BIOMASS CHANGES IN NORTH-WESTERN NAMIBIA: FIRST RESULTS FROM A REMOTE SENSING MODELLING APPROACH

Jochen Richters

University of Bonn, Department of Geography, Bonn, Germany; richters(at)rsrg.uni-bonn.de

ABSTRACT

The development of a vulnerability index for the evaluation of environmental changes in north-western Namibia is a central research topic within the interdisciplinary research project ACACIA (Arid Climate Adaptation and Cultural Innovation in Africa). The calculation of aboveground phytomass (= biomass) and its seasonal productivity by using a mesoscale biosphere model based on satellite data is of specific interest. The research area, Kaokoveld (north-western Namibia), is characterised by a strong hydro-climatic gradient with an annual precipitation range from 380mm/a in the north-eastern part of the research area to 50 mm/a at the border of the Namib Desert. Small-scale vegetation patterns with fractions of savannah, woody savannah, open and closed shrub land and grassland reflect this climatic gradient and the heterogeneous relief. The research area is partly used by local herders of the Himba people as pasture ground for their livestock. This causes problems such as overgrazing and degradation of the vegetation. Together with the impact of climate change the known ecological gradients have aggravated during the past decade.

With the remote sensing based regional biosphere model (RBM Kaokoveld) quantitative information about biomass changes and pasture ecology can be determined. The growth and the reduction of biomass can be observed using the theory of Monteith (1972) and Running et al. (2000). In this modelling approach, biomass production is derived from the combination of incoming solar radiation, normalized difference vegetation index (*NDVI*), resulting from MODIS data, and a bio-physical conversion factor, which describes the ability of plants for net primary production (*NPP*). The regional biosphere model allows detailed information on an area-wide biomass balance to be extracted using remote sensing. This balance describes the production as well as the consumption of biomass by cattle and game and its natural decomposition. The modelling approach runs on medium temporal and spatial scales with a decadal time step and a spatial resolution of 1 by 1 km^2. The results of this modelling approach have been checked and evaluated in three different ways. Thus, the model provides reliable data.

The model uses a four-year time series of MODIS data from 2000 to 2003, with biomass changes and degradation areas as results. In the detailed result for the years 2001 and 2002, in wide areas of Kaokoveld, a reduction of biomass production by more than 10 g/m^2 can be observed. These changes may be explained by the different rainfall patterns between the two observed years 2001 and 2002.

Keywords: NPP, biomass model, MODIS, Namibia

INTRODUCTION

The ability of plants to build up organic matter from light and Hcarbon dioxide by using photosynthesis is a foundation pillar for the life on earth. Vegetation plays a key role in the development of the planet. The use of remote sensing data for observing the Earth's surface allowed large-scale studies of changes in the biosphere for the first time. While the observation of vegetation and the carbon cycle through remote sensing has been mostly carried out at a global scale (T1,2,3,4), hardly any studies were done for regional analysis.

Besides empirical approaches to derive plant biomass from remote sensing data a wide field of physical-based models are available. The empirical approaches use the regression between a vegetation index (e.g. *NDVI*) and measured biomass data (e.g. 5,6,7). Another concept is used for the physical-based models, where the key factors for plant development are extracted from remote sensing data to calculate the production of plant biomass.

Moderate resolution spaceborne sensors such as MODIS (Moderate Resolution Imaging Spectro-radiometer) onboard the Terra and Aqua satellites, and AVHRR (Advanced Very High Resolution Radiometer) onboard the NOAA (National Oceanic and Atmospheric Administration) series satellites are tools to monitor land cover at national, regional and global scales. AVHRR and MODIS have wide observation swaths and high observation frequencies. For example, MODIS observes the entire globe every two days with its 2,330-km wide swath (2). By using five different daily data products from MODIS onboard EOS-1 TERRA and two constant datasets, namely a digital elevation model and global soil information, the aboveground biomass in terms of net primary production (*NPP*) can be calculated as 10-day time steps and as an annual sum.

Since 1973 scientists try to model biomass production. Monteith (8) was the first to calculate biomass by linking the incoming radiation to agricultural production through an empirical biophysical conversion factor. Potter et al. (1) used this approach for global biomass calculations and extended it to natural vegetation. Running et al. (9) introduced this concept for the calculation of the MODIS *NPP* product by using satellite data to derive the fraction of photosynthetic active radiation from remote sensing data. In contrast to these approaches, the regional biosphere model ‘RBM Kaokoveld’ is a regional modelling approach to determine the aboveground *NPP* on a temporal scale of 10 days and a spatial resolution of 1×1 km^2.

In the semi-arid research area of north-western Namibia the aboveground biomass and the natural vegetation are important items for the pasture system of the local herders of the Himba people. Variation in precipitation may cause drought and thus overgrazing of the declining vegetation and starvation among the cattle. Especially the grass layers as well as the litter from trees are the main feeding sources. The study area of Kaokoveld is located in the north-western part of Namibia between 17° and 19° south and 12° to 14° east (Figure 1).

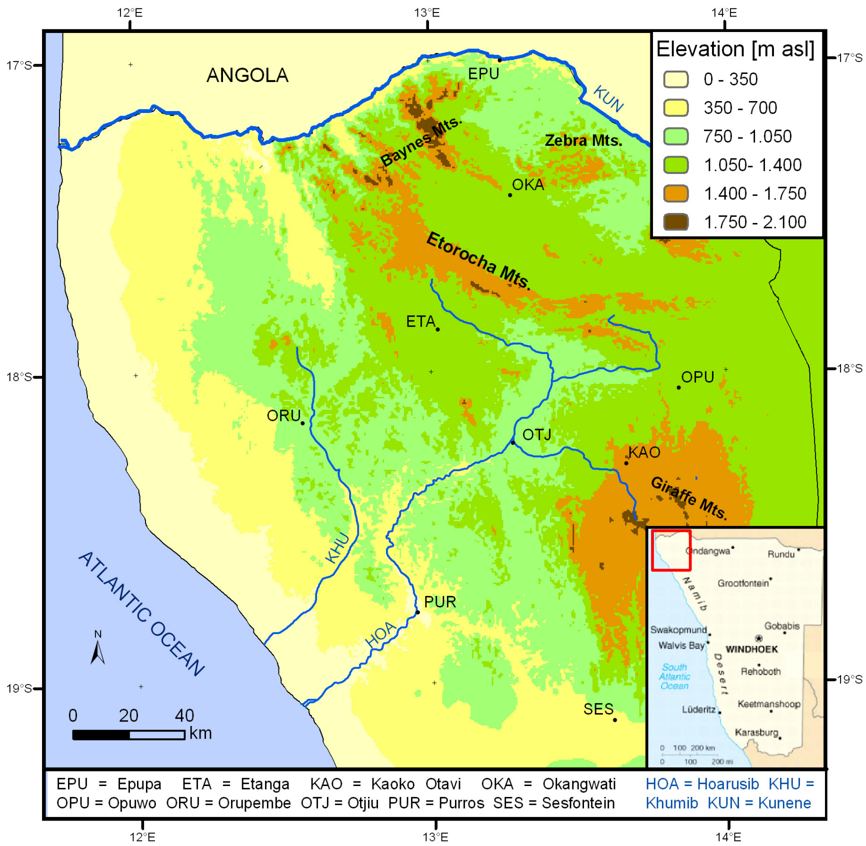


Figure 1: Overview map of the research area.

The area is mostly covered by semi-arid shrub land and savannah with a strong precipitation gradient from about 380 mm/a in the north-east to 50 mm/a at the border of the Namib Desert. Due to the small-scale relief, a heterogeneous pattern of open and close shrub lands, savannahs and woody savannahs has developed.

The topography of the region is determined by the great escarpment oriented to the western slope down to the Atlantic Ocean. The plain of the skeleton coast gently reaches up from the shoreline to about 500 m. The main ridges and basins range from 800 to 1,300 m and are overtopped by a number of mountains such as Zebra Mts., Baynes Mts. or Giraffe Mts. with heights of up to 2,600 m. The area is structured by three main fluvial systems. The Kunene River builds the northern border of Namibia and is one of three perennial rivers of Namibia, whereas the other rivers in the research area such as Khumib and Hoarusib are episodic.

“Net primary production, sensu stricto, is the total photosynthetic gain of vegetation per unit ground area and per time unit” (10). The *NPP* comprises the part of respiration cost. The gross growth of plant biomass is called biomass production. Thereby it is necessary to differentiate between the below- and aboveground biomass (11). In the approach of this paper just the above ground biomass is observed due to the limitations of optical remote sensing techniques, but also because the approach aims at providing information on the amount of pasture and the possibilities for cattle feeding.

METHODS

Experiments of Monteith (8,12) showed that the increase of plant biomass (*NPP*) from well drained manuring crops can be represented by the following Eq. (1):

$$NPP = APAR \cdot LUE \tag{1}$$

where *NPP* is the net primary production, *APAR* is the absorbed fraction of photosynthetically active radiation and *LUE* is an empirical light use efficiency factor. Seller (13), Asrar et al. (14) and Frouin & Pinker (15) have shown that *PAR* and *APAR* can be derived from remote sensing data by using the normalized difference vegetation index (*NDVI*) which uses the wavelength in the red (*RED*) and infrared (*NIR*):

$$NDVI = \frac{NIR - RED}{NIR + RED} \tag{2.a}$$

and

$$\frac{APAR}{PAR} \approx NDVI \tag{2.b}$$

where *PAR* is the photosynthetically active radiation. Thus, spectral vegetation indices like the *NDVI* have a strong link to the fraction of photosynthetically active radiation that is absorbed (*APAR*) (14,16). When the *APAR* is derived from *NDVI* and driven by the photosynthetically active radiation within 10 days and is converted by the *LUE*, the biomass production per time step can be expressed as in Eq. (3):

$$NPP = NDVI \cdot PAR \cdot LUE \tag{3}$$

where *NPP* is the net primary production, *NDVI* is the portion of *APAR*, *PAR* is the incoming solar radiation in the photosynthetic spectrum and *LUE* is a biophysical conversion factor. In the regional biosphere modelling approach, *PAR* is derived from a budget modelling approach (17), with the potential solar radiation calculated from the geographical location and relief parameter (18,19). The incoming energy is diminished by the transmission of the local atmospheric conditions and reduced to the photosynthetically active radiation by a factor of 0.48. The *LUE* is a conversion factor which transforms the incoming energy from the photosynthetically active wavelength into the produced biomass of green vegetation. This factor primarily depends on the treated biome representing the different coverage of grass, tree and bare soil. Furthermore, the *LUE* is influenced by relief and soil properties. Finally, the *LUE* depends on the weather conditions which control the opening and closing of stomata. That is why temperature stress and water stress are taken into account. While temperature stress – as suggested in (1) for the global scale – is not relevant to the Namibian research area, water stress is the most limiting factor of biomass production. As neither rainfall gauges nor rainfall estimations are available in a useful spatial resolution, water stress is derived from a comparison between potential and effective evapotranspiration (20,21).

The input data for the modelling consists of four different datasets from the MODIS sensor and two auxiliary datasets. All MODIS datasets are available as daily data with a spatial resolution of 1×1 km^2. Before these datasets can be used in the model, they must be combined to 10-day composites and resized to the same spatial extent, resolution and projection. The *NDVI* in Eq. (3) is derived from the MODIS dataset MOD09GHK (Surface Reflectance) as default calculation from channels 1 and 2. The MODIS dataset MOD11 (Land Surface Temperature and Emissivity) is used to obtain the physical parameters *temperature* and *emissivity*. These parameters are used for the examination of temperature stress and water stress which modify *LUE*. The water stress is also influenced by water vapour, derived from the MODIS dataset MOD05 (Total Precipitable Water). Additionally, the cloud cover per time step is also extracted from this data set. The *LUE* primarily depends on the biome description of each modelling cell acquired from the yearly MODIS dataset MOD44b (Vegetation Continuous Fields). Furthermore, two constant datasets for relief and soil information are integrated into the model. The global digital elevation model GTOPO30 from NASA DAAC (22) is used for the potential growth efficiency and for the calculation of the potential insolation (17). The Digital Soil Map of the World (DSMW) published by FAO (23) is the best available soil information for the study area. It is sufficient for this regional modelling approach. The following flowchart (Figure 2) shows the paths of the input datasets and of the intermediate products for the biomass calculation.

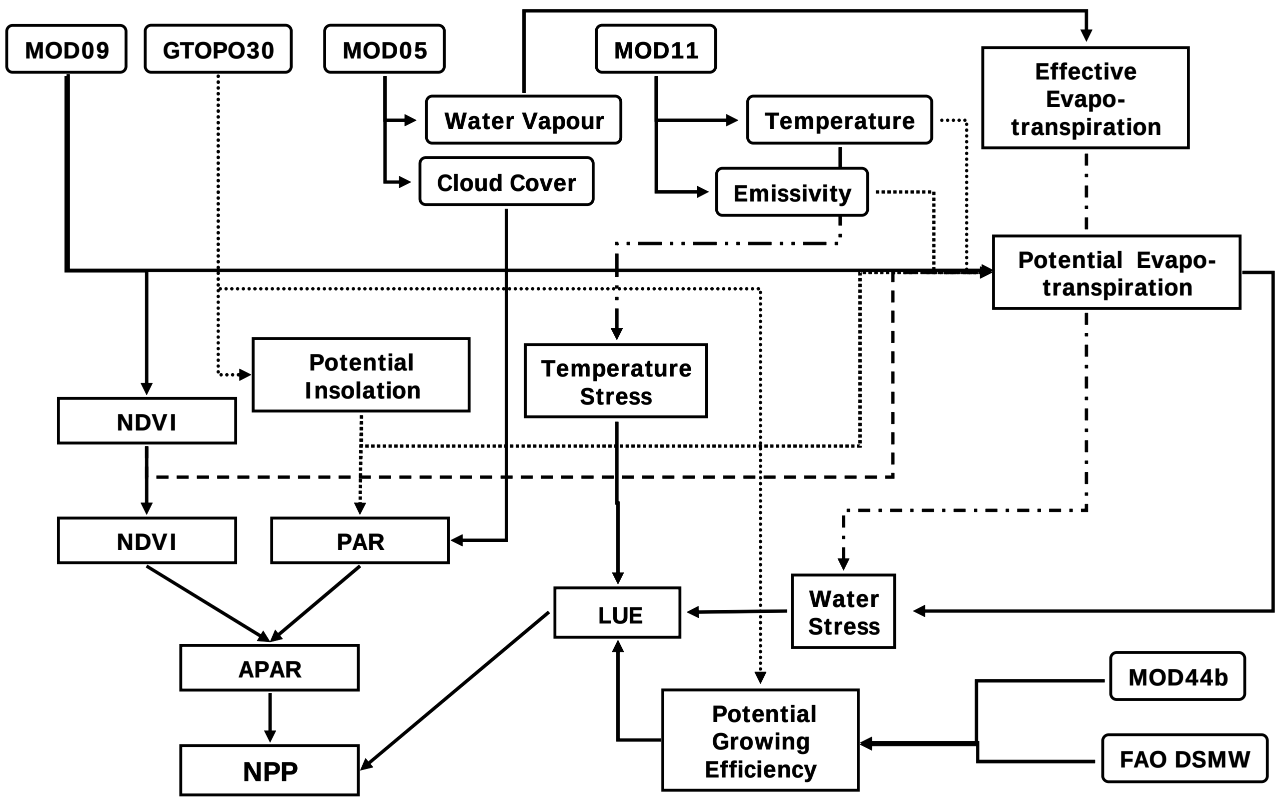


Figure 2: Flowchart of input data for the regional biosphere model RBM. Four MODIS datasets and two auxiliary datasets are integrated into the model.

The light use efficiency (*LUE*) is calculated within the model in two steps. On a yearly basis, the potential growth efficiency (*PGE*) is related to the vegetation composition of each modelling cell and combined with soil and relief information. The vegetation composition is represented by the coverage of grass/herbal layer and tree layer within the cells from the MODIS MOD44b dataset and the maximum biophysical conversion factor under best growing conditions for each coverage type. These conversion factors are empirically derived from literature (1,9,21,24). Slope and height are derived from the DGM GTOPO30 and used to build a relief factor scaling from 0 to 1 to adjust the maximum biophysical conversion factor. On steep slopes, biomass production is limited due to relief (25). Different soil properties also limit biomass production. A soil scaling factor from 0 to 1 is determined depending on texture as proxy data for potential water storage capacity and on soil C/N relation as proxy data for soil nutrient (26). This spatially distributed data is derived from FAO's digital soil map of the world. The two factors which represent relief and soil are mostly invariant over the year within the model and are combined with the potential growth efficiency (PGE) per modelling cell by using a fuzzy logic approach (27,28).

On the basis of the 10-day time steps, temperature und water stresses are used to diminish the *PGE* to the level of the actual *LUE*. While the temperature stress is widely scaled and does not minimise biomass production, water stress plays an important role in a semi-arid climate (29,30). The temperature is calculated from the MODIS MOD11 data product as the mean of day and night time temperatures using a minimum-maximum approach to get the daily temperature (31). They are then calculated as the mean over ten days. The temperature stress factor is calculated by Eq. (4):

$$T_{Stress} = 0.8 + 0.02T - 0.0005T^2 \quad (4)$$

where T is the temperature for each model cell.

The derivation of the water stress factor is more important, because water is the most limiting factor for plant growth and biomass production (32). The water stress, calculated from the potential evapotranspiration (*PET*) in comparison to the effective evapotranspiration (*EET*), follows Eq. (5):

$$W_{Stress} = 0.5 + 0.5\frac{EET}{PET} \quad (5)$$

The potential evapotranspiration (*PET*) is derived from an evaporation model based on the Priestley-Taylor equation (33). In former studies (34,35) it has been shown that the input parameter for the calculation of evaporation can be derived from remote sensing data at a local scale. For the *RBM*, these ideas have been adapted to be used at a regional scale using MODIS data. The evaporation model uses the incoming solar radiation, which is already calculated for the estimation of photosynthetically active radiation (*PAR*). In combination with MODIS surface temperature and emissivity it is used to calculate the heat budget for evaporation. This energy amount is then transferred to potential water vapour. For the estimation of the effective evapotranspiration (*EET*) the MODIS MOD05 water vapour product is used. It measures the total amount of water content in the atmosphere above a raster cell. While just about 10% of the water vapour can drop as rainfall to earth, most of the moisture stays in the lower parts of the atmosphere (31). A lot of climatologic studies in the semi-arid tropics in general and in the survey area in particular showed that rainfall events are primarily caused by convective processes and not by cyclones (36,37,38). Thus, the measured water vapour content of each raster cell is used as estimation for effective evaporation caused by convective rainfall.

Just as the calculation of the influence of relief and soil for the derivation of the potential growth efficiency (*PGE*), temperature and water stress are also defined as linear scaling parameters from 0 to 1. In contrast to the first step, these factors are not linked by fuzzy logic but are directly combined with *PGE* to *LUE* as the mean from T_{stress} and W_{stress} for each cell. Combining the described factors to derive *LUE* guarantees that the local weather as well as the more invariant features from soil and relief conditions are taken into account.

RESULTS

The regional biosphere model (RBM) is used to calculate biomass at a spatial resolution of 1×1 km^2 and a temporal resolution of ten days. The result of this calculation for the year 2002 is presented in Figure 3. The basis for this modelling is a time series of the described MODIS datasets.

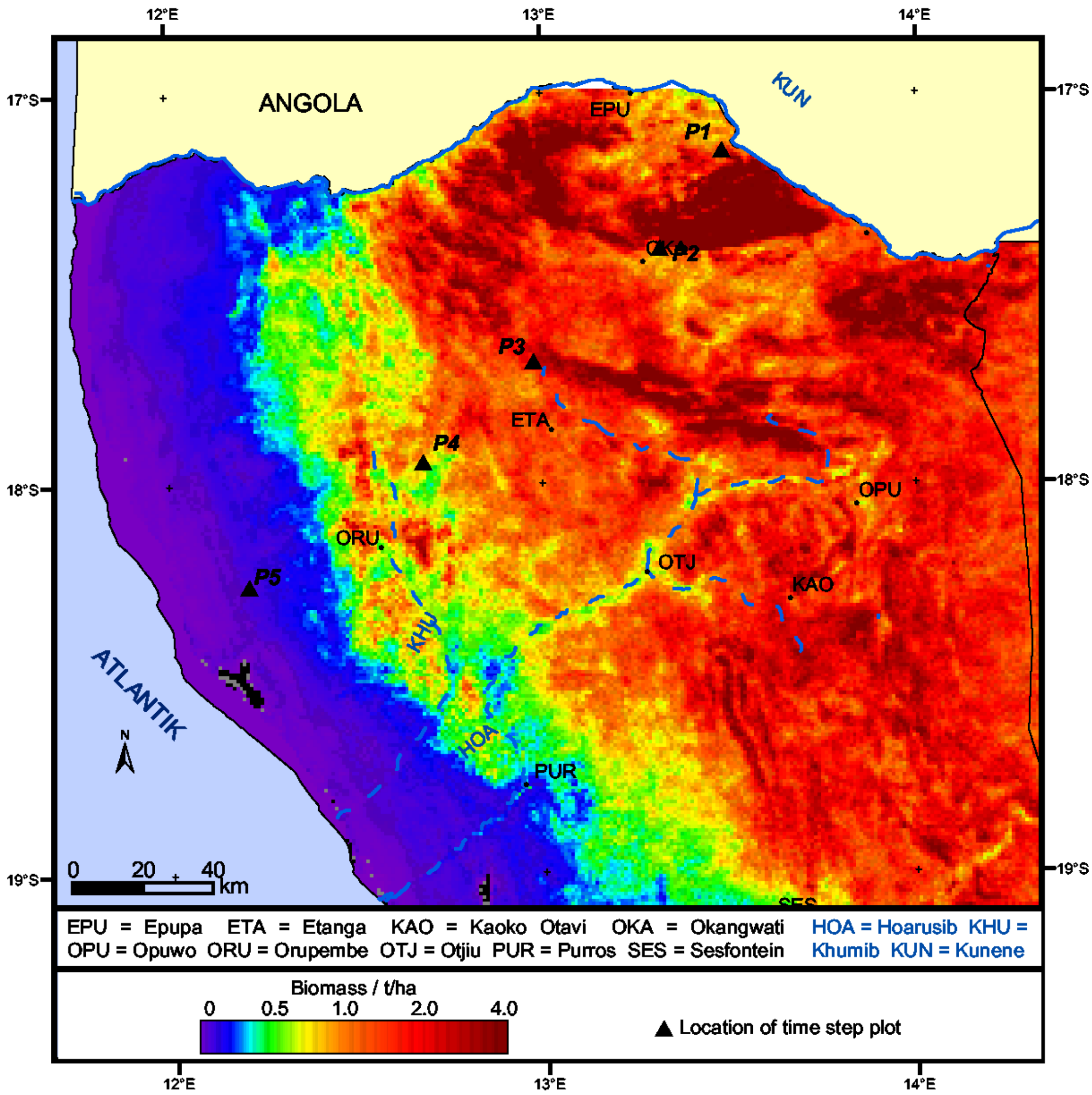


Figure 3: The calculated total biomass for the research area in northern Namibia summed up for 2002 as a result of the modelling. The maximum spots of biomass production are the higher mountains such as the Zebra Mts. north-east of Okangwati with high tree coverage. P1 to P5 are the locations of the time series plots as visualised in Figure 4.

There is a distinct gradient in the distribution of plant biomass from NE to SW. Some mountainous areas such as the Zebra Mountains (north-east of Okangwati) or the Etorocha Mts. (northern Opuwo - Etanga) show extraordinarily high biomass production caused by a high percentage of tree cover. The *LUE* of a single raster cell depends on the empirical conversion factor, which is higher for areas with high tree coverage. While the deeper parts of the basins and valleys in the centre of the research area produce about 2.1 t/ha of biomass, the biomass growth on the downward slope of the Namib Desert is almost zero.

The annual product as illustrated in Figure 3 is the sum of the primary result from the model, this means a product of 10-day biomass production. This data can be visualised as time series along a gradient from the north-eastern part of the research area to the south-western part into the Namib Desert as presented in Figure 4.

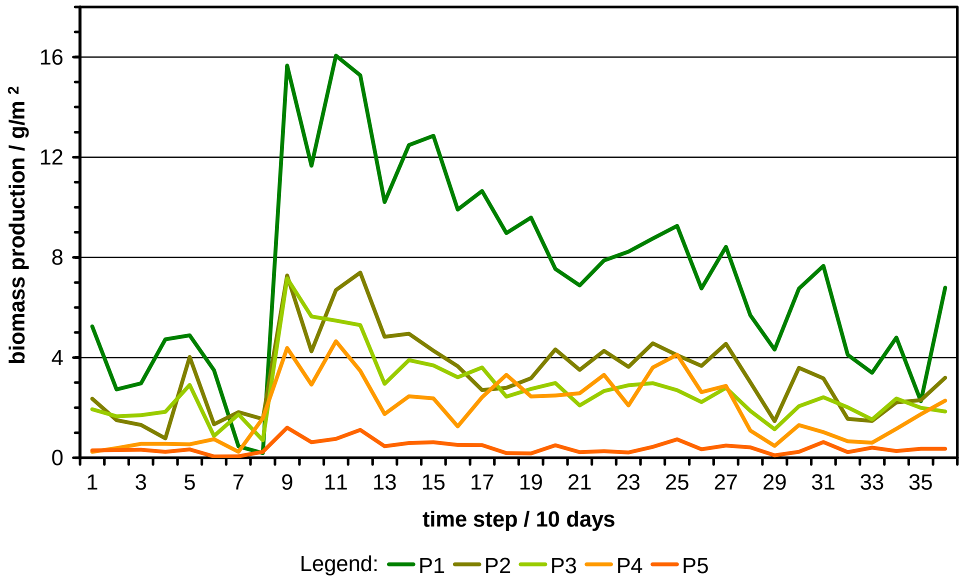


Figure 4: Time series plots of the year 2002 biomass production from selected sites (P1 – P5) as marked in figure 3. The strong increase of the biomass production reflects - with some delay- the rainy season in the beginning of the year (time step 1-7).

Figure 4 shows a general increase of biomass production during the rainy season, which starts at time step 8 (10–19 March 2002) for all observed spots (P1 – P5). A smaller production peak for the spots P1, P2 and P3 can be detected for the fourth to fifth time step (1–19 February 2002), due to higher precipitation events in the north-western part of the research area in early February (personal communication). The strong increase of biomass development during the main rainfall events in March can be explained by the fast reaction of grass layer biomass, whereas especially in P1 the long attenuation of biomass production is a result of the tree coverage of 25 percent.

As a first step to discover vegetation changes, an evaluation of the biomass model is performed to assure the resulting quality. Afterwards, vegetation changes can be derived by comparing the development of biomass over different years.

DISCUSSION

Evaluation of Results

In general the evaluation of a regional modelling approach is difficult. This holds especially true for the research area in the semi-arid north-western Namibia. Nevertheless, an assessment of the input parameters as well as an evaluation of the results have been done. A main driving factor within the RBM is the distribution of shrubs, trees, grass layer and bare soil. Viljoen (39) describes a detailed plant study of Kaokoveld and presents a vegetation and coverage map of the area. The comparison of tree and grass coverage confirms the data from the MOD44b data. All the used MODIS data are at least classified as “stage 2 validated” data, which means that the “product accuracy has been assessed over a widely distributed set of locations and time periods via several ground-truth and validation efforts” (40) and guarantees a trustworthy quality of the input data. During the SAFARI2000 campaign in southern Africa in 2000, the MODIS sensor and its data products were validated in the Etosha National Park, Namibia, located eastern of the research area (41).

While the research process is still going on, three types of evaluation of the resulting data have been accomplished. First, a comparison of modelling results with data from literature was made. Secondly, the modelling results were compared to ground-based field data and finally the resulting dataset for the year 2002 was compared with other biomass data from the MODIS *NPP* product.

In the literature on plant ecosystems and global distribution of biomass, the net primary production (*NPP*) in the arid to semi-arid zone ranges from 0.5 to 4 t/ha (42,43,44), which corresponds to the results from the regional biosphere model. In more specific literature about the Kaokoveld and its vegetation in particular, biomass measurements correspond quite well to the RBM results. Concerning the basin of Omuramba (South of Epupa), Casimir & Bollig (45) measured a mean biomass production of 0.86 t/ha. The mean biomass production for the research area is about 0.87 t/ha.

From field trips in 2002 and 2003, biomass data from various spots all over the research area were collected with a distance-dependent sampling strategy. The data consists of grass biomass data, tree properties measurements, vegetation cover estimations and detailed descriptions of spot sides. The grass biomass data was collected by harvesting the grass layer (1×1 m^2) and weighing it. As the field trips were conducted after the maximum phenologic period at the beginning of the drying season, it was not necessary to dry the samples (32,45). This data can be used for independent evaluation of the modelled results, because it represents the real situation on the ground. Due to the problem of comparing 1×1 km^2 modelling results with rather small-scale field collected data, a minimum of ten 1×1 m^2 of grass biomass on each spot were collected. An average of this data for each spot is used to calculate a correlation. In Figure 5, the resulting linear correlation between the grass layer biomass of the field data and of the modelling results is calculated for the modelling year 2002. A sample size of 84 spots was used for this evaluation. The variance comprises about 82%. For a regional modelling approach this is very positive.

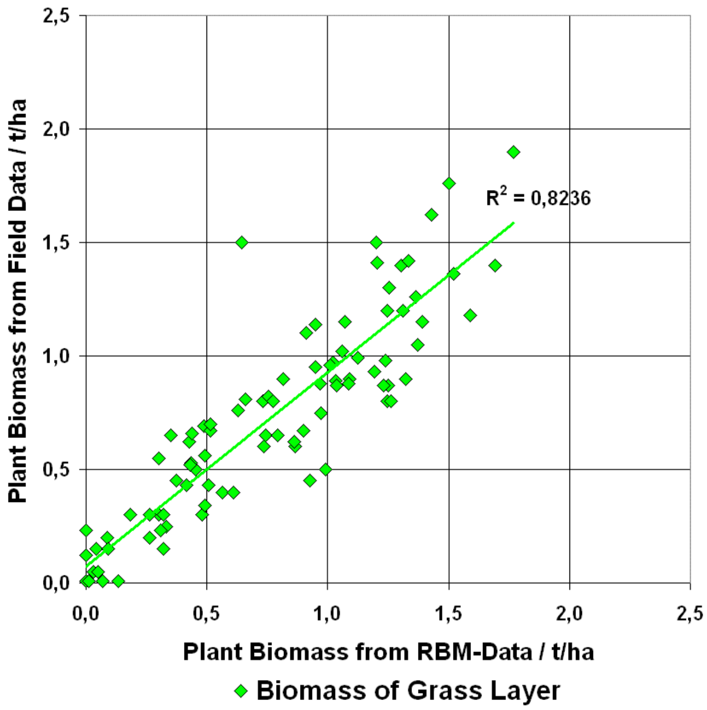
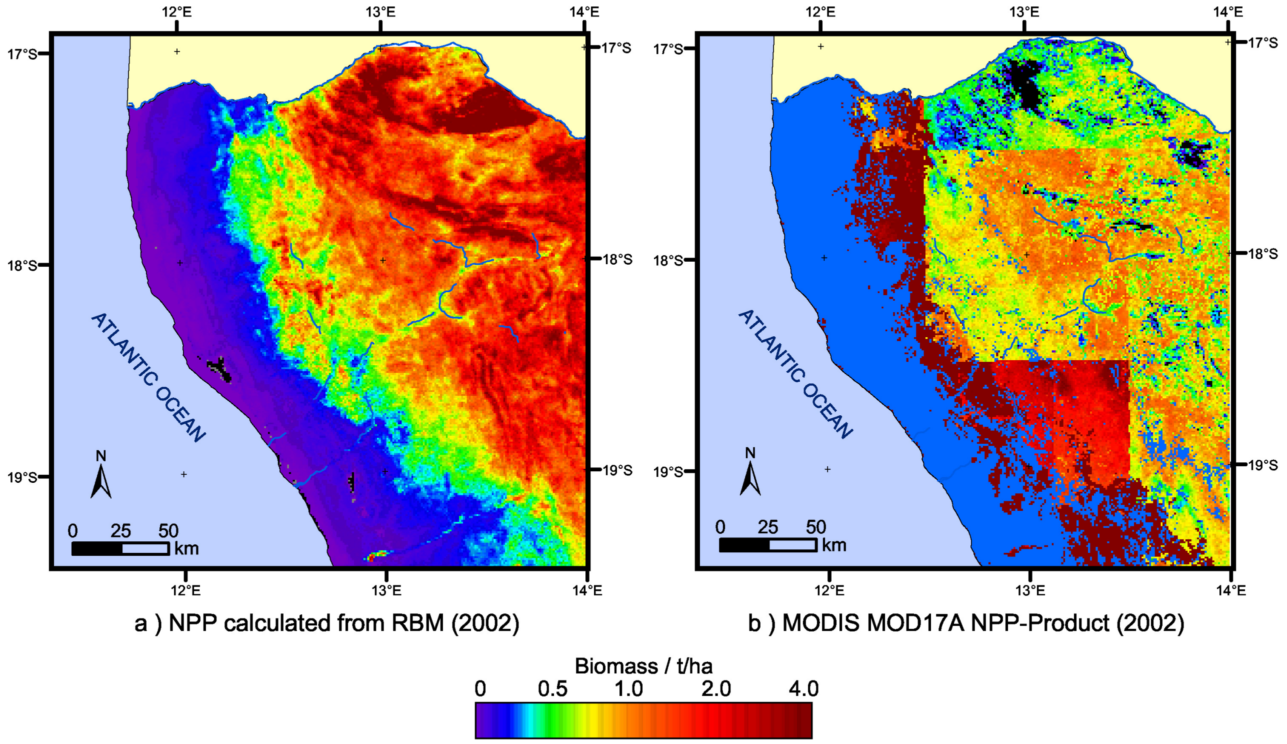


Figure 5: Correlation between grass biomass data from the field and from modelling data. The lower vegetated spots correspond closely to the regression line, while the higher biomass values scatter wider. The variance R^2 of this regression is 82.4%.

A comparison with other global or regional vegetation models (e.g. CASA (1), Biome-BGC (9) or C-Fix (46)) is usually difficult because of the different spatial sizes of raster cells and their model complexity. Most of these models simulate the whole carbon cycle with coupled nitrogen and soil moisture dynamics. A possible solution to this problem is a comparison with biomass data from other sources. The USGS publishes also a global MODIS *NPP* product (47). These datasets are freely available via http access and cover the research area. By using a global approach, the conditions of specific regions of the world cannot be mapped in detail. That is why the MOD17A *NPP* product contains a lot of block artifacts within the data (Figure 6).



a) NPP calculated from RBM (2002)

b) MODIS MOD17A NPP-Product (2002)

Figure 6: Comparison of biomass production from different modelling approaches: On the left hand the results from the RBM and on the right hand the results from MODIS17A NPP product, both summed for the year 2002. The regional model result shows a much smoother image without block artifacts. The colour representations of both datasets were scaled to the same legend.

In order to compare the two datasets derived from our model approach on the one hand and the MODIS dataset on the other, the biomass production over one modelling year is visually compared. By recalculating the results from the MODIS17A product at the spatial and temporal scales of the RBM output, a true visual comparison can be made. The block artifacts within the MODIS dataset and some data gaps in the northern part of the research area are very distinct. The approach in (47) uses global climate data with a spatial resolution of 1°×1° to parameterise the growing conditions. Probably because of an imprecise adaptation to the modelling cells, the coarse resolution of the input data can also be found in the results.

Table 1: Statistical comparison of the MODIS17A3 NPP product and the result of the 'RBM Kaokoveld' for the year 2000 as displayed in figure 6.

	Minimum / t/ha	Maximum/ t/ha	Mean / t/ha	STDEV / t/ha	Total /t
MOD17A3 (2002)	- 3,597	6,029	0,530	0,674	3.958.360
RBM Kaokoveld (2002)	0	4,132	1,194	0,813	9.533.970

The statistical comparison proves the tremendous differences between the two datasets. While the 'RBM Kaokoveld' has a minimum of 0 determined by the system, the MOD17A3 dataset provides a negative productivity. This unrealistic result may be caused by an imprecise adjustment of the global MODIS NPP product. The yearly maximum of productivity is much higher for MOD17A3, but the mean is less than half the mean of the 'RBM Kaokoveld'. In total, the MOD17A3 dataset yields a much lower total production than the 'RBM Kaokoveld'.

Biomass changes in Northern Namibia

The promising results from the biomass modelling can now be used for the detection of vegetation changes over several years. A wide range of change detection methods exist in the field of remote sensing (48,49). For this study, a simple differencing technique is used to compare annual biomass data from the years 2001 and 2002. Figure 7 clearly shows a decrease of vegetation between the years 2001 and 2002 in most of the research area. These changes can be explained through differences in the rainfall patterns over the research area.

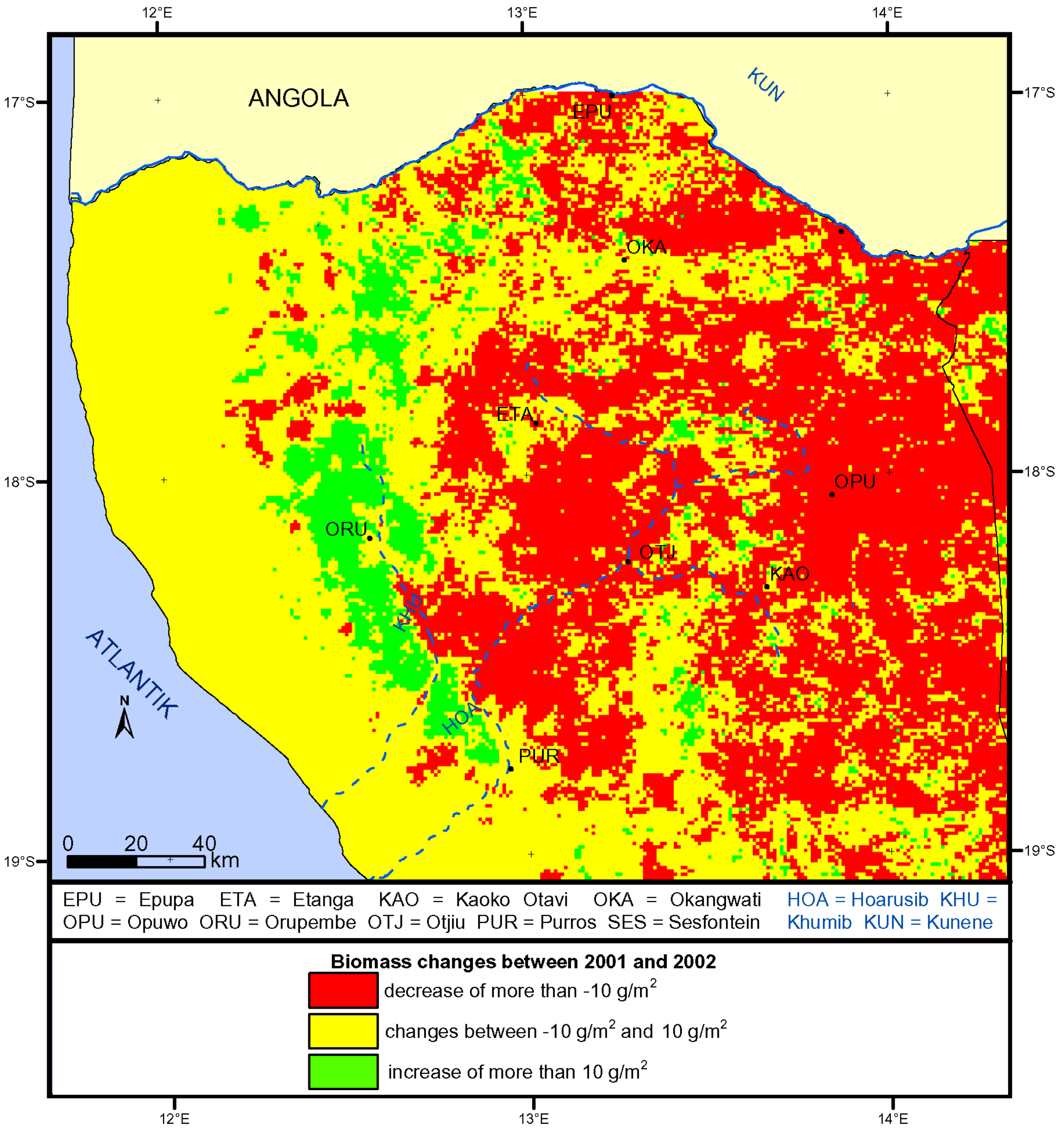


Figure 7: Biomass changes between two modelling years 2001 and 2002.

Even if there are rather no rainfall gauges to measure the precipitation, we have the subjective assessment of yearly rainfall by the local cattle herders of Himba people. The year 2001 has generally been evaluated as a good rainy season whereas the year 2002 was just sufficient and caused less biomass production in most parts of the Kaokoveld. The results of the 'RBM Kaokoveld' confirm these statements. Furthermore, the modelling results show that in contrast to the general trend, the margin of Namib Desert produced more biomass in 2002 than in 2001, in some areas more than 10 g/m^2.

CONCLUSIONS

Biomass production and vegetation development are important parameters for the understanding of ecosystem changes. The presented biomass model 'RBM Kaokoveld' uses known approaches for the derivation of aboveground biomass from remote sensing data at a regional level. Such a regional approach allows a better representation of the area-wide real situation at the ground. The most important advantage of the model itself is the exclusive use of globally available and cost-free datasets. The model is fixed in its regional scale of $1\times1km^2$ and in its temporal resolution of 10 days.

In general, the evaluation of raster datasets is difficult because of the lack of good ground data. On the one hand, the comparison with directly measured field data, as realized for this study, reveals the reliability of the model results. On the other hand, the 'RBM Kaokoveld' bears comparison with the global MODIS NPP dataset.

By comparing the yearly modelling results, changes within the vegetation and in its productivity can be detected. Analysing these changes over several years (like one or two decades) may reveal long-term processes like degradation. Such long-term time series of input data are not yet available, either; so far, the solid results of the RBM Kaokoveld have provided a promising starting point for further research.

ACKNOWLEDGEMENTS

This research has been carried out within the special research project of SFB389 ACACIA, part project B7. ACACIA is an acronym for Arid Climate Adaptation and Cultural Innovation in Africa. This project is funded by the Deutsche Forschungsgemeinschaft (DFG) under title SFB 389-04.

REFERENCES

1 Potter C S, J T Randerson, C B Field, P A Matson, P M Vitousek, H A Mooney & S A Klooster, 1993. Terrestrial ecosystem production: A process model based on global satellite and surface data. Global Biogeochemical Cycles, 7:811-841

2 Justice C, E F Vermote, J R Townshend, G Defries, D P Roy, F G Hall, V V Salomonson, J L Privette, G Riggs, A Strahler, W Lucht, R B Myneni, Y Knyazikhin, S W Running, R R Nemani, Z Wan, A Huete, W van Leeuwen, R Wolfe, J-P Muller, P Lewis & M Barnsley, 1998. The Moderate Resolution Imaging Spectroradiometer (MODIS): Land remote sensing for global change research. In: IEEE Transactions on Geoscience and Remote Sensing, 36(4): 1228-1249

3 Reich P B , D Turner & P Bolstad, 1999. An approach to spatially-distributed modeling of net primary production (NPP) at the landscape scale and its application in validation of EOS NPP products. Remote Sensing of Environment, 70: 69-81

4 Running S W, R R Nemani, F A Heinsch, M Zhao, M Reeves & H Hashimoto, 2004. A continuous satellite-derived measure of global terrestrial primary production. BioScience, 54(6): 547-560

5 Lieth H, 1975. Modelling the primary production of the world. In: (Hrsg.): Primary Productivity of the Biosphere, edited by H Lieth & R H Whittacker (Springer, Berlin) 237-263

6 Esser G, J Hoffstadt, F Mack & U Wittenberg, 1994. High Resolution Biosphere Model: Documentation Model. Version 3.00.00 (Mitteilungen des Institut für Pflanzenökologie der Justus-Liebig-Universität Gießen) Vol. 2, 68 pp.

7 Sannier C A, J C Taylor, W du Plessis & K Campbell, 1998. Realtime vegetation monitoring with NOAA-AVHRR in Southern Africa for wildlife management and food security assessment. International Journal of Remote Sensing, 19(4): 621-639

8 Monteith J L, 1972. Solar radiation and productivity in tropical ecosystems. Journal of Applied Ecology, 9: 747-766

9 Running S W, P E Thornton, R Nemani & J M Glassy, 2000. Global terrestrial gross and net primary productivity from earth observing system. In: Methods in Ecosystem Science, edited by O E Sala, R B Jackson, H A Mooney & R W Howarth (Springer, New York, Berlin, Heidelberg) 44-57

10 ORNL DAAC, 2002. Estimation of NPP for Grasslands. http://www.daac.ornl.gov/NPP/html_docs/grassland.html

11 Sala E O & A T Austin, 2000. Methods of estimating aboveground net primary productivity. In: Methods in Ecosystem Science, edited by O E Sala, R B Jackson, H A Mooney & R W Howarth (Springer, New York, Berlin, Heidelberg) 31-43

12 Monteith J L, 1977. Climate and the efficiency of crop production in Britain. Philosophical Transactions of the Royal Society, 281: 277-294

13 Sellers P J, 1987. Canopy reflectance, photosynthesis and transpiration. II. The role of biophysics in the linearity of their interdependence. Remote Sensing of Environment, 21: 143-183

14 Asrar G, R B Myneni, B J Choudhury, 1992. Spatial heterogeneity in vegetation canopies and remote sensing of absorbed photosynthetically active radiation: a modelling study. Remote Sensing of Environment, 41: 85-103

15 Frouin R & R T Pinker, 1995. Estimating Photosynthetically Active Radiation (PAR) at the Earth's Surface from Satellite Observations. Remote Sensing of Environment, 51: 98-107

16 Myneni R B, R R Nemani & S W Running 1997. Estimation of Global LAI and FPAR from radiative transfer models. IEEE Transactions on Geoscience and Remote Sensing, 35: 1380-1393

17 Swift L W, 1976. Algorithm for solar radiation on mountain slopes. Water Resources Research, 12: 108-112

18 Federer C A, 2002. Brook90 - a simulation model for evaporation, soil water and stream flow. Compassbook: http://www.compassbook.com

19 Swift L W & K R Knoerr, 1973. Estimating solar radiation on mountain slopes. Agricultural Metrology, 12: 329-336

20 Ritchie J T, 1972. Model for predicting evaporation from row crop with incomplete cover. Water Resources Research, 8:1204-1213

21 Seaquist J W, L Olsson & J Ardö, 2003. A remote sensing-based primary production model for grassland biomes. Ecological Modelling, 169: 131-155

22 NASA DAAC, 1996. GTOPO30 Documentation. http://edcdaac.usgs.gov/gtopo30/README.asp

23 FAO, 1996. Digital Soil Map of the World and Derived Soil Properies. Land and water media series, 1. http://www.fao.org/ag/agl/agll/dsmw.htm

24 Thornton P E 2000. User's Guide for BIOME-BGC, Version 4.1.1 (Numerical Terradynamic Simulation Group, School of Forestry, University of Montana, USA) 22 pp.

25 Klink H-J, 1996. Das Geographische Seminar: Vegetationsgeographie (Westermann Verlag, Braunschweig)

26 Scheffer F, L Beyer, H-P Blume, P Schachtschabel, K Auerswald, G Brümmer, K H Hartge, H Stanjek, U Schwertmann, W R Fischer, R Horn, M Renger, I Kögel-Knabner, O Strebel & K Stahr, 1998. Lehrbuch der Bodenkunde. 14th edition (Ferdinand Enke Verlag, Stuttgart) 494 pp.

27 Traeger D H, 1994. Einführung in die Fuzzy-Logik (BG Teubner Verlag, Stuttgart) 176 pp.

28 Zimmermann H-J, 1991 Fuzzy Set Theory and its applications. 2nd edition (Kluwer Academic Publishers, Boston) 544 pp.

29 Long S P, M B Jones & M J Roberts (eds.), 1992. Primary productivity of grass ecosystems of the tropics and subtropics (Chapman & Hall, London) 267 pp.

30 Archibold O W, 1995. Ecology of World Vegetation (Chapman & Hall, London) 510 pp.

31 Weischet W,1995. Einführung in die Allgemeine Klimatologie (Teubner, Stuttgart) 276 pp.

32 Schulte A, 2002. Stabilität oder Zerstörung? Veränderungen der Vegetation des Kaokolandes unter pastoralnomadischer Nutzung. In: Interdisziplinäre Perspektiven zu Kultur- und Landschaftswandel im ariden und semiariden Nordwest Namibia, edited by M Bollig, E Brunotte & T Becker (Kölner Geographische Arbeiten, Köln) 77: 101-118

33 Priestely C H B & R J Taylor, 1972. On the assessment of surface head flux and evapotranspiration using large-scale parameters. Monthly Weather Review, 100: 81-92

34 Jiang L & S Islam, 1999. A methodology for estimation of surface evapotranspiration over large area using remote sensing observations. Geophysical Research Letters, 26: 2773-2776

35 Nishida K, R Nemani, S W Running & J M Glassy, 2003. An operational remote sensing algorithm of land surface evaporation. Journal of Geophysical Research, 108: 4270-4274

36 Sander H & T Becker, 2002. Klimatologie des Kaokolandes. In: Interdisziplinäre Perspektiven zu Kultur- und Landschaftswandel im ariden und semiariden Nordwest Namibia, edited by M Bollig, E Brunotte & T Becker (Kölner Geographische Arbeiten, Köln) 77: 57-68

37 van der Merwe J H, 1983. National Atlas of South West Africa. Nasionale Atlas van Suidwes-Afrika (Cape Town) 186 pp.

38 Menz G, 1994. Biomasse und Satellitenfernerkundung - Zur Berechnung von Karten der oberirdischen Phytomasse von Kenya aus NOAA-AVHRR-Daten. Basler Geomethodisches Colloquium, 19: 149-188

39 Viljoen P J, 1980. Veldtrips, Verspreiding van die Groter Soogdiere, en Enkele Aspekte van die Ekologie van Kaokoland. Master thesis (University of Pretoria, Fakulteit Wisen Natuurkunde) 233 pp.

40 USGS, 2003. MODIS Land Quality Assessment.

41 Nickeson J, D Landis & J L Privette (editors), 2003. SAFARI 2000 CD-ROM Series. Volume 3. CD-ROM. National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Maryland, U.S.A. Available from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. http://www.daac.ornl.gov

42 Alberda, 1977. Possibilities of dry matter production from foliage plants under different climatic conditions. In: Proceedings of the XIII. International Grassland Congress, edited by E Wojahn & H Thöns (Leipzig) 61-69

43 Rodin L E, N T Bazilevich & N H Rozov, 1975. Productivity of the world's main ecosystems (Natural Academy of Science, Washington) 13-26

44 Legel S, 1989. Nutztiere der Tropen und Subtropen. Vol.1: Rinder (Leipzig) 476 pp.

45 Casimir M & M Bollig, 2002. Ökologische Grundlagen der mobilen Weidewirtschaft der Himba in Nord-Namibia. In: Interdisziplinäre Perspektiven zu Kultur- und Landschaftswandel im ariden und semiariden Nordwest Namibia, edited by M Bollig, E Brunotte & T Becker (Kölner Geographische Arbeiten, 77, Köln) 207-219

46 Veroustraete F, J Patyn & R B Myneni 1994. Forcing of a simple ecosystem model with fAPAR and climatic data to estimate regional scale photosynthetic assimilation. In: Vegetation, Modelling and Climate Change Effects (Academic Publishing, The Hague) 151-177

47 Running S W, R Nemani, J M Glassy & P E Thornton, 1999. MODIS daily photosynthesis (PSN) and annual net primary production (NPP) product (MOD17), Algorithm Theoretical Basis Document V.3.0

48 Lu D, P Mausel, E Brondízio & E Moran, 2004. Change detection techniques. International Journal of Remote Sensing, 25: 2365-2401

49 Coppin P, I Jonckheere, K Nackaerts, B Muys & E Lambin, 2004. Digital change detection methods in ecosystem monitoring: a review. International Journal of Remote Sensing, 25: 1565-1596