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Modeling of Land-Use and Land-Cover Change (LUCC) in Western Africa using Remote Sensing

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Zusammenfassung: *Modellierung von Landnutzungs- und Landbedeckungsänderungen in West-Afrika mit Hilfe von Fernerkundung*. Der Beitrag behandelt die Erfassung und Modellierung von Landbedeckungs- und Landnutzungsänderungen in einem Untersuchungsgebiet in den wechselfeuchten Tropen in West-Afrika (Einzugsgebiet des Ouémé in Benin) im Rahmen des IMPETUS Projekts. Für die Erfassung von landwirtschaftlichen Flächen aus Fernerkundungsdaten wird ein Entscheidungsbaum-Klassifikator eingesetzt. Durch Analyse multitemporaler Satellitenbilder werden die Veränderungen ermittelt und durch die Einbeziehung von „driving forces" das den Wandel bestimmende Prozessgefüge erklärt. Auf der Grundlage dieses Prozessverständnisses wird eine Modellierungskette aufgebaut, um Szenarien zukünftiger Entwicklung der Landnutzung- und Landbedeckung zu berechnen. Diese Ergebnisse sind wichtige Informationsgrundlagen für Entscheidungsträger in Sinne einer nachhaltigen Entwicklung in einem sich rasch wandelnden Ökosystem.

Summary: This article discusses the assessment and modeling of land-use and land-cover changes in a study area in the semi-humid tropics in West-Africa (Catchment of the upper Ouémé in Benin) within the framework of the IMPETUS project. A decision tree classification method was used to derive agriculturally used areas from remote sensing data. Changes in the extent of agricultural area was analysed on the basis of multi-temporal satellite data. The underlying LUCC process and driving forces are explained using additional socio-economic data. Based on this process understanding a model chain was set up to compute scenarios of future LUCC development. These results serve as an important basis for decision makers with regard to sustainable development in a rapidly changing system.

1 Introduction

The impacts of global change on land cover have a strong spatio-temporal component, causing them to be very unevenly distributed over the earth's surface. According to statistics published by the United Nations Environmental Programme (UNEP 2000), more than 500 million hectares of land, including agricultural areas, is affected by land degradation in Africa. The annual rate of deforestation is currently greater than 10 million hectares. In Northwest and West Africa these land use changes are additionally superimposed and increased by a dry period, now having lasted for more than 30 years. This has lead to a significant shortage of sweet water resources – the greatest problem water management faces in the 21st century (Obasi 1999). These facts point to a dramatic change of the cover of land surfaces with serious impacts on processes of the ecosystem, biogeochemical cycles and the human societies affected by it. The investigation of these changes and the upset of management plans for a sustainable use of fresh water is an important challenge for the scientific community. Therefore the IMPE-

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TUS project (Integrated Approach to the Efficient Management of Scarce Water Resources in West Africa) based at Cologne and Bonn Universities was founded.

Due to the fact, that vegetation is a key parameter within the hydrological cycle, one central focus of the ongoing research is a satellite-based detection of so called "Hot Spots", especially endangered areas with high rates of land cover change. Using a multidisciplinary approach, colleagues from a number of scientific disciplines (meteorology, hydrology, botany, geography, soil science, hydrogeology, agricultural science and cultural anthropology) are involved in investigating the details of the hydrological cycle under various conditions.

Recording of land surface by employing various optical sensor systems by the "Land Surface" module is the basis for the development of model-based scenarios of land use change. The approaches to model building are mainly founded on the concepts developed by the international Land Use and Land Cover Change (LUCC) group of the International Human Dimension Program for Global Environmental Change (IHDP). The results obtained are meant to be a meaningful contribution for integrative strategic planning in the future, with the aim of minimizing the ecological and socio-economic impacts of these changes.

After focusing the remote sensing activities in the first phase of the project (2001–2004) on the compilation of time series of land cover and land use maps (IMPETUS 2003), the present second phase (2004–2006) is concerned with, 1. a better understanding of the underlying determining factors for the changeability of land cover in order to parameterise it, and 2. to develop regional models of land use change on the basis of this comprehension of the processes involved.

2 Area of Investigation

The catchment of the Upper Ouémé is the study area which is situated in the north west of the Republic of Benin (location of the catchment between 8° 58′ and 10° 11′ N and 1° 30′ and 2° 47′ E) and covers an area of estimated 10000 km^2 (Fig. 1).

The climate of the study area is tropical semi-humid (STRAHLER & STRAHLER 2000, WILL 1996). It belongs, more precisely, to the Sudan–Guinea Zone with a unimodal rainfall distribution. There is a characteristic change in the humid conditions between the rainy season (end of March until end of September) and the dry season (October to March). At the Parakou weather station the mean annual rainfall is approximately 1100 mm with 20% variability (WILL 1996).

Topography

The terrain of the study area shows little difference in altitude (between 300 m asl. and 400 m asl.), except for some isolated inselbergs in the vicinity of the geological "Kandi fault".

Vegetation

The vegetation within the Upper Ouémé Catchment belongs to the transition zone

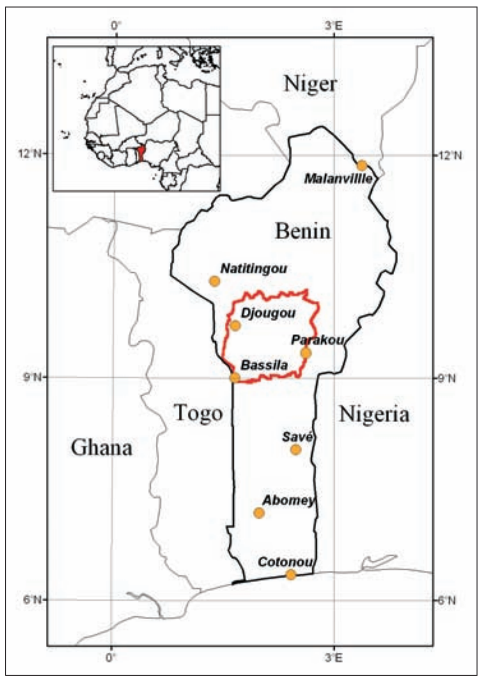

Fig. 1: Location of the study area (upper Ouémé catchment) in Benin, West-Africa.

between the "northern Guinea Zone" and "southern Sudan Zone" which is characterised by forest and wood savannas (Adjanohoun & Ake 1967).

Wide parts of the vegetation within the catchment are subject to bush fires within the dry period. These fires are mainly caused by humans. Grazing by cattle also modifies the species composition. Additionally, the influence of farming, mainly shifting cultivation, leads to a heterogeneous vegetation pattern within the study site (IMPETUS 2003).

3 Population and economy

Benin covers an area of approximately 114 922 km^2 and had 6 752 600 inhabitants in 2002 (INSAE 2004). There was a strong population growth of around 3.2 % (INSAE 2004) between 1992 and 2002. The average population density is 59 inhabitants per km^2. The population is unequally distributed; in the southern part of Benin, in the department Atlantique, 249 inhabitants per km^2 were registered in 2002, whereas in the north western district of Atacora, only 26.5 inhabitants lived on a square kilometre (INSAE 2004).

Due to high population density in the northern and southern departements of Benin as well as problems with exhausted soils and decreasing precipitation, migration to less dense populated areas within Benin has been observed (Doevenspeck 2004). The study area, which has a comparatively low population density of 28 inhabitants per km^2, is subject to immigration and agricultural colonization.

Agriculture takes place mostly on a small scale. Crop production is dominated by subsistence farming, but production for regional markets is also an important source of income. Production is undertaken mostly without any machinery. The main crops are yams, manioc, maize, millet and peanuts. Cotton and cashew are the most important cash crops. Due to a national credit system and organized production networks, fertilizer and pesticides are de facto only available for cotton. For the other crops it lacks of money in most of the small scale farming households.

Land-use classification in the study area is a challenge because of strong inner annual vegetation dynamics, small field sizes, a heterogeneous landscape and strong atmospheric interferences.

4 Data

In the study area, strong changes in land-use and land-cover (LUCC) have taken place over the last 10 years. To assess the land-cover and land-use changes in the study area, LANDSAT data from three different time steps are utilised. One is from LANDSAT TM (13. 12. 1991), the two other from LANDSAT ETM + (26. 10. 2000 and 29. 10. 2001). Data taken in October at the end of the rainy season are best suited for land-cover classification because vegetation types are easily distinguishable and the bush fire season has not yet begun. Additionally atmospheric influence is low due to the absence of clouds and dust. Unfortunately, for 1991 only a scene acquired in December was available, so constraints because of burned areas have to be kept in mind.

5 Methods

The land-use and land-cover changes in the study area are mainly caused through expansion of agricultural land. To extract only one class of interest (agricultural used areas), a decision tree classification approach was developed. Decision trees are tools to segment multidimensional datasets (e. g. multi-spectral LANDSAT data) starting from a root node to as many end leaves as necessary.

The core of this method is the decision rule (split), which divides the dataset in a binary way into subsequent portions. There are many automated solutions for decision rules (Friedel & Brodley 1997), but in this study a set of thresholds derived by training areas are used. The test at each node will produce a binary information output, for example:

$$X_{ni} = \begin{cases} 1 \; if \; k_i \leq u_n \\ 0 \; if \; k_i > u_n \end{cases}$$

where X_{ni} is the test result for test n, k_i, the tested pixel and u_n the set threshold. If X is tested positive, then the recognized pixel is passed on to the next decision until the last decision node is reached and all pixels are assigned to a class.

It was easy to separate a class that includes fields from all other classes (natural vegetation etc.) through channel 5 of the LANDSAT data which is sensitive to the water content of surfaces. After this first separation, a further six splits separated similar classes (village, heavy degraded areas, inselberg) until a final target class was reached. Separation from fallows, which are part of the local production system, is not difficult because natural vegetation is covering the areas already in the first fallow period.

The performance of this classification approach was tested with ground truth data and show good results. Comparison with GPS-measured field areas indicates that 82% were classified correctly. However, errors are possible if objects are very small and mixed pixels occur. This is likely on small pathways or very young settlements because spectral signal of thatched huts can't be separated from agricultural fields.

To apply the decision tree to all datasets, the satellite data have to be radiometrically comparable. A dark object subtraction technique was applied (Chavez 1996) before the data of both dataset are classified. Nevertheless, the boundary conditions in the decision tree classifier had to be slightly adapted for the scene from 1991 to exclude areas which were affected by bushfires. Due to spatially inhomogeneous atmospheric distortions in the 2001 data, which could not be corrected with the COST-Model, the scene was separated into a clear and a hazy part using the tasselled cap transformation (Crist & Kauth 1986, Huang et al. 2002). For these two parts the parameters in the decision tree classification were adjusted to allow for different reflectances.

Based on these results, the changes of LUCC were calculated. Therefore a post classification approach was used. Long term changes were visible comparing the data of 1991 and 2000, the short term dynamics were identifiable in the one year period between 2000 and 2001.

6 Change assessment

The results of the decision tree classification contain information about agricultural areas, for three different time steps (1991, 2000 and 2001). To facilitate process understanding with regard to the observed changes, classification was performed respectively for the separate administrative units within the catchment. These five municipalities show different configurations concerning population dynamics, land-use history and land-cover. Parakou and Djougou have a long history of agricultural

Tab. 1: Changes in population and used areas for agriculture (Source: INSAE 2004 and own calculations).

Municipality	Area [km²]	Population 1992		Population 2002		Population growth rate [1992–2002]
		absolute	density	absolute	density	
Bassila	5727	46416	8,10	74664	13,04	4,87
Djougou	3932	134099	34,11	181175	46,08	3,05
N'Dali	3759	45334	12,06	66367	17,66	3,88
Parakou	456	103577	226,92	148451	325,23	3,66
Tchaourou	6855	66382	9,68	106661	15,56	4,86

land use, whereas N'Dali, Bassila and Tchaourou are characterised by large areas of natural savannah.

Tab. 1 shows some basic figures of the population and the changes between 1992 and 2002. All municipalities show high population growth values in the last ten years. Population density ranges between 13 and 325 inhabitants per km^2 in 2002, whereas the municipality of Parakou represents only urban area and is therefore not comparable. The highest growth rate is not found in the urban areas but in the less dense populated rural municipalities (Bassila, Tchaourou). This is caused by high in-migration by farmers from the north-western districts (mainly Atacora) and from abroad who are searching for fresh and fertile soils. The change detection analyses affirm that the highest change rates occur there (Tab. 2, Fig. 2).

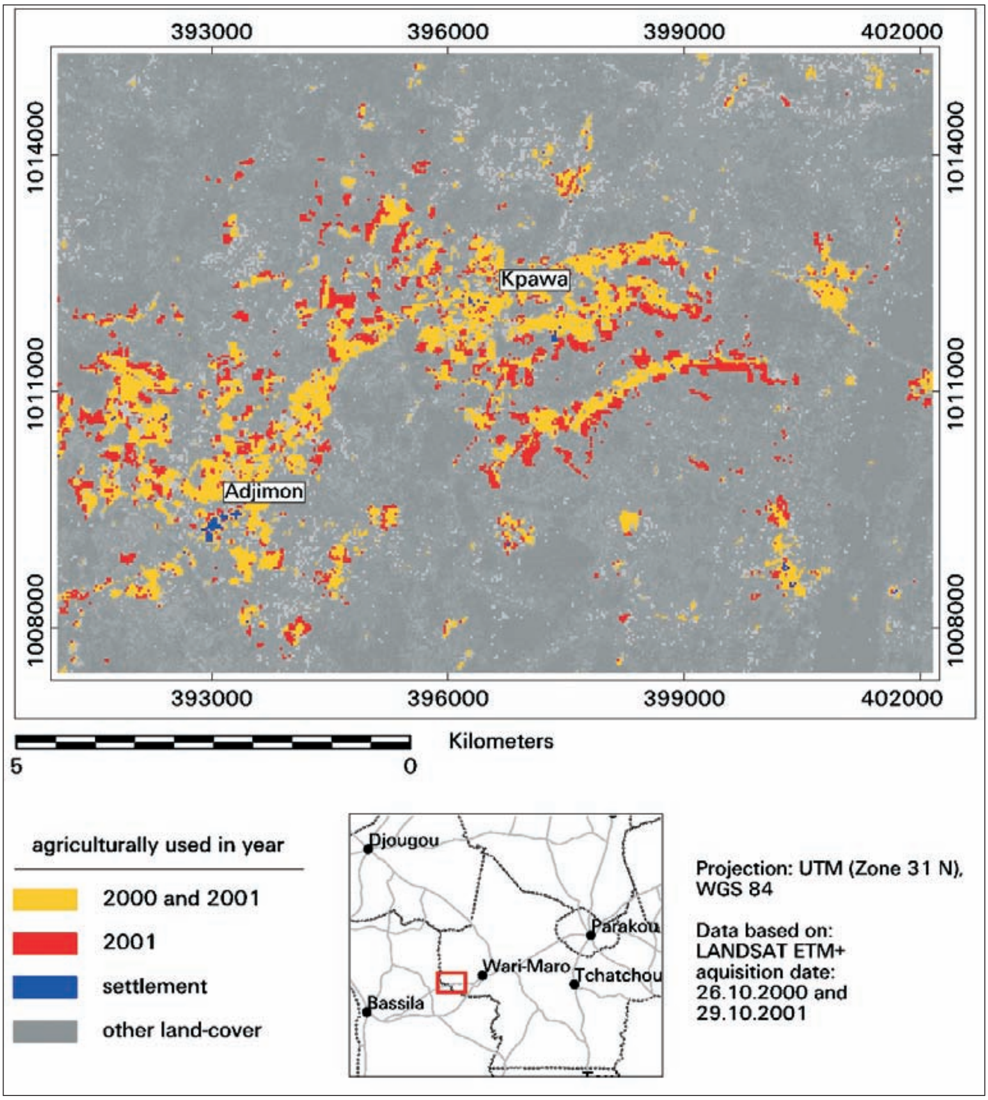

Fig. 2: An example of agricultural colonization in the study area. Results derived from LANDSAT data.

Tab. 2: Changes in agriculturally used areas (Source: own calculations).

Municipality	Area [km²]	% field areas of total	
		1991	2000
Bassila	5727	2,13	5,02
Djougou	3932	16,1	25,35
N'Dali	3759	6,28	9,31
Parakou	456	25,6	40,37
Tchaourou	6855	2,96	10,54

In contrast, some parts of the study area had a long lasting history of agricultural land-use and show comparatively high population densities (mainly around the city of Djougou). Farmers have increasing problems in maintaining the necessary fallow cycle. In these areas, some surfaces show evidence of heavy degradation and lack fertile soils. In the near future, increased pressure on the ecosystem and emigration seems likely.

By using remotely sensed data, not only are analyses on a spatially aggregated level possible, but also spatially explicit findings can be derived. In Fig. 2, agricultural colonization between 2000 and 2001 is illustrated. In this example, a high inflow of migrants took place since an existing small path was enlarged to a road in 1997 (see also Doevenspeck 2004).

Within five years about 20 new villages were created between Wari-Maro and Bassila. The extension of field areas into savannah area is apparent in the map.

7 LUCC Modeling

For sustainable development it is important that decision makers have sound information about possible future developments under specific boundary conditions (scenarios). In this context, the future state of land-use and land-cover is an important parameter with regard to the hydrologic cycle, food security and conflict avoidance. Therefore a number of land-use land-cover change (LUCC) models have been developed within the last decades. Due to the different tasks they have been developed for, a huge variety of concepts, complexity and needed input parameters can be found (Briassoulis 2000, U.S. EPA 2000, Parker et al. 2002).

Therefore it was a challenge to choose a model concept for our study area which met all the demands regarding spatial resolution, availability of input parameters, set up and computing time. It represented an asset that a sound process understanding of the driving forces, the actors and the spatial pattern of the land-use and land-cover changes was available in reason of intensive interdisciplinary research within the IMPETUS project (IMPETUS 2003).

After having extensively tested different LUCC models, a model chain was constituted (Fig. 3). The main model used, CLUE-S (Conversion of Land-use and its Effects), was developed at Wageningen University (for model description see Verburg et al. 2002). It represents a spatially explicit dynamic model and had been successfully tested in different tropical environments (Verburg et al. 2004, Verburg et al. 2004a).

In land-use modelling, especially in developing countries, the availability of sound information about the input parameter is not always guaranteed. To overcome this problem, our model chain utilizes the models in different spatial resolutions (Fig. 3).

On a local scale along a road of 40 km length, it works in a spatial resolution of 30 m × 30 m. For this area, the available data base is comparatively good because a detailed survey concerning the socio-economic conditions (IMPETUS 2003) had been undertaken.

For the regional scale covering an area of 100 km × 100 km, the spatial resolution is 90 m × 90 m. For the whole catchment of the Ouémé in the sub-national scale (100 km × 450 km), the modelled pixel size amounts to 1000 m × 1000 m. It is an interesting research topic to investigate the scale dependency of the results. At the local scale, a detailed process understanding can be gained and transferred into smaller scale models. On the other hand, the results of sub-national and regional scale can be used as external driving forces for larger scale modelling. With this approach it is possible to deal with reduced availability of input data and the higher complexity of the LUCC processes by moving to smaller spatial scales.

The setup of the CLUE-S model requires probability layers for each land-cover class, conversion information and future demand scenarios. Influences of different driving forces on land-use and land-cover were calculated with logistic regression including as predictors:

- distance to road
- distance to important settlements
- population density
- soil suitability
- protected forests.

To assess the goodness of fit of the logistic regression models, the ROC method was used (Pontius & Schneider 2000). This is an estimation similar to the R^2 for ordinary linear regression equations. The area under the calculated ROC-curve gives an estimation value which is between 0.5 (no explanation) and 1 (perfect explanation). For the land-cover classes in the study area those values are between 0.69 and 0.99 which means, that the chosen driving forces are able to explain the land-cover situation quite well.

Based on the yearly demand for each land-cover/land-use the model try to find a solution for every calculated year based on the probably data and conversion restrictions. This is done through an iterative procedure.

The first model run simulated the basic land-use and land-cover patterns in an acceptable manner (Fig. 4). The main drivers for agricultural land-use are distance to street and population density, which is visible in the modelled output result. Distance to street shows a slightly overrepresentation in the modelled result, which is due to high prediction power in the logit equations.

Despite these promising first results some questions remain unsolved. For instance, the boundaries of the protected forest,

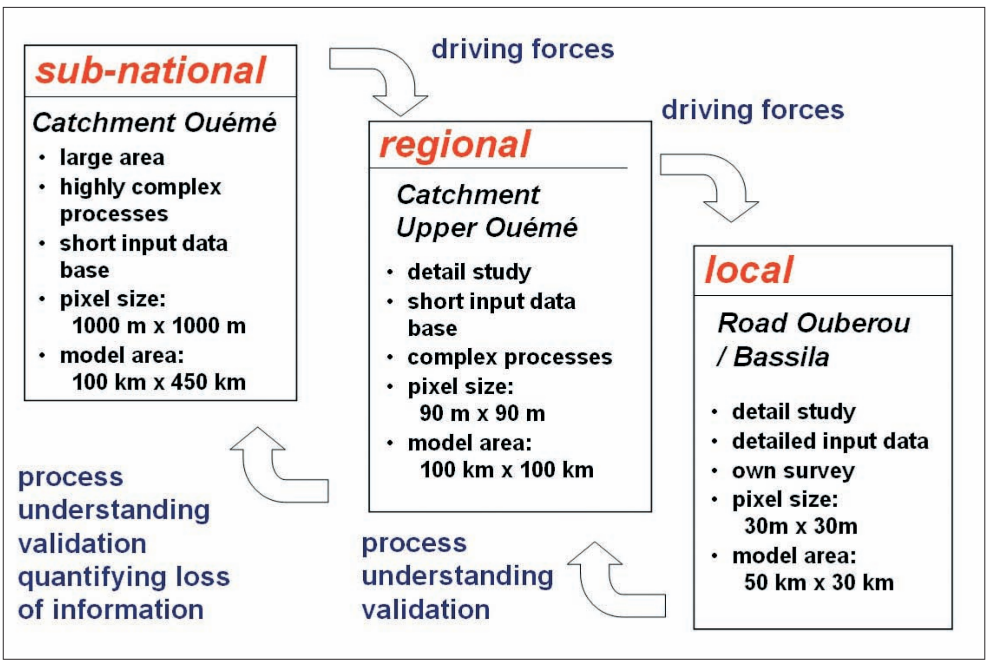

Fig. 3: Scheme of the model chain to compute scenarios of future land-use and land-cover.

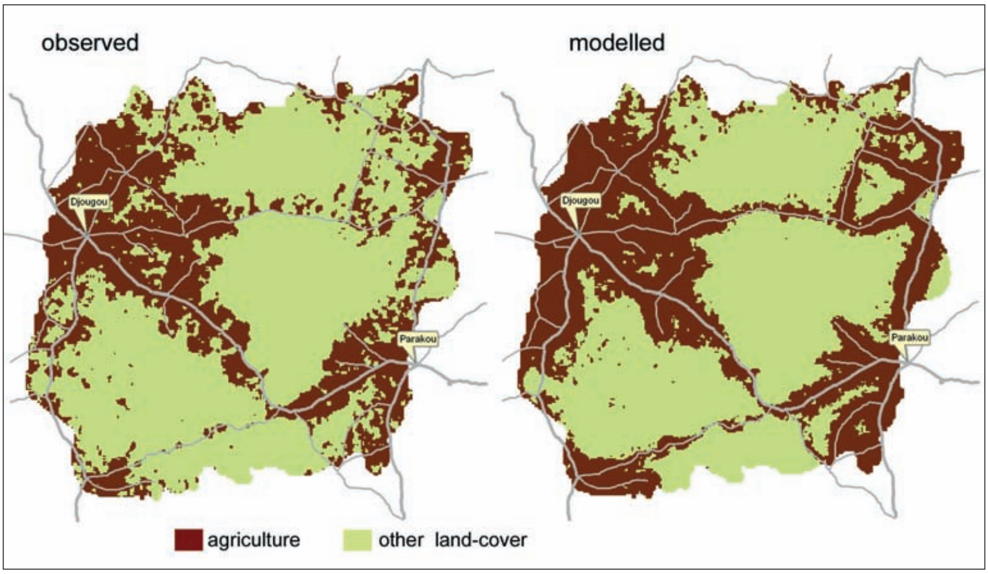

Fig. 4: Agriculturally used areas in the upper Ouémé Catchment for the year 2000. Left: derived from LANDSAT, right: modelled with CLUE-S (starting from 1991).

where agriculture is prohibited by law, are sometimes violated by settlers. Another point is that, especially in Africa, human behaviour is strongly influenced by religious or social constraints (e. g. Voodoo). Such driving forces are very hard to assess and to "pixelise" but they can have strong influence on the pattern of change. To deal with this "soft" parameter represents a challenge for future studies.

8 Conclusions

The study area in central Benin has been subjected to strong land-use and land-cover changes within the last decade caused by accelerating agricultural expansion. In this paper, a decision tree classifier is used to assess agricultural areas for different years. The extension rate of agricultural land is heterogeneous due to history of land use, actual migration rates and availability of arable land. Based on the results of the change detection, intensive field work in the framework of the IMPETUS project and additional socio-economic data, a detailed process understanding was established. This lead to the set up of a land-cover and land-use model chain in different spatial scales which is the framework to compute scenarios for future developments. The first outcome of the model regarding agricultural expansion was promising and proves that the concept can provide basic information for decision makers and sustainable management concepts.

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References

Adjanohoun, E. & Ake Assi, L., 1967: Inventaire floristique des forêts claires subsoudanaises et soudanaises en Côte d'Ivoire septentrionale. – Ann. Univ. Abijan, Fasc. Sc., Vol. 3: 89–147.

Briassoulis, 2000: Analysis of Land Use Change: Theoretical and Modeling Approaches. – The Web Book of Regional Science. (www.rri.wvu.

edu/regscweb.htm). (WV: Regional Research Institute) West Virginia University.

Chavez, P.S., 1996: Image-based atmospheric corrections – revisited and improved. – Photogrammetric Engineering & Remote Sensing **62** (9): 1025–1036.

Crist, E.P. & Kauth, R.J., 1986: The tasseled cap de-mystified. – Photogrammetric Engineering & Remote Sensing **52** (1): 81–86.

Doevenspeck, M., 2004: Migration im ländlichen Benin – Sozialgeographische Untersuchungen an einer afrikanischen Frontier. – Studien zur Geographischen Entwicklungsforschung, Saarbrücken, S. 282, in press.

Friedl, M.A. & Brodley, C.E., 1997: Decision tree classification of land cover from remotely sensed data. – Remote Sensing of Environment **61:** 399–409.

Huang, C., Wylie, B., Homer, C., Yang, L. & Zylstra, G. (2002): Derivation of a tasseled cap transformation based on LANDSAT 7 at-satellite reflectance. – Int. Journal of Remote Sensing **23** (8): 1741–1748.

IMPETUS (2003): IMPETUS Westafrica. Final Report 01. 05. 2000–30. 04. 2003. Cologne.

INSAE (2004): Troisième Recensement Général de la Population et de l'Habitation, Février 2002. Résultats définitifs. Cotonou.

Obasi, G.O.P. (1999): Hydrology and water resources: a global challenge for WMO. – Lecture at the 14th Conference on Hydrology – 79th Annual Meeting of the American Meteorological Society. Dallas, Texas.

Parker, D.C., Manson, S.M., Janssen, M.A., Hoffmann, M.J. & Deadman, P. (2003): Multi-Agent Systems for the Simulation of Land-Use and Land-Cover Change: A Review. – Annals of the Association of American Geographers **93** (2): 314–337.

Pontius, R.G. & Schneider, L.C. (2000): Land-use change model validation by a ROC method. – Agriculture, Ecosystems and Environment **85:** 269–280.

Strahler, A. & Strahler, A. (2000): Introducing Phyiscal Geography. – New York.

UNEP (2000): GEO-2000. http://www.grid.unep.ch/geo2000/ov-e/0004.htm, accessed at the 05. 01. 2005.

U.S. EPA (2000): Projecting Land-Use Change: A Summary of Models for Assessing the Effects of Community Growth and Change on Land-Use Patterns. EPA/600/R-00/098. – U.S. Environmental Protection Agency, Office of Research and Development, Cincinnati, OH. 260 pp.

Verburg, P.H., Soepboer, W., Veldkamp, A., Limpiada, R., Espaldon, V. & Mastura, S.S.A. (2002): Modeling the Spatial Dynamics of Regional Land Use: The CLUE-S Model. – Environmental Management **30** (3): 391–405.

Verburg, P.H., Overmars, K.P. & Witte, N. (2004): Accessibility and land use patterns at the forest fringe in the Northeastern part of the Philippines. – The Geographical Journal **170** (3): 238–255.

Verburg, P.H., Veldkamp, A., Engelsman, W., van Zalinge, R., van Mensvoort, M.E.F. & Overmars, K.P. (2004a): The use of models to assess the impact of land use change on ecological processes: case-studies of deforestation in SE Asia. – Gerold, G., Fremerey, M. & Guhardja, E. (Hrsg.): Land use, nature conservation, and the stability of rainforest margins in Southeast Asia. – 475–494 (Springer-Verlag) Berlin.

Will, H. (1996): Fernerkundung und Weideökologie in der subhumiden Savannenzone NW-Benin – Anwendung der Satellitenfernerkundung (LANDSAT-TM, SPOT) im Rahmen von weideökologischen Aufgabenstellungen. – Karlsruher Schriften zur Geographie und Geoökologie; Institut für Geographie und Geoökologie der Universität (TH) Karlsruhe.

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