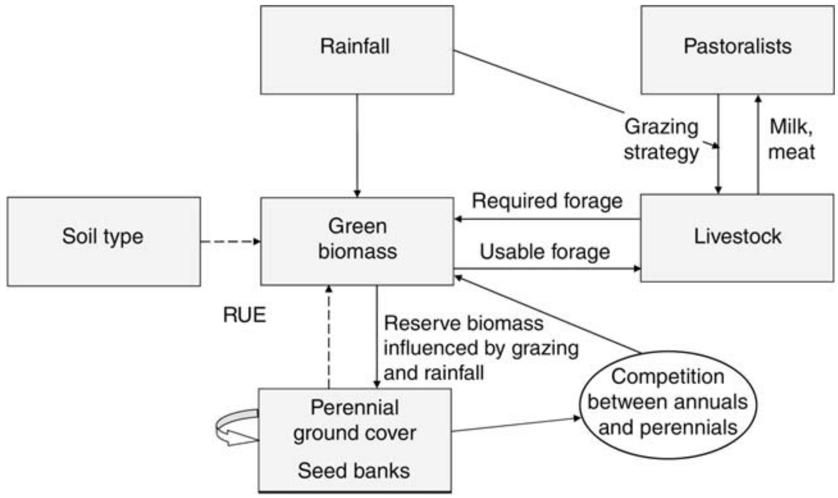

FIG. 2. Causal diagram indicating the influential factors on vegetation and livestock dynamics in the model. Current rainfall is translated into green biomass according to the rain use efficiency (RUE). This parameter depends, in this study, on soil type, perennial ground cover, and longevity of the two seed banks. The perennial ground cover is affected in reality by current rainfall and grazing only indirectly via photosynthesis of green biomass. For simplification, this relationship is mapped directly into the model rule (cf. Table 7).

grazing (UFG). RSP consists of cells with deep soil. DSP, RFD, and UFG consist of cells with shallow soil. One time step represents one year, starting in November with the onset of the rainy season. In reality, the traditional grazing strategy presented was only applied for up to 40 years. Hence, it cannot be judged whether this strategy was sustainable. The modeled time span was chosen to be longer than the planning horizon of the pastoralists and on a scale in which grazing impact on the vegetation is visible. Hence, a time span of 100 years is modeled after the onset of grazing.

Process overview and scheduling.—Here, the processes of the model are briefly specified to allow a general overview of the model and the dynamics. For a detailed description of each of the processes, see *Sub-models*. The processes are presented according to their sequence within one time step. For the causal relations between the processes, see also Fig. 2.

Process 1: Rainfall. The precipitation $r(t)$ in each rainy season is randomly chosen according to the underlying rainfall distribution.

Process 2: Production of green biomass (i.e., usable forage). The green biomass of the annual and perennial grasses is determined by three factors: precipitation, soil type, and in the case of perennials its previous ground cover (cf. Fig. 2). For perennials, the impact of grazing on green biomass production is modeled indirectly via the ground cover (see Process 4). This characteristic determines to which extent rainfall can be used to produce green biomass (reflected in the parameter rain use efficiency [RUE]). For annuals, grazing affects green biomass indirectly via the seed bank status. First, biomass growth of perennial grasses is modeled. Annual grasses produce biomass according to the space left by perennial grass tufts, and according to precipitation and seed bank status.

Process 3: Livestock demographics and grazing strategy. Livestock demographics dependent upon the availability of usable forage and the grazing strategy are modeled; a constant birth rate is assumed. The ratio between available and required biomass determines the grazing pressure. If available biomass is insufficient on a pasture, the next pastures are used earlier. If the total available forage is insufficient, a certain percentage of animals die or are sold or hired out to relatives.

Process 4: Feedback of grazing and rainfall on perennial ground cover (reserve biomass). At the end of a time step the perennial ground cover is adjusted. Perennial ground cover is classified into four states: no, low, middle, high. The perennial ground cover depends on (1) current rainfall, (2) grazing pressure, (3) time of grazing (in dry season or all year round), and (4) perennial ground cover of the previous year. Finally, the degree of seed bank depletion per cell is adjusted.

Initialization.—The proportions of the pasture types with different soil properties correspond to the pastures of the households of the village Omuramba: rainy-season pasture, 10%; dry-season pasture, 45%; reserves for drought, 18%; and the rest, 27%, is unsuitable for grazing. The perennial ground cover of all cells was set to "middle." In order to minimize the effect of the initial conditions, 40 years without grazing have been simulated. Afterward, the livestock number was initialized according to the available forage.

Sub-models.—

1. *Rainfall*.—The highly stochastic precipitation is modeled using four classes (drought, below average, average, above average). The mean annual rainfall of Omuramba (r_{mean}) is about 280 mm/yr. As no sufficient

TABLE 2. Rainfall classes used in the model and underlying frequency distribution of rainfall derived from the data set of Ambalantu.

Class	Description	Range	Rain values	Frequency (%)
−2	drought	$r(t) < 0.5r_{mean}$	$0.25r_{mean}$	12
−1	below average	$0.5r_{mean} \leq r(t) < 0.75r_{mean}$	$0.625r_{mean}$	16
0	average	$0.75r_{mean} \leq r(t) < 1.25r_{mean}$	r_{mean}	43
1	above average	$1.25r_{mean} \leq r(t)$	$1.375r_{mean}$	29

Notes: Classification is based on unpublished data from the Weather Bureau Windhock, Namibia. For more details on rain frequency in the Kunene Region, see Sander and Becker (2002:63).

data are available on the variability of rainfall at Omuramba, the frequency distribution of the rainfall classes is taken from Ombulantu, a site 200 km to the east. The mid-point of the class is used as the rain value associated with each class (Table 2, column 4).

2. *Growth of green biomass.*—In this area, the woody layer is not seen as an important fodder source for cattle both from a local and a scientific point of view. First, woody shrubs and bushes are rare, in particular in the plain pastures which are mainly used by cattle (Schulte 2002*a*). Moreover, the leaves of the highly dominant tree species *Colophospermum mopane* are characterized by a high content of tannins and are therefore barely palatable. Interviews with Himba herdsmen in the Omuramba basin have shown that woody species are not regarded as being an important fodder source for cattle (Bollig and Schulte 1999).

Hence, only the grass layer is included in the model. For the grass layer we assume a linear relationship between biomass and precipitation with the intercept equaling zero (Lauenroth and Sala 1992, O'Connor et al. 2001). The slope of this function represents the rain use efficiency (RUE) measured in $\text{Mg}\cdot\text{ha}^{-1}\cdot\text{mm}^{-1}$ (cf. Eqs. 1 and 2). In our model, the parameter RUE depends on soil type for annual grasses and both this and ground cover $c(t)$ for perennials (see Table 3). The values for annual grasses are based on empirical data of *Schmidtia kalahariensis* (A. Linstädter, *unpublished data*). For perennial grasses, expert knowledge and specifications found in the literature are used (Le Houérou et al. 1988:1, Le Houérou 1984:221). The applied classification of perennial cover $c(t)$ depends on the soil type (Table 4).

It is assumed that no green biomass is taken over from the previous year, thus natural decay is implicitly included in the model.

TABLE 3. Rain use efficiencies (RUE, $\text{Mg}\cdot\text{ha}^{-1}\cdot\text{mm}^{-1}$) for perennial and annual grasses dependent on soil type and ground cover $c(t)$ in time step t (in the case of perennials).

Soil type	Perennials				Annuals
	$c(t) = 0$	$c(t) = 1$	$c(t) = 2$	$c(t) = 3$	
Deep	0	3	4	4.8	2.78
Shallow	0	1.5	2	2.4	1.35

The green biomass of perennials at time t is calculated by

$$b_i^{\text{per}}(t) = \text{RUE}[(\text{st}_i, c_i(t)] \times r(t) \qquad (1)$$

and the green biomass of annuals at time t by

$$b_i^{\text{ann}}(t) = \text{RUE}(\text{st}_i) \times r(t) \qquad (2)$$

for all cells i, $i = 1, \ldots, 1600$. The current perennial ground cover on i is $c_i(t)$ and st_i soil type.

The interspecific competition between annual and perennial grasses is modeled implicitly. It is assumed that perennial grasses out-compete the annuals, since they occupy the available space first. Hence annuals may only occupy the space left by perennials. We assume that green biomass has an upper limit due to restricted abiotic resources such as water, nutrients, and sunlight. If the sum of annual and perennial grass biomass exceeds this limit, the biomass of the annuals is correspondingly diminished. The limit is assumed to be $\text{cap}_{\text{dp}}\pm = 1.5$ Mg/ha on deep soil and $\text{cap}_{\text{sh}} = 1$ Mg/ha on shallow soil (Schulte 2002*b*).

For annuals holds, if the seed bank is empty on a grid cell, no green biomass is produced.

3. *Palatable biomass.*—Only a portion of the whole green biomass serves as forage. The causes are: grazing efficiency (the proportion of total herbage livestock can harvest) and forage loss (due to trampling, decomposition, and so on). In the literature, often the proper use factor pf is used to cover all three aspects. Proposed values for pf range from 0.25 to 0.5 (0.45 [de Leeuw and Tothill 1993], 0.25–0.3 [Guevara et al. 1996:350], 0.5 [Le Houérou 1984:233], 0.25–0.3 [Le Houérou 1989:110]). We first use $\text{pf}_{\text{per}} = \text{pf}_{\text{ann}} = 0.45$ in the model, not distinguishing

TABLE 4. Classification of perennial ground cover $c(t)$ (%) for deep and shallow soils.

Cover class	$c(t)$	Ground cover (%)	
		Deep soil	Shallow soil
No	0	0	0
Low	1	1–30	1–15
Middle	2	31–60	16–30
High	3	61–90	31–45

Notes: For shallow soil, the perennial ground cover is assumed to be half of the range of the deep soil. A perennial ground cover higher than 90% does not occur under natural circumstances.

TABLE 5. Overview of the four compared strategies (T, A1, A2, and A3).

Grazing strategy used	Traditional strategy	Alternative strategy		
	T	A1	A2	A3
Seasonal resting	yes	no	no	yes
Spatial extension				
DSP	yes	no	no	no
RFD	yes	yes	no	no

Note: Key to abbreviations: DSP, dry-season pastures; RFD, reserves for drought.

between annuals and perennials. However, later on in the study, the influence of different grazing values for annuals and perennials on the assessment of the grazing strategies is investigated by a sensitivity analysis.

In a next step, the available palatable biomass $b_{\text{av}}^{\text{past}}$, where past = RSP, DSP, RFD, is calculated by summing up the green biomass of annuals (b_i^{ann}) and perennials (b_i^{per}) on all cells i belonging to pasture past:

$$b_{\text{av}}^{\text{past}} = \sum_{i \in \text{past}} b_i^{\text{per}} \times \text{pf}_{\text{per}} + b_i^{\text{ann}} \times \text{pf}_{\text{ann}}. \quad (3)$$

4. *Demographics of livestock*.—Only cattle demographics (no small livestock) are included in the model analysis. Calving rates are 0.4 per year and cow (Bollig 2000). Since just under 50% of the livestock are females, a total constant cattle growth rate of $g_c = 0.2$ is used (Bollig and Schulte 1999). A decrease in livestock numbers is caused either by drought-induced mortality, by slaughtering for meat consumption, or by hiring out to relatives. All these processes are summarized and modeled by a constant mortality rate $\text{prob}_{\text{mort}}$. The next section provides a detailed description of the circumstances under which mortality takes place in the model.

5. *Grazing strategy*.—The grazing strategy applied from 1960 to 1995 (traditional strategy) is compared to three alternative strategies. The three alternative strategies are constructed in such a way so that, in each case, a certain aspect of the traditional strategy is altered. Therefore, let us look first at the characteristics of the traditional strategy, T.

1) Seasonal resting on dry-season pastures:

a) Use of rainy-season pastures (RSP) by the whole herd in the rainy season, by lactating animals in the dry season (portion of lactating animals: $p_l = 0.2$ of the herd [Bollig and Schulte 1999:85]).

b) Resting of dry-season pastures (DSP) in the rainy season, grazing in the dry season by non-lactating animals (if the forage is insufficient on RSP, then DSP1 is already used in the rainy season).

2) Spatial extension:

a) DSP is divided into three parts (DSP1, DSP2, DSP3), with use of DSP2 and DSP3 only if DSP 1 (or DSP2, respectively) is used up; otherwise these pastures are rested for the whole year.

b) Reserves for drought (RFD) are used only if all DSP are used up; otherwise they are rested the whole year.

In applying alternative strategies A1 and A2, seasonal resting for DSP is dropped and RSP and DSP are used all year round. RFD are retained with A1, but not with A2. Alternative strategy A3 maintains seasonal resting of DSP and RFD, but involves a complete utilization of the total pasture in each year (cf. Table 5 for a short overview of the four strategies).

The explicit translation of these different management strategies into model rules is made by some intermediate steps, which are briefly mentioned (for details, see Appendix A). First, the biomass required to feed the entire herd $b_{\text{req}}^{\text{past}}(t)$ is calculated for each pasture. Next, the grazing pressure $\text{gp}^{\text{past}}(t)$ per pasture is classified by calculating the ratio of available to required biomass and compared to a threshold th_1. The grazing pressure $\text{gp}^{\text{past}}(t)$ may take three values: no grazing pressure, moderate, or heavy. If grazing pressure is too high (higher than threshold th_2), cattle are moved from RSP to DSP or DSP to RFD or die with a probability of $\text{prob}_{\text{mort}}$ (see Table 6).

Alternative scenarios are modeled, whereby purchase of livestock is part of the management strategy. Two purchase strategies are compared to the strategy without purchase (oP): (P1) purchase, but without using the reserves for drought, and (P2) purchase, using the reserves for drought.

The number of animals purchased is determined according to the following rule: Animals are purchased as long as the mean grazing pressure on the total used pasture remains moderate.

6. *Ground cover of perennials*.—The ground cover of the perennial grasses $c(t)$ depends on four factors: current precipitation, grazing pressure, time of grazing (only in dry season or all year round), and perennial ground cover of the previous year $c(t-1)$ (cf. Fig. 2). In Table 7, the dynamics of $c(t)$ in dependence on these four factors is listed. The dynamics are assumed to be the same for deep and shallow soil. The values originate from either empirical investigation (A. Linstädter, *unpublished data*) or from expert knowledge. For a detailed justification of the values for each single case, see Appendix B.

7. *Seed bank dynamics*.—We assume that the seed bank of perennials decreases either by germination or by

TABLE 6. In the event that the available biomass is insufficient, and hence the quotient of available and required biomass does not reach a threshold, the corresponding action is indicated for each pasture.

Biomass insufficient on:	Action
Rainy-season pasture	early movement to DSP1
Dry-season pasture 1 (DSP1)	use of DSP2
Dry-season pasture 2 (DSP2)	use of DSP3
Dry-season pasture 3 (DSP3)	use of reserve for drought
Reserves for drought	dying/sale/renting of livestock

TABLE 7. Adjustment of perennial ground cover $c(t)$ for each cell at time t, dependent upon previous ground cover states (0, 1, 2, 3), $c(t-1)$, current precipitation, and grazing pressure (including time of grazing).

Condition	Ground cover: No grazing pressure				Moderate grazing pressure				Heavy grazing pressure			
Previous ground cover	0	1	2	3	0	1	2	3	0	1	2	3
Grazing in rainy season and dry season												
Above average precipitation	1	2	3	3	1	1	2	2	0	1	1	1
Average precipitation	1	1	2	3	0	0	1	1	0	0	1	1
Below average precipitation	0	1	2	3	0	0	1	1	0	0	0	0
Drought	0	0	1	2	0	0	0	1	0	0	0	0
Grazing in dry season only												
Above average precipitation	1	2	3	3	1	2	2	3	1	1	2	3
Average precipitation	1	1	2	3	0	1	2	3	0	1	1	2
Below average precipitation	0	1	2	3	0	0	1	2	0	0	1	1
Drought	0	0	1	2	0	0	1	2	0	0	0	1

Note: Five levels are differentiated (no grazing, grazing the whole year [moderate or heavy], and grazing only during dry season [moderate or heavy]).

the natural decay of seeds. Replenishment from inside the habitat cell i can only take place if $c(t) > 0$ in cell i. If $c(t) = 0$, a counter, reflecting the depletion of the seed bank in cell i, is incremented by one. If the counter passes a certain threshold sl_{per}, the seed bank of the cell is assumed to be empty. Only if the seed bank is not empty (counter $< sl_{per}$) and rainfall is high enough, may $c(t)$ may rise from class 0 to class 1 (cf. Table 7). In this case, the seed bank is assumed to be refilled and the counter is reset to zero. The dynamics of the seed bank for the annuals are modeled in a corresponding manner. But here, the seed bank only decreases under simultaneous high grazing pressure and low rainfall. However, one year with at least average rainfall or only moderate grazing pressure resets the counter to zero. This means that the seed bank is refilled. Once again, if the counter passes a certain threshold sl_{ann}, the seed bank is assumed to be empty for that cell.

Recolonization of previously empty cells is modeled in a very simple manner. Whenever one cell exists somewhere on the grid, where the perennials/annuals are not extinct, each empty cell may be recolonized with a certain probability $prob^{ent}_{per}$, $prob^{ent}_{ann}$ for both plant functional types respectively in years with at least average rainfall.

8. *Parameter set*.—Table 8 shows the names of all parameters of the model, their values and their ranges in the sensitivity analysis.

Computer experiments: sensitivity analysis.—The model results may depend on the chosen parameter set. For this reason, most of the parameters listed in Table 8 were varied in a suitable range (cf. Table 8, column 4). Using Latin hypercube sampling, 200

TABLE 8. List of parameters, default parameter set, and parameter ranges for sensitivity analysis

Parameter	Abbreviation	Value	Parameter range or value for sensitivity analysis
Total pasture size (km^2)		1600	1600
Portion of RSP	a^{RSP}	0.10	0–0.55
Portion of DSP	a^{DSP}	0.45	0–0.55
Portion of RFD	a^{RFD}	0.18	0–0.55
Portion of UFG	a^{UFG}	0.27	0.27
Recolonization probability for annuals	$prob^{ent}_{ann}$	0.5	0–1
Recolonization probability for perennials	$prob^{ent}_{per}$	0.5	0–1
Seed bank longevity of the annuals (yr)	sl_{ann}	10	1–10
Seed bank longevity of the perennials (yr)	sl_{per}	10	1–10
Threshold 1 (respective ratio between available and required biomass)	th_1	1.5	0.5–3
Threshold 2 (respective ratio between available and required biomass)	th_2	0.9	$0.75th_1$
Dry matter intake (Mg/TLU and yr)	d	2.5	1–4
Proper use factor for perennial grasses	pf_{per}	0.45	0–1
Proper use factor for annual grasses	pf_{ann}	0.45	0–1
Mean annual precipitation (mm)	r_{mean}	280	280
Mortality rate of livestock	$prob_{mort}$	0.8	0.4–1
Cattle growth rate	g_c	0.2	0–1
Capacity limit of grass biomass per cell on deep soil (Mg/ha)	cap_{dp}	1.5	1–4
Capacity limit of grass biomass per cell on shallow soil (Mg/ha)	cap_{sh}	1	$cap_{dp}/2$
Portion of lactating animals	p_l	0.2	0.2

Note: Key to abbreviations: RSP, rainy-season pasture; DSP, dry-season pasture; RFD, reserve for drought; UFG, area unsuitable for grazing; TLU, tropical livestock unit.

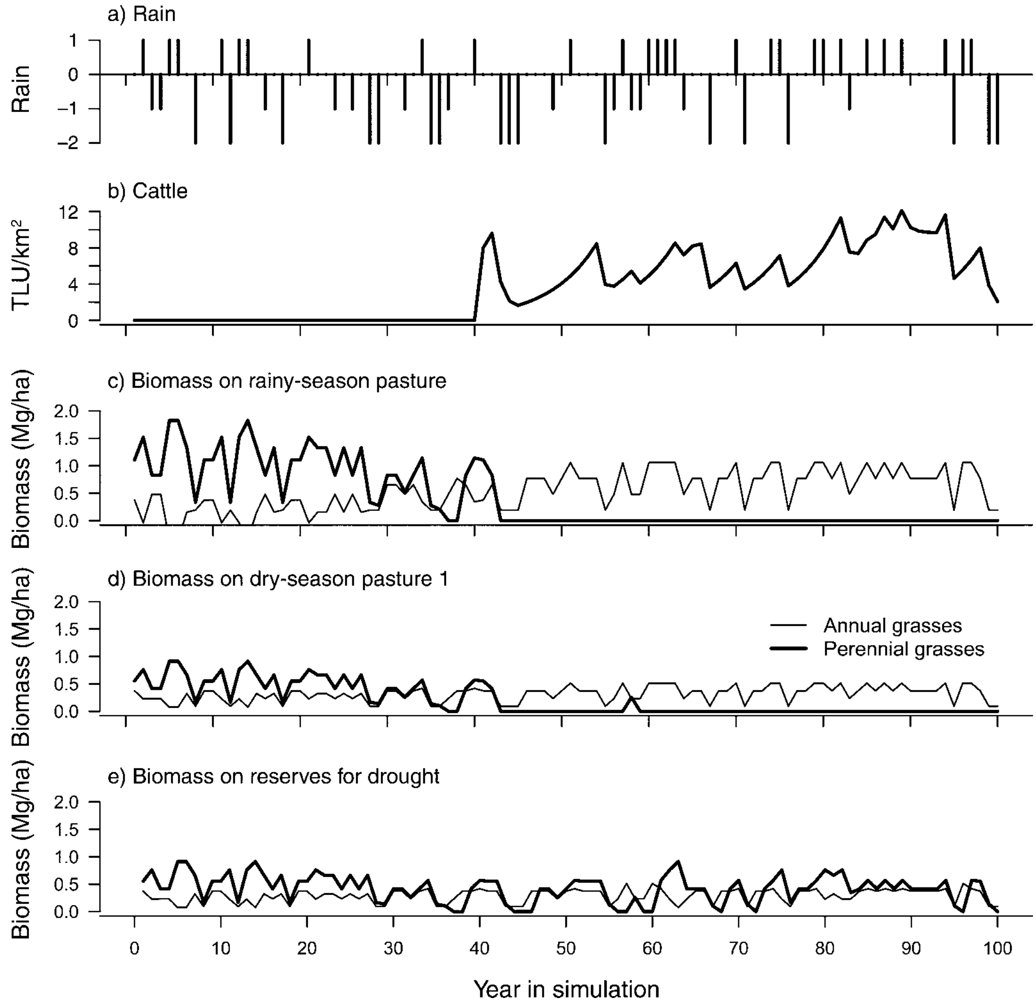

FIG. 3. (a) Rain (measured in classes, from −2 [drought] to 1 [above average]; see Table 2), (b) cattle number (in tropical livestock units, TLU), (c–e) biomass production of annuals and perennials for one random simulation run on different pastures, mapped for 100 years, the first 40 years without grazing (see Table 8 for the parameter set).

parameter sets were generated using the software SIMLAB 2.2 (Saltelli et al. 2004). This method, by stratifying the input space into N desired strata, ensures that each input factor has all portions of its distribution represented by input values. In this study, uniform distributions are assumed. In particular, since we have no information on the particular soil seed bank dynamics, the parameters describing longevity of the seed bank of annuals and perennials were varied.

For each of the parameter sets, the output variables mean cattle number, mean perennial ground cover, and mean biomass of annuals and perennials were calculated for the four considered strategies (T, A1, A2, A3) after 100 years of grazing, over 5000 runs.

RESULTS

Traditional strategy in the long run

One random run.—One main objective of our model is to investigate the sustainability of the traditional pastoral-nomadic land management practiced by the Himba up to 1995. Hence, the long-term impact of the strategy on pasture quality was evaluated. For a better understanding of the model, one randomly chosen rainfall scenario drawn from the assumed rainfall distribution is mapped for 100 years. For this scenario, cattle number, green biomass of annual and perennial grasses on the different pasture types (Fig. 3), and the perennial ground cover (Fig. 4) are all calculated.

To minimize the effect of initial conditions during the first 40 years, no grazing takes place (Fig. 3b). The results indicate that without grazing all pastures are dominated by perennials (Fig. 3c–e). After the onset of grazing, the pasture shifts from perennial to annual dominance. In both cases, with and without grazing, biomass is highly dependent on stochastic rainfall. Due to the close connections among rainfall, available forage, and livestock demography, cattle numbers also reflect precipitation dynamics. After a long drought (43–

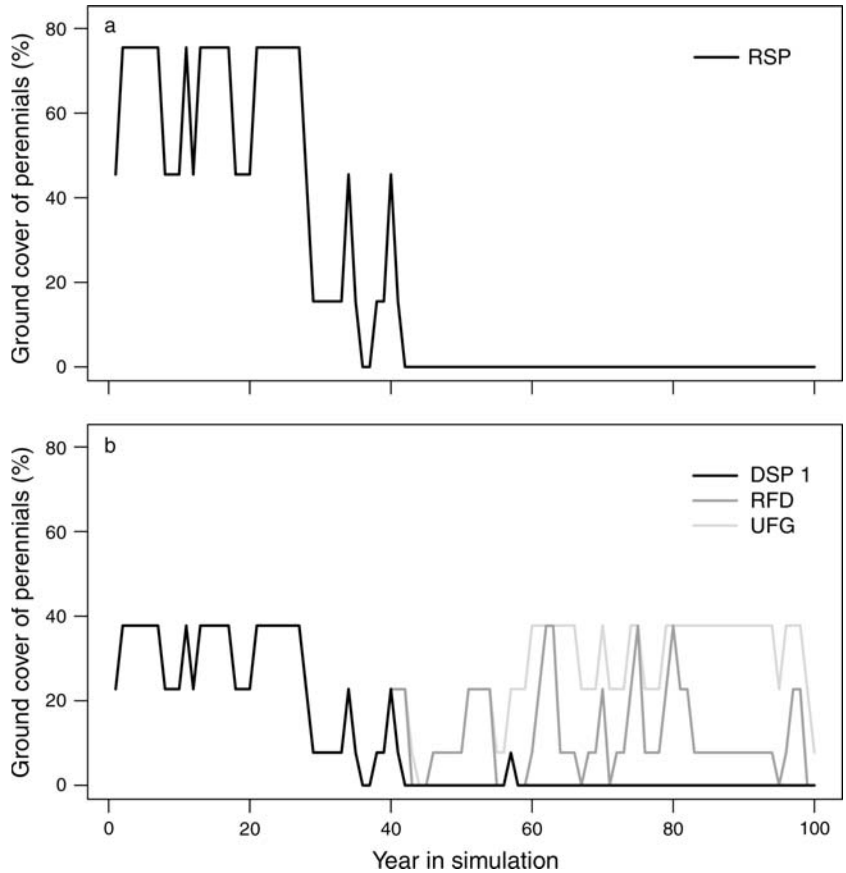

FIG. 4. Perennial ground cover for the rain scenario shown in Fig. 3a for different pastures mapped for 100 years, the first 40 years without grazing (see Table 8 for the parameter set). Abbreviations are: RSP, rainy-season pasture; DSP, dry-season pasture; RFD, reserves for drought; UFG, area unsuitable for grazing. Note that in panel (b) the first 40 years without grazing and ground cover overlap for DSP, RFD, and UFG.

45 years), livestock numbers need some time to recover. The influence of grazing is highest on RSP and DSP1. Here the perennial ground cover is zero in almost every year.

The perennial ground cover of the first DSP (situated on shallow soil) lies between 0 and 7% (cf. Fig. 4). On the other DSP (not mapped) and the RFD, the perennial ground cover is higher due to less grazing pressure. During multi-year droughts (43–45 years) the perennial ground cover, even on pastures not used for grazing (UFG), reaches 0. Regarding only the used pastures (RSP, DSP, RFD), it is not clear whether the decrease of ground cover and biomass of the perennial grasses (in years 43–45) is a result of grazing or of drought conditions. Therefore, we made attempt to separate grazing and drought effects.

The classification of the perennial ground cover into only four classes apparently leads to dynamics that are more pronounced than if they were based on a more detailed classification. For instance, in our model, an increase of perennial ground cover from 0% to 7% can take place within only one year on rainy-season pastures. This recovery would take more time in reality.

Model calibration.—In order to validate the model, it is helpful to compare its outcome with existing data. For the Omuramba area, data are available for the 1994/1995 season (12 000 cattle on 1520 km^2 [cf. Casimir and Bollig 2002:217]). For the whole northern Kunene Region, continuous cattle data are available from censuses of vaccination campaigns for the time span 1975–1995 (Bollig 2002:191) (on 55 000 km^2). The data of the whole area can not be simply downscaled, since the landscape configuration differs strongly inside the northern Kunene Region. For downscaling the following procedure was implemented. It is assumed that the dynamics in the Omuramba area are the same as in the whole region, however using the Omuramba data from 1994 as a benchmark (12 000 cattle on 1520 km^2 equals 7.89 TLU/km^2). Consequently, the livestock density (TLU/km^2) in Omuramba for the other years can be extrapolated from the data in Bollig (2002). Afterward, these data are compared to the simulated cattle number (Fig. 5).

Rainfall data are used from the Kamanjab station situated ~300 km southeast of Omuramba (unpublished data from the Weather Bureau Windhoek, Namibia).

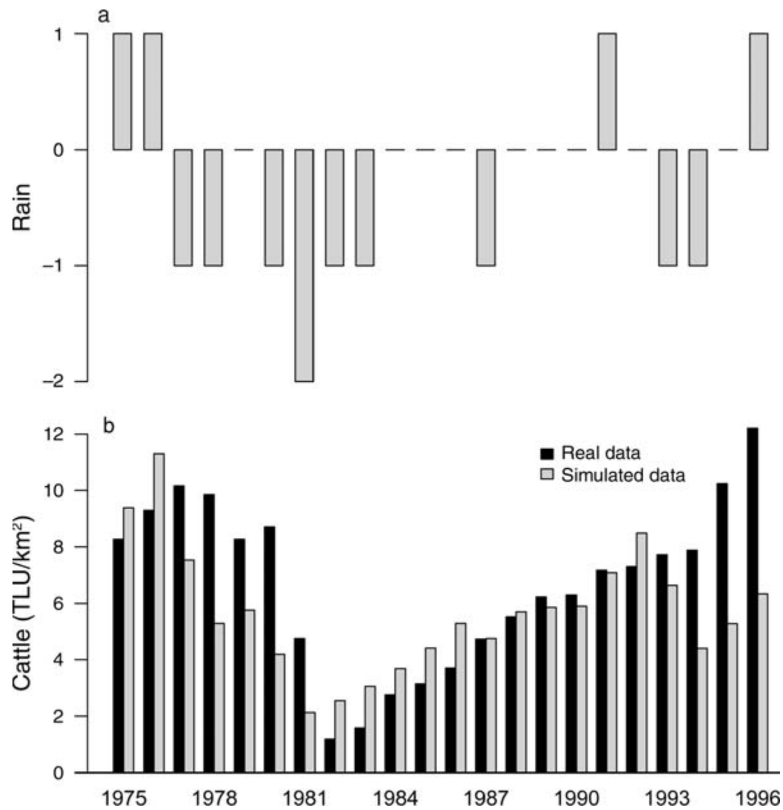

FIG. 5. (a) Rainfall in Kamanjab (unpublished data from the Weather Bureau Windhoek, Namibia; measured in classes, from −2 [drought] to 1 [above average]; see Table 2) and (b) cattle number (tropical livestock units, TLU) simulated for rainfall data from Kamanjab compared to cattle data from Bollig (2002:191).

The correlation coefficient between the two data series ($R^2 = 0.58$) indicates that the model adequately describes the cattle dynamics. However for two time spans, 1975–1976 and 1995–1996, the model overestimates (for the first time span) or underestimates (for the second) the cattle numbers.

The deviation in the mid-1990s is probably a result of the following three reasons. First, the distribution of supplementary feeding of molasses by the Namibian government during times of drought. Second, throughout the 1980s, cattle were bought from the Okakarara area and Kwanyama (Ohta 2000). Third, the further extension of the borehole program may have added to the increase in cattle numbers. Several dozen boreholes were drilled throughout the 1990s. However, it is hard to quantify all three factors and there may still be some doubts if these three factors explain the increase adequately.

Average model behavior.—It is necessary to separate the influence of grazing and rainfall variability on biomass dynamics. By a high number of repeated runs (5000) with different rainfall scenarios based on the same rainfall distribution, the impact of the particular order of rain events is eliminated. With grazing (according to the traditional strategy), mean perennial ground cover reaches a steady state after a short time, since the seed bank is assumed to be very long in this analysis (Fig. 6, Table 8). This shows that grazing has a high impact on all pasture types. The mean perennial ground cover is lowest for RSP (perennial ground cover near zero) and increases as the pasture is used less. The values correspond to ecological field data from the study site Omuramba (Schulte 2002*b*).

The impact of grazing on perennial ground cover can be translated into the amount of biomass produced by perennial grasses and due to the competitive connection between the two functional groups to the biomass

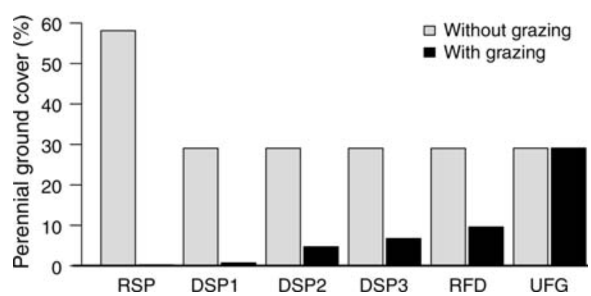

FIG. 6. Mean perennial ground cover over 5000 runs, in the steady state, for different pastures without and with grazing applying the traditional strategy T (see Table 8 for the parameter set). Abbreviations are described in Fig. 4.

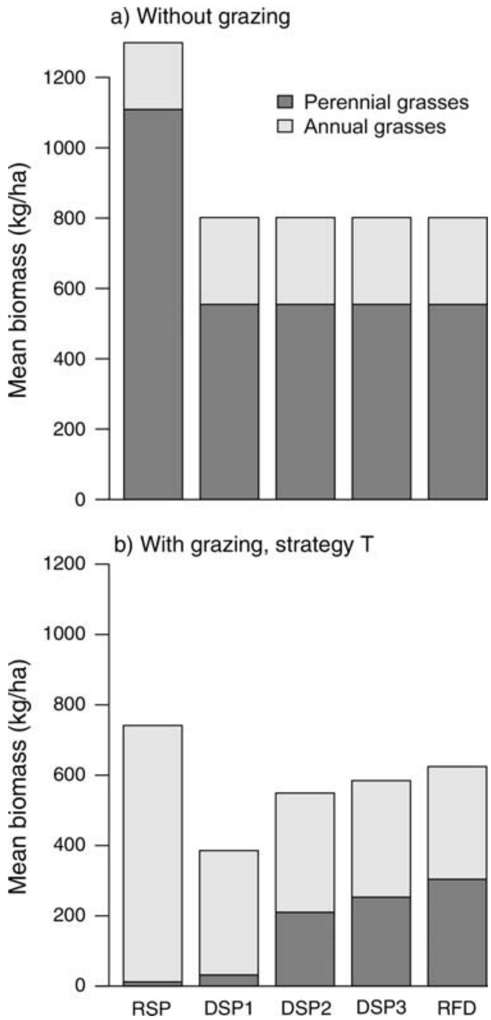

FIG. 7. Mean biomass production for annuals and perennial grasses in the steady state for different pasture types over 5000 runs for traditional strategy T: (a) without grazing and (b) with grazing applying strategy T (see Table 8 for the parameter set). Abbreviations are described in Fig. 4.

produced by annuals (Fig. 7a, b). With grazing, the dominance of perennial grasses changes to a dominance of annual grasses on all pastures. The lower mean biomass production on DSP and RFD is caused by the lower rain use efficiency on shallow soils compared to RSP which are located on deep soils.

Comparison of traditional grazing strategy with alternative strategies

The assessment of whether the traditional management strategy can be judged as sustainable depends strongly on the sustainability criterion. With regard to, for example, species composition on the RSP, the traditional grazing strategy cannot be judged as sustainable. However, the productivity of the pastures does not decrease over time. First, we can analyze whether the traditional strategy is more suitable in comparison with alternative strategies. Second, we can examine whether components of the traditional management system exist that should be either maintained or discontinued since they are of less importance with respect to the considered criteria.

Fig. 8 shows to what extent grazing pressure is realized for the four different strategies averaged over 5000 simulation runs and over the whole time span. It is apparent that, when applying the traditional strategy (T), grazing pressure is quite heterogeneous. Heavy grazing impact all year round takes place on RSP. The first dry-season pasture is used in part already in the rainy season. DSP2, DSP3, and RFD are not used every year and if so, then only in the dry season. The alternative strategy (A1) and, even more, (A2) release pressure on the rainy-season pastures, but the DSP are now used continuously and not seasonally. Alternative strategy (A3) shows a heterogeneous grazing pressure comparable to T, without any whole-year resting.

For all four strategies, the mean state of perennial ground cover, mean green biomass of annuals and perennials and mean cattle number at the end of the considered time horizon of 100 years grazing are calculated (averaged over 5000 runs; Tables 9, 10).

Applying the alternative strategies with more homogeneous use, the perennial ground cover increases on RSP and partly on DSP1, but decreases in general on the other pastures (DSP, RFD). This result is carried forward on the perennial biomass.

The reduction of total perennial biomass goes along with a slight increment of total annual biomass. However, considering total biomass, the traditional strategy has the highest production, including spatially and temporally heterogeneous use.

The crucial economic criteria the cattle number identifies the traditional strategy T as the strategy that guarantees the highest cattle number, due to the rest for DSP and RFD during the rainy season and the possibility of spatial extension (Fig. 9; oP, without purchase). Using all pastures except RFD all year round (A1) diminishes the cattle number on average by almost 15%. Without the protection of RFD (A2), the reduction of livestock compared to T is 25%. As long as on DSP and on former RFD resting is granted during the rainy season (A3), the mean cattle number decreases only slightly compared to T. Hence, the granting of rest periods during the rainy season for parts of the pasture is most important.

Purchase of livestock

We were interested in understanding what influence is exerted by a change in the underlying socioeconomic conditions. We took the purchase of livestock as an example. The results of over 5000 simulation runs are depicted in Fig. 9. Remember, purchase is only allowed as long as grazing pressure stays moderate.

Purchase applied to the traditional strategy T, leads to a higher livestock number. The biomass can be used

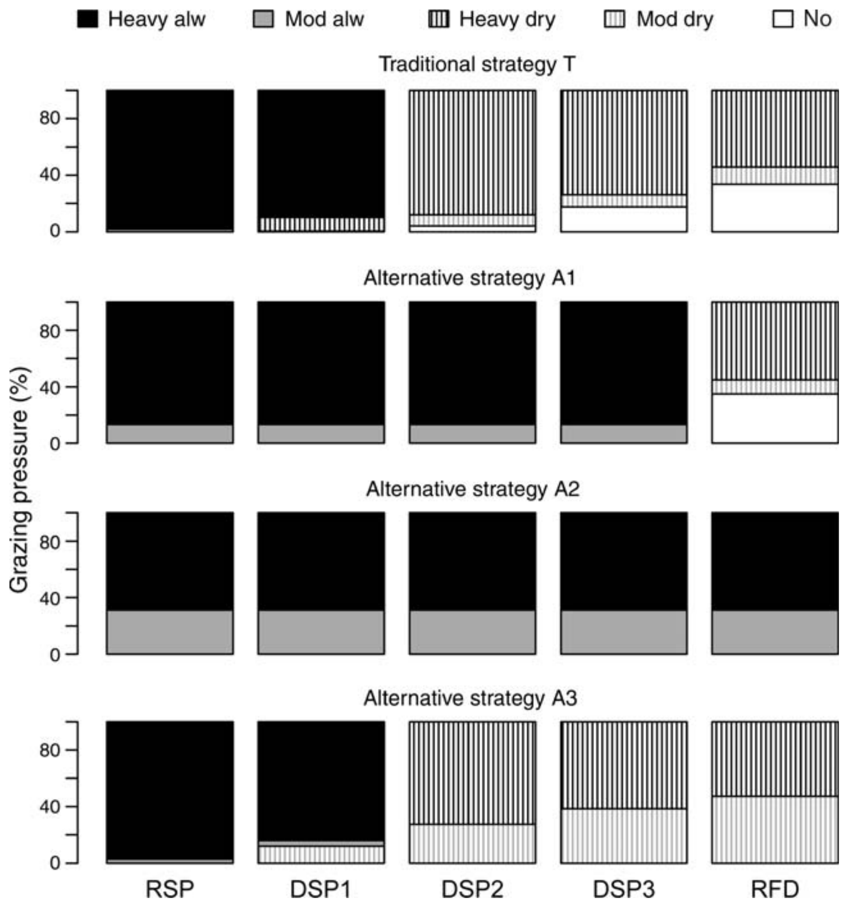

FIG. 8. Resulting mean grazing pressure on the different pastures applying traditional grazing strategy T vs. alternative strategies A1, A2, and A3, calculated over 5000 runs and averaged over the whole time span (see Table 8 for the parameter set). Abbreviations for grazing are: Heavy alw, heavy grazing the whole year; Mod alw, moderate grazing the whole year; Heavy dry, Heavy grazing in dry season and resting in rainy season; Mod dry, moderate grazing in dry season and resting in rainy season; No, no grazing. Abbreviations for pasture types are as in Fig. 4.

more effectively after a drought and low cattle numbers, the livestock can be restocked.

Applying alternative strategy A1, purchase can increase mean livestock numbers (oP, 8310; P1, 8810; P2, 9460 cattle), but these will still be lower than livestock numbers achieved under traditional strategy without purchase (9640 cattle). Under strategy A2 the cattle number even decreases slightly when applying purchase strategy P2. In this case, the positive effect on the cattle number by purchase is reduced by the negative effect on biomass production through not resting of DSP and RFD in the rainy season and no resting of RFD for the whole year. Under A3 (with the granting of rest periods during rainy season) almost as many livestock can be kept as when applying the traditional strategy.

Sensitivity analysis

Conducting a sensitivity analysis, the question is addressed of how strongly the superiority of the traditional strategy T, when compared to alternative strategies A1, A2, A3, depends on the chosen parameter set. From the 200 parameter sets generated by Latin-hypercube sampling, those were determined, where alternative strategies (A1, A2, A3) resulted in higher mean cattle numbers (averaged over 5000 runs after 100 years of grazing) than the traditional strategy T.

The results show that the application of the traditional strategy T leads to a higher livestock number for

TABLE 9. Mean cattle number and mean perennial ground cover for RSP (rainy-season pasture), DSP1 (first dry-season pasture), and RFD (reserve for drought) after 100 years of grazing averaged over 5000 runs for the traditional strategy T compared to the alternative strategies A1, A2, and A3.

Strategy	Mean no. cattle $E(n)$	Mean perennial ground cover $E(c)$				
		RSP	DSP1	DSP2	DSP3	RFD
T	9640	0.2	0.7	4.6	6.5	9.2
A1	8310	1.1	0.6	0.6	0.6	8.8
A2	7270	2.3	1.2	1.2	1.2	1.2
A3	9250	0.3	1.1	5.1	5.8	6.2

TABLE 10. Mean available biomass of annuals and perennials for RSP (rainy-season pasture), DSP (first dry-season pasture) and RFD (reserve for drought) after 100 years of grazing averaged over 5000 runs for the traditional strategy T compared to the alternative strategies A1, A2, and A3.

	Mean available biomass $E(b_{av}^{past})$, kg/ha							
	Total		RSP		DSP1		RFD	
Strategy	Annuals	Perennials	Annuals	Perennials	Annuals	Perennials	Annuals	Perennials
T	385	174	721	9	349	34	318	295
A1	391	100	705	57	349	29	319	301
A2	393	66	685	117	347	58	347	58
A3	388	157	719	15	347	46	329	227

Note: Key to column headings: Annuals, annual grasses and forbs; Perennials, perennial grasses.

91% of all parameter sets (not presented here in detail). The 9% of parameter sets where one of the alternative strategies is superior were caused by one or a combination of the following three reasons:

1) The thresholds th_1 and th_2 for the ratio between available biomass to required biomass are relatively small ($th_1 < 0.7$; $th_2 < 0.5$). These low values of th_1 and th_2 do not seem to be realistic.

2) The proper use factor for perennials, pf_{per}, is much smaller than the one for annuals, pf_{ann}. The alternative strategies lead to a higher portion of annuals. Hence, a much higher proper use factor of annuals compared to perennials imposes higher cattle numbers for the alternative strategies. This assumption seems to be unrealistic to us (see *Discussion*).

3) The portion of dry-season pasture (DSP), a^{DSP}, is very small (increase of RSP accordingly). For an extremely small portion of dry-season pasture, the positive effect of resting during the rainy season on DSP applying T is negligible and the negative effect of high pressure on RSP predominates. This is an extreme case of the considered parameter range.

In summary, the predominance of the traditional strategy (T) holds under realistic parameter ranges.

Discussion

Role of heterogeneous pasture use

The central question of our study was to identify components of the traditional Himba strategy (practiced from 1960 to 1995) that are essential for sustainability. Our approach was to compare the traditional strategy with strategies where particular aspects were altered. This is extremely relevant at present; since the mid-1990s, certain parts of the former practiced strategies have been changed. For instance, the protection of reserves for drought and the coordination of movements to dry-season pastures have been partly abandoned.

In our analysis, two components of the traditional strategy were detected as crucial for high biomass production:

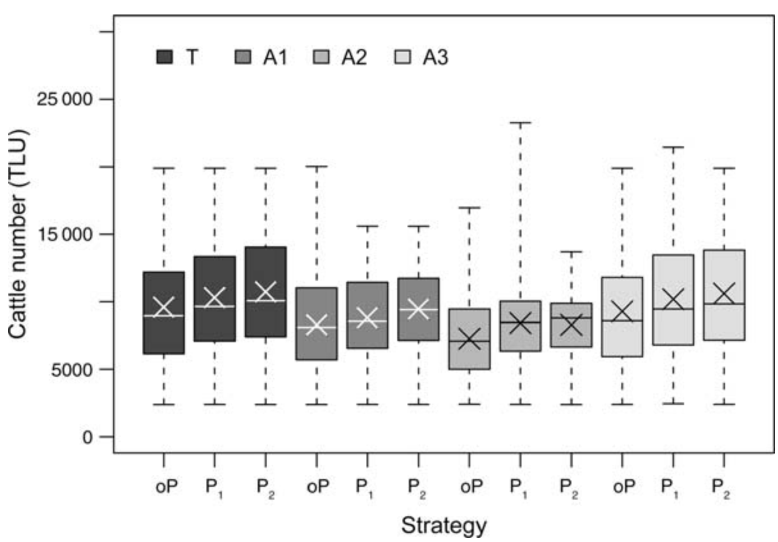

FIG. 9. The case of livestock purchase under different grazing strategies, with box-and-whisker plots showing cattle numbers in TLU (tropical livestock units), applying traditional grazing strategy T and alternative strategies A1, A2, and A3 averaged over 5000 runs after 100 years of grazing (see Table 8 for parameter set). Abbreviations are: oP, without purchase; P_1, purchase without using reserves for drought; P_2, purchase using reserves for drought. The box covers the central 50% of the values, and the whiskers show the range of the data. The median is shown by the horizontal line across the box; the mean is indicated by the "×".

1) Intra-annual heterogeneity of resource use by resting of the dry-season pastures during the rainy season.

2) Interannual heterogeneity of resource use by granting of reserves for drought and use of dry-season pastures situated further away only if the closer ones are used up.

Let us consider these two components in more detail.

Resting of pastures during the rainy season.—The traditional system is characterized by a continuous high grazing pressure close to the permanent settlements and a resting of dry-season pastures (DSP) during the rainy season. In our model, this system was compared to a homogeneous and continuous pasture use. The comparison of both strategies revealed a trade-off effect: homogenous pasture use relieves pressure on the rainy-season pastures, but increases the pressure on DSP and allows no resting in these areas. Model results suggest that the resting of the dry-season pastures during the rainy season is particularly important. It leads to a higher regeneration potential for the biomass. Furthermore, the plant populations of the grasses can produce higher numbers of seeds. With continuous land use, this regeneration potential is strongly reduced, especially under heavy grazing pressure. Our findings are supported by other studies in semiarid range lands (Sternberg et al. 2000, Oba et al. 2001:836). Resting during the rainy season promotes biomass production, flowering, and seedling success of the grasses (O'Connor and Everson 1998). The importance of an appropriate timing of resting is widely acknowledged (among them Hanley 1979, Westoby et al. 1989, Hary et al. 1996, Stafford Smith 1996, Niamir-Fuller and Turner 1999, Tainton and Danckwerts 1999).

Granting of reserves for drought.—Conserving pastures for times of drought is shown to be of ecological and economic significance (cf. Niamir-Fuller 2000). They are key resources in years with scarce forage (Scoones 1995). Hence, the fluctuations in rainfall are not directly carried over to forage availability and livestock number—a smoothing in stock numbers over the years is the result. Furthermore, the reserves for drought and DSP located further away are not used in wet years and hence are rested effectively. In Müller et al. (2007), a sophisticated range management system practiced on a commercial farm in Namibia is analyzed and discussed. It showed that biomass production benefits considerably from resting periods in wet years, because vegetation can regenerate more effectively under these favorable growing conditions.

Summarizing, the traditional Himba management system is based on a spatially and temporally heterogeneous use of pastures. Its success has two aspects: (1) flexibility and (2) restriction. The herders extended the spatial range of use flexibly, but were restricted in time and order of pasture use. This management system led to an effective build up and use of an ecological buffer of the system the reserve biomass (cf. Wiegand et al. 2004). However, it is not easy to judge whether the traditional system of the Himba can be termed sustainable. It is a multi-layered problem and depends on the considered scale. On a small scale the rainy-season pastures are covered exclusively by annuals and are prone to degradation. But on the scale of the total system, the productivity is maintained.

Why do pastoralists apply a heterogeneous land use?—Numerous pastoralists worldwide apply management strategies where pastures are rested during the rainy season for use in the dry season (e.g., Turkana of Kenya, Jie of Uganda [cf. Coughenour 1991]). Often, it is not the explicit management purpose to rest the vegetation during the rainy season. Other aspects of land use unintentionally cause this grazing regime above all water availability. During the rainy season, more productive areas are used, where water is only available temporally. If pasture areas are situated far away from water points, they are not used annually and, therefore, rested. Turkana pastoralists use some of the least productive rangelands in the rainy season and gradually move to areas of higher productivity as the dry season progresses (Coughenour 1991). Cooler temperature, lacking water resources, parasites, and higher competition among pastoralists during the rainy season on the more productive sites are quoted as possible reasons for this opposite pattern.

Steep mountain pastures not accessible for cattle are a key factor for the successful use of spatially heterogeneous rangelands. Medium-distance seed dispersal (several kilometers for anemochorous dispersal units) from these areas may insure the recolonization of degraded areas with locally depleted soil seed banks. Reserves for drought, which are difficult to access and have limited water resources, have the same ecological function.

The installation of new boreholes in the area in the 1980s facilitated the access to water. This indicates that the experience gained from the Sahel was not incorporated in Namibia. Reasons can be found in the political conditions in apartheid South Africa. South Africa's administration was firmly set on the modernization and rationalization of African agriculture and livestock husbandry, an extensive borehole drilling program was an essential part of this. The program was pushed by the administration to win the hearts and minds of locals in the end Kaokoland was a war-area.

Some remarks on the assumptions and limitations of the model.—Our results are sound even if the parameter sets are varied in realistic ranges. Some exceptions are rendered by a detailed sensitivity analysis. It shows that results are strongly dependent on the proper use factor of annual grasses compared to perennial grasses. On the study site, the perception of grazing values of the annual grass species *Schmidtia kalahariensis* and of the perennial species *Stipagrostis uniplumis* differs considerably between Himba herdsmen and range ecologists (Bollig and Schulte 1999). Range ecologists consider perennial grasses to have inherently higher values than annuals, because they produce more leaf material (Bollig and Schulte 1999). Investigations of the nutritional value of the two grass species on the study site support the superiority of the proper use factor of the perennial grass species (Casimir and Bollig 2002). In sharp contrast, Himba herdsmen rank *Schmidtia k.* of high value (Bollig and Schulte 1999).

The authors are aware that assuming a constant birth and mortality rate is a very strong model simplification. The Himba observe that cattle do not get pregnant after a drought (Bollig 2006). In reality, mortality rates fluctuate from year to year. Sale of livestock is not analyzed by the presented model explicitly (in contrast to purchase). This future scenario could be investigated by varying the mortality/offtake rate from year to year.

Regarding the mobility pattern, it is assumed in this study that livestock is moved to the next dry-season pasture as soon as the ratio of available and required biomass falls below a certain threshold of biomass availability. This "push option" of pasture use, though, is accompanied by a "pull option." If herders have the information that a good pasture is available at a close distance (due to favorable, spatially heterogeneous rainfalls), they will move to this pasture, even if the natural resources of the current pasture have not been fully exploited. This aspect will be included in a spatial-explicit model in the future. Furthermore, in such a model the aspect of erosion will be investigated which threatens areas where perennials have completely disappeared.

What happens to the state of the rangeland system if socioeconomic conditions change?

The Himba land management is currently affected by numerous external and internal factors. From these factors, we have analyzed the key factor "livestock purchase" on the vegetation composition, productivity and herd dynamics.

Purchasing livestock—common on most commercial farms—may have both positive and detrimental effects on land use sustainability. On the one hand, livestock performance can be more effectively adapted to years with high biomass production caused by high rainfall. On the other hand, livestock purchase may disappoint the highly important but unplanned rest periods of the pastures in post-drought years (cf. Müller et al. 2007). Unplanned rests are unintended rests for parts of the pasture. After prolonged droughts and resulting break-downs of livestock numbers, parts of the pastures may not be needed for certain periods of time, since livestock need some time to reach pre-drought numbers. Hence an effective regeneration of these parts of the total pasture area is ensured (see Stafford Smith and Foran 1992, Müller et al. 2007).

Our study shows that livestock purchase may lead to a considerable decline in vegetation quality. However, as long as the traditional grazing strategy is maintained (which allows a rest of certain parts of the pasture in the rainy season), the decline in productivity does not considerably affect livestock numbers. The livestock number kept on the pasture increases in total. In contrast, if the land management implies continuous grazing without reserves for drought, purchase of livestock will lead to a considerable decline in pasture productivity. For the long term, less livestock can be kept on the farm compared to a scenario without purchase options.

In summary, the use of simulation models is promising for a thorough analysis of changing socio-economic conditions as well as climate change. The model allows the investigation of the consequences of socio-economic changes in traditional strategies (Vetter 2005). This approach enables us to address the even more crucial question in the future what the (ecological and socio-economic) boundary conditions permitting sustainable land use are.

Analyzing local knowledge to contribute to the equilibrium vs. nonequilibrium discussion

Interest in local knowledge has been growing in recent years, due to recognition of its relevance for sustainable resource use (Berkes et al. 2000). In this field, local knowledge can often be only observed in practiced actions. Here, simulation models can help to connect local with global scientific knowledge: They allow the investigation of the significance of certain components of traditional management strategies for sustainability. This fosters a comprehensive understanding of underlying dynamics. Basic principles of sustainable management and its boundary conditions can be hypothesized. This is the basis for an application to other management systems.

Some remarks regarding the current equilibrium vs. non-equilibrium discussion: Semiarid ecosystems are primarily driven by fluctuating rainfall, which masks the effects of grazing on vegetation productivity (Stafford Smith 1996). This may lead to under or overestimation of grazing impact (Niamir-Fuller 2000). Using the simulation model in our study, the influence of rainfall fluctuations and grazing on pasture dynamics could be separated. Our results substantiate the hypothesis that both, biotic and abiotic factors are essential for vegetation dynamics on different temporal and spatial scales. First, the strong effect of rainfall and a recommendation for a close adaptation of livestock numbers to available forage is supported as long as a second aspect is taken into account: the importance of the timing of grazing and resting. These two aspects are shown to have strong impact on biomass production and species composition.

Second, Illius and O'Connor (1999) discussed the role of key resource areas for an increased risk of degradation on rainy-season pastures (RSP). Our study supports this hypothesis. Due to the interannual heterogeneous use, dry-season pastures situated further away and reserves for drought act as key resources (Scoones 1995). Their availability limits livestock numbers. Degradation on rainy-season pastures is higher, if key resources are readily available. Considerable shifts in dominance patterns connected with losses of productivity take place on RSP. Nevertheless, spatial and temporal heterogeneity of land use renders a higher productivity of the total system.

In summary, the investment into the ecological buffer of vegetation, i.e., the reserve biomass, is crucial for the maintenance of long-term productivity in semiarid rangelands. Therefore, two components of the traditional Himba strategy are highly significant: Intra-annual heterogeneous use which grants seasonal resting for the pasture and interannual heterogeneous use by allotting reserves for times of drought. These two components need to be maintained under changing conditions in the northern Kunene Region. Furthermore, we hypothesize that these are important basic principles for sustainable range management in semiarid regions in general.

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APPENDIX A

Calculation of required biomass and grazing pressure per pasture (*Ecological Archives* A017-075-A1).

APPENDIX B

Detailed explanation of the model rules regarding perennial ground cover (*Ecological Archives* A017-075-A2).