MODELLING OF LAND-USE CHANGES IN A WEST AFRICAN CATCHMENT

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ABSTRACT:

Land-cover and land-use changes are an important part of global change but determine as well livelihoods at local and regional level. The knowledge of change trajectories and possible future conditions is important for a sustainable development strategy. Further on, reliable scenarios with spatial explicit simulations are needed as planning tools for decision makers. This paper describes an example application to gain this knowledge for an area in the semi humid tropics which was performed within the framework of the IMPETUS project.

The study investigates the current trends in land-cover change in a West African catchment in central Benin. During the last decade a high rate of expansion of agricultural area is observed. Through logistic regression the determinants of the spatial pattern of land-cover and land-use is analyzed. Some distance factors and population density as predictors have a high prediction strength measured with the ROC method. Based on these regression results future land-use changes are simulated with the CLUE-S framework, a statistic-dynamic approach developed at the University of Wageningen. The simulation results can serve as planning tools to compare different policy measures.

1. INTRODUCTION

Land-cover change is one of the most important drivers of global change (Lambin 1999) and affects many parts of human-environment systems. Changes in the condition and composition of the land-cover affects climate (IPCC 2001) changes in biogeochemical cycles and energy fluxes (Melillo et al. 2003) and affect thereby livelihoods (Vitousek et al. 1997). Changes are often nonlinear and might trigger feedbacks to the system, that distress conditions of living and threaten vulnerability of people (Kasperson et al 1995). Therefore not only the assessment of land-cover change trajectories but also the projections of possible future conditions under certain assumptions are an elementary task to ensure sustainable conditions (GLP 2005, Veldkamp & Lambin 2001).

Recent studies of land-cover changes in West-Africa showed that agricultural expansion is the most dominant trajectory of land-cover change (Wood et al. 2004, Braimoh & Vlek 2005) which involves loss of savannas and forests. For tropical regions and especially for West-Africa estimates of deforestation are rare and unsure (Lambin et al. 2003).

Beside the assessment of land-use and land-cover changes, analyses of the underlying processes are much more complicated. In the last years several concepts are proposed that describe the relationship, functioning and feedbacks of land-cover (environment), land-use (economy) and socio-cultural background (Geist & Lambin 2001, Briassoulis 2000). A deeper understanding of the change processes is possible through modelling of the system as relationships of driving forces and land-cover (change) is established and verified (Veldkamp & Lambin 2001). The aim of the study is an analysis and description of future scenarios of land-use change up to 2025 on the basis of satellite and easy accessible socio-economic data to demonstrate the feasibility as input for decision support tools.

The study is part of the integrative GLOWA IMPETUS project that investigates the impacts of global change on the water cycle on a regional scale in Morocco and Benin (for a further description see Speth et al. 2002).

2. STUDY AREA

The study area is the upper Ouémé catchment in central Benin, approx. 100 km x 100 km (Figure 1). 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". Located in the sub-humid tropical Sudan-Guinea-Zone, the climate is characterized by a unimodal rainy season from May to October with mean annual rainfall of approximately 1100 mm. The vegetation within the upper Ouémé catchment belongs to the transition zone between the "northern Guinea Zone" and "southern Sudan Zone" which is characterised by forest and woody savannas.

The study area, which has a comparatively low population density of 28 inhabitants km^{-2} (Benin: 59 km^{-2}), is subject to in migration and agricultural colonization (Doevenspeck 2004). Due to relatively fertile soils and available land farmers from northern parts of Benin (mainly department Atacora) move to the study area. In addition to a high natural growth rate this result in a high net population growth rate of 3.8 % per year (calculated for 1992 – 2002 from census data, INSAE 2003).

According to an agricultural micro census which was carried out 1998, 92 % of the rural population in Benin is associated with agriculture and 50 % of them are active farmers or cattle-breeders (PADSA 2001). The agricultural production is characterized as small-scale farming system with low external inputs and fallow cycles. Due to a national credit system and organized production networks, fertilizer and pesticides are hardly available for other crops than cotton. The main crops are yams, manioc, maize, millet and peanuts. Cotton and cashew are the most important cash crops.
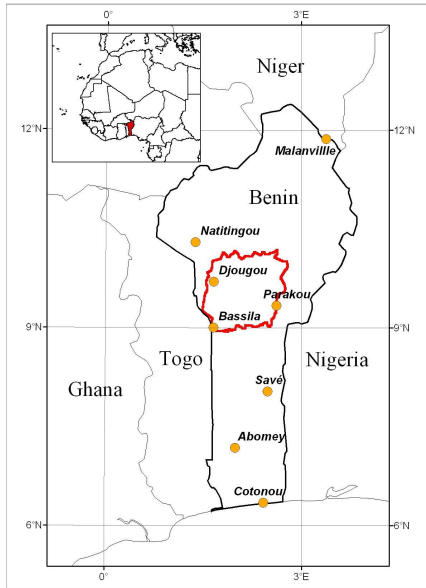
Figure 1: location of the study area

3. DATA AND METHODS

3.1 Data used in this study

To derive information about ongoing land-use and land-cover dynamics, different data sources are used. For the characterization of land-cover and their changes satellite data from 1991 (LANDSAT TM, 13-12-1991, dry season) and 2000 (LANDSAT ETM+, 26-10-2000, end of rainy season) were processed. To gain more insight into the dynamics and to analyse the drivers of change, additional socioeconomic data are used. These are primarily census data on village level from the national census 1992 and 2002 (INSAE 1995, INSAE 2003). In 1998 an agricultural pre-census was carried out (PADSA 2001), which helped to interpret and verify the results in their magnitude. To model future land-use changes additional spatial explicit datasets were created, which represents infrastructural and biophysical drivers. They include location of villages (counted in the census), roads (digitized from street map and improved with the satellite data), location of protected forests (digitized from street map) and suitability of soils for agriculture (derived from digitized soil maps). In different case studies a number of important driving forces for land-use modelling are encountered (Geoghegan et al. 2001, Geist & Lambin 2001, Briassoulies 2000), but in Benin, as well as in other developing countries, data availability is very difficult. E.g. information about land tenure is not available in Benin as most of the agricultural use land is not under private ownership but under village management.

3.2 Methods to derive land-cover information and land-cover changes

The satellite data from 1991 and 2000 were classified independently with the maximum likelihood approach. An independent treatment was necessary due to different phenological states of the vegetation cover. During the dry season up to ca. 80 % of the surface is destroyed by bush fires.

The classification covered 16 classes: forest and savannah types, settlement, agricultural fields, water areas and vegetation free (inselbergs). Additionally, the classification from 1991 dataset contains a class "burned area". Classification of different crops is not possible because many of the field are far below 1 ha and sometimes hardly ever identifiable as field during interpretation.

The class's fields, village areas and inselbergs have high spectral similarities due to resembling cover material. False classified pixels on inselbergs are removed with a SRTM digital elevation model. False classified village area is identified with a fuzzy classification approach. Only if both produced class membership layers indicate village area this class is adopted.

The accuracy of the land-cover data is only given for the data from 2000 as ground truth data are not available for the 1991 data set. Ground measurements from different field campaigns and aerial photos for a representative profile which are collected in 2003 are used as reference data. Combining these ground information an overall accuracy of 82% was achieved.

3.3 How to model future changes?

In general three different modelling techniques are described: Statistic-mathematical models are mostly non-spatial and are used to model the economic side with respect to land-cover change (Angelsen 1999). Agent based methods try to model the behaviour of agents of change and their impacts on land-cover / land-use and their feedback (Parker et al. 2003, Bousquet & Le Page 2004.). Another approach tries to find an integrative solution of the problem. They consider dynamic feedbacks, scale issues and temporal dynamics in a spatial explicit way (Pijanowski et al. 2002, Verburg et al. 2002). The CLUE-S integrated modelling approach e.g. work with an arbitrary set of driving forces but through spatial and temporal constraints highly complex simulation condition emerges. This approach was selected as modelling framework. For a further description of the CLUE-S modelling framework see Verburg et al. (2002).

The relationship between current land-cover and land-use configuration of the study area is established through logistic regression for each land-cover type and a set of defined driving forces as following:

$$Log\left(\frac{P_i}{1-P_i}\right) = \beta_0 + \beta_1 X_{1,i} + \beta_2 X_{2,i} \ldots + \beta_n X_{n,i}$$

where P_i = probability of the occurrence of a specific land-use type

X_i = predictors (driving forces)

β_n = regression coefficients.

Evaluating the inverse of the regression equation for each grid cell results in a probability layer which serve as input for the iterative land-cover allocation for time step t_{i+1}.

With stepwise selection of significant predictors a final set of driving forces with the corresponding regression coefficients is obtained. Goodness of fit for the logistic regression results are measured with the ROC method (Pontius & Schneider 2000). This gives an estimation of the ability of the model to score a randomly drawn positive sample higher than a randomly drawn negative sample.

The application of the model was carried out on a spatial aggregated level due to computation time (regression and modelling) and due to lack of detailed spatial drivers. Results of the land-cover classification are aggregated to a pixel size of 500m x 500m with an adaptive method to retain the spatial distribution pattern of the land-cover types. Pure fields are no longer visible at this scale but agricultural production system includes fallow areas for soil regeneration. If a 500m cell contains more than 10 % current used fields the class agricultural area is assigned to the cell, which captures also the

scattered isolated fields according the land-cover classification system of the FAO (Di Gregorio & Jansen 2000). That procedure results in an about three times higher total area for agriculture which had to be counted for during scenario building. In the same manner cells for settlements and forests are calculated with a threshold of 20 % respectively. Calculations for other spatial scales are left for further studies.

The demand for future land-cover is given on a global level (non-spatial) and calculated for different scenario assumptions. The demand can be extracted from macro-economic modelling, but such is not available at the desired resolution. Calculations are done with extrapolations on the basis of estimated future land requirements with population projections[*] and field reference data (Mulindabigwi 2005).

Additionally, area and conversion restrictions for specific combinations of land-cover types are established and incorporated into the scenarios.

4. RESULTS

4.1 Land-cover configuration in central Benin

The study area in central Benin is characterized by a high fraction of quasi natural savannah and forest areas. The location of the huge areas is determined by colonial introduction of protected regions, mainly for hunting. The most prominent example is the 'Foret classée de l'Ouémé Superieure' in the middle of the study area (see Figure 2). Two other big forest areas are in the very south of the catchment. In the north-western part, around the town Djougou, extended areas with long lasting agricultural production are found. Population density in this municipality is relatively high with 34 inhabitant's km^{-2}, compared to the southern ones, where density is below 10 km^{-2}. Generally, the production intensity (as field density) is higher around main cities causing also shorter fallow cycles. But there are also regions with scattered fields in remote areas with obviously no completed road access.

For a better comparison the 16 classes are combined to four main land-cover classes: settlement, agricultural area, forest and dense savannah and other (mainly bush savannah, sparse vegetated are and water).

4.2 Land-use change dynamics

The comparison of the two land-cover maps is hampered by the fact, that about 35% of the catchment area of the 1991 land-cover map is affected by bush fire and therefore a precise determination of the effective land-cover is not possible. This is mostly the case for different kinds of savannas and forest. Agricultural used areas are assumed not to be affected by fire which is not always true, as harvested fields are also burned sometimes.

The most dominant short time change process is temporal destruction of vegetated areas by bush fires (see Table 1). Bushfires are in most cases man made but sometimes out of control and affect huge areas. The second man made land-cover change is the expansion of agricultural land at the expense of forest and savannas. In the catchment area classified field areas increased by nearly 76 % in nine years, which is a net rate of 6.5 % per year. There might be an overestimation of the figure because of burned fields that are inside the class 'burned area'.

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[*] Unpublished work of M. Doevenspeck. Population for village level is calculated as weighted fraction of projected numbers of departments.
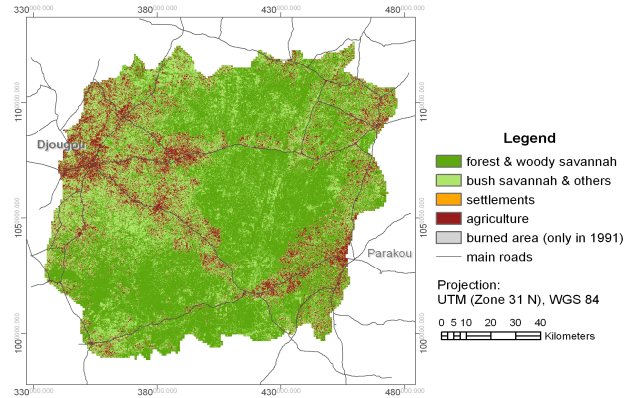

Figure 2: Land-cover map of upper Ouémé catchment from the year 2000

Unfortunately there are no reliable data about the production of agricultural crops available to estimate intensification of production. Through our field campaigns and the work of others (Mulindabigwi 2005, Doevenspeck 2004) hardly any intensification is visible. Fertilizer is not sufficient available for most farmers and mechanisation is on a very low level. In the department Donga that cover the western part of the catchment only 27 % of the farmers apply fertilizer and that generally for cotton production (PADSA 2001). So the demand for the growing population is acquired through extension of fields. Where enough land is available farmers extend the agricultural frontier into remaining forest areas, or shorten the fallow period. In the densely settled region around Djougou farmers already complain declining soil fertility and shortage of land (Mulindabigwi 2005). Decrease of area of settlements is due to classification errors in the 1991 dataset because of spectral indistinguishability with dry and sparse vegetated areas.

	1991		2000	
	ha	% of total	ha	% of total
Forest	613010	42.1	733507	50.4
Savannah	222432	15.3	522132	35.8
Settlement	2882	0.2	1379	0.1
Fields	112419	7.7	197799	13.6
Burned areas	504081	34.6		

Table 1: change in land-cover for upper Ouémé catchment. Data derived from classification of LANDSAT scenes.

4.3 Analysis of driving forces and conditions

The first step in setting up a model using the CLUE-S framework is the selection of driving forces that determine the spatial configuration of land-cover and land-use. As the main land-cover change is the expansion of agricultural land modelling of future land-cover is focused on this type of land-use.

The following socio-economic drivers are used in this study:

- Population density calculated from village data with 10 km search radius as an overall measure of activity
- Distance to village and roads as primary parameter of access to infrastructure
- Cost weighted distance to major settlements, calculated for settlements > 5000 inhabitants including different types of roads. This variable represents the locations of access to important goods and services.
- Location of protected forests as measure of land tenure.

As a kind of biophysical parameter the suitability of soil for agricultural production is included. This dataset is derived from the general soil map of Benin, aggregated into three classes of good, medium and not usable for production[*]. These parameters are used as predictors to fit a logistic regression model with each land-cover class as dependent variable. The results are shown in Table 2. As an overall measure of the goodness of fit the ROC curve is calculated and the area under the curve (AUC). The AUC value score between 0.5 and 1 with 1 indicating perfect model prediction ability.

The quality of the logistic regression results for class other savannah is very bad (AUC = 0.6) and therefore coefficients are not used. This class serves furthermore as balance for changes in the demand for the other classes, so a value of 0.5 is given as constant and coefficient respectively to receive a probability layer value of 0.5.

The value exp(b) indicate the change in odds if the predictor variable is changed by one unit. If the value is > 1 then the connection is positive i.e. the probability increases if the value of the predictor variable increases.

Population density is positive correlated with land-cover type settlement and agriculture but has a negative effect on natural vegetation. The coefficients for distance measures are very small, that normally indicates a very small influence on the dependent variable. As the units are in meters the effect is still visible at scale of kilometres in the study area. The location of protected forests is a very good predictor of forest areas, as this variable implies as a kind of tenure variable the use of the area as forest resource. Interestingly the data on soil suitability for agricultural production has a limited prediction force. This is due to the character and resolution of the soil maps from Benin. They represent the general soil type which is often found far bellow the effective topsoil. In many cases the hillwash from the pediplanes determine the soil conditions at field level (Junge 2004) but this information is not available at the scale of the study.

4.4 Future land-cover / land-use distribution

The definition of future scenarios are based on the results from the calculated changes from LANDSAT data and on extrapolations based on census data. Calculating the agricultural
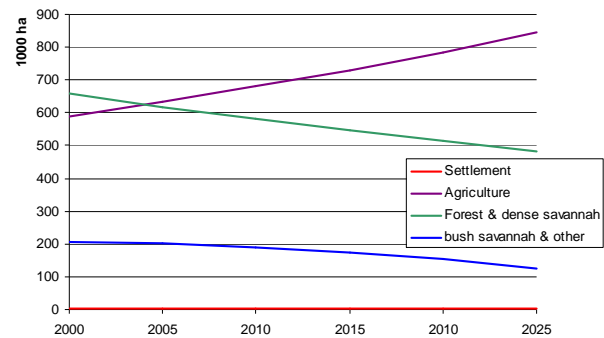
Figure 3: global estimates for land-cover distribution for the upper Ouémé catchment.

area per capita would result in a future bias because people can leave farm employment and search for other incomes, manly in the growing cities as shortage of land is increasing. Therefore percentage of people who have an active farm employment is calculated which is nearly 21 % for the region. In all scenarios population density is a dynamic driving force i.e. an updated population density layer for each run.

4.4.1 Expansion scenario

This first scenario assumes an ongoing acceleration of the agricultural expansion in the region. The ratio of active agricultural people to total amount of people is expect to be the same in the near future, as changeover of farmers into cities in search for off-farm income is balanced by agricultural migrants from other parts of the country. Extrapolating the agricultural land based on the figure received through the change detection the fraction of real agricultural land use would be > 65 % which is not possible under the current production conditions. A future threshold of maximum usable area is difficult to determine because it depends on the external inputs to shorten the fallow periods.As spatial grid size is aggregated the future agricultural area is calculated only for the fraction of actual agricultural use land based on the projections of active agricultural people (Figure 3). Loss of forest is estimated as nearly inverse of the increase in agricultural area. Only on 2015 bush savannah &

	Settlement		Agriculture		Forest & dense savannah		Tree savannah & others	
predictor	coef	exp(b)	coef	exp(b)	coef	exp(b)	coef	exp(b)
constant	-1.54800		3.98662		-2.16278		0.5	
population density	0.00260	1.00260	0.01409	1.01419	-0.01426	0.98585		
Distance								
Road	-0.00123	0.99877	-0.00021	0.99979	0.00014	1.00014		
Village	-0.00004	0.99996	-0.00009	0.99991	-0.00003	0.99997	not used (0.5)	
major settlement	-1.20400	0.29999	-0.00003	0.99997	0.00005	1.00005		
protected forests			-1.86243	0.15530	2.88720	17.94294		
Soils								
not usable								
medium	0.41770	1.51847	-0.33335	0.71652	0.38976	1.47662		
good								
AUC	0.961		0.88		0.89			

All variables are significant at $p < 0.001$

Table 2: Coefficients of logistic regression for land-cover types in central Benin

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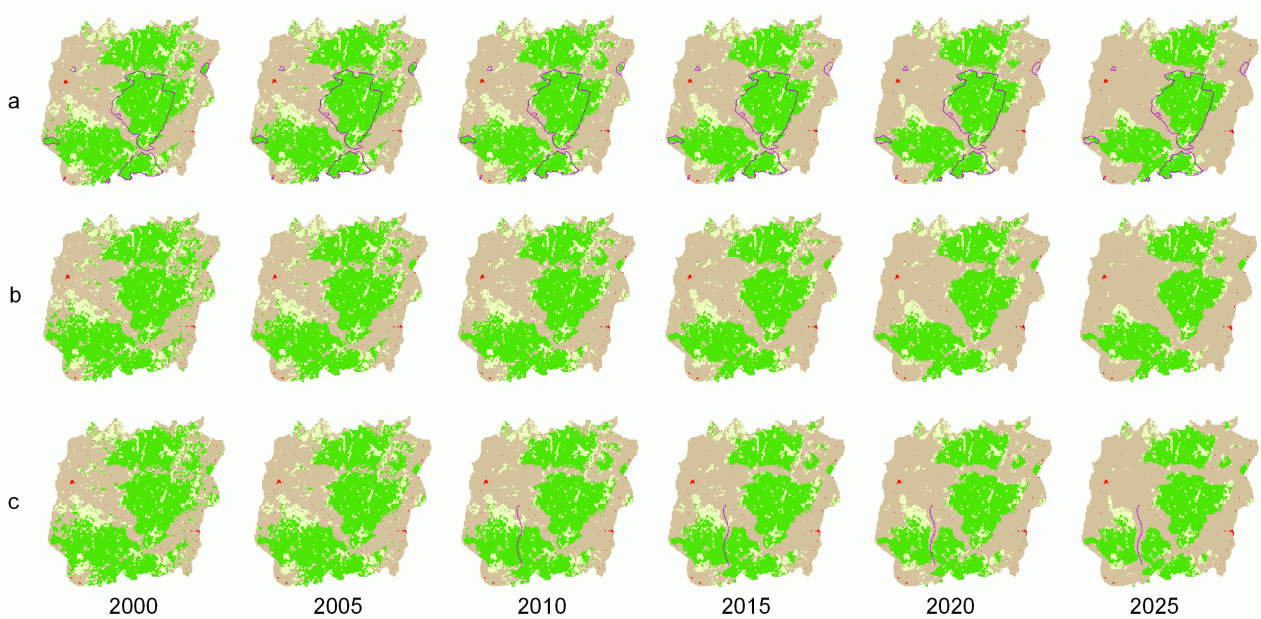[*] Thanks to Claudia Hiepe for producing this data set

Figure 4: Results of three scenarios of future land-cover in the upper Ouémé catchment (Settlements: red, agriculture: brown, forests: green, other savannas: light green). Expansion scenario (a), removal of forest (b), construction of a new road (c). Protected forest and new road are shown in violet.

others decrease as agricultural area is extended on these generally marginal lands. Development of settlements is difficult to estimate as many possibilities are plausible. So a very slow growth is chosen as this class is not very prominent in the study area and a separate urban growth model is not used.

Results of the model run are shown in Figure 4. It is apparent that the main part of the future agricultural area is allocated around the main cities due to the high combined influence of access to main markets and population density. Access to the protected forests is not prohibited in this scenario but inhibition threshold is high as land is owned by government. But with ongoing extension and pressure on land these areas are also converted to agriculture at the edges. Little protected forest like in the upper east and the middle west nearly disappear by 2025. The big forest in the middle of the catchment is just to the beginning already occupied by farmers at the western side. Another run demonstrate the effects of the policy decision of a complete removal of the protection status and return of the land to the village administration (Figure 4, b). Status of the other forest is strictly protected.

4.4.2 Road construction scenario

The second scenario is a simulation of the construction of a new road in 2010 from Partago to Doguè (Figure 4, c) through a region of reminding forest that is not protected. As a consequence of this hypothetical infrastructure innovation as relieve of pressure on the protected forests the creation of two new villages is assumed along the road. Population is estimated to be 2000 people in 2025. Reference for such an evolution is given by Doevenspeck (2004). Therefore all socio-economic drivers are dynamic and updated appropriately. The control of the protection forests is assumed to be good so the status quo inside those areas is obtained. As the results demonstrate such a decision clearly attracts people to clear forest for agricultural production.

5. DISCUSSION AND CONCLUSION

The presented study describes the current trends in land-cover change and demonstrates the setup of a model environment to simulate possible future scenarios. As sources of reliable data are scarce the prediction of land-cover is done with census data and an arbitrary set of distance measures which indicate however a good explanatory power. But analysis of field data and spatial explicit land-cover change detection (Thamm et al. 2005) indicate that the frontier of agricultural expansion can be located at relatively remote situations with limited access. This encourage the findings of Gobin et al. (2002) that pure distance factors are not solely a prediction variable as often used according the von Thünen model. It is rather a set of socio-cultural factors that determine the exact spatial land-cover and land-use distribution. It will be a challenge to define more spatial explicit drivers at the scale of the study.

The data about biophysical conditions are limited which result in insufficient regression parameters. The construction of such data or proxy parameters should be a further task also.

However, the application of the model can be an important input in regional land-use planning to balance the effect of different policy measures or changes in infrastructural conditions. It is planned for the future work of the IMPETUS project to incorporate current planning ideas from the administration of regional and national level and to construct decision support tools for different stakeholders.

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REFERENCES

Angelsen, A., 1999. Agricultural expansion and deforestation: modelling the impact of population, market forces and property rights. *Journal of Development Economics* 58, pp. 185-218.

Bousquet, F. & Le Page, C., 2004. Multi-agent simulations and ecosystem management: a review. *Ecological Modelling* 176(3-4), pp. 313-332.

Braimoh, A. & Vlek, P., 2005. Land-cover change trajectories in northern Ghana. *Environmental Management* 36(3), pp. 356-373.

Briassoulis, H., 2000. Analysis of Land Use Change: Theoretical and Modelling Approaches. *The web book of regional science*

Di Gregorio, A. & Jansen, L.J., 2000. Land Cover Classification System (LCCS), Technical report, FAO.

Doevenspeck, M., 2004. Migration im ländlichen Benin. Sozialgeographische Untersuchungen an einer afrikanischen Frontier', PhD thesis, University of Bonn.

Geist, H.J. & Lambin, E.F., 2001. What drives deforestation? A meta-analysis of proximate and unerlying causes of deforestation based on subnatinal case study evidence. *LUCC Report Series* 4, pp.116.

Geoghegan, J.; Villar, S.; Klepeis, P.; Mendoza, P.; Ogneva-Himmelberger, Y.; Chowdhury, R.; Turner, B. & Vance, C., 2001. Modelling tropical deforestation in the southern Yucatan peninsular region: comparing survey and satellite data, *Agriculture, Ecosystems and Environment* 85, pp. 25-46.

GLP, 2005. Science plan and implementation strategy. *IGBP Report No. 53 / IHDP Report No. 19.*

Gobin, A.; Campling, P. & Feyen, J., 2002. Logistic modelling to derive agricultural land use determinants: a case study from southeastern Nigeria. *Agriculture, Ecosystems & Environment* 89(3), pp. 213-228.

INSAE, 2003. Troisième récensement general de la population et de l'habitation 2002. Cotonou

INSAE, 1995. Recensement general de la population et de l'habitation 1992. Cotonou

IPCC, 2001. *Climate Change 2001: Synthesis Report. Summary for policymakers.*

Irwin, E. & Geoghegan, J., 2001. Theory, data, methods: developing spatially explicit economic models of land use change. *Agriculture, Ecosystems and Environment* 85, pp.7-24.

Junge, B., 2004. Die Böden im oberen Ouémé Einzugsgebiet: Pedogenese, Klassifikation, Nutzung und Degradierung, PhD thesis, University of Bonn.

Kasperson, J.X.; Kasperson, R.E. & Turner II, B.L., 1995. *Regions at risk: comparisons of threatened environments*, United Nations University Press, Tokyo, New York, Paris.

Lambin, E.; Baulies, X.; Bockstael, N.; Fischer, G.; Krug, T.; Leemans, R.; Moran, E.; Rindfuss, R.; Sato, Y.; Skole, D.; Turner II, B. & Vogel, C., 1999. Land-Use and Land-Cover Change (LUCC) Implementation Strategy, *IGBP Report* 48

Lambin, E.; Geist, H. & Lepers, E., 2003. Dynamics of land-use and land-cover change in tropical regions. *Annual Review of Environment and Resources* 28, pp. 205-241.

Melillo, J.; Field, C. & Moldan, B., 2003. *Interactions of the major biogeochemical cycles*, Island Press, Washington, DC.

Mulindabigwi, V., 2005. Influence des système agraires sur l'utilisation des terroirs, la séquestration du carbone et la sécurité alimentaire dans le bassin versant de l'Ouémé supérieure au Bénin. PhD thesis, University of Bonn.

Orthmann, B., 2005. Vegetation ecology of woodland-savanna mosaic in central Benin (West Africa): Ecosysem analysis with focus on the impact of selective logging. PhD thesis, University of Bonn.

PADSA, 2001. Prerécencement de l'agriculture. Ministère de l'Agriculture de l'Elevage et de la Pêche Benin.

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), pp. 314-337.

Pijanowski, B.; Brown, D.G.; Manik, G. & Shellito, B., 2002. Using Neural Nets and GIS to Forecast Land Use Changes: A Land Transformation Model. *Computers, Environment and Urban Systems* 26(6), pp. 553 - 575.

Pontius, R.G. & Schneider, L., 2001. Land-cover change model validation by an ROC method for the Ipswich watershed, Massachusetts, USA, *Agriculture, Ecosystems and Environment* 85, pp. 239-248.

Speth, P.; Diekkrüger, B. & Christoph, M., 2002. IMPETUS West Africa. An integrated aproach to the efficient management of scare water resources in West Africa - case studies for selected river catchments in different climatic zones. GLOWA Status Report, pp. 61-67.

Thamm, H.; Judex, M. & Menz, G., 2005. Modelling of Land-Use and Land-Cover Change (LUCC) in Western Africa using Remote Sensing', *Photogrammetrie Fernerkundung Geoinformation* 3/2005, pp. 191-199.

Veldkamp, A. & Lambin, E., 2001. Predicting land-use change. *Agriculture, Ecosystems and Environment* 85, pp. 1-6.

Verburg, P.; Soepber, W.; Veldkamp, A.; Limpiada, R.; Espaldon, V. & Mastura, S., 2002. Modelling the spatial dynamics of regional land use: the CLUE-S model. *Environmental Management* 30(3), pp. 391-405.

Vitousek, P.M.; Mooney, H.A.; Lubchenco, J. & Melillo, J.M., 1997, Human Domination of Earth's Ecosystems. *Science* 277(5325), pp. 494-499.

Wood, E.C.; Tappan, G.G. & Hadj, A., 2004. Understanding the drivers of agricultural land use change in south-central Senegal. *Journal of Arid Environments* 59(3), pp. 565-582.