Case Studies (Subject Area 3: Atmospheric Chemistry and Physics)

A Study of Climate Change and Anthropogenic Impacts in West Africa*

Rüdiger Wittig[1**], **Konstantin König**[2], **Marco Schmidt**[3] and **Jörg Szarzynski**[4]

[1]Institute of Ecology, Evolution and Diversity, J.W.Goethe-University, 60323 Frankfurt am Main, Germany
[2]Institute of Physical Geography, J.W.Goethe-University, 60325 Frankfurt am Main, Germany
[3]Resesarch Institute Senckenberg, 60326 Frankfurt am Main, Germany
[4] Center for Development Research (ZEF), Division Ecology and Natural Resources, Walter-Flex-Str. 3, 53113 Bonn, Germany

** **Corresponding author** (R.Wittig@em.uni-frankfurt.de)

DOI: http://dx.doi.org/10.1065/espr2007.02.388

Please cite this paper as: Wittig R, König K, Schmidt M, Szarzynski J (2007): A Study of Climate Change and Anthropogenic Impacts in West Africa. Env Sci Pollut Res 14 (3) 182–189

Abstract

Background, Aim and Scope. During the last decades ecological conditions in West Africa have dramatically changed. Very evident is the climate change, which has resulted in a southward shift of the climate zones, e.g. a spread of the desert (Sahara) into the Sahelian zone. After the drought period of the early 1970s and 1980s, livestock density increased resulting in an intensification of grazing pressure. This anthropogenous phenomenon leads to similar landscape changes as those caused by the climate.
Only very few investigations exist on vegetation dynamics, climate changes and land use changes for the Sudanian zone. The paper presents data on changes of precipitation, of land use, of the geographical range of species, and of the composition of the flora, which have to be regarded as proofs of the sahelisation of large areas of the Sudanian zone.

Materials and Methods:

- Area of investigation: Burkina Faso.
- Precipitation data analysis: precipitation data from 67 stations; time series analysis and geo-statistical spatial interpolation.
- Analysis of land use change: Landsat satellite MSS and ETM+ data, acquired for two different dates between 1972 and 2001 analyzed by the software ERDAS/IMAGINE version 8.6 and ArcView 3.2 with the Spatial Analyst extension. Intensive ground truthing (160 training areas).
- Inventory of the flora: based on the data of the Herbarium Senckenbergianum (FR) in Frankfurt, Germany, and of the herbarium of the university of Ouagadougou (OUA), Burkina Faso, as well as on various investigations on the vegetation of Burkina Faso carried out in the years 1990 to 2005 by the team of the senior author.
- Life form analysis of the flora: based on the inventory of permanent plots.

Results and Discussion:

- Precipitation: Remarkable latitudinal shift of isohyets towards the South translates to a general reduction of average rainfall in great parts of the country. The last decade (1990–1999) shows some improvement, however, the more humid conditions of the 1950's and 1960's are not yet established again.
- Landcover change: In the study region the extent of arable fields and young fallows increased during the last 30 years from 580 km² in 1972 to 2870 km² in 2001. This means an average land cover conversion rate of 0.9% per year for the 6 departments considered.
- Change of the distribution of Sahelian and Sudanian species: Several species, mentioned in older literature as strictly Sahelian, today also occur in the Sudanian zone. Parallel to the spread of former strictly Sahelian species into the Sudanian zone, some former Sahelo-Sudanian species have withdrawn from the Sahel.
- Changes of the life form spectra of the flora: Considering their life form spectra, the flora of heavily grazed and of protected areas in the Sudanian zone show great differences. On areas intensively grazed the percentage of therophytes is evidently higher than on protected areas. Just the opposite is true for the phanerophytes. Their percentage is higher on the protected area than on the grazed zones.

At the first glance, it is obvious to link the changes in flora and vegetation with the climate changes that have occurred during the last five decades (decrease of annual precipitation). However, not only climatic conditions have changed, but also population has increased, the percentage of land intensively used for agriculture and pasturing has increased and the time for soil regeneration today is much shorter than it was some decades ago. Thus, the landscape of the Sudanian zone has become a more Sahelian character. A comparison of the flora of an intensively used area of the Sudanian zone with that of a protected area shows a remarkable change in the life form spectra. The spectrum of the intensively used area is almost identical with that of the typical Sahelian flora. This comparison shows that the anthropogenic influence plays a greater role in the sahelisation of the Sudanian zone than the climate change.

Conclusion. Climate change and anthropogenic influence both, lead to a sahelisation of landscape and flora. Thus in many parts of the Sudanian zone of West Africa sahelisation phenomena will remain and even increase independently from the reestablishment of the more humid climate conditions of the 1950ies.

Recommendations and Perspectives. In order to maintain some parts of the characteristic Sudanian landscape with its characteristic flora and vegetation, the number and size of protected areas should be augmented. For all protected areas it has to be ensured, that protection is reality, i.e. respected an understood by local people, not only fiction.
As long as the enlargement of intensively used areas continues the sahelisation of flora, vegetation and landscape will continue too.

Keywords: *Acacia*; Burkina Faso; land use; life form spectra; precipitation; sahelisation; Sudanian zone

* **ESS-Submission Editor:** Dr. Jörg Römbke (j-roembke@ect.de)

Introduction

During the last decades ecological conditions in West Africa have dramatically changed. Very evident is the climate change, which has resulted in a southward shift of the climate zones, e.g. a spread of the desert (Sahara) into the Sahelian zone. Especially in climate sensitive regions, where rainfed and irrigated agriculture is the main source of food security and income, concerns about the variability in rainfall, its temporal and spatial distribution, must be taken very seriously. This seems to be particularly true of West Africa where significant alterations in precipitation during the great Sahelian drought of the early 1970s and 1980s affected great parts of West Africa in terms of ecological, economic, and societal aspects. After this drought period livestock density increased resulting in an intensification of grazing pressure. This anthropogenous phenomenon leads to similar landscape changes as those caused by the climate. In literature generally for these changes the term 'desertification' is used (e.g. Aubreville 1949, Delwaulle 1973, Glantz & Orlovsky 1983, El-Baz & Hassan 1986). 'Sahelisation', the analogous term for the Sudanian zone, up to now only rarely occurs in literature (e.g. Togola et al. 1975, Gavaud 1989/1990). On the one hand, this is obviously due to the fact that 'desertification' is a general term, not only meaning the originating of true deserts, but including any type of "land degradation in arid, semi arid and dry subhumid areas" (UNCCD, Article 1). On the other hand, it might be related to the fact that from the Sudanian zone much less concrete proofs of changes have been published than from the Sahelian zone. Only very few investigations exist on vegetation dynamics, climate changes and land use changes for the Sudanian zone (e.g. Hahn-Hadjali 1998, Kéré 1998, Devineau 2000, Fournier et al. 2000, Hahn-Hadjali et al. in press). In the following for Burkina Faso we present data on changes of precipitation, of land use, of the geographical range of species, and of the composition of the flora which have to be regarded as proofs of the sahelisation of large areas of the Sudanian zone.

1 Material and Methods

1.1 Area of investigation

Burkina Faso, a landlocked country in West Africa, situated between 9° to 15° N and 6° W to 3° E covers an area of 274,000 km² and has more than 13 million inhabitants. Most of the country belongs to the Sudanian zone, but in the North also the Sahelian zone is represented. The climatic part and some of the botanical results presented in our paper cover the entire country, while the other part of the paper focusses on the province of Gourma and particularly on selected regions situated south of Fada N'Gourma in the northern Sudanian zone (**Fig. 1**), where permanent plots (observation sites) have been established (see below). The vegetation of this area forms a mosaic of various types of woodland, of grass, shrub and tree savannas, of fallows, and of gallery forests. At present, the region receives an annual precipitation of 825 mm which is restricted to the rainy season lasting from April to October.

The observation sites marked in Fig. 1 comprise 1 km² each. One observation site (Natiabouani) is situated in a protected area only sporadically grazed by wild animals, the other one (Kikideni) is located in an area heavily grazed by cattle. Within these observation sites five permanent plots of size 1 ha each were located to include the different habitat types.

1.2 Precipitation data analysis

To determine the rainfall variability in Burkina Faso, precipitation data from 67 stations (synoptic, climatic, and agrometeorological stations) were analysed (sources: Météorologie Nationale, Burkina Faso; FAO, Agrometeorology Group 2000). A homogeneous series of gauge data, i.e. monthly rainfall totals, was used as a base for geo-statistical spatial interpolation. We applied the kriging technique as a widely accepted method for interpolating and estimating unknown values of a variable at unsampled points by using measured values from other points (see e.g. Isaaks & Srivastava 1989, Armstrong 1998, Webster & Oliver 2001). From a statistical point of view, kriging is a Gaussian process regression used in geostatistics to approximate or interpolate data. Gridding procedures and contour maps are generated by SURFER 7.0 software package (http://www.goldensoftware.com/products/surfer/surfer.shtml).

We used the Surfer's default linear variogram with a kriging algorithm incorporating the following essential details: 1.) When computing the interpolation weights, the algorithm considers the spacing between the point to be interpolated

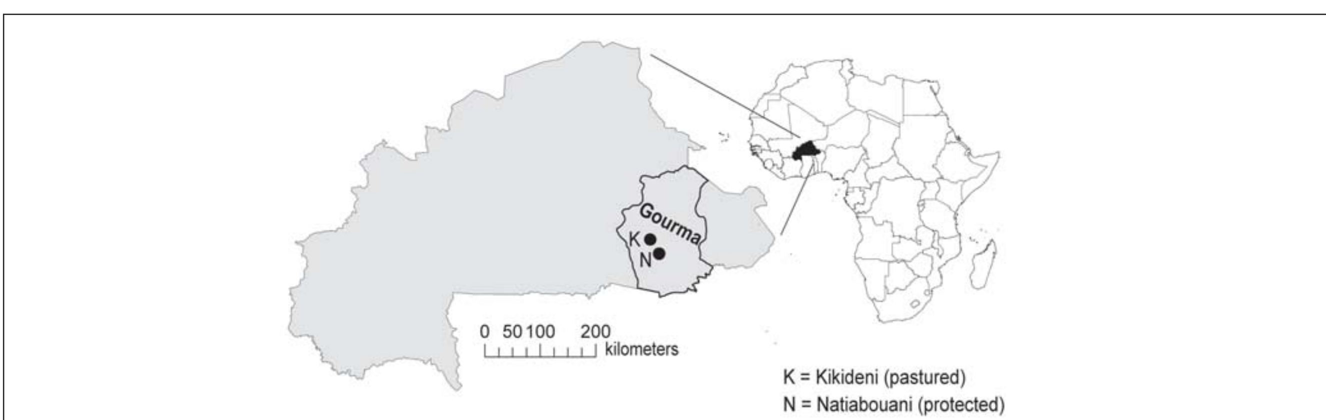

Fig. 1: Areas of investigation: Entire Burkina Faso (decadal means of precipitation, and plant distribution maps); Province of Gourma (land use); observation sites at Kikideni and Natiabouani (analyses of life form spectra)

and the data locations. The algorithm considers the inter-data spacings as well. This allows for declustering. 2.) When computing the interpolation weights, the algorithm considers the inherent length scale of the data. For example, the topography in Burkina Faso, or in West Africa in general, varies much more slowly in space than does the topography for example in the East African Rift Zone. Considering two observed elevations separated by e.g. ten kilometres, in Burkina Faso it would be reasonable to assume a linear variation between these two observations, while in the East African Rift Valley such an assumed linear variation would be unrealistic. The algorithm adjusts the interpolation weights accordingly. Surfer's implementation of the Nugget Effect follows the recommendation of Cressie (1991, Section 3.2.1). The Nugget Effect is partitioned into two sub-components: the error variance and the micro variance. Both of these sub-components are non-negative, and the sum of these two sub-components should equal the apparent non-zero intercept.

1.3 Analysis of land use change

Landsat satellite MSS and ETM+ data, acquired for two different dates between 1972 and 2001, were used to estimate the increase of the proportion of agricultural fields in the study area. All images were obtained at the end of the rainy season to minimize effects of exogenous factors like phenological states and different sun angles. In this period fields have been already harvested and can be clearly distinguished from surrounding savannas.

Pre-processing of satellite images involves radiometric normalization and geo-referencing. Radiometric normalization was conducted by using the COST atmospheric correction (Chavez 1996) and calibration coefficients of Markham & Barker (1986). Geometric accuracy of the recent ETM+ images was improved to 35 m with 25 ground control points sampled on street crossings and dams of water reservoirs. Historical images were co-registered to the recent scene with a relative accuracy of 30 m. Both images were resampled to a 60 m resolution. All analyses were accomplished with the software ERDAS/IMAGINE version 8.6 and ArcView 3.2 with the Spatial Analyst extension.

During two field campaigns in October 2000/01 intensive ground truthing was conducted in the study region. In total, 160 training areas were selected by a stratified random sampling procedure, where structural vegetation parameters were measured according to a standardized methodology. By this procedure 44 agricultural fields and young fallows (1–2 years old) were identified in the field. The whole data set was separated randomly to two parts. The first data set (80 training sites) was used for supervised classification of recent land use, the second (80 test sites) for independent testing of classification accuracy, which is defined as the proportion of correctly classified pixels. Landsat bands 3,4,5, the first two components of a tasseled cap transformation, the mean soil adjusted vegetation index (MSAVI), and a digital elevation model were used for a land cover classification of the study area. Spectral signatures of land use classes were extracted. These signatures were implemented in an unsupervised classification of the historical satellite scene. Classes, which indicate fields and young fallows were identified through interpretation of aerial photos from 1978 with a spatial resolution of several meters. Analyses of land use changes were conducted under reference of recent administrative boundaries (departments) available in a GIS environment to make results interpretable for local stakeholders and to allow comparison with future analyses.

1.4 Inventory of the flora

The floristic maps for Burkina Faso given in this paper are based on the data of the Herbarium Senckenbergianum (FR) in Frankfurt, Germany, and of the herbarium of the University of Ouagadougou (OUA), Burkina Faso, as well as on various investigations on the vegetation of Burkina Faso carried out in the years 1990 to 2005 by the team of the senior author (see e.g. Wittig et al. 2000, 2002). The maps were established by the logiciel SIG <<ArcGIS 8.3>> (reference <<WGS 84>>).

The life form analysis of the flora is based on the inventory of the permanent plots described in section 2.1. In all of the one hectar plots of the observation sites (see Section 1.1) 5 or 10 smaller plots of 10 m x 10 m were implemented randomwise. For each of the 10 m x 10 m all species of herbaceous vascular plants and for each of the 20 m x 50 m plots all woody species were recorded. The results were combined for the calculation of the spectra of life forms (Raunkiaer 1934). This inventory was done in September 2001.

2 Results

2.1 Precipitation

As reviewed from literature a general trend analysis of historical time series has revealed statistically significant decreases of mean annual precipitation up to 25% and a delayed onset of the rainy season up to 30 days in the last 25 years for specific regions in Ghana and Burkina Faso (Neumann et al. 2006). Our analysis of average precipitation in Burkina Faso regarding the five decades from 1951–1999 (**Fig. 2**, see overleaf) revealed the appearance of the 400 mm isohyet in the northern part of the country in the 70's, whereas the 1,200 mm isohyet in the south-western part disappeared. The latitudinal shift of isohyets towards the South translates to a general reduction of average rainfall in great parts of the country. The last decade (1990–1999) shows some improvement, however, the more humid conditions of the 1950's and 1960's are not yet established again. The northern-most zone of Burkina still remained drier as well the south-western part where annual totals higher than 1,000 mm are still absent. These findings contribute to the question of the 'recovery' of rainfall in the Sahel, as elaborated by Nicholson (2005) as well as to findings from other scientists like Dai et al. (2004) who state a recent sahel drought. Additionally, they also clearly underline the necessity of detailed spatial analysis of climatological data to cope with the problem of the high spatial heterogeneity of precipitation fields in West Africa.

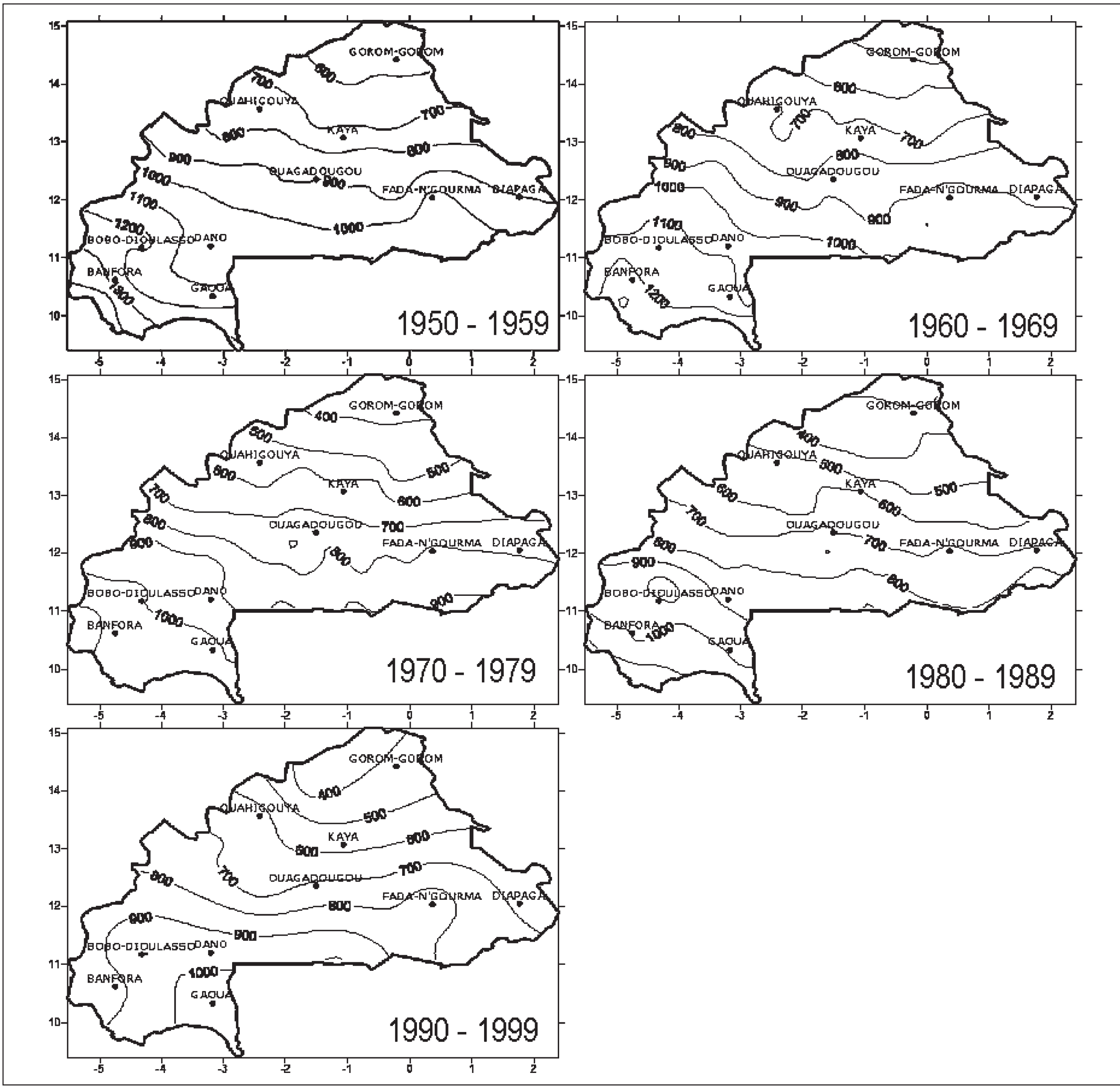

Fig. 2: Spatial map of mean annual precipitation (decadal means) in Burkina Faso for the period from 1950 to 1999 (data from: Météorologie Nationale, Burkina Faso, FAO – Agrometeorology Group, Rome 2000)

2.2 Landcover change

Results of land use classification are shown in **Fig. 3**. Agricultural fields were classified with an overall classification accuracy of 91%. For the year 2001, in the department of Fada N'Gourma 150,000 ha are classified as arable land. This is about 45% of it's whole surface. As shown by **Fig. 4** there has been a strong increase in arable fields in all departments of the province of Gourma. Today the proportion of agricultural areas ranges from 20% in Soudougui to over 60% in Diapangou.

In the study region the extent of arable fields and young fallows increased during the last 30 years from 580 km² in 1972 to 2,870 km² in 2001. This means an average land cover conversion rate of 0.9% per year for the six departments considered. Especially regions near the protected areas show very high land cover conversion rates. Additionally, regions of traditional intensive agriculture in the North and East of the study region were extended.

2.3 Change of the distribution of Sahelian and Sudanian species

Several species, mentioned in older literature as strictly Sahelian, today also occur in the Sudanian zone. Striking examples are *Acacia ehrenbergiana*, whose southern border after Nongonierma (1977) some decades ago was situated

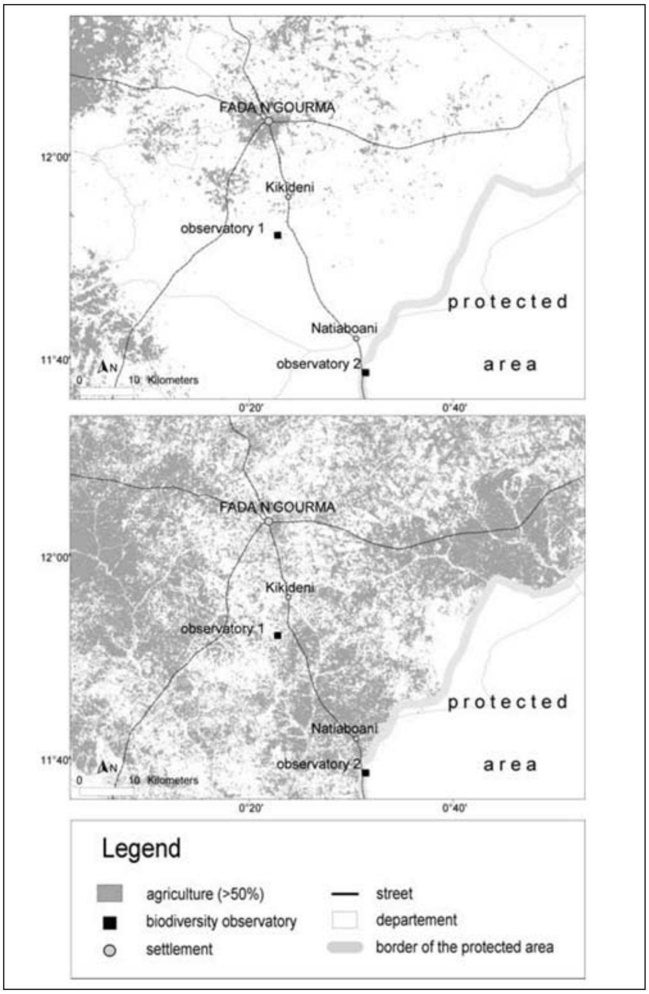

Fig. 3: Extension of crop fields (grey areas) in the province of Gourma (North Sudanian Zone) in 1973 (above) and 2001 (below) identified from satellite images

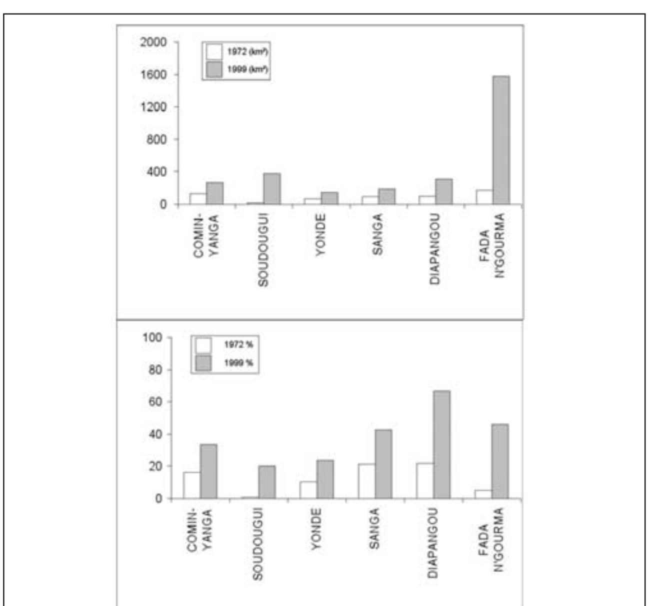

Fig. 4: Amount of crop fields in the departments of the province of Gourma in 1972 and 1999 (above: absolute area size; below: percentage of the surface of the department)

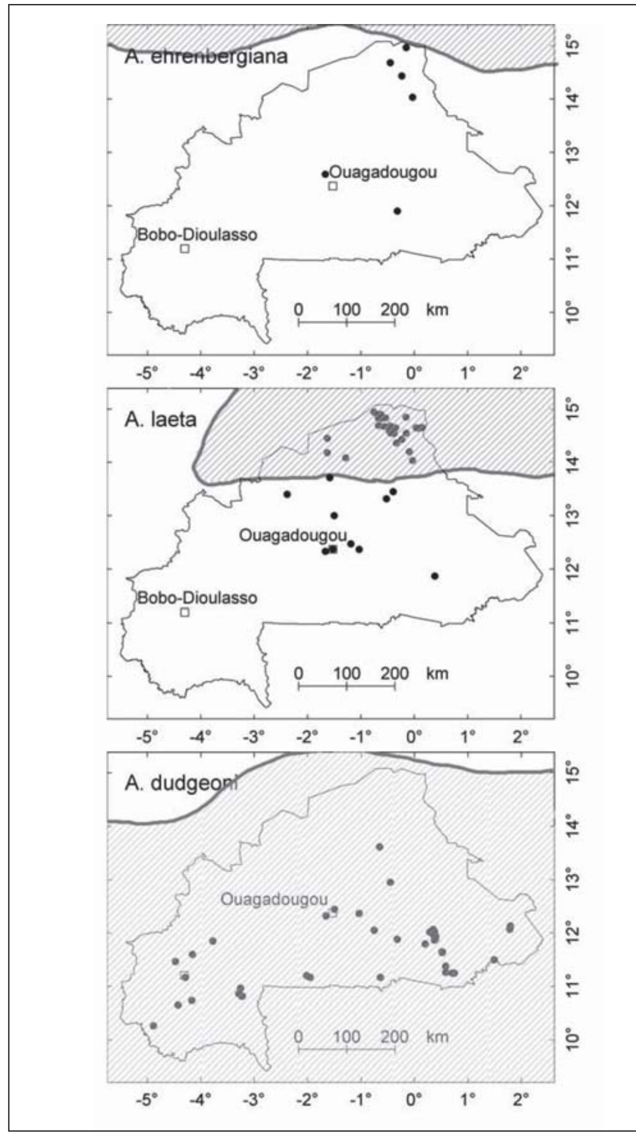

Fig. 5: Former areas of *Acacia ehrenbergiana*, *A. latea* and *A. dudgeoni* (hatched; after Nongonierma 1977), and actual findings of these species in Burkina Faso (after Wittig et al. 2004)

north of Burkina Faso (**Fig. 5**) and *Acacia laeta*, which was strongly restricted to the Sahel (see Fig. 5). Today both species grow more than 200 km south of the border described by Nongonierma (1977). Parallel to the spread of former strictly Sahelian species into the Sudanian zone, some former Sahelo-Sudanian species like *Acacia dudgeoni* (see Fig. 5) have withdrawn from the Sahel.

2.4 Comparison of the flora of grazed and protected areas in the Sudanian zone

Considering their life form spectra, the flora of heavily grazed and of protected areas in the Sudanian zone show great differences (**Fig. 6**, see overleaf). On areas intensively grazed the percentage of therophytes is evidently higher than on protected areas. Just the opposite is true for the phanerophytes. Their percentage is higher on the protected area than on the grazed zones.

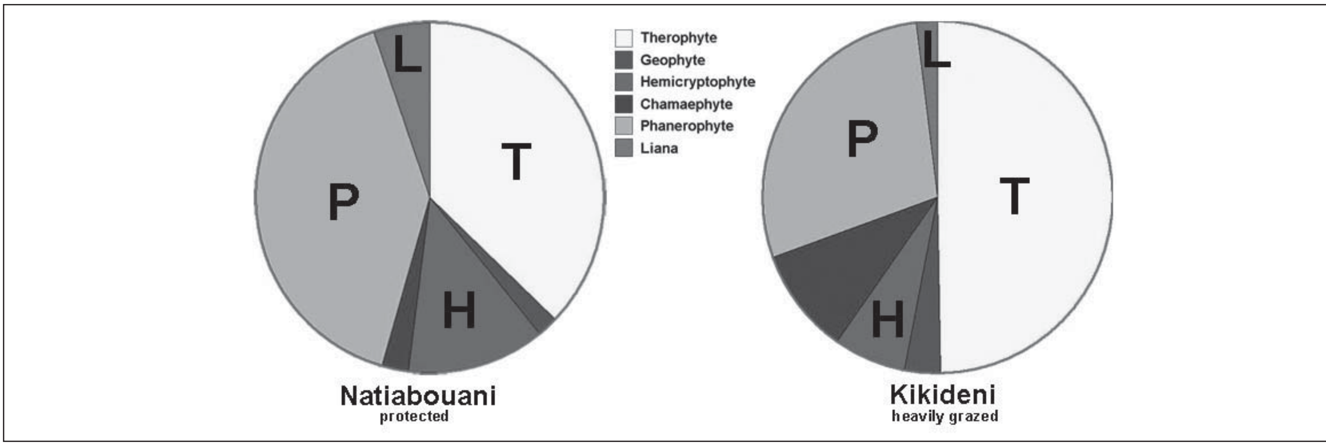

Fig. 6: Life form spectra of intensively grazed and of protected permanent plots in the Sudanian zone of Burkina Faso

3 Discussion

The annual precipitation is the most important factor for the distinction between the different climate zones of West Africa. A significant reduction of precipitation, as experienced during the great Sahelian drought of the early 1970s and 1980s, has been proved by various authors (e.g. Folland et al. 1986, Le Houérou 1996, Nicholson 2000). However, detailed time series analysis on the level of a single country are still rare. Our results, which fill in this gap, clearly show the shifting of Sahelian conditions (600 mm isohyet) up to some 150 km into the Sudanian zone during the 1980s. Not only the North Sudanian zone was effected by this climatic sahelization, but Subsahelian conditions, the southern border of which is represented by the 700 mm isohyet, even reached the northern part of the South Sudanian zone. Although the 1990s show a slight shifting of the isohyets back to the North there is still a difference of about 100 km between the location of the 600 mm isohyet in the 1950s and 1990s. It is fairly clear that these dynamic spatio-temporal patterns of precipitation have strong implications on crop production and food security in Burkina Faso. The described development of high variability of rainfall can be regarded as a significant feature for great parts of West Africa that must be seriously taken into account. Analysing the complex reasons for the described variability in rainfall, its temporal and spatial distribution, is still one of the major challenges for environmental scientific research. The spectra of hitherto existing hypotheses includes those focussing on global oceanic-atmospheric circulation patterns (Folland et al. 1986, Nicholson & Kim 1997, Nicholson 2000, Rowell et al. 1992, 1995), the influence of land cover changes (Bigot et al. in press, Brou et al. 1998, Xue 1997), and effects due to changes in atmospheric composition, i.e. aerosol concentrations (Tegen et al. 1996) as well as greenhouse gas and sulphate aerosol emissions (Hulme & Kelly 1993). However, these issues still remain unresolved. Although inter-seasonal and inter-annual variability in precipitation in part has been successfully forecasted for West Africa (Stockdale et al. 1998) there is still a lack of knowledge in predicting climate changes on decadal or notably multi-decadal timescales (Hulme 1998). In addition, results from General Circulation Models (GCM), as often applied in frame of the above mentioned publications, are essential to understand large-scale coherences, but do not necessarily match the requirements of regionally to locally orientated biodiversity research. Therefore we investigated the cross-scale linkage between detailed biophysical and hydro-meteorological processes calibrated at the experimental sites to responses at the larger grid resolution. The results of our investigations support the idea that regional variability in precipitation with regard to its temporal and spatial distribution is considerably linked to significant changes in vegetation cover.

As mentioned in the introduction, many authors do not differentiate between desertification and sahelization. In the literature it is generally accepted that desertification often is anthropogenously driven by the intensification of land use. In a recent meta-analysis Geist & Lambin (2004) review the proximate causes of desertification and land degradation mentioned in 132 case studies. In Africa 48% of the considered studies suggest intensification of agriculture and extension of cropland production as one the main causes of desertification. Furthermore, through the expansion of croplands into former rangelands, stocking rates of cattle increase dramatically in the remaining areas. The local concentration of cattle results in overgrazing leading to the degradation of vegetation in terms of biomass and species composition (Dube & Pickup 2001). That is why we can consider the intensification of land use also as the driving force in the process of sahelisation. The Sahelian zone traditionally is to a much higher degree an open landscape than the Sudanian zone. Thus, the land use changes reported in Fig. 3 and 4 physiognomically aggrevate, without any doubt, the aspect of large parts of the Sudanian landscape into a Sahelian one (**Fig.** 7and 8).

It is well-known that climate change as well as land use change can lead to an extension or to a diminution of the area of species. As shown above, such changes have occurred in the Sudanian zone, both leading to a more Sahelian character. Therefore it is no wonder that some Sahelian species have enlarged their area towards the Sudanian zone and that some species preferring areas of higher precipitation have left the Sahel. In Burkina Faso the latter phenomenon was

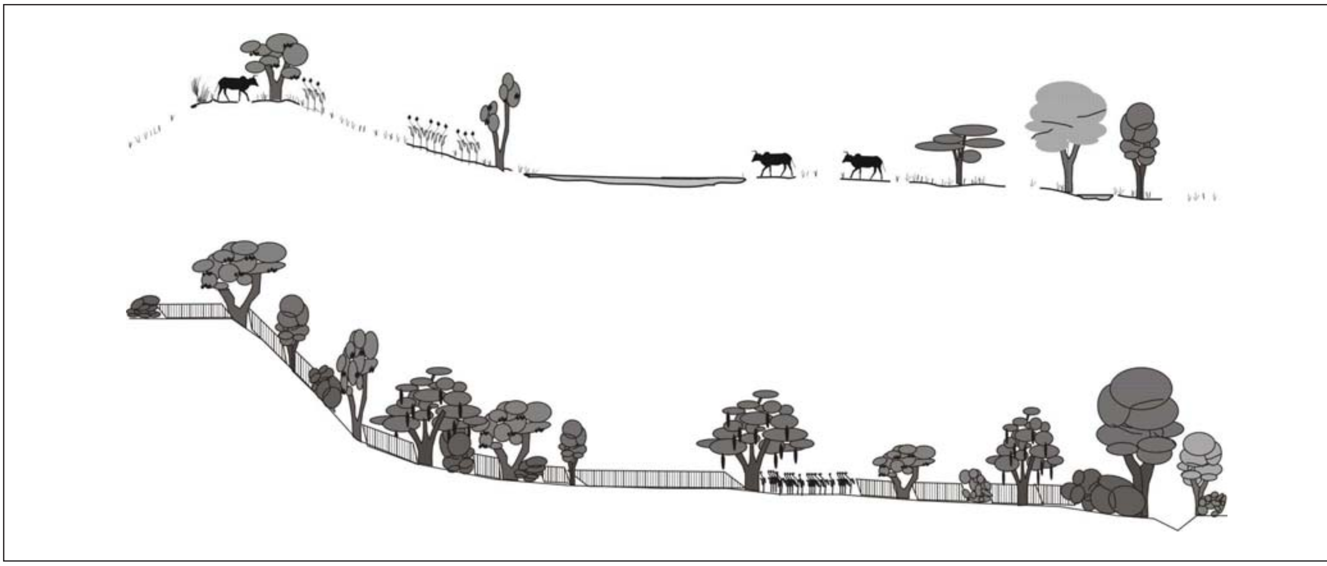

Fig. 7: Traditional Sahelian landscape (above) and traditional Sudanian landscape (below) (from Wittig et al. 2002)

Fig. 8: The intensification of land use causes a Sahelian character of the Sudanian landscape (environs of Tenkodogo, Sudanian zone, Burkina Faso; foto Wittig 1986)

studied in detail by Ganaba & Guinko (1995) by the example of *Pterocarpus lucens*. Togola et al. (1975) regard the mortality of *Bombax costatum* in Mali as an indicator of sahelisation of the Sudanian zone. Guinko & Bélem Ouedraogo (1998) name *Cassia tora, Ctenidium elegans, Echinochloa colona, Sida cordifolia, Schoenefeldia gracilis* and *Ziziphus mauritiana* as examples for Sahelian species which meanwhile frequently occur in the Sudanian zone. All these species are not equally distributed in the Sudanian zone but only grow on sites heavily influenced by man, i.e. road sides and eroded land.

As shown by Schmidt et al. (2005), who presented a grid map (grid size 1.0) of the life form spectra of the flora of Burkina Faso, therophytes represent the dominating life form type of the Sahel of Burkina Faso. In this area their number amounts to more than 50% of the species, while the percentage of the phaneropyhtes is only about 25%. In the Sudanian zone, however, therophytes and phanerophytes (including lianas) both represent one third of the total number of species. Considering the dominant life form types, the flora of the heavily grazed permanent plots in the Sudanian zone has a strong Sahelian character, while the flora of the protected plots still shows the characteristic Sudanian life form spectrum. It has to be mentioned that, in our study, the higher percentage of therophytes in the grazed permanent plots is only true for the species number, not for the cover (see Hahn-Hadjali et al. in press). However, other authors report also a direct replacement of perennial by annual plants, e.g. of *Andropogon gayanus* by *Elionurus elegans* in the Niono region of Mali (Breman & Cissé 1977). The comparison of a protected and an intensively used area located closely together (i.e. no climatic differences exist) shows that the anthropogenic influence plays a greater role in the sahelisation of the Sudanian zone than the climate change.

4 Conclusions

Considering climate, landscape and flora, some parts of the Sudanian zone today show a Sahelian character. While the reasons for the climate change are not clear, it is very obvious that the changes in landscape character and in the floristic composition are mainly anthropogenically driven, although one cannot exclude that the climate changes also have some responsibility. However, we can be sure that, as long as there is no turn towards a more sustainable agriculture, changes of landscape and flora will continue even if the climatic conditions of the middle of the last century would return.

Acknowledgement. The authors would like to thank Dr. Karen Hahn-Hadjali (Frankfurt) and Dr. Adjima Thiombiano (Ouagadougou) for the permission to use some of their field-data and Dick Byer for the revision of the English. Financial support was given by the Federal Ministry of Education and Research (BMBF) within the frame of the project BIOTA-West. We also have to thank two anonymous reviewers for their careful work which helped us to improve our paper.

References

Armstrong M (1998): Basic Linear Geostatistics. Springer, Stuttgart
Aubreville A (1949): Climats, Forest, et Desertification de l'Afrique Tropicale. Societe de Editions Geographiques, Maritime et Coloniales, Paris
Bigot S, Brou Yao T, Bonnardot V, Servat E (2002): Stabilité interannuelle des précipitations en Côte d'Ivoire de 1950 à 1996. In: Lanen HAJ v, Demuth S (eds), Friend 2002 – Regional Hydrology: Bridging the gap between research and practice. IAHS publication No. 274, pp 507–513
Breman H, Cissé AM (1977): Dynamics of Sahelian Pastures in Relation to Drought and Grazing. Oecologia 28, 301–315
Chavez PS (1996): Image-based atmospheric corrections – Revisited and revised. Photogrammetric Engineering and Remote Sensing 62, 1025–1036
Brou Yao T, Servat E, Paturel JE (1998): Activités humaines et variabilité climatique: Cas du sud forestier ivorien. In: Servat E, Hughes D, Fritsch J-M, Hulme M (eds), Water resource variability in Africa during the XXth century. IAHS publication No. 252, pp 365–373
Cressie, N (1991): Statistics for Spatial Data, John Wiley & Sons, New York, 900 pp
Dai A, Lamb PJ, Trenberth KE, Hulme M, Jones PD, Xie P (2004): The recent Sahel drought is real. Int Journal of Climatology, 24, 1323–1331
Delwaulle JC (1973): Desertification de l'Afrique au sud du Sahara. Bois et Forêts des Tropiques 149, 3–20
Devineau JL (2000): Écologie des principales espèces ligneuses alimentaires et four-ragères dans un système culture-jachère (sud-ouest du Burkina Faso). In: Floret C, Pontanier R (eds), La jachère en Afrique tropicale. John Libbey Eurotext, Paris, pp 441–450
Dube OP, Pickup G (2001): Effects of rainfall variability and communal and semi-commercial grazing on land cover in sourthern Agrican rangelands. Climate Research 17, 195–208
El-Baz F, Hassan MHA (1986): Physics of desertification. Martinus Niehoff, Dordrecht
Folland CK, Palmer TN, Parker DE (1986): Sahel rainfall and worldwide sea temperatures, 1901–85. Nature 320, 17
Fournier A, Yoni M, Zombre P (2000): Les jachères à Andropogon gayanus en savane soudanienne dans l'ouest du Burkina Faso: Flore, structure, déterminants et fonction dans l'écosystème. Etudes flor veg Burkina Faso 5, 3–32
Ganaba S, Guinko S (1995): Zustand und Dynamik des Gehölzbestandes in der Umgebung des Mare d'Oursi (Burkina Faso). Etudes flor veg Burkina Faso 2, 3–14
Geist HJ, Lambin EF (2004): Dynamic causal patterns of desertification. Bioscience 54, 817–829
Glantz MH, Orlovsky N S (1983): Desertification: A review of the concept. Desertification Control Bull 9, 15–22
Gavaud M (1989/1990): Nature et localisation de la dégradation des sols au Sénégal. Cah ORSTOM, sér Pédol 25 (3) 253–262
Guinko S, Bélem Ouédraogo M (1998): La flore du Burkina Faso. In: Bâ AT, Madsen JE, Sambou B (eds), Atelier sur flore, végétation et biodiversité au Sahel. AAU Reports 39, 43–65
Hahn-Hadjali K (1998): Les groupements végétaux des savanes du sud-est du Burkina Faso (Afrique de l'ouest). Etudes flor veg Burkina Faso 3, 3–79
Hahn-Hadjali K, Schmidt M, Thiombiano A (2003): Phytodiversity dynamics in pastured and protected West African savannas. Proceedings of the 17th AETFAT Congress, Addis Abeba (21.09–26.09–2003) (in press)
Hulme M, Kelly PM (1993): Exploring the linkages between climate change and desertification. Environment 35, 4–11 and 39–45
Hulme M (1998): The sensitivity of Sahel rainfall to global warming: implications for scenario analysis of future climate change impact. In: Servat E, Hughes D, Fritsch J-M, Hulme M (eds), Water resource variability in Africa during the XXth century. IAHS publication No. 252, pp 429–436
Isaaks EH, Srivastava R (1989): An Introduction to Applied Geostatistics. Oxford University Press, Oxford
Kéré U (1998): Végétation et utilisation des plantes spontanées dans la région de Tenkodogo (Burkina Faso). Etudes flor veg Burkina Faso 4, 55 p
Le Houérou HN (1996): Climate change, drought and desertification. J Arid Envir 34, 133–185
Markham BL, Barker JL (1986): Landsat MSS and TM post-calibration dynamic ranges, exoatmospheric reflectances and at-satellite temperatures. EOSAT Technical Notes, pp 3–8
Neumann R, Jung G, Laux P, Kunstmann H (2006): Climate trends of temperature, precipitation and river discharge in the Volta Basin of West Africa. International Journal of River Management (in press)
Nicholson S (2005): On the question of the 'recovery' of the rains in the West African Sahel. Journal of Arid Environment 63, 615–641
Nicholson SE (2000): The nature of rainfall variability over Africa on time scales of decades to millennia. Global and Planetary Change, 26 137–158
Nicholson S, Kim J (1997): The relationship of the El Niño Southern Oscillation to African rainfall. Int J Climatol 17, 117–135
Nongonierma A (1977): Contribution à l'étude biosystématique du genre *Acacia* Miller en Afrique occidentale. IV. Distribution bioclimatique des différents taxa. Bull. de l'I.F.A.N. T. 39, sér A n° 2, pp 318–339
Raunkiaer C (1934): The Life Forms of Plants and Statistical Plant Geography. Clarendon Press, Oxford. (Reprint 1977) Arno Press, New York
Rowell DP, Folland CK, Maskell K, Ward MN (1995): Variability of summer rainfall over tropical north Africa (1906–92): Observations and modelling. Quart J Roy Met Soc 121, 669–704
Rowell DP, Folland CK, Maskell K, Owen J, Ward MN (1992): Modelling the influence of global sea surface temperatures on the variability and predictability of seasonal Sahel rainfall. Geophysical Research Letters Vol. 19, No. 9
Schmidt M, Kreft H, Thiombiano A, Zizka G (2005): Herbarium collections and field data-based plant diversity maps for Burkina Faso. Diversity and Distributions 11, 509–516
Tegen I, Lacis AA, Fung I (1996): The influence on climate forcing of mineral aerosols from distributed soils. Nature 380, 419–422
Togola M, Cissé MI, Breman H (1975): Evolution de la végétation du ranch de Niono depuis 1969. In: Inventaire et cartographie des pâturages tropicaux africains. Actes du Colloque, 3–8 mars, Bamako, Mali. CIPEA, Addis Ababa, pp 195–201
Webster R, Oliver MA (2001): Geostatistics for environmental Scientists. John Wiley & Sons, Chichester
Wittig R, Hahn-Hadjali K, Krohmer J, Müller J (2000): Nutzung, Degradation und Regeneration von Flora und Vegetation in westafrikanischen Savannenlandschaften. Ber R-Tüxen Ges 12, 263–281
Wittig R, Hahn-Hadjali K, Krohmer J, Müller J, Sieglstetter R (2002): La végétation actuelle des savanes du Burkina Faso et du Bénin – Sa signification pour l'homme et la modification de celle-ci par l'homme (aperçu des résultats d'un projet de recherche duré des années). Etudes flor veg Burkina Faso 7, 3–16
Wittig R, Schmidt M, Thiombiano A (2004): Cartes de distribution des espèces du genre *Acacia* L. au Burkina Faso. Etudes flor veg Burkina Faso 8, 19–26
Xue Y (1997): Biosphere feedback on regional climate in tropical North Africa. Quart J Roy Met Soc 123, 1483–1515

Received: July 11th, 2006
Accepted: February 22nd, 2007
OnlineFirst: February 23rd, 2007