Agent based modeling and simulation of a pastoral-nomadic land use system

Patrick Kuckertz, Oliver Ullrich, Anja Linstädter, Ewald Speckenmeyer
{kuckertz|ullrich|esp}@informatik.uni-koeln.de, anja.linstaedter@uni-koeln.de
Universität zu Köln
Pohligstraße 1, 50969 Köln

Abstract

Almost half of Africa is covered by arid savannas, which are used as rangelands and are the source of livelihood for a vast population. To sustain pasture quality, degradation has to be avoided and efficient and sustainable land use strategies are needed. This paper describes the development of a simulation model representing the range management strategies of the Himba people in north-western Namibia. The model recognizes spatial factors and the impact of management decisions on ecosystem dynamics. The paper also describes the process of creating and validating a software application, and implementing the model.

1 Introduction

Savannas are a mixed grass-tree biome and one of the most important vegetation types for livestock farming worldwide. They cover approx. 33 million km² [2] and at least 35% of the South African subcontinent [19]. Their arid to semi-arid climate aggravates crop cultivation, which is why livestock keeping is often the source of livelihood for people living in these regions. Like in any other dryland, low rainfall, which is also highly variable in time and space, makes livestock keeping risky [3;4]. Today land degradation caused by climate change and over-exploitation posts another serious threat to livelihood security. Efficient and sustainable land use strategies adapted to highly variable and changing environmental conditions are thus an important tool to counter these effects [6;11].

The mechanisms of land degradation and the interactions between land use strategies and ecosystem dynamics are complex and not yet fully understood [7]. In this context, not only temporal dynamics but also the spatial heterogeneity of natural resources (forage and water) seem to be of crucial importance for management decisions [12]. In the past two decades, many studies have used modeling approaches to come to a functional understanding of sustainable management strategies in drylands [see review in 20]. However, the decision-making processes of local land users are still not adequately incorporated into models.

This paper aims to contribute to our understanding of land use strategies in arid ecosystems by integrating pastoral-nomadic mobility decisions into a spatially explicit model. As agent-based modeling and simulation is a promising tool for modeling decision-making and its feedback on natural resources in social-ecological systems [13], this approach has been chosen. The model is thus an example of an agent-based land-use model, which combines a cellular landscape model with agent-based representations of decision-making, integrating the two components through interdependencies and feedbacks between agents and their environment [15]. Specifically, our model represents mutual relationships between natural processes and cattle herd grazing on savanna rangelands in north-western Namibia, populated by the Himba people.

2 System description

The pastoral-nomadic Himba people populate the Omuramba basin in north-western Namibia. Because of a long-lasting political and economical isolation and the geographic remoteness of the region [5], the Himba retained their local ecological knowledge of herd management. This is why data on herd population dynamics, vegetation dynamics and strategies of herd management – as a "good practice" approach – help to understand which aspects of herd mobility and social networks are central aspects of a sustainable management.

The Himba are an ethnic group of approximately 30.000 people who live for the main part in the Kaokoland area in Namibia's Kunene province [4]. They have been living in this region as pastoral nomads for over 200 years. Cattle are not only their main food source but also status symbol, financial resource and medium of exchange. The Himba community is organized in households representing clan structures consisting of 20 to 30 people who keep about 200 to 300 cattle. This paper focuses on the Himba living in the Omuramba basin. The intramontane basin is situated in the north of the Kaokoland region at the border to Angola and covers an area of ca. 40x40km (1.600 km²). About 70 to 100 people live in this area, the cattle stocking rate is about 2.5 TLU/km² (Tropical Livestock Unit = 1 cattle of 250 kg).

The arid Mopane savanna of the Omuramba basin is a typical vegetation for this region [1]. Due to high grazing intensity, the grass layer is dominated by annual grasses and forbs [9]. A dry and a rainy season alternate in the course of the year. Rainy season lasts from November to April, dry season from May to October.

The herd management of the Himba comprises season-dependent mobility between pastures to assure a constant fodder supply for the herds. It also serves to minimize soil and pasture degradation [14;18]. Herd movements and pasture use are coordinated by the Himba community, and contraventions are sanctioned [4;17].

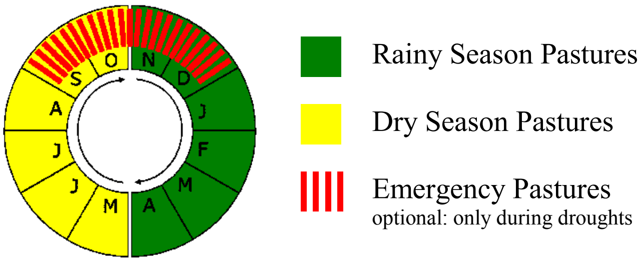
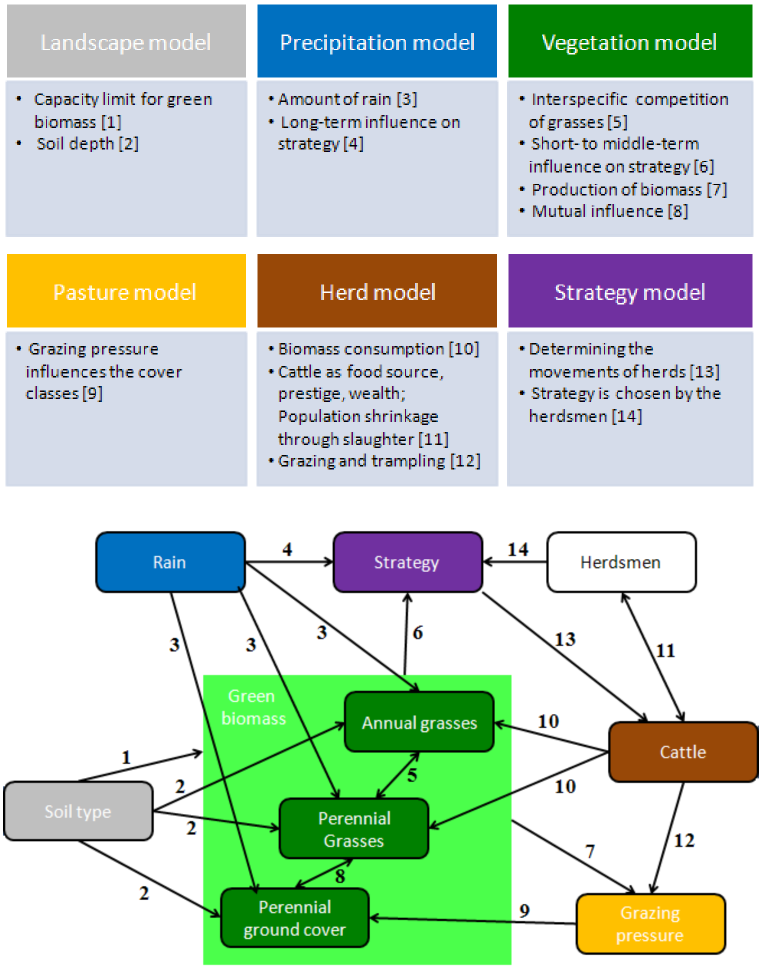


Figure 1: Anual herding cycle of the Himba [Source: 12]

A herd management applied within the last 50 years consists of typical seasonal movements of livestock across local pastures, which can be described as an annual herding cycle (see Figure 1). It is to let cattle herds graze on river side areas in rainy seasons and to move them to areas with boreholes which are situated far from rivers during dry seasons. In case of drought events access to specific pastures is given, which serve as fodder reserves and are not to be used in better years.

3 Modeling

The agent-based simulation model expands an existing spatially implicit model [14] by adding spatial aspects like topography, soil attributes, and the relative location of pastures and water sources. The influence of individual management decisions on the vegetation is reevaluated every day.



Landscape model

- Capacity limit for green biomass [1]
- Soil depth [2]

Precipitation model

- Amount of rain [3]
- Long-term influence on strategy [4]

Vegetation model

- Interspecific competition of grasses [5]
- Short- to middle-term influence on strategy [6]
- Production of biomass [7]
- Mutual influence [8]

Pasture model

- Grazing pressure influences the cover classes [9]

Herd model

- Biomass consumption [10]
- Cattle as food source, prestige, wealth; Population shrinkage through slaughter [11]
- Grazing and trampling [12]

Strategy model

- Determining the movements of herds [13]
- Strategy is chosen by the herdsmen [14]

Figure 2: Submodels and their mutual influences

An agent-based simulation model consists of agents, thus of attributes and of behavior determining rules, of an environment in which the agents move, and of their mutual influence [10]. The model introduced here is a composition of six submodels (see Figure 2) in which the environment is represented by a landscape, a pasture and a vegetation model. The hierarchical agents with their rules of behavior implement a herd and a strategy model. In the following section all submodels are described explicitly.

The landscape model provides the representation of the Omuramba basin. It subdivides the investigation area by a grid of 80x80 cells, each one representing an area of 500x500m (25ha). Each cell is assigned to a specific type of soil (see Figure 3). The 6400 cells are classified as follows: 1,765 cells (27.6%) belong to soil potentially used in rainy seasons, 2,546 cells (39.8%) to soil potentially used in dry seasons, 395 cells (6.2%) to soil reserved for droughts and 1,666 cells (26.0%) are classified as not usable. The properties of 26 cells (0.4%) are unknown.

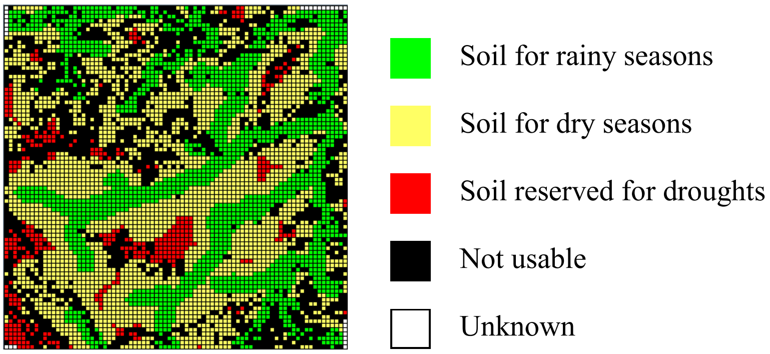


Figure 3: Landscape model of the Omuramba basin. The grid represents an area of 40x40km, and is divided into 6400 raster cells (25 ha each)

Source of this allocation is a digital elevation model based on satellite images [12]. This model classifies the Omuramba basin into 6400 raster cells of 25 ha, and uses altitude, slope and flow accumulation calculations to determine certain spatial characteristics like accessibility, topography, relative position to rivers, and soil depth. To represent a pasture, a number of neighboring cells are pooled corresponding to maps and distance parameters.

Class	Annual Rain value *r(t)*	Probability
Drought	70mm	0,12
Below average	175mm	0,16
Average	280mm	0,43
Above average	385mm	0,29

Table 1: Classification of annual precipitation into classes, their mean value used for simulation, and their probability of occurrence [Source: 14]

Because of scarce data from the study region, precipitation is represented in a simplified model [14]. Annual precipitation data obtained from a nearby weather station are classified into four rainfall categories (see Table 1). At the beginning of each simulated year a random rain class is determined according to a probability distribution. Interannual dynamics are unknown and therefore randomized.

While a simulation step in the implicit model covers one year, the spatially explicit model has a daily resolution. To determine the daily amount of precipitation the annual amount of rain $r(t)$ (see Table 1) in the region is uniformly distributed among the 181 days of the rainy season.

Relevant aspects of vegetation dynamics are considered in the vegetation model. The modeled grass layer includes annual and perennial grasses. Annual grasses conclude their whole life cycle in a single vegetation period and outlast unfavorable seasons as seed in the soil. Perennial grasses cover the soil the whole year.

Plant growth is updated daily. It is determined by the growth functions (1) and (2) which use the amount of precipitation $r(t)$ and the degree in which the vegetation can make use of it [14]. This degree is termed as rain use efficiency (RUE).

Perennial biomass growth: $$b_i^{per}(t) = RUE[sd_i, c_i(t)] \times r(t) \qquad (1)$$

Annual biomass growth: $$b_i^{ann}(t) = RUE(sd_i) \times r(t) \qquad (2)$$

To calculate primary production of annual grasses b_i^{ann} (measured in kg dry mass per hectare) of a cell i, the RUE has to be determined in dependence of soil depth sd_i (see Table 2). The RUE for perennial vegetation growth b_i^{per} depends on the type of soil and on the ground cover density c of grasses. A dense grass layer is more able to utilize precipitation more efficiently than a sparse one. Cover values are assigned to four classes, 0 standing for minimal and 3 standing for maximal cover. The determination of cover class c of a cell i in the year t depends on precipitation $r(t)$, soil depth sd_i, the previous year's cover class $c_i(t-1)$ and grazing pressure.

The parameter grazing pressure provides information about how strong a cell has been exploited by cattle herds in the last year. It is measured by the ratio of grown to consumed and trampled biomass.

Soil depth *sd*	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	1,3

Table 2: Rain Use Efficiency of deep and shallow soils, and for perennial grasses and annual plants, in dependence of previous year's grazing pressure.

Because savanna environments do not provide infinite capacity for plants (biomass capacity for shallow soil: 1.5Mg/ha, for deep soil: 1Mg/ha), there is an interspecific competition between annual and perennial grass species. This competition is modeled by preferring the growth of perennial grasses and hence allowing them to occupy available space first. The natural plant decay is implemented by specific decay rates of plant groups (annuals and perennials). The biomass of perennial grasses monthly decreases by 5%, the biomass of annual grasses by 20%. Additionally the annual grass biomass is set to zero at the end of the dry season because natural decay accelerates considerably with the onset of the first rains.

Herds are modeled as hierarchical agents. Herd agents choose a context-specific mobility decision out of a pool of principal decisions according to their rules of behavior. Their subsidiary agents represent groups of cattle, which move randomly over their dedicated pasture. For a change of pasture all groups reunite to a single herd and move to the new pasture.

Grazing offtake, i.e. the amounts of grass biomass consumed by cattle, depends on grass types' proportion of the total biomass of a cell (6.85kg per cattle and day). The loss due to trampling (about 10kg/day) is calculated likewise. The demographic herd development includes births (calving rate: 20% per year), age caused deaths and the slaughtering and selling of cattle.

The physical shape of the cattle herds and subherds is modeled as a counter. If the current cell does not provide enough fodder for the group, the counter is incremented, otherwise stepwise decremented down to zero. The group is considered to be starved and taken out of the simulation when the counter reaches 28, because cattle can only stay without food for four weeks. The consequences of human behavior are integrated into the model through grazing management strategies. Human mobility decisions are the major aspect of this model, because of their great importance for ecosystem dynamics.

The patterns of pasture utilization are embedded into the agents' behavioral rules. They are designed to account for both foreseeable and unforeseeable environmental changes by appointing scheduled and unscheduled pasture alterations. An exemplary set of rules is shown in Figure 4. With the help of an additional set of simulation parameters, e.g. number and sizes of herds, potential vending options, or the level of stock reduction rates, the agents' strategy is further specified.

```
Check at beginning of DS: if DSP provides enough fodder        then go there
                                                               else go to RFD
Check at beginning of RS: if RSP provides enough fodder        then go there
                                                               else stay on p
Check every day t: if p does not provide enough fodder then
        if p is RSP then
                if DSP provides enough fodder
                        then go there
                        else go to RFD
        if t is in RS then
                if p is DSP and (RSP provides enough fodder or DSP provides enough fodder)
                        then go there
                        else go to RFD
                if p is RFD and (RFD provides enough fodder or DSP provides enough fodder)
                        then go there
                        else increase PSC
        if t is in DS then
                if p is DSP then
                        if another DSP provides enough fodder
                                then go there
                                else go to RFD
                if p is RFD then
                        if DSP provides enough fodder
                                then go there
                                else increase PSC
        if PSC >= 28 then die
```

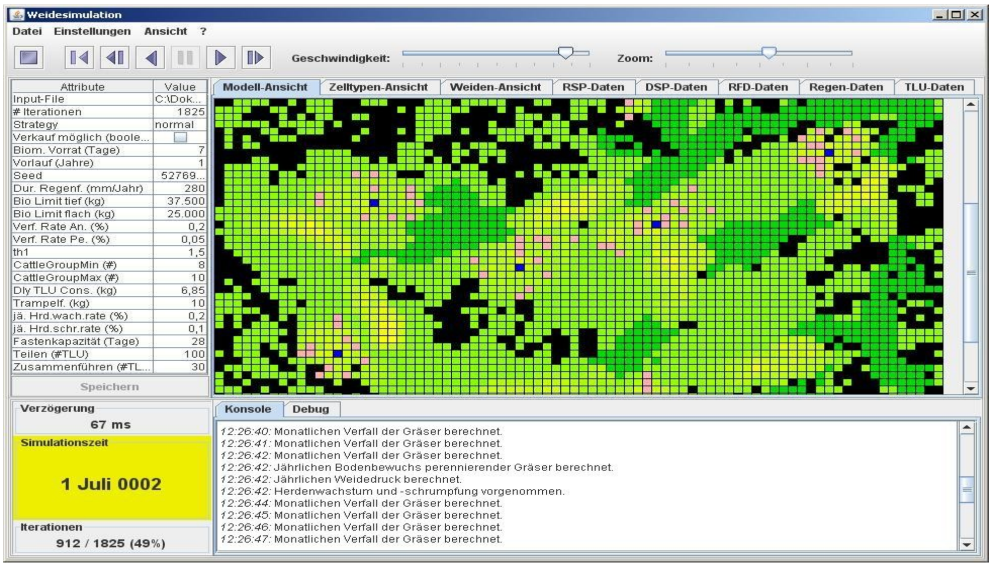
Figure 4: Exemplary set of rules (p: current pasture, t: current day, RS: rainy season, DS: dry season, RSP: available rainy season pasture, DSP: available dry season pasture, RFD: available pasture reserved for drought, PSC: physical shape counter)

4 Implementation of an agent-based simulation application

The designed model has been implemented in an interactive simulation tool to assess the effects of various pasture management strategies in an arid savanna ecosystem [8]. To support field operability the application should be platform independent and involve no license fees. For this purpose a visual simulation and analysis software has been developed in Java.

Experts are able to control scenarios through interactive parameter adjustments within the developed application. The simulation run is visualized through schematic views on pasture and vegetation models (see Figure 5). The application supports preliminary interpretation and evaluation of simulation results. It is possible to export data streams to auto generated Excel files to allow importing to statistical programs for further processing.

The cattle herds and groups are designed as hierarchical agents implementing the herd and strategy models. The agents move across a grid of cells according to their behavioral rules. This cellular automaton implements the landscape, precipitation, vegetation, and pasture models. The current states of the cells derive from environmental conditions (like precipitation and grazing pressure) and their previous states. Mutual influences of the cells due to their neighbourships do not exist. The agents interact with each other implicitly through occupying and grazing down the pastures. Interaction between the agents and the cellular automaton is expressed through grazing pressure and biomass recovery.



Attribute	Value
Input-File	C:\Dok...
# Iterationen	1825
Strategy	normal
Verkauf möglich (boole...	☐
Biom. Vorrat (Tage)	7
Vorlauf (Jahre)	1
Seed	52769...
Dur. Regenf. (mm/Jahr)	280
Bio Limit tief (kg)	37.500
Bio Limit flach (kg)	25.000
Verf. Rate An. (%)	0,2
Verf. Rate Pe. (%)	0,05
th1	1,5
CattleGroupMin (#)	8
CattleGroupMax (#)	10
Dly TLU Cons. (kg)	6,85
Trampelf. (kg)	10
jä. Hrd.wach.rate (%)	0,2
jä. Hrd.schr.rate (%)	0,1
Fastenkapazität (Tage)	28
Teilen (#TLU)	100
Zusammenführen (#TL...	30

Verzögerung: 67 ms

Simulationszeit: 1 Juli 0002

Iterationen: 912 / 1825 (49%)

```
12:26:40: Monatlichen Verfall der Gräser berechnet.
12:26:41: Monatlichen Verfall der Gräser berechnet.
12:26:42: Monatlichen Verfall der Gräser berechnet.
12:26:42: Jährlichen Bodenbewuchs perennierender Gräser berechnet.
12:26:42: Jährlichen Weidedruck berechnet.
12:26:42: Herdenwachstum und -schrumpfung vorgenommen.
12:26:44: Monatlichen Verfall der Gräser berechnet.
12:26:45: Monatlichen Verfall der Gräser berechnet.
12:26:46: Monatlichen Verfall der Gräser berechnet.
12:26:47: Monatlichen Verfall der Gräser berechnet.
```

Figure 5: Application screenshot

The evaluation of potential pasture management strategies has to be based upon reliable data. This is why close attention was paid to validating the models. Because of a lack of detailed datasets a data driven validation turned out to be difficult. Therefore function and theory based validation were applied. In the course of function based validation [10] the reactions of the submodels to given stimuli were tested and compared to the analytically expected behavior. The influence of chance was eliminated by replacing random values by predetermined values for a better comparison. Results show that biomass production corresponds with analytically expected values.

In the course of theory based validation simulation runs of the spatial explicit model were compared to those of the spatially implicit model with the same parameter configuration. It was shown that significant results like cattle population demographics concurred in tendencies (see Figure 6). The deviation in total numbers is caused by the different nature of the two models. In contrast to the spatial explicit model the implicit model makes no difference between potential and actually used pastures, and thus systematically overestimates cattle numbers.

In the implicit model the less significant dataset of the biomass composition of perennial and annual grasses is calculated with low accuracy in the event of heavy grazing pressure. Apparently the spatially explicit type of modeling is of significant effect in this case.

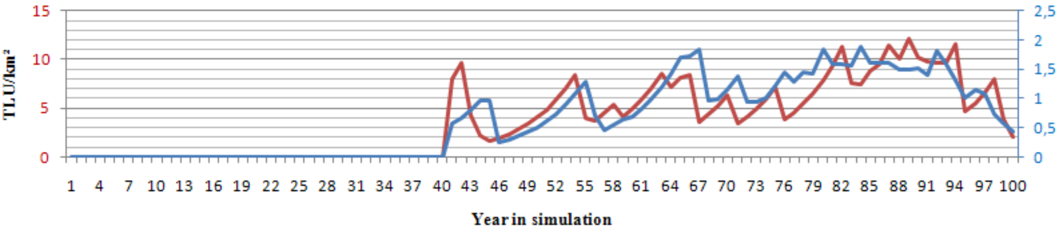


Figure 6: Comparison of herd population dynamics (red: spatially implicit model [14], blue: spatially explicit model)

5 Conclusions and further research

Based on a spatially implicit model an agent-based model for analyzing pasture management strategies of the Himba people living in the Omuramba basin has been designed, implemented and validated. Through the explicit consideration of spatial effects, the impact of pastoral-nomadic management decisions on arid ecosystems can be modeled. In particular consequences of human behavior on the ecosystem of the region have been visualized by modeling pasture management strategies for the first time.

Some possible directions for further development are a more realistic handling of precipitation and a better representation of interspecific competition. Second, a revision of the herd model would allow cattle groups to move without being restricted by pasture boundaries and allow different herds to use the same pastures at the same time. This might converge to the classic swarm behavior of Reynolds [16].

In future work the consequences of different pasture management strategies will be analyzed and compared with the help of the simulation software. In an additional subproject the influence of social networks on the risk management in arid ecosystems will be studied.

6 References

[1] *Becker, T.; Jürgens, N.*: Vegetation along climate gradients in Kaokoland, North-West Namibia. Phytocoenologia 30 (2000), p. 543-565.

[2] *Beerling, D. J.; Osborne, C. P.*: The origin of the savanna biome. Global Change Biology 12 (2006), p. 2023-2031.

[3] *Behnke, R. H.; Kerven, C.*: Redesigning for risk: tracking and buffering environmental variability in Africa's rangelands. Natural Resource perspectives 1 (1994), p. 1-7.

[4] *Bollig, M.*: Risk management in a hazardous environment – a comparative study of two pastoral societies. New York: Springer (2006), p. 1-324.

[5] *Bollig, M.*: The colonial encapsulation of the north-western Namibian pastoral economy. Africa 68 (1998), p. 506-535.

[6] *Bollig,M.; Schulte, A.*: Environmental change and pastoral perceptions: degradation and indigenous knowledge in two African pastoral communities. Human Ecology 27 (1999), p. 493-514.

[7] *Gillson, L.; Hoffman, M. T.*:Rangeland ecology in a changing world. Science 315 (2007), p. 53-54.

[8] *Kuckertz, P.*: Entwurf und Entwicklung einer Anwendung zur Simulation des Weidemanagements des Volks der Himba in Namibia. Diploma Thesis, University of Cologne (2010).

[9] *Leggett, K.;Fennessy, J.; Schneider, S.*: Does land use matter in an arid environment? A case study from the Hoanib River catchment, north-western Namibia. Journal of Arid Environments 53 (2003), p. 529-543.

[10] *Liebl, F.*: Simulation – Problemorientierte Einführung. München, Wien: Oldenbourg Verlag (1995), p. 203f.

[11] *Linstädter, A.*: Landscape ecology of savannas – from disturbance regime to management strategies. In: *Bollig, M.; Bubenzer, O.* (eds.), African Landscapes: Interdisciplinary Approaches. New York, London: Springer (2008), p. 79-103.

[12] *Linstädter, A.; Bolten, A.*: Space matters – sustainable range management in a highly varable environment. Atlas of Cultural and Environmental Change in Arid Africa. Cologne: Africa Praehistorica 21 (2007), p. 104-107.

[13] *Mathews, R.; Gilbert, N.; Roach, A.; Polhill, J.; Gotts, N.*: Agent-based land-use models: a review of applications. Landscape Ecology 22 (2007), p. 1447-1459.

[14] *Müller, B.; Linstädter, A.; Frank, K.; Bollig, M.; Wissel, C.*: Learning from local knowledge: modeling the pastoral-nomadic range management of the Himba, Namibia. Ecological Applications, Volume 17 (2007), p. 1857-1875.

[15] *Parker, D. C.; Manson, S. M.; Janssen, M. A.; Hoffmann, M. J.; Deadman, P.*: Multi-agent systems for the simulation of land-use and land-cover change: a review. Annals of the Association of American Geographers 93 (2003), p. 314-337.

[16] *Reynolds, C. W.*: Flocks, Herds and Schools: A Distributed Behavioral Model. Computer Graphics, Volume 21/4 (1987), p. 25-34.

[17] *Sander, H.; Bollig, M.; Schulte, A.*: Himba Paradise lost. Stability, degradation, and pastoralists management of the Omuhonga Basin. Die Erde 129 (1998), p. 301-315.

[18] *Schulte, A.*: Stabilität oder Zerstörung? Veränderung der Vegetation des Kaokolandes unter pastoralnomadischer Nutzung. Kölner Geographische Arbeiten 77 (2002), p. 101-118.

[19] *Solbig, O. T.; Medina, E.; Silva, J. F.*: Biodiversity and Savanna Ecosystems processes. A Global Perspective. Berlin: Springer (1996).

[20] *Tietjen, B.; Jeltsch, F.*: Semi-arid grazing systems and climate change: a survey of present modeling potential and future needs. Journal of Applied Ecology 44 (2007), p. 425-434.