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An expert-based ecosystem services assessment under land use and land cover changes and different climate scenarios in northern Ghana, West Africa

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ABSTRACT

Land use and land cover change (LULCC) is the result of complex human-environmental interactions which influence the provision of ecosystem services. Many people in low-income countries, especially small-scale farmers, are highly dependent on natural resources and, therefore, rely on the provision of such services. The Upper East Region (UER) belongs to the poorest areas within Ghana and is characterized by subsistence agriculture, high poverty rates and illiteracy. High population densities, low fertilizer input, heavily weathered soils and weather extremes contribute to land degradation and decreasing yields. Modeling interactions between important driving forces of LULCC and relevant ecosystem services (ES) can help to determine the consequences of LULCC, to identify key actions to counteract the negative impacts on relevant ecosystem services, and to communicate the results to policy makers. The Bayesian Belief Network (BBN) is a non-spatial statistical model and allows the analysis and simplified visualization of complex system interactions by directed acyclic graphs and probabilistic dependencies of system components. Due to data and knowledge gaps in the West African context, experts were the main source of information for developing the BBN, testing scenarios, and validating the BBN. Finally, more than 90 experts from Ghana, WASCAL (West African Science Service Center on Climate Change and Adapted Land Use) and agricultural extension officers from the UER were involved in the BBN development process. The most important drivers of LULCC were identified based on a mixed-method approach including questionnaires with scientists from Ghana and WASCAL. Key ES were chosen from an online survey with the WASCAL community. The BBN structure was developed in a focus group discussion with WASCAL scientists. Probabilities of parameters were identified with data from literature, maps, crop models, statistics, and expert knowledge; and validated by scientists at the WASCAL Competence Center. Key ES were food from crops and freshwater provision. Further, soil erosion control was chosen as a measure for analyzing possible synergies and trade-offs between food and water provision. The focus of the BBN was set to food provision from rain-fed crops in the rainy season (sorghum, millet, maize, legumes, and rice), irrigated crops in the dry season (rice and tomato) and water provision in the rainy and dry season. Parameter settings considered, for instance, changes in population, available cropland, income levels, agricultural programs, and rainfall variability. The results of the study show that in the current situation, there is a 75% probability that the food demand during the dry season can be covered by food provision produced by the previous rainy season if all food is consumed in the UER (deducting the harvest loss) and if no additional food sources are used. In contrast, there is only a 37% probability that food from crops will be sufficient in the following rainy season (before harvest) because much less is produced during the dry season, and food storage is very primitive. Among other findings, the study revealed that an increase in income levels might be more effective than improved agricultural programs, increased market demand, increased irrigation, reduced soil erosion, and reduced post-harvest loss for contributing to food security. The same is true for the scenario of increasing population and decreasing total cropland. In none of the scenarios, the vitamin A demand could be covered by cultivated crops, which indicates a high risk of malnutrition. For water provision, there is a probability of 15% for the dry season to experience water scarcity and a 10% probability for the following rainy season. Soil erosion control showed slightly an increase in food provision but had no effects on water provision in the model. However, high uncertainties exist for data and model reliability. For example, groundwater flows could not be estimated for water provision, and expert estimates partly showed high variances. On the other hand, scientists at the WASCAL Competence Center were willing to use the BBN further. In addition, the BBN behaved according to the system understanding and is, therefore, a good starting point for further improvements and adaptations to policy and scientific needs.

KURZFASSUNG

Änderungen in Landnutzung und Landbedeckung sind Folgen komplexer sozio-ökologischer Wechselwirkungen, welche die Bereitstellung von Ökosystemleistungen (ÖSL) beeinflussen. Viele Menschen in einkommensschwachen Ländern, vor allem die Kleinbauern, sind stark von den natürlichen Ressourcen und folglich von den ÖSL abhängig. Die „Upper East Region" (UER) in Nordghana gehört zu den ärmsten Regionen innerhalb Ghanas und ist von kleinbäuerlicher Subsistenzlandwirtschaft, großer Armut und Analphabetismus geprägt. Hohe Bevölkerungsdichten, niedrige Düngemittelzugaben, stark verwitterte Böden und Wetterextreme führen zur Bodendegradation und schwindenden Erträgen. Die Modellierung der Interaktionen zwischen wichtigen Triebkräften der Landnutzungsänderungen und relevanten ÖSL kann helfen, die Konsequenzen von Landnutzungsänderungen zu bestimmen und Schlüsselmaßnahmen zu identifizieren, um die negativen Auswirkungen auf ÖSL entgegenzuwirken und die Ergebnisse an politische Entscheidungsträger weiterzugeben. Das Bayesian Belief Network (BBN) ist ein nicht-räumliches, statistisches Modell, welches die Analyse und vereinfachte Visualisierung von komplexen Systeminteraktionen durch gerichtete, azyklische Graphen und deterministischen Abhängigkeiten zwischen Systemkomponenten ermöglicht. Wegen Daten- und Wissenslücken im westafrikanischen Kontext dienten hauptsächlich Experten als Informationsquelle, um das BBN zu entwickeln, um Szenarien zu testen und das Modell zu validieren. Insgesamt waren mehr als 90 Experten aus der wissenschaftlichen Gemeinschaft in Ghana, aus WASCAL (West African Science Service Center on Climate Change and Adapted Land Use) sowie Vertreter vom landwirtschaftlichen Beratungsdienst der UER an der Modellentwicklung beteiligt. Die wichtigsten Triebkräfte der Landnutzungsänderungen wurden anhand eines Mixed-Method-Ansatzes mit Wissenschaftlern aus Ghana, WASCAL, Fernerkundung und Literaturanalyse identifiziert. Die entscheidenen ÖSL wurden mittels eines Online-Fragebogens mit den Wissenschaftlern aus WASCAL erfasst. Die BBN-Struktur wurde durch eine Fokusgruppendiskussion mit Wissenschaftlern von WASCAL entwickelt. Das BBN wurde mit Daten aus Literatur, Karten, Pflanzenwachstumsmodellen, Statistik und Expertenwissen gefüllt. Es wurde mit Wissenschaftlern vom WASCAL-Kompetenzzentrum validiert. Die wichtigsten ÖSL waren die Nahrungsmittelversorgung durch den Feldfruchtanbau und die Trinkwasserbereitstellung. Zudem wurde die Bodenerosionskontrolle als Maßnahme zur Analyse von möglichen Synergien und Zielkonflikten zwischen Nahrungsmittelversorgung und Trinkwasserbereitstellung genommen. Der Fokus vom BBN wurde auf die Nahrungsmittelversorgung durch Regenfeldbau in der Regenzeit (Sorghumhirse, Perlhirse, Mais, Leguminosen und Reis), bewässerten Anbau in der Trockenzeit (Reis und Tomaten) und die Trinkwasserbereitstellung jeweils in der Regen- und Trockenzeit gesetzt. Parametervorgaben waren unter anderem die Gesamtbevölkerung in der UER, verfügbares Ackerland, Einkommensniveaus, landwirtschaftliche Programme und Niederschlagsschwankungen. Die Studie konnte unter anderem aufzeigen, dass in der derzeitigen Situation eine Wahrscheinlichkeit von 75% besteht, dass der Nahrungsmittelbedarf der ländlichen Bevölkerung in der Trockenzeit vom Angebot gedeckt wird, welches in der vorangegangenen Regenzeit produziert wurde, wenn alle Produkte in der UER konsumiert werden (abzüglich der Ernteverluste) und keine zusätzlichen Nahrungsquellen genutzt werden. Jedoch gibt es eine Wahrscheinlichkeit von nur 37% in der darauffolgenden Regenzeit vor der nächsten Ernte, dass die Nahrungsmittel ausreichen, da deutlich weniger in der Trockenzeit produziert wird und die Nahrungsmittellagerung sehr primitiv ist. Des Weiteren zeigen die Ergebnisse der Studie, dass eine Erhöhung des Einkommens eher zur Nahrungssicherheit beiträgt, als die Verbesserung landwirtschaftlicher Programme, die Verbesserung des Marktbedarfs, die Verbesserung der landwirtschaftlichen Bewässerung, die Reduzierung der Bodenerosion, und die Reduzierung der Nacherntverluste. Das Gleiche gilt für das Szenario der zunehmenden Bevölkerung und

abnehmenden Verfügbarkeit von Ackerland. In keinen der Szenarien konnte der Vitamin-A-Bedarf durch die Anbaufrüchte gedeckt werden, was auf ein hohes Risiko der Mangelernährung hinweist. In Bezug auf die Trinkwasserbereitstellung gab es ein Risiko von 15%, dass es Wasserknappheit in der Trockenzeit geben könnte und 10% Wahrscheinlichkeit der Wasserknappheit in der darauffolgende Regenzeit. Die Kontrolle der Bodenerosion zeigte einen leichten Anstieg des Nahrungsmittelangebots, hatte jedoch keinen Effekt auf die Trinkwasserbereitstellung in dem Modell. Jedoch herrschen große Unsicherheiten bezüglich der Verlässlichkeit der Daten und des Modells. Zum Beispiel konnten die Grundwasserströmungen für die Wasserversorgung nicht bestimmt werden und die Expertenschätzungen zeigten teilweise hohe Abweichungen. Andererseits waren die Wissenschaftler am WASCAL Kompetenzzentrum daran interessiert, das BBN zu nutzen. Zudem verhielt sich das BBN entsprechend der Systemverständnisses und ist daher ein guter Ausgangspunkt, um weitere Verbesserungen und Anpassungen an die politischen und wissenschaftlichen Bedürfnisse vorzunehmen.

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LIST OF ABBREVIATIONS

BAU	Business as usual
BBN	Bayesian Belief Network
BMBF	German Federal Ministry of Education and Research
dryS	Dry season
ES	Ecosystem Services
FAO	Food and Agriculture Organization of the United Nations
CoC	Competence Center
CPT	Conditional Probability Table
GDP	Gross domestic product
GIS	Geographic Information System
GSS	Ghana Statistical Service
LULCC	Land use and land cover change
LUP	Land use planning
MOFA	Ministry of Food and Agriculture
NGO	Non-governmental organization
rainyS	Rainy season
RS	Remote sensing
SU	Settlement unit
SWSC	Soil water storage capacity
TLU	Tropical Livestock Unit
UER	Upper East Region
WASCAL	West African Science Service Center on Climate Change and Adapted Land Use

1. INTRODUCTION

1.1 Background and context of the study

The provision of ecosystem services is essential to ensure human life and well-being (Costanza et al., 1997; Daily, 1997; MA, 2005). Especially in low-income countries, people are more directly dependent on ecosystem services than in developed countries (UNDP, 2005). The degradation of ecosystems and related functions and services are threatening people´s livelihoods (MA, 2005). Ecosystem degradation processes in low-income countries are related to population growth, poverty, lack of economic and technological resources, and slow educational progress (IPCC, 2014; MEA, 2005). People have a low coping capacity due to high poverty and illiteracy (Ibid.). But also climate variability and harsh environments contribute to people´s vulnerability (Lesk et al., 2016). It is often a combination between social and ecological factors which affect livelihoods. There exists a close interaction between people and the environment which can be described as socio-ecological system (Berkes and Folke, 1992; Ostrom, 2009). The dependency of human societies on ecosystems is also reflected in the concept of ecosystem services (de Groot, 2006). Ecosystem services are the "benefits that humans obtain from ecosystems" (MEA, 2005; p. 53) through ecosystem processes and functions (Haines-Young and Potschin, 2010).

Land use and land cover change (LULCC) threatens the resilience of socio-ecological systems and the provision of ecosystem services due to the fact that it is often related to land degradation (Lambin and Meyfroidt, 2010). Land degradation leads to declines in ecosystem quality and, therefore, to reduction in ecosystem services provision (Chazdon, 2008; Sala et al., 2000). Land cover refers to the biophysical (e.g. soil, and water) land surface while land use is related to any human management and activity affecting land. Land use change means either a shift into another land use or the intensification of the current land use (Turner and Meyer, 1994). Land cover change deals with modification (change of a condition within the land cover category) and conversion (change to another land cover class) (Ibid.). LULCCs are classified as anthropogenic and biophysical driving forces and direct and indirect drivers (Díaz et al., 2015; Lambin et al., 2003). Anthropogenic drivers refer to human-induced LULCC (social, political, economic, demographic, technological, cultural), for example, population growth, agricultural intensification, and deforestation (Lambin et al., 2003). Conversely, for example, climate variability, soil properties and topography belong to biophysical driving forces with direct effects. Direct drivers have a proximate local effect while indirect drivers are underlying and diffuse causes of direct drivers, for example, governance systems or legal regulations (Ibid.).

LULCC and its driving forces can be identified by different approaches. Land cover conversion can be revealed by remote sensing by comparing land cover maps with temporal difference (Lambin et al., 2003), e.g. urban sprawl and deforestation. Also spatially explicit driving factors such as distance to roads, rivers or urban centres can be analyzed by remote sensing and GIS (e.g. Adanu et al., 2013; Braimoh and Vlek, 2005; Owusu et al., 2013). On contrary, land modifications and changes in land use intensity are difficult to identify only by remote sensing. Additional measurements in field are required, e.g. soil samples to assess soil degradation or biomass samples for primary production support data from remote sensing (Forkuor, 2017; Zoungrana, 2015). Driving forces of LULCC that are not spatially explicit, especially indirect drivers, can be rather captured by methods from social sciences (Díaz et al., 2015; Lambin et al., 2003; Van Vliet et al., 2015). For example, Campbell et al. (2005) used apart from remote sensing also extensive household surveys, key Informant Interviews and community workshops to identify in particular indirect drivers of LULCC in a district of Kenya. A comprehensive list of drivers of LULCC and its human-environmental effects can only be identified by interdisciplinary approaches and methods (Liverman and Cuesta, 2009; Rindfuss and Stern, 1998).

The Upper East Region in northern Ghana represents a socio-ecological system under LULCC with low coping capacity and high dependency on natural resources. About 38% of the population is considered to be food insecure (CFSVA, 2012). The reasons for food insecurity are manifold and partly interlinked (IPCC, 2014; Mertz et al., 2010; Reenberg, 2001; Tschakert, 2007). Climate variability has been triggering famines for a long time (Lesk et al., 2016), and weather extremes in West Africa could increase with climate change (Salack et al., 2016; Sylla et al., 2016). In addition, population growth puts pressure on natural resources in the Upper East Region. In literature, especially the role of climate change for environmental and socio-economic changes in West Africa, i.e. climate variability, has been discussed controversy (Antwi-Agyei et al., 2016; Mertz et al., 2010; Reenberg, 2001; Tschakert, 2007). For example, a large-scale study in Senegal, Mali, Burkina Faso, Niger, and Nigeria by Mertz et al. (2010) revealed that climate factors were perceived as less relevant for decreasing livestock, crop and pasture production. However, perceived drivers of LULCC are often related to short-term problems and climate change has, in contrast, long-term effects (Eguavoen, 2012; Nielsen and Reenberg, 2010). Many studies on LULCC in northern Ghana identified population growth, especially in rural areas, as driver of LULCC (Agyemang, 2012; Bugri, 2008; Dietz et al., 2013; Owusu et al., 2013; Yaro, 2007). Population growth increased the pressure on agricultural areas. In the past, long fallow periods allowed the regeneration of agricultural area but, today, agricultural area is under permanent use with low or no fertilizer input which resulted in land degradation (Aniah et al., 2013; Bugri, 2008; Dietz et al., 2013; Owusu et al. 2013; Yaro, 2007). The missing fertilizer input is also related to high poverty of farmers who cannot afford to purchase fertilizer. Agricultural expansion was always limited due to historically high population densities in the Upper East Region (Owusu et al., 2013; Yiran et al., 2011). Programs by the government or NGOs to enhance ecosystem services provision exist, especially for food and water security (e.g. MOFA, 2012; UNDP Ghana, 2017). Ghana has made progress in reaching the Millennium Development Target by halving the proportion of people who suffer from hunger (MDG Ghana, 2012, p. 20). However, the districts in northern Ghana are still behind the national average and effects of national programs are very uncertain with respect to future development. An assessment of causal interdependencies can help to identify triggering effects and the effectiveness of countermeasures within a socio-ecological system. More information on the analysis of drivers of LULCC and land use planning in Ghana and in the Upper East Region is provided in the attached papers I-III. In addition, papers IV and V provide information on the concept of ecosystem services in land use planning, socio-ecological systems and resilience.

The study was part of WASCAL (West African Science Service Center on Climate Change and Adapted Land Use) and funded by the BMBF (German Federal Ministry of Education and Research). WASCAL is a West African-German scientific collaboration with a focus on enhancing the resilience of coupled human-environmental systems regarding climate variability and other environmental changes (WASCAL, 2016). WASCAL set up a Competence Center and a Graduate School Program. It was accompanied by a Core Research Program where I was working in work package 6.1 Land Use Impact Modeling. The Competence Center contributes to the development of local research capacity and is based in Ouagadougou, Burkina Faso. The core research sites were located in the Vea catchment in northern Ghana, northern Benin and south-western Burkina Faso.

1.2 Scope and objectives

This study aimed at an assessment of ecosystem services under different scenarios of LULCC and seasonal rainfall patterns in the Upper East Region of Ghana. The main objectives of the study were:

1. Identification of a) the main drivers of LULCC, and b) the most important ecosystem services
2. Assessment of the impact of the main drivers of LULCC on the most important ecosystem services
3. Suitability of different land management options (e.g. soil erosion control) to improve the provision of ecosystem services and, therefore, rural livelihoods.

The objectives were covered in four papers:

I) **Kleemann**, J., Inkoom, J.N., Thiel, M., Shankar, S., Lautenbach, S., and Fürst, C. (2017) Peri-urban land use pattern and its relation to land use planning in Ghana, West Africa. Landscape and Urban Planning, 165:280-294. http://dx.doi.org/10.1016/j.landurbplan.2017.02.004

II) **Kleemann**, J., Baysal, G., Bulley, H.N.N., and Fürst, C. (2017) Assessing driving forces of land use and land cover change by a mixed-method approach in north-eastern Ghana, West Africa. Environmental Management, 196:411-442. http://dx.doi.org/10.1016/j.jenvman.2017.01.053

III) **Kleemann**, J., Celio, E., Nyarko, B., Jimenez-Martinez, M., and Fürst, C. (2017) Assessing the risk of seasonal food insecurity with an expert-based Bayesian Belief Network approach in northern Ghana, West Africa. Ecological Complexity, 32:53-73. http://dx.doi.org/10.1016/j.ecocom.2017.09.002

IV) **Kleemann**, J., Celio, E., and Fürst, C. (2017) Validation approaches of an expert-based Bayesian Belief Network in northern Ghana, West Africa. Ecological Modelling, 365:10-29. https://doi.org/10.1016/j.ecolmodel.2017.09.018

Paper I dealt with similarities and differences in patterns and drivers of LULCC in the peri-urban area of Bolgatanga in northern Ghana and Takoradi in southern Ghana in a mixed-method approach. The role of land use planning within the context of this study was analyzed. In paper II, I focused on the drivers of LULCC in the rural area of the Upper East Region and further elaborated on the methodological approaches used in paper I. In paper III, I described the modeling approach to assess ecosystem services, specifically food provision, under different land use and land cover and climate scenarios in the Upper East Region. Paper IV handled the validation of the Bayesian Belief Network and gave insights in the reliability of the model structure, model components and results.

Furthermore, I was co-author of two papers which do not belong to the core part of this thesis but contributed to the understanding and development of theories and concepts providing the basis for the thesis. In paper V, the concept of socio-ecological systems, marginality and resilience in development studies was investigated. I contributed to the conceptualization of the paper and provided input of the theoretical understanding of the resilience of socio-ecological systems by a literature review. This study completed the preparatory study of potential conceptual and methodological approaches to assess linked social and ecological systems. Further, in paper VI, the use of the ecosystem services concept and its operationalization in participatory land use planning was discussed in different regional and thematic contexts. I provided input to the conceptualization of participatory planning and ecosystem services. In addition, I contributed to the results and discussion part with insights from my study. Figure 1 shows an overview of the contribution of the publications to this doctoral thesis.

V) Callo-Concha, D., Sommer, J.H., **Kleemann**, J., Gatzweiler, F.W. and Denich, M. (2014) Marginality from a Socio-ecological Perspective. In: von Braun, J. and F. W. Gatzweiler (eds.) Marginality - Addressing the Nexus of Poverty, Exclusion and Ecology. Springer, pp. 57-65.

VI) Opdam, P., Albert, C., Fürst, C., Grêt-Regamey, A., **Kleemann**, J., Parker, D., La Rosa, D., Schmidt, K., Villamor, G.B., and Walz, A. (2015) Ecosystem services for connecting actors – lessons from a symposium. Change and Adaptation in Socio-Ecological Systems, 2:1-7.

The dissertation is structured as follows. In the chapter of material and methods, the description of the study area, the methodological approach and the overall framework with the research process is provided. The results´ section shows a comparison between the rural and urban/peri-urban drivers of LULCC presented in paper I and II and future development of the current rural drivers and related changes in land use types and crop types. In addition, LULCC scenarios and their impact on food and water provision are presented. Different measures against food insecurity are shown and its economic value in crop yield is estimated. Furthermore, due to the fact that water provision was not considered in paper III and IV, details of the results from the water-related BBN part are presented. Additionally, potential synergies and trade-offs between food provision, water provision and soil erosion control are provided. The discussion covers the interpretation of the results and the critical reflection on methodological strengths and weaknesses of this study. Following the conclusion, suggestions for improving the BBN are provided in the outlook. The summary from the individual papers as contribution to the respective chapter is shown in the chapters 2.2.5, 3.1.5, 3.2.5, and 4.2.4 (chapter 3 was split into two contribution sections due to different context). The published papers are presented in Annex B (partly only with abstract due to copyright restrictions).

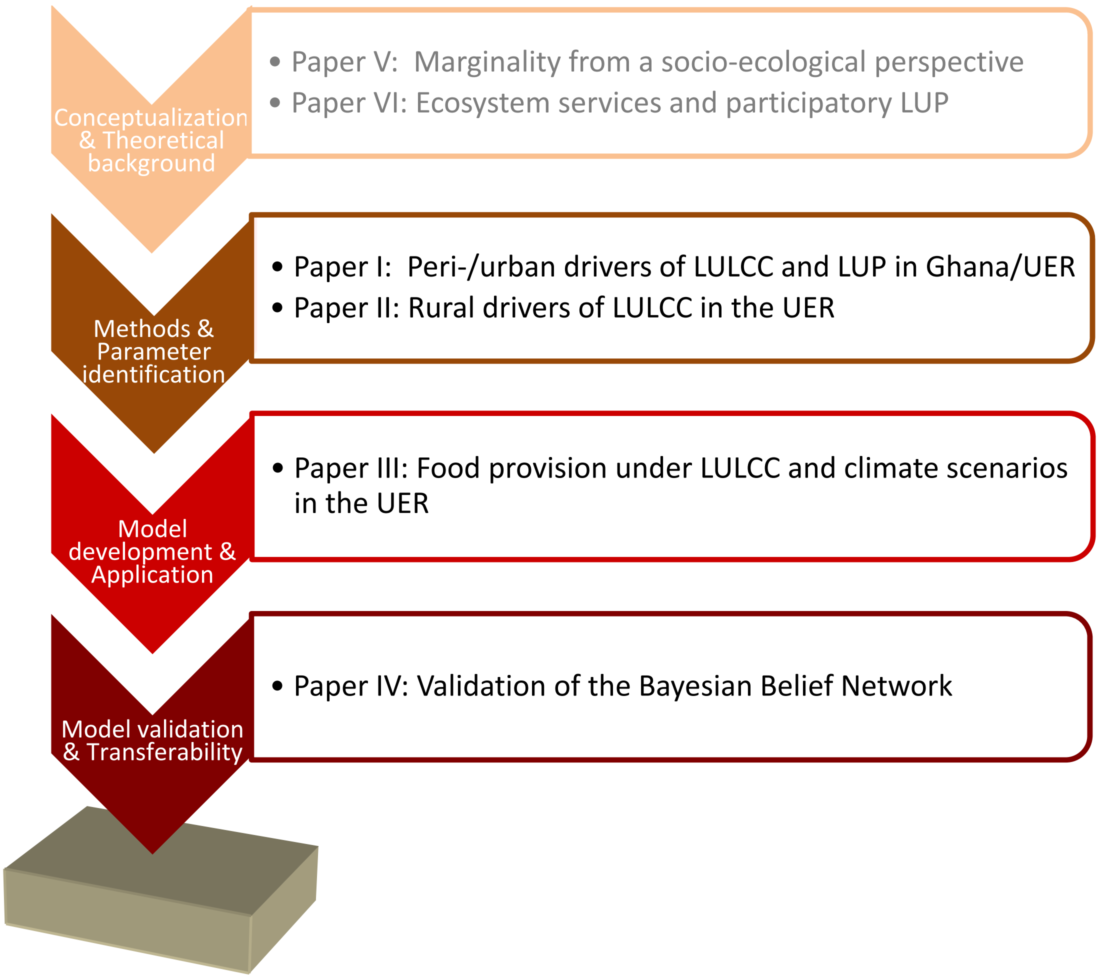


Figure 1: Development process of the publications and their contribution to this doctoral thesis. Paper V and paper VI are represented in pale because they do not belong to the core part of the thesis and contributed only indirectly as preparatory work. The papers are presented in Annex B. LULCC= Land use and land cover change, LUP= Land use planning; UER= Upper East Region

2. MATERIALS AND METHODS

2.1 Study area: the Upper East Region

The system boundary of the studied socio-ecological system is based on the regional administrative demarcation. The Upper East Region is located in northern Ghana (Figure 2), close to the border of Burkina Faso and Togo. Bolgatanga is the capital of the Upper East Region (Bolgatanga Municipality No. 11 in Figure 2). The Upper East Region (UER) is part of the Sudanian and Guinean Savanna Zone as agro-ecological zone. The region is characterized by a distinct seasonality with a rainy season between May and October and a dry season between November and April. Rainfall variability is increasing (Herrmann et al., 2005; Hulme, 2001), which makes food production increasingly insecure (Roncoli et al., 2001).

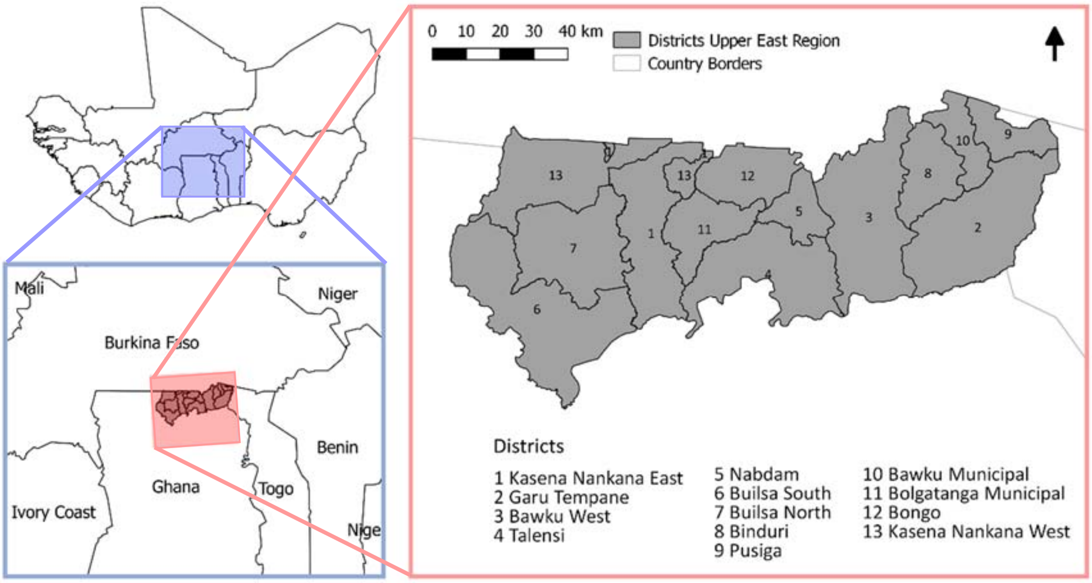
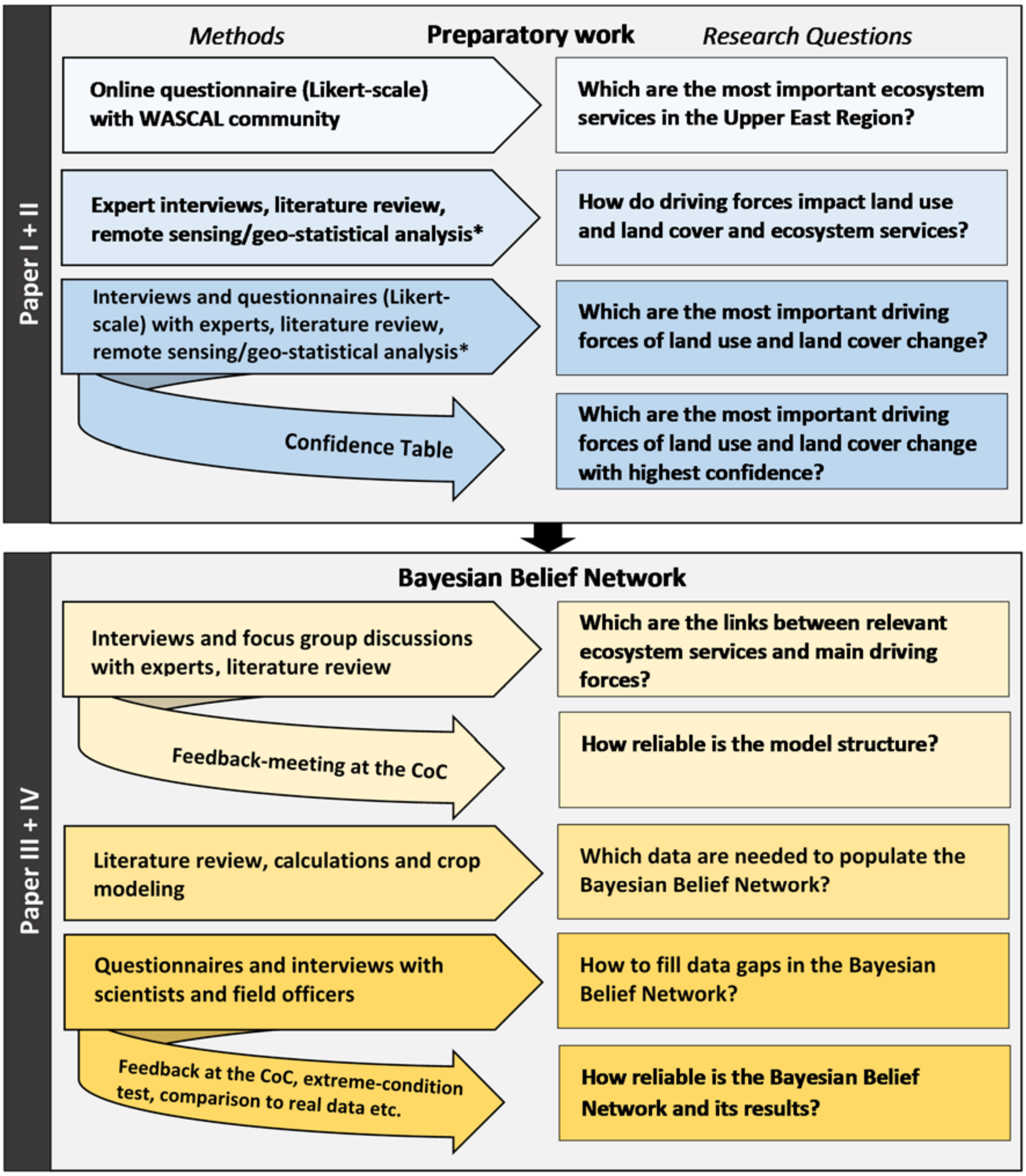


Figure 2: The Upper East Region is located in northern Ghana in West Africa (blue box on the left). The map in the red box on the right shows the districts of the Upper East Region (OpenStreetMap, 2017; SADA, 2016 and QGIS Version 2.18.0).

The UER represents a rural area in West Africa with low socio-ecological resilience. The region belongs to the poorest areas within Ghana and is characterized by low educational status and high illiteracy. It covers 3.7 % (8,842 km²) of the total land area (238,535 km²) and belongs to the smallest provinces in Ghana, but more than one million people live in the area (GSS, 2012). About 80% of the population is engaged in small-scale rain-fed subsistence farming (Birner et al., 2005). Most important crops are maize, sorghum, and millet; these are intercropped mainly with groundnuts or beans. Vegetables and rice are grown in irrigated areas or in rain-fed lowlands. The main farm types are compound farms and bush farms. On compound farms, primarily food for subsistence in the immediate vicinity of the houses is produced, while on bush farms (agriculture in remote areas) also cash crops are produced. Migration to southern Ghana during dry season is a strategy to cope with food shortage in the UER (Quaye, 2008) and to earn money as labor force (Van der Geest et al., 2010).

2.2 Methodological framework



**The analysis of remote sensing data and the geospatial statistics were conducted by co-authors of paper I and II.*

Figure 3: Research process with research questions (right) and methods which were needed to answer the questions (left). Arrows indicate methods to assess the reliability of findings and the model. In addition, a critical reflection of the methods and approaches was conducted in each paper. CoC= Competence Center; BBN= Bayesian Belief Network.

The framework in Figure 3 provides the sub-questions of the objectives and the methodological steps. The main data source was expert knowledge (chapter 2.2.1). A summary of methodological approaches is provided in chapter 2.2.2. The main model was the Bayesian Belief Network with a focus on the temporal dimension (chapter 2.2.3). Approaches of reliability and validation of methods, the model and the results are described in chapter 2.2.4.

2.2.1 Expert knowledge as information source

Due to a lack of available data for a modeling approach in the study area, experts were the main source of information providing reasoned arguments, human interpretation or potential action (Banks, 1999). Experts can also help to interpret available data and give arguments for inconsistencies or conflicts within data interpretation. Experts are people with the following characteristics (Hoffman et al., 1995; Wachsmuth, 1993):

- They have long-time experience in either a specific theme or spatial area.
- They have professional training and privileged access to scientific information.
- Their performance shows specific skills: accuracy, reliability, reputation, erudition, proficiency.
- They can separate relevant from non-relevant information: their knowledge is task-, case- and objective-oriented.
- They can represent a cross-section on current debates on the topic.

Experts were chosen as information source for the identification of the most important drivers, the most important ecosystem services and their interactions, but also for interpretation of the model structure, its components and outputs in order to validate the model. Different expert groups were involved in the different stages of model development (Table 1). The expert group selection was based on specialized knowledge, availability, willingness, and dependent on respective tasks. For example, scientists at the WASCAL Competence Center served as main feedback-group for BBN validation. The difference in the expert group for the identification of rural and urban drivers of LULCC was due to missing WASCAL experts on urban driving forces. In addition, the BBN focus was set on rural interactions. Therefore, urban planning officers were only asked for urban drivers of LULCC. (Urban and rural drivers were later compared for similarities and differences.) For more details on the expert groups, please see Figure 3, Table 2 in paper I, Table 4 in paper II, Annex A in paper III, and Figure 2 in paper IV. Experts from paper II were also consulted in paper III + IV. Representatives of agricultural, rural planning on district level, i.e. agricultural extension officers (mentioned as "field officers" in this study), were contacted for filling the locally specific Conditional Probability Tables (CPTs) of the BBN. They were also consulted to report on the BBN structure. In total, about 58[1] researchers and 37 representatives from agricultural planning were involved in the BBN development process.

[1]The exact number of researchers could not be identified because the online survey was anonymous and researchers might have been counted twice.

Table 1: Main expert groups for the different steps of model development. In addition to the expert groups in this table, the WASCAL community was asked to select the main ecosystem services. Furthermore, selected long-term residents were asked as knowledgeable people for urban pattern, processes and main urban drivers of land use and land cover change (LULCC). CPT= Conditional Probability Table, BBN= Bayesian Belief Network, ES= Ecosystem services.

Expert group ID

A= WASCAL scientists in Germany	**D= Officers of agricultural planning**
B= Scientists in Ghana	**E= Officers of urban planning**
C= WASCAL scientists at the Competence Center	**F= ES Working group**

	Expert group ID					
	A	**B**	**C**	**D**	**E**	**F**
Identification of pattern, processes and main rural drivers of LULCC	■	■				■
Identification of pattern, processes and main urban drivers of LULCC					■	
Identification of main ecosystem services	■		■			■
Identification of causal relations between drivers, LULCC and ES	■	■				■
Selection of main causal relations and development of the BBN	■					
Feedback on BBN structure and components	■	■	■	■		■
Fill-in of CPTs (data input for the BBN nodes)	■	■		■		■
Feedback on BBN output			■			

2.2.2 Summary of methodological approaches

Methods from social and natural science were applied (Figure 4). For example, participation was facilitated by focus group discussions, interviews and questionnaires. With regard to the most important ecosystem services (ES), the ES working group pre-selected ten ES out of the list provided in Kandziora et al. (2013) according to scientific demands (e.g. measurability, relevance for the context): 1) Global climate regulation, 2) natural hazard protection with erosion control, 3) pollination and/or biological control, 4) crops as income (focus on cash crops), 5) crops as subsistence (for food), 6) fodder, 7) biomass for fuel, 8) timber for construction, 9) freshwater and 10) cultural ES (definitions and indicators according to Kandziora et al., 2013). An anonymous online survey with the WASCAL community was conducted between March and June 2014 where the most important ES on local and regional level for the three WASCAL core research sites in south-west Burkina Faso, northern Benin and northern Ghana (the UER) were identified. The questionnaire was designed with importance levels in Likert scale from 1 (least important) to 5 (very important) of the selected ES. If desired, the respondent could add comments to justify his/her answer.

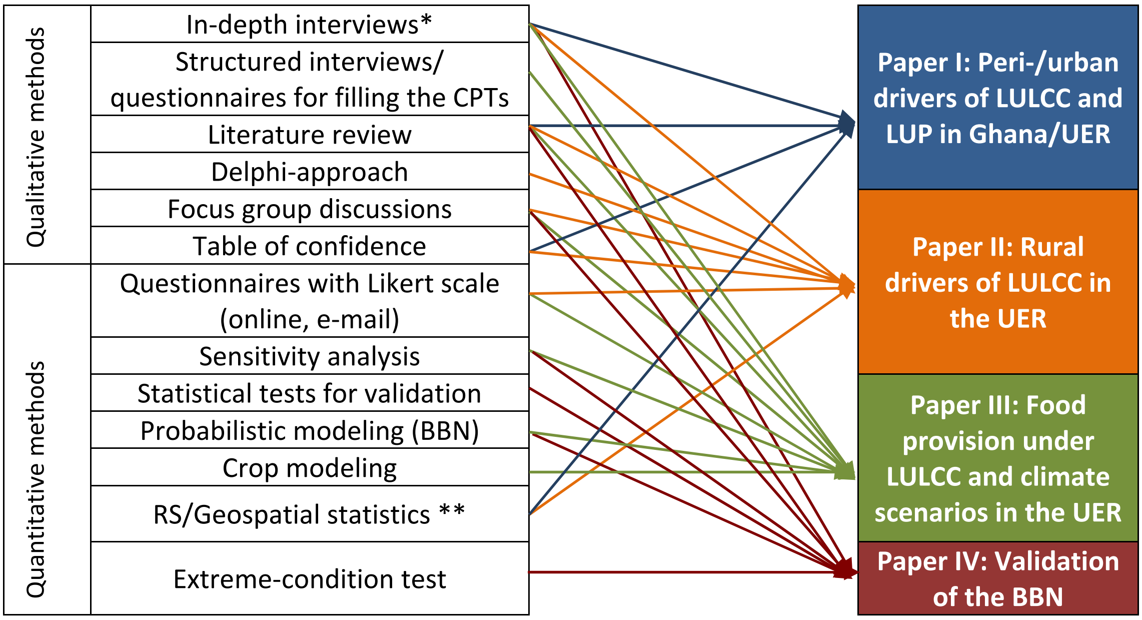
The development of the BBN started with a literature review and interviews with experts in Ghana. The expert interviews served for the identification of the drivers of LULCC and their causal interactions with land use types and ecosystem services. The interviews were taken as basis for the questionnaire on most relevant drivers of LULCC. The interviews were analyzed based on a content analysis. After a first text analysis, I conducted a coding to conceptually validate and/or extend my hypothesis (Hsieh and Shannon, 2005; Mayring, 2000) by using the qualitative data analysis software ATLAS.ti (ATLAS.ti, 2014). In the questionnaire, scientists assigned influence levels by Likert scale from 0 (no influence) to 5 (very high influence) of 34 drivers of LULCC.

The analysis of driving forces of LULCC was complemented by remote sensing, geoformation systems and geospatial statistics that were conducted by the co-authors in paper I and II. In paper I, peri-urban differences between 2007 and 2013 in Bolgatanga (northern Ghana) and Takoradi (southern Ghana) were analyzed. A manual digitalization of each building in a 5 km x 5 km focus area was performed because it was difficult to discriminate buildings from bare soil in remote sensing data. The analyses of urban sprawl were based on parameters like number and size of settlement unit (SU), total size of the built-up area, built-up density, and the average size of SU. High resolution data were taken from DigitalGlobe via GoogleEarth. In paper II, changes between land use/land cover and spatially referenced demographic and biophysical data of the UER were analyzed between 2001 and 2013. Land use and land cover data were taken from MODIS land cover product (MCD12Q1) in moderate resolution (500 x 500 m). Changes were detected through the raster calculator function in ArcGIS 10.1. A multiple regression analysis was applied to understand the relationships between rural LULCC and drivers of rural LULCC (Hersperger et al., 2010). Details on the methodological approaches are provided in paper I and II.

After the identification of most relevant drivers by scientists in WASCAL and Ghana, a broad BBN structure was presented to scientist in WASCAL in Germany. In order to reduce complexity for the expert consultation, the BBN was divided into a land use-related BBN part, a water-related BBN part and a crop-related BBN part. The scientists were assigned to the respective BBN according their field of expertise. The scientists specified the BBN part by adding and changing nodes, links and states in focus group discussions. Finally, the three BBN parts were merged into one BBN, and three representatives of each BBN part were asked for their feedback. Additional feedback was gathered from officers in agricultural planning and WASCAL scientists at the Competence Center.

The BBN nodes on crop yield were complemented by two crop models – APSIM and DSSAT – in order to receive information on crop yields under different climate scenarios. APSIM (Agricultural Production Systems sIMulator; APSIM, 2016) was used to model crop yields in rainy season and rice yields in dry season. APSIM modules consider characteristics and interactions among plant, soil, climate and management. DSSAT (Decision Support System for Agrotechnology Transfer; Jones et al., 2003) was chosen to model yields of vegetables since APSIM does not have this functionality. Details of the BBN development process are described in paper III and IV.

Quantitative approaches for the BBN were, e.g., the Mann-Whitney U test and descriptive statistics. Data were analyzed and displayed with SPSS (version 17.0) and STATA (version 13.1). The Mann-Whitney U test is a non-parametric test of two independent variables (Hollingsworth et al., 2011; SPSS, 2013a) and was applied for the estimated conditional probabilities between the different expert groups to analyze data variability and reliability. The Wilcoxon signed-rank test was applied for a non-parametric test of two dependent variables (SPSS, 2013b) to analyze changes in current and future estimates of drivers of LULCC. Furthermore, the software Netica (Norsys Software Corporation, 2016a) was used for the Bayesian Belief Network (BBN) and the sensitivity analysis of the BBN. Methods and approaches of validation and reliability are presented in chapter 2.2.4.



** The in-depth interviews in paper I were conducted by a co-author.*
***The analysis of remote sensing data and geospatial statistics were conducted by co-authors of the papers.*

Figure 4: Methods assigned to the papers I-IV; RS= remote sensing; CPTs= Conditional Probability Tables; BBN= Bayesian Belief Network, LULCC= Land use and land cover change, LUP= Land use planning, UER= Upper East Region.

2.2.3 The Bayesian Belief Network

Different modeling approaches exist for assessing ecosystem services. The suitability of the model is dependent on the purpose of the study, data availability and user group (Kelly et al., 2013). For the purpose of this study, a model was needed that:

- reflected human interpretation of causal dependencies,
- could be applied at the regional level,
- had good visual features (for political recommendation and participation),
- dealt with data gaps and specifically considered uncertainty,
- allowed the combination of qualitative data (expert knowledge, literature) and quantitative data (statistics),
- could be flexibly adapted as soon as new information was available,
- and provided directly a model output.

A BBN was considered to be a suitable model to fulfill the above-mentioned requirements (Jensen, 2001; Kelly et al. 2013; Kjærulff and Madsen, 2005; Reichert and Omlin, 1997; Uusitalo, 2007). A BBN is a graphical statistical model that represents a set of variables and their conditional dependencies via directed graphs (Figure 5). Influences and occurrence of events are described probabilistically either by statistical analysis where data is available or by experts in the case of lacking data availability or missing data access. Nodes are differentiated into parent nodes and child nodes. In the BBN that is presented in this study, parent nodes are named as input nodes (input parameters for the model) and child nodes are represented by interim and output nodes (Kjærulff and Madsen, 2005). The Conditional Probability Table (CPTs) in the child node represent the likelihood of event occurrence given different states of the parent nodes. BBNs have their strengths in prediction, system understanding, decision making with uncertainty, social learning, and the combination of qualitative and quantitative data (Kelly et al., 2013). The possibility to combine statistical (quantitative) data with expert knowledge (qualitative data) is especially helpful for the concept of socio-ecological systems where different disciplines and therefore various approaches and data types come together.

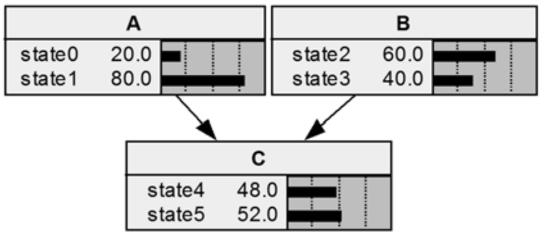


Figure 5: Example of a Bayesian Belief Network with two parent nodes (A and B) influencing the child node (C).

The temporal dimension of the Bayesian Belief Network

The temporal dimension was a relevant issue in this study. The BBN was separated in dry and rainy season due to the different system components. Food and water provision show different patterns of provision (Figure 6). Potential water provision in the Upper East Region has its peak in August (GMSA, 1998), and no new water is provided during the dry season. In addition, potential water provision stays at a higher level of provision than food. However, water quality and water access are limiting factors (Asare, 2004; IWMI, 2007). Food insecurity is a major problem in the Upper East Region. The highest risk of food shortage is during the rainy season where no new crops have yet been harvested (between January and April; Quaye, 2008). Food provision is highest after the harvest of all crops at the end of the rainy season (end of August to November; Bamler, 2016; Quaye, 2008) and a second, smaller peak of food provision is at the end of the dry season from irrigated crops. Food production was assessed at the two peaks (see Figure 6). However, poor population groups have no or very limited access to the smaller food peak since irrigated crops are produced, sold or consumed mainly by the higher income class (> 1000 Cedis/household/year). Only 0.4% of the Upper East Region is irrigated (GSS, 2008; Hjelm and Dasori, 2012). The majority of the population lives from the food produced during the rainy season. They ration and store the food until the next harvest. Malnutrition is another reason for food insecurity. The micronutrient deficiency of vitamin A (FAO Ghana, 2009) was taken into consideration. In addition, different LULCC scenarios were taken into account and the influence of these changes on ES provision assessed. Since feedback loops are not possible in the BBN (Jensen, 2001; Uusitalo, 2007), I followed the suggestion in Celio et al. (2014), where a stepwise approach was chosen. They used the output of modeling step one as input for step two, i.e. posterior probabilities of land use categories in t_0 were taken as input for land use in t_1.

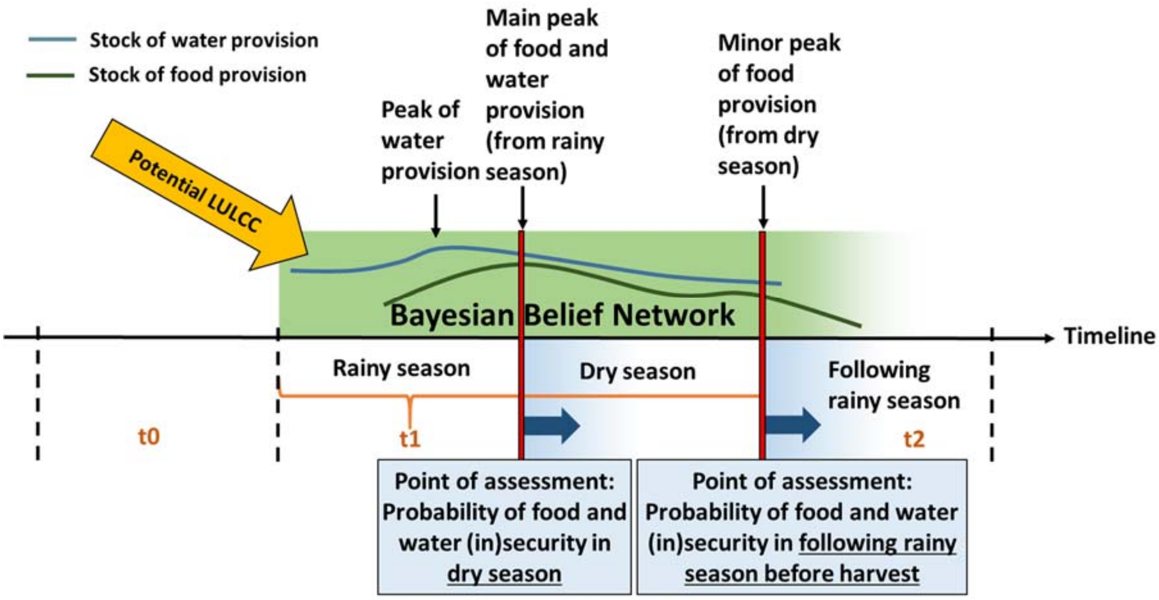


Figure 6: Temporal dimension of the BBN (paper III); LULCC= Land use and land cover change.

2.2.4 Validation and reliability

The validation of data and the model is key to provide confidence in the findings of a study. In contrast to verification, validation does not imply the presentation of the truth but is rather characterized by the establishment of legitimacy by arguments and methods (Oreskes et al., 1994). A mixture between validation approaches and reliability checks were used in this study. For paper I and II, the reliability of findings from the different methods was analyzed in the table of confidence (Table 2). The table of confidence is based on Mastrandrea et al. (2011) for the IPCC Fifth Assessment Report and the Millennium Ecosystem Assessment (MA, 2005) and was further developed by Jacobs et al. (2015) to evaluate the reliability of a finding. The evidence levels are related to the number of methods that can provide information on a specific research topic. The agreement levels are defined by the accordance or discordance of findings from respective methods. In paper I and II, I refined the table of confidence by suggesting defined thresholds for agreement levels in order to reduce subjectivity.

Table 2: Table of confidence adapted from Jacobs et al. (2015) based on Mastrandrea et al. (2011) and MA (2005); used in paper I and II.

Level of confidence	Limited evidence	Medium evidence	Robust evidence
High Agreement	Medium	High	Very high
Medium Agreement	Low	Medium	High
Low Agreement	Very low	Low	Medium

In paper III, methods were critically discussed and a sensitivity analysis of the BBN was conducted. The sensitivity analysis does not imply a validation of the model but allows the identification of the nodes with the highest influence. Consequently, those nodes should be estimated with the highest accuracy (Coupé et al., 1999). In the Netica software, the entropy reduction (also named mutual information) was used for the sensitivity analysis calculated with the binary logarithm in bits (Norsys Software Corporation, 2016b).

In paper IV, a mixture between validation approaches and reliability strategies were applied (overview in Table 1 in paper IV). Rykiel (1996) suggests a combination between quantitative and qualitative approaches to validate ecological models. Conceptual model validity, data validity and operational validity is recommended for models, where large amounts of data are used and a high level of understanding of the system is required (red cycle in Figure 7). Operational validation means the testing of the model output. For example, statistical tests between real and simulated data are widely used (Mayer and Butler, 1993; Power, 1993). Conceptual model validity reflects the correctness, or at least justification, of underlying theories and assumptions for the intended use of the model (Rykiel, 1996). Data validity is related to quality control and to ensure that data meet specific standards. This includes also the interpretation of data. In my study, the comparison of BBN output with real data and expert opinion, the extreme-condition test and the sensitivity analysis was conducted for operational validity. In the extreme-condition test, the model structure and results should react logically for extreme combinations of factors. For conceptual model validity, "face validity" (feedback by knowledgeable people) and the cross-check of nodes with literature was used. Scientists at the WASCAL Competence Center and officers of agricultural planning gave feedback on the BBN structure and output. For data validity, data and output was compared to historical data, literature (e.g. experiments and official data from ministries), which were not used in to develop the BBN or fill in CPTs and, therefore, could serve as validation approach. In addition, qualitative statements from experts were analyzed which were not included in the BBN development process. Furthermore, the Delphi approach (Okoli and Pawlowski, 2004) was applied for the results of the questionnaire on most important drivers of LULCC. The Delphi approach is used to reduce variance and to potentially reach a consensus on future developments among participants (McKenna, 1994; Hsu and Sandford, 2007). In all papers, methods and approaches were critically discussed.

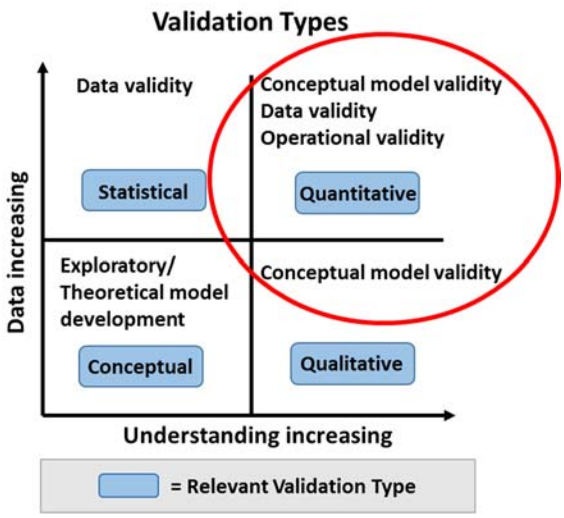


Figure 7: Validation types for ecological models adapted from Rykiel (1995); red circle shows the focus of the study.

2.2.5 Contributions from papers to chapter 2 (Materials and methods)

Table 3: Overview of the contribution by the respective paper to chapter 2. BBN= Bayesian Belief Network, CPTs= Conditional Probability Tables, ES= Ecosystem services, FAO= Food and Agriculture Organization of the United Nations, LULCC= Land use and land cover change, LUP= Land use planning, MOFA= Ministry of Food and Agriculture, UER = Upper East Region, WASCAL= West African Science Service Center on Climate Change and Adapted Land Use.

Paper	General contribution
Paper I: Peri-/urban drivers of LULCC and LUP in Ghana/UER	**Methods of parameter identification for the BBN and reliability check:** • Interviews with land use planners, literature analysis of historical land use planning in Ghana, and remote sensing/geospatial statistics were used to identify patterns and drivers of peri-urban LULCC in Bolgatanga (northern Ghana) and Takoradi (southern Ghana). • The table of confidence of the findings from the three methods enabled the analysis of the reliability of the results from the different methods and allowed a comparison of similarities and differences of peri-urban LULCC and its driving forces under different geographical, historical, cultural and economic development.
Paper II: Rural drivers of LULCC in the UER	**Methods of parameter identification for the BBN and reliability check:** • Patterns and drivers of rural LULCC in the UER were identified and analyzed by interviews and questionnaires with scientists in Ghana and WASCAL, a literature analysis of drivers of LULCC in the UER, and remote sensing/ geospatial statistics. • The table of confidence of the findings from the four methods allowed an analysis of the reliability of the results from the different methods.
Paper III: Food provision under LULCC and climate scenarios in the UER	**Methods for the BBN development process and reliability check:** • A combination of literature analysis, statistics, modeling approaches and expert knowledge was required to build the BBN, to fill the BBN with data, and to validate results. • Focus group discussions, interviews and literature with WASCAL scientists in Germany were conducted to identify causal relationships between the parameters and to build the BBN. • Focus group discussions with WASCAL scientists in West Africa reflected on strengths and weaknesses of the BBN structure and allowed minor adaptations. • Results from crop models, calculations and data from literature were used to fill in the CPTs. • Interviews were conducted to complement the CPTs where no other data sources were available. • The BBN, its results and applied methods were critically discussed.

Paper IV: Validation of the BBN	**Validation approaches and reliability check of the model structure, its components and output:** • The statistical comparison of estimated conditional probabilities between and within expert groups allowed the analysis of data variability and reliability. • The sensitivity test showed the node with highest influence in the BBN. • The comparison of the BBN output with real data from FAO and MOFA reflected on reliability of the model output. • Focus group discussions with WASCAL scientists in West Africa were conducted to reflect on scenarios (model output) and model applicability. • The BBN structure and its nodes were additionally assessed by officers for agricultural planning. • Nodes and links of the BBN were critically cross-checked with information from literature and different expert groups. • The extreme-condition test of the BBN output was used to assess the general model behavior.
Paper V: Marginality from a socio-ecological perspective	**Theoretical understanding:** • The theoretical understanding of socio-ecological systems, resilience, mixed-method approaches, integrated assessments and modeling served as background information and contributed to the usage of integrative and interdisciplinary approaches in this study and the development of the BBN.
Paper VI: Ecosystem services and participatory LUP	**Theoretical understanding:** • The understanding of the ES concept and its implementation in land use planning in different regional and thematic contexts including local participation facilitated the consideration of land use planning within this study in the context of Ghana.

3. RESULTS

3.1 Parameter identification for the Bayesian Belief Network

3.1.1 Most relevant ecosystem services

In total, 22 researchers (PhD students and senior researchers) participated in the survey on local and regional ES in the three core research sites of WASCAL but only nine people answered the questions of most important ES specifically for the regional level of the UER. Out of the ten selected ecosystem services, crops for food provision (for subsistence) has been regarded as the most important ecosystem service on regional level; with no variance and only one outlier on a neutral opinion (Figure 8). Therefore, the emphasis of the Bayesian Belief Network was placed on food provision from crops. Freshwater provision, crops as income source and natural hazard protection, such as trees, shrubs and stones against wind and water erosion, had similar importance levels. High variance existed for fodder provision for livestock, biomass for fuel and the provision of cultural services. Food provision and water provision were selected for the BBN, and also soil erosion control as a natural hazard protection was considered.

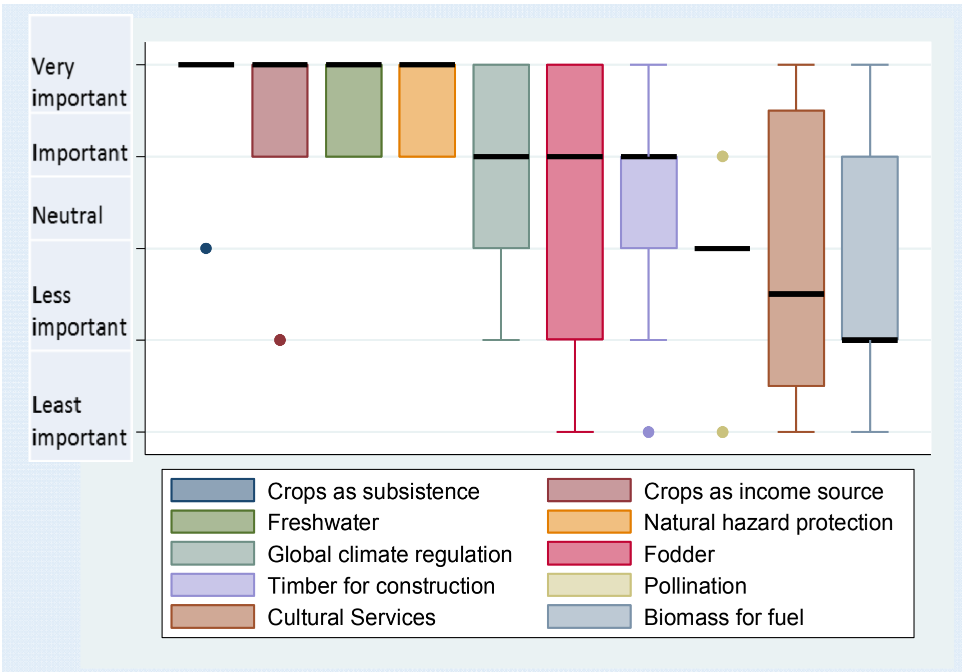


Figure 8: Range of the ten ecosystem services on regional level for the Upper East Region represented as box plot; named by nine participants from the WASCAL community in an anonymous online survey (box plots in STATA 13.1).

3.1.2 Most relevant drivers of land use and land cover change in the UER

Qualitative interviews were used as basis to develop and design the questionnaire of the most important drivers of land use and land cover change (LULCC) in the Upper East Region (UER); for narratives see paper II. Figure 9 shows a summary from the expert interviews in Ghana in 2013. Direct and indirect drivers of LULCC were differentiated. Furthermore, agricultural/rural and urban driving forces of LULCC in the UER were analyzed in paper I (urban) and paper II (agricultural/rural). When comparing urban with rural drivers, it can be seen that population growth is an important direct rural and urban driver of LULCC (Table 4). Furthermore, customary land tenure is the most relevant indirect urban and rural driver, even though many drivers could not be analyzed for urban LULCC. Contrasting confidence levels are provided for roads as driver of LULCC. There is high confidence that the road network is a driving force of rural LULCC but it has a low confidence level as driver for urban LULCC. Similarly, mining has a low confidence as an urban driver but medium confidence as a rural driver of LULCC.

3.1.3 Influence of drivers on food and water provision and potential future development of rural drivers of LULCC

The influence of drivers of LULCC on food and water provision and future trends in driving forces were analyzed. Table 4 is based on questionnaires from different expert groups. The influence of drivers of LULCC on food and water provision is based on information from five experts in Ghana, the trend of drivers of LULCC was provided by 21 experts from Ghana and WASCAL (including the five experts from Ghana), and the table of confidence comes from the mixed-method approach in paper II. More questions could not be asked about the impact of drivers of LULCC on ES due to the fact that the questionnaire was already too extensive. It was necessary to decide on whether to ask about the relevance of the parameter as a driver or about its influence on ES.

The experts were asked to rank the drivers according their expectations regarding the future impact of the driver on LULCC (Table 5). Since food provision was the most relevant ecosystem service, future drivers of LULCC were classified as drivers with potential negative effect on food provision (also named as threat), as potential supportive measures for food provision, and as drivers with positive as well as negative relation to food provision (see also Annex Table A1). The main drivers of land degradation and ES depletion mentioned by the experts in Ghana were population growth, rainfall variability, wood extraction, mining, bush fires and currently applied (traditional) agricultural practices. With a focus on food provision, potential threats with high and very high confidence level are rural and urban population growth, rainfall variability, bush fires and currently applied agricultural practices.

Among supportive measures for food security, only agricultural extensification has a clearly positive effect on food provision due to cropland expansion and dry season gardening but at the same time, they have a negative effect on water provision. In general, there seems to be many trade-offs between food and water provision (Table 5). A potential synergy between food and water provision could be conservation agriculture, among others. A statistical analysis with the Wilcoxon signed-rank test showed that ten drivers with potential positive and negative effects on food provision significantly increase from the current state to the future but this includes also drivers with low confidence level, e.g. agricultural medium-scale investments. Lowest importance as a future driver among all drivers of LULCC is the change in religious patterns.

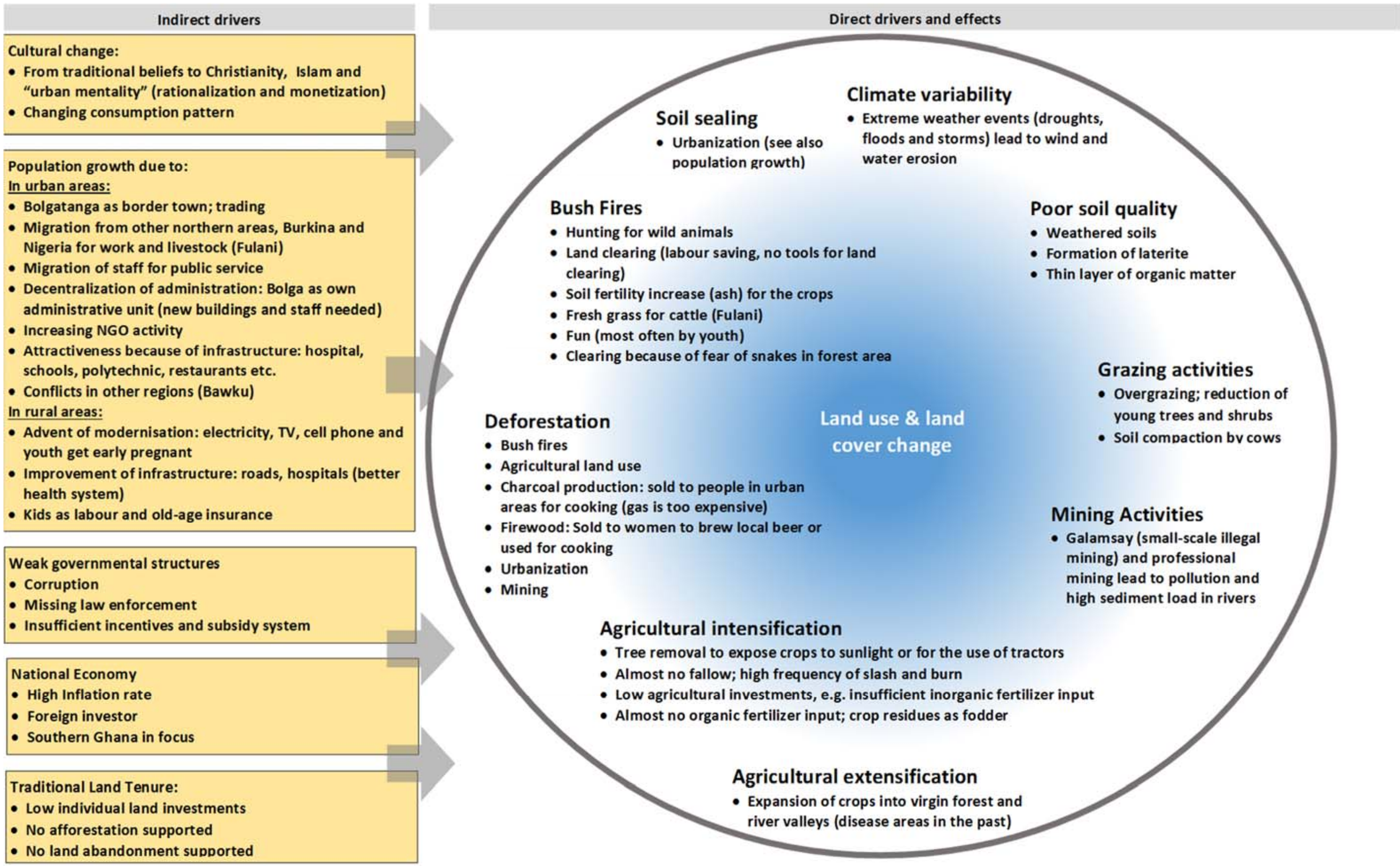


Figure 9: Summary of direct and indirect drivers with negative effects on land use and land cover change and ecosystem services provision in the Upper East Region.

Table 4: Urban (paper I) and agricultural/rural drivers (paper II) of land use and land cover change (LULCC) in the Upper East Region based on a mixed-method approach according to confidence levels (description in chapter 2.2.4); - = not analyzed; confidence levels for urban drivers derived from expert interviews, geospatial statistics and a literature review; confidence levels for agricultural drivers derived from expert interviews, questionnaires, geospatial statistics and a literature review.

Classification of driver	Potential drivers of LULCC	Level of confidence as driver of rural LULCC	Level of confidence as driver of urban LULCC
Direct driver: Anthropogenic	Population growth rural	**Very High**	**High**
	Population growth urban (urbanization)	**High**	**High**
	Agricultural intensification: modern	**Medium**	**Medium**
	Agricultural intensification: traditional	**High**	**Medium**
	Agricultural extensification	**High**	**Medium**
	Conservation agriculture	**Low**	-
	Irrigation (dams, rivers)	**Medium**	-
	Dry season gardening	**Medium**	-
	Improved crop varieties	**Low**	-
	Use of wood (especially fuel wood)	**Very High**	-
	Mining	**Medium**	**Low**
	Bushfires	**High**	-
	Livestock	**High**	-
	Road network	**High**	**Low**
Direct driver: Biophysical	Soil type and fertility	**High**	-
	Topography	**Low**	-
	Rainfall variability	**High**	-
	Temperature variability	**Low**	-
	Wind intensity	**Low**	-
Indirect driver: Demographic	Migration	**Medium**	-
	Labor shortage	**Medium**	-
Indirect driver: Cultural	Change in religious patterns	**Low**	-
	Level of education	**Medium**	**Medium***
	Customary land tenure system	**High**	**High**
Indirect driver: Economic	Rising living standard	**Low**	-
	Financial capital of rural farmers (poverty)	**High**	-
	Foreign agricultural medium-scale investments	**Very Low**	-
	International funding/ development aid	**Low**	-
	Credits by family, bank, government or NGO	**Low**	-
Indirect driver: Technological	Science and research	**Very Low**	-
	Service by extension officers	**Low**	-
Indirect driver: Political	Governmental laws	**Low**	**Medium**
	National agricultural programs	**Low**	-
	Fertilizer subsidies	**Low**	-

** Educational facilities were assessed.*

Table 5: Impact of drivers of land use and land cover change (LULCC) on food and water provision with future trend (change of the median value); ranked according to influence on food security. Arrows show a stagnation or increase of the median value as future driver. - = negative impact; -/+ = can have both, positive as well as negative impact; + = positive impact, o = neutral; manageable drivers with positive impact on food security but potentially negative impact on water security or vice versa could indicate a trade-off; Likert scale: 0= no influence; 5= very high influence.

Potential drivers of LULCC	Impact of driver on food provision	Impact of driver on water provision	Level of confidence as driver of rural LULCC	Median of current driver (Likert scale)	Trend of driver (change of the median)
Potential threats for food provision					
Population growth rural	-	-	Very High	4	→
Population growth urban (urbanization)	-	-	High	3	↗
Agricultural intensification: traditional	-	+	High	3	→
Bush fires	-	-/+	High	3	→
Rainfall variability	-	-/+	High	4	↗
Mining	-	-	Medium	2	↗
Labor shortage	-	o	Medium	2	↗
Changes in religious patterns	-	-	Low	1	→
Temperature variability	-	-/+	Low	3	→
Wind intensity	-	o	Low	1	↗
Supportive measures for food provision					
Agricultural extensification	+	-	High	3	→[a]
Dry season gardening	+	-	Medium	2	→
Impact on food provision can be positive and/or negative					
Use of wood (especially fuel wood)	-/+	-	Very High	3	→
Livestock	-/+	-	High	3	→
Soil type and fertility	-/+	-	High	3	↗
Improved roads	-/+	-	High	2	↗*
Financial capital of rural farmers	-/+	-/+	High	2	↗*
Customary land tenure	-/+	unknown	High	3	→
Migration	-/+	-/+	Medium	2	↗
Commercial agriculture	-/+	-/+	Medium	2	↗*
Level of education	-/+	o	Medium	2	↗*
Irrigation with dams and rivers	-/+	-	Medium	2	↗
Conservation agriculture	-/+	+	Low	1	→
Rising living standard	-/+	-/+	Low	3	↗*
Improved crop varieties	-/+	-/+	Low	2	↗*
Topography	-/+	-/+	Low	2	→
International funding/ development aid	-/+	-/+	Low	2	→
Credits by family, bank, government	-/+	-/+	Low	1	↗

Service by extension officers	-/+	-/+	Low	2	↗
Governmental laws	-/+	-/+	Low	2	↗ *
National agricultural programs	-/+	-	Low	2	↗ *
Fertilizer subsidies	-/+	-	Low	2	↗
Research	-/+	-/+	Very Low	1	↗ *
Agricultural medium-scale investments	-/+	-/+	Very Low	1	↗ *

** = Significant increase from current to future ($p \leq 0.05$) with Wilcoxon signed-rank test and Bonferroni-correction.*

a = Merged with traditional agriculture in the questionnaire of relevant drivers of LULCC.

The analysis with descriptive statistics showed that variability increases between the answers from the experts with regard to the future influence of the drivers of LULCC. The majority of the drivers (60%) showed the trend to increase in future, and these include drivers with positive as well as negative impact on food and water security. The majority of the drivers with potential negative effects on food and water security are regarded as more important drivers than those with positive impacts (see Table 5). Experts were sure (with low variance in answers) that among potential threats to food and water provision, rural population growth will stay at a high level, and that urban population growth could further increase. Rainfall variability represents the highest median Likert value of 5 as future driver of LULCC (5 = most important driver).

3.1.4 Future changes in land cover and crop types

As an additional option for validating the BBN, experts were asked about their expectations on future development of land use and land cover in a questionnaire (Figure 10 and Figure 11). Experts identified an increase in cropland and urban area and a decrease in bush savanna, water bodies and grassland (Figure 10). Therefore, a relation between population pressure and a high demand for wood and agricultural areas is indicated. Experts were not sure about the changes in tree plantations. There exists also a variance for bare land. Changes in crop types show an increase in maize and a decrease in cotton production (Figure 11). Furthermore, there is a slight increase in soybean, cowpea and groundnut. High variations exist for millet, sorghum, Bambara beans and rain-fed rice. At the end of the questionnaire, there was an open question which other plants are cultivated. Mango was mentioned by three experts with a potential increase in future.

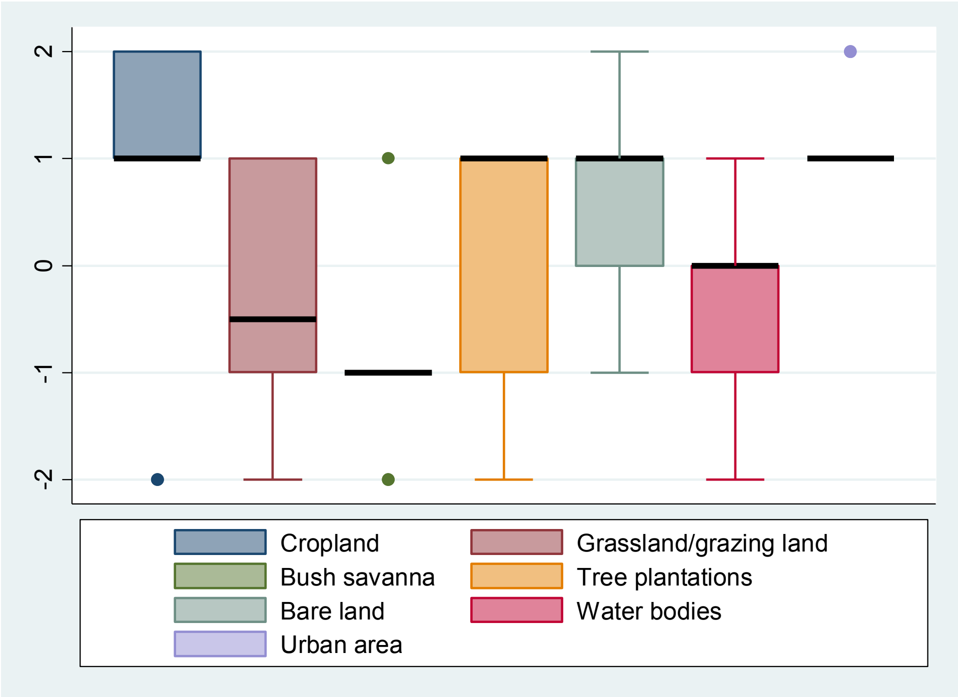


Figure 10: Expected land use and land cover within the next 10 years as forecast by experts (n=21); -2= significant decrease; 0= no change; 2= significant increase (box plots in STATA 13.1).

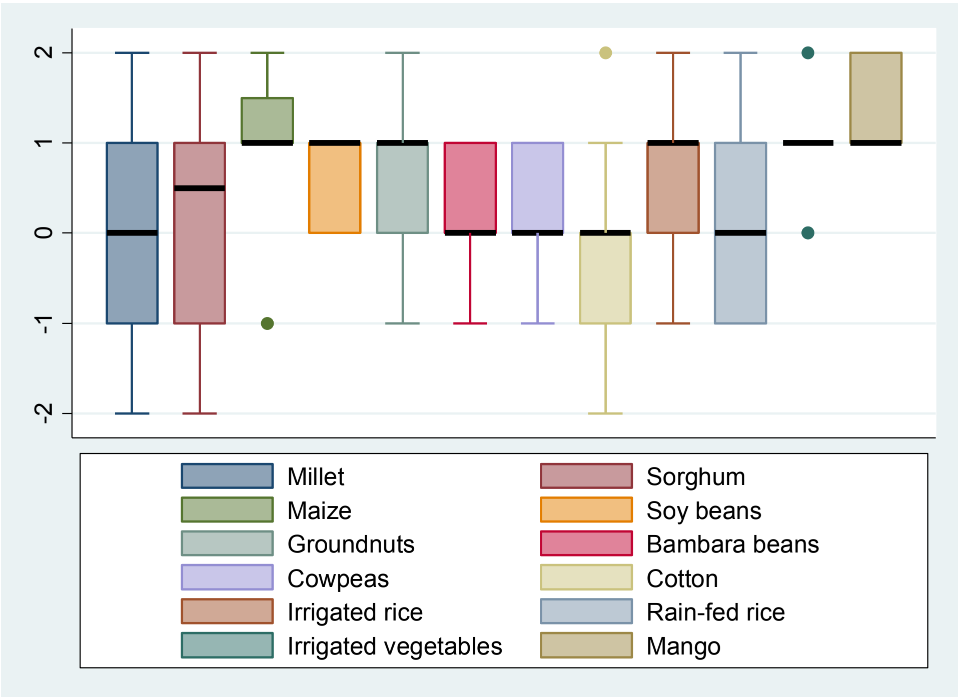


Figure 11: Expected changes in crop types within the next 10 years as forecast by experts (n=21); -2= significant decrease; 0= no change; 2= significant increase (box plots in STATA 13.1).

3.1.5 Contributions from papers to chapter 3.1 (Parameter identification for the Bayesian Belief Network)

Table 6: Overview of the contribution by the respective paper to chapter 3.1. BBN= Bayesian Belief Network, LULCC= Land use and land cover change, LUP= Land use planning, UER = Upper East Region, WASCAL= West African Science Service Center on Climate Change and Adapted Land Use.

Paper	General contribution
Paper I: Peri-/urban drivers of LULCC and LUP in Ghana/UER	**Parameter identification for the BBN (see Table 4, urban drivers) and identification of causal interactions between parameters:** • Spatial patterns of the peri-urban fringe and drivers of urban development of Bolgatanga (the capital of the UER) were compared with those of Takoradi located in southern Ghana. • Urban development in Bolgatanga was dominated by small-scale scattered settlement units which could indicate urban sprawl. The splitting up of land in continuously smaller parcels leads to fragmentation of land. The small parcels become useless for agriculture but they are still suitable for settlements. • Population growth was identified as an important direct driver of urban development with high confidence in Takoradi and Bolgatanga. • Customary land tenure was identified as an important indirect driver of urban development with high confidence in Bolgatanga due to the dominance of inheritance rights.
Paper II: Rural drivers of LULCC in the UER	**Parameter identification for the BBN (see Table 4, rural drivers) and identification of causal interactions between parameters:** • Population growth, especially in rural areas, is with very high confidence an important driver of LULCC. • Related to the intensive land use and land pressure, the current (traditional, low-input) farming system, bush fires, livestock, and road network are also relevant direct drivers of LULCC with high confidence. • Climate variability was the main biophysical direct driver, while the financial capital (i.e. poverty) of farmers and the customary tenure system are listed as important indirect drivers with high confidence. • Governmental laws, credits, the service by extension officers, conservational agriculture, and foreign medium-scale investments in agricultural are currently not driving LULCC.
Paper III: Food provision under LULCC and climate scenarios in the UER	**Fine-tuning of parameters and causal interactions between parameters** • Parameters of the BBN were further specified (links, nodes, states, definitions) by focus group discussions with the WASCAL scientists in Germany and at the Competence Center. For example, scientists at the Competence Center helped to clarify the temporal dimension of food availability.

	• The potential countermeasures against food insecurity were specified to: an increase in income levels, improved agricultural programs, increased market demand, increased irrigation, reduced soil erosion, and reduced post-harvest loss.

3.2 The Bayesian Belief Network of food and water provision

The Bayesian Belief Network (BBN) is based on a dry season and rainy season part with the main difference that rainfall parameters are only present in the rainy season part (specific differences are described in paper III). Both seasonal parts are merged by the output nodes, which are food from crops and water provision (Figure 12, Annex Table A2 and A3; selected nodes in Table 7). Input nodes can be distinguished in human-related parameters (e.g. income levels), rainfall parameters (e.g. amount of rainfall), countermeasures against food and water insecurity (e.g. agricultural programs and soil erosion control), and land use/cover-related parameters (e.g. total cropland in the UER). Interim nodes are crop-, water- or land use-related indicators. With regard to storage, food but not water is stored. Drinking water is mainly taken from groundwater by hand dug wells and boreholes or from surface water in rivers (experts and GSS, 2013). Rainwater harvesting is almost not practiced in the UER (0.1% of the population; GSS, 2013). The BBN output nodes reflect total food provision in the UER in billion kilocalories and water provision in million m^3. The kilocalories surplus was considered to be stored for the following season. The food demand of the population in the UER was calculated based on food need per person per day, the total population and the length of the respective season. In this analysis, the food and water *demand* was regarded as food and water *use.* The food demand in Ghana is on average 2118 kcal/day/capita (FAO Ghana, 2009). In times of food shortage, people reduce the number and portion of daily meal (Quaye, 2008). Therefore, real food intake might be less than 2118 kcal/day/capita. In the BBN output nodes, also the vitamin A content and the economic value of crops was assessed since both issues were seen as relevant by the experts in the regional context. The vitamin A deficiency was estimated because it plays a dominant role in malnutrition in West Africa (FAO Ghana, 2009).

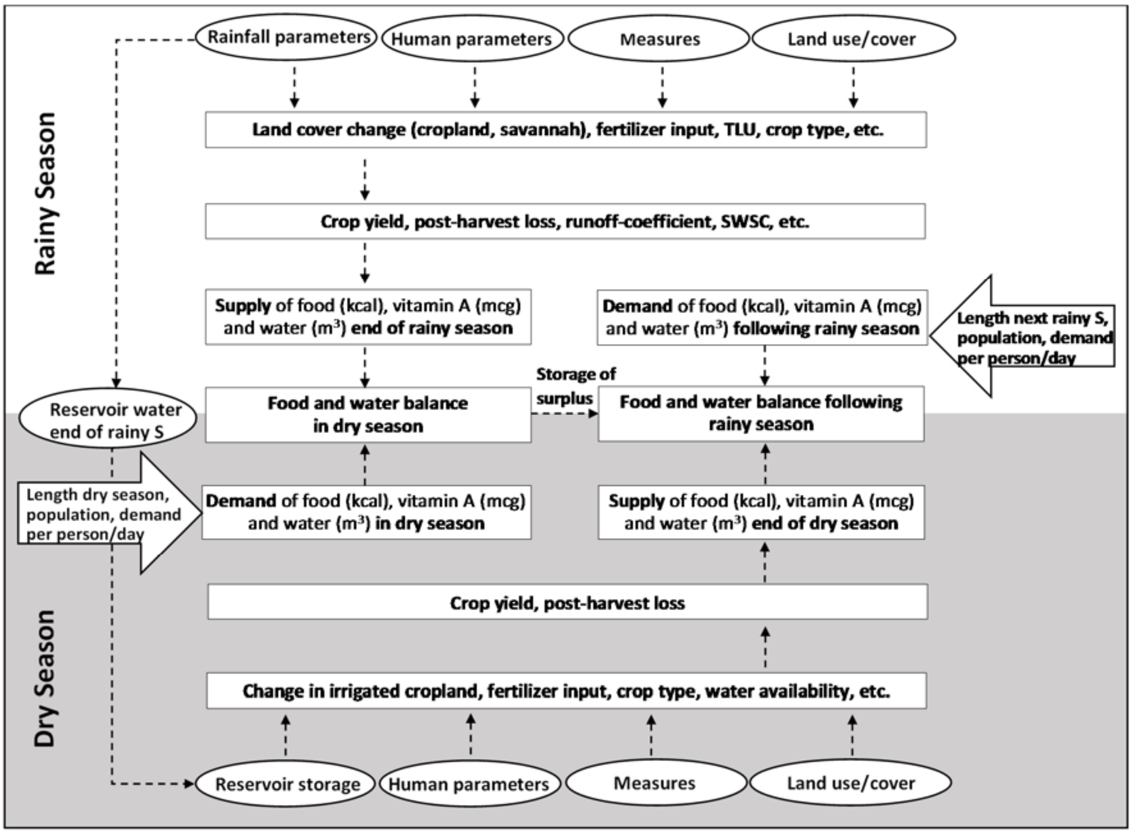


Figure 12: Schematic overview of Bayesian Belief Network with interlinkages between rainy season and dry season. LULCC= Land use and land cover change, S= season, SWSC= Soil water storage capacity, TLU= Tropical Livestock Unit.

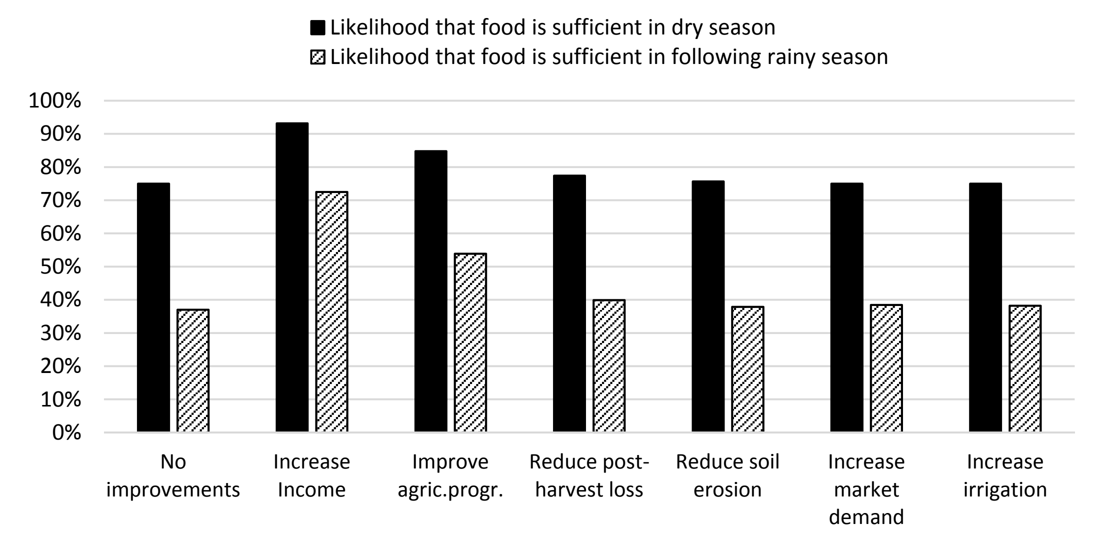
Table 7: Selected Conditional Probability Tables (CPTs) for the rainy and dry season with unit and source (see Annex Table A2 and A3 for complete table), including joint nodes of rainy and dry season.

Conditional Probability Tables of selected nodes		
Node Specification	**Division of unit**	**Source**
Rural population in Upper East Region in rainy season	800 000 – 830 000 830 000 – 860 000 860 000 – 890 000	GSS (2010); in dry season: 100,000 people less because approx. 100,000 people are migrating (Van der Geest et al., 2010)
Rainfall in rainy season (mm)	650 – 750 (low) 750 – 950 950 – 1100 1100 – 1400 (high)	Navrongo 1977-1997 and Bolgatanga weather station 1998-2013 (38 events)
Length of rainy season in days	90 – 120 (short) 121 – 180 181 – 220 (long)	Navrongo 1977-1997 and Bolgatanga weather station 1998-2013; agronomic definition: “the rainy season starts after the first of April with a 3-days-cumulative rainfall amount higher than 20 mm and not followed by a dry spell of more than 7 days. The rainy season end of this method is marked by the last rainfall higher than 5 mm/day after the first September with any rainfall higher than 5 mm/day during the twenty following days” (p. 1289 in Ibrahim et al., 2012); average length of rainy season: 160 days (FAO, 2005b); length of dry season coordinated with length of rainy season

Crop types of previous year (t0) in rainy season	Sorghum and millet Maize Legumes Rice	Agro-Maps FAO (2015) data from the Upper East Region; average values from 2000 to 2011
Used cropland of previous year (t0) in hectares in rainy season	300 000 – 350 000 350 000 – 400 000 400 000 – 450 000	Agro-Maps FAO (2015) data from Upper East Region from 1997 to 2011 (sweet potato excluded)
Inorganic fertilizer per ha in kg under different soil types and agricultural programs	No or max. 5 18 36	36 field officers from the Upper East Region
Manure per ha in kg under different soil types and amount of livestock per household	No or max. 10 250 2500	30 field officers from the Upper East Region
Yield from crops in rainy season in kg per ha	0 – 500 500 – 1000 1000 – 1500 1500 – 2000 2000 – 2500	Crop model APSIM; modeling with Navrongo 1977-1997 and Bolgatanga weather station 1998-2013 for each crop type; planting dates were taken from Bamler (2016); dry season: rice modeling with APSIM; vegetables modeling with DSSAT; applications and management from MOFA (2011)
Water type	Hand-dug well Borehole River close River far away	32 field officers from the Upper East Region
Joint nodes of rainy and dry season		
Node Specification	**Division of unit**	**Source**
Vitamin A balance of the following rainy season in billion mcg	0 0 – 1 1 – 5 5 – 10 10 – 20 20 – 30 30 – 40	Calculation based on supply of vitamin A end of the dry season and the rainy season, and vitamin A demand in the dry season (opposed to the vitamin A demand in the rainy season)
Food balance of the following rainy season in billion kcal	-50 to -200 -200 – 0 0 – 150 150 – 200 […] 800 – 1000 1000 – 1500 […] 3000 – 3500	Calculation based on the total food supply end of the rainy and dry season, reduced by the food demand (= use) from the dry season
Accessible water in rainy season in million m^3	2 – 3 […] 11 and more	Calculation based on water access in % and water in rainy season (rainfall) in million m^3; no deduction of water used by people during dry season because enough water is potentially available but access is the limiting factor (IWMI, 2007)
Available reservoir water end of rainy season (for irrigation in dry season) in million m^3	100 – 140 140 – 180 180 – 200 and more	Calculation based on reservoir storage capacity and potential water from rainfall

3.2.1 Scenarios of food provision

In the current situation, there is a 75% probability that the food demand during the dry season can be covered by food produced by the previous rainy season if all food is consumed in the UER (deducting the harvest loss) and if no additional food sources are used. In contrast, there is only a 37% probability that food from crops will be sufficient in the following rainy season (before harvest) because much less is produced during the dry season, and food storage is very primitive (see paper III for more results). Figure 13 reflects the options to increase food security under current population and weather uncertainty with an increase in income levels, the improvement of agricultural programs, an increase in market demand, the improvement of irrigation, the reduction of soil erosion, and the reduction of post-harvest losses. Highest probability for food provision is provided if income levels of farmers increase especially for the purchase and application of fertilizer. The increase in irrigation do not show higher levels of food security than the scenario without intervention because the irrigation scenario is only applied for the dry season and only with very small expansion. Figure 13 also shows that countermeasures in the rainy season are more efficient than those in the dry season, since more people farm in the rainy season and benefit from the measure. The scenarios of food provision under changing population, available cropland, changing income levels and agricultural programs as well as different climate scenarios and their sensitivity analysis are presented in paper III. Also in these scenarios, an increase in income level turned out to be the measure with the highest probability of food provision.



No improvements	"Business as usual": current cropland, crop types, income levels, post-harvest loss, soil erosion, irrigated area and irrigation efficiency
Increase income	Income increases by livelihood diversification, e.g. petty-trading.
Improve agricultural programs	Agricultural programs influence the input of inorganic fertilizer and commercial farming by the national fertilizer subsidy program and out-grower schemes.
Reduce harvest loss	A reduction in post-harvest loss could be reached by e.g. improved storage and harvesting techniques.

Reduce erosion	A reduction in soil erosion could be achieved especially by stone bunds.
Increase market demand	Creating market opportunities for the cultivated crops in the rainy season could result in higher market sales.
Increase irrigation	Increased irrigation efficiency, and expansion of irrigated cropland in dry season could result in higher total crop yields.

Figure 13: Countermeasures against food insecurity with current population and weather uncertainty (paper III).

In none of the scenarios, the vitamin A demand could be covered. The vitamin A demand could be only possibly reached if a higher crop share of legumes, a higher fertilizer input and more cropland were provided. Legumes have a high vitamin A content and can be eaten raw (Stadlmayr et al., 2010) while other crops need to be cooked, and due to cooking, the vitamin A content will get lost. In Figure 14, the economic value of cultivated crops on the local market in the rainy season is shown. The focus was placed on the rainy season because only a small share of crops is cultivated during the dry season. The highest likelihood of the highest value for crops (US$ 1500-2000 million) among all improvements is provided for the scenario with an increase in income due to the fact that income directly affects fertilizer input and this has the strongest influence on crop yields. Furthermore, experts see the influence of income, if spent on crop inputs, higher than the impact of agricultural programs.

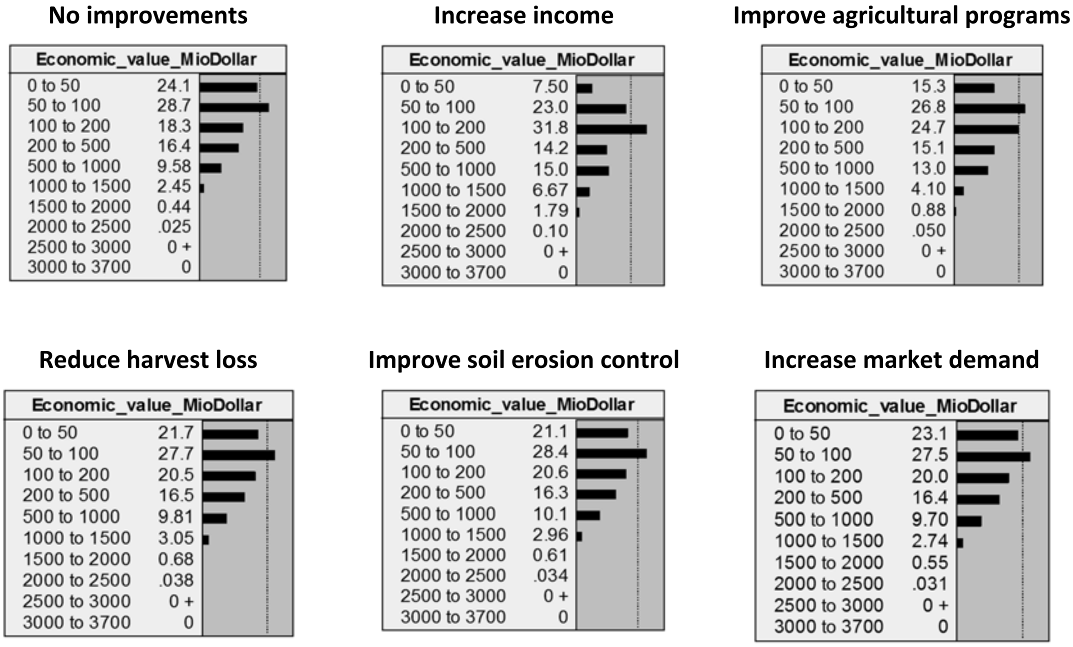


Figure 14: Economic value of rain-fed crops in rainy season under weather uncertainty with different measures.

3.2.2 Scenarios of qualitative and quantitative water provision

Qualitative water provision

The qualitative water provision for human consumption is dependent on the water type (Asare, 2004), for example, if water from a hand dug well, a borehole or a river is used. It was discussed with scientists at the WASCAL Competence Center if water quality also depends on the income level since bottled water has a better quality than water from boreholes and especially from rivers. However, the Ghana Statistical Service shows that bottled water is not used in the UER (GSS, 2012 and GSS, 2013). In contrast, experts in Ghana mentioned that the water type is not defined by income. Therefore, the water type was set as parent node. Water quality in the rainy season is with 47.5% higher than in dry season with 40.7% (Figure 15). Especially the use of water from rivers as drinking water during the dry season was mentioned by experts to be risky due to stagnating water.

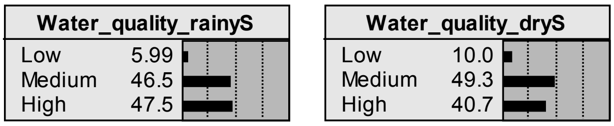
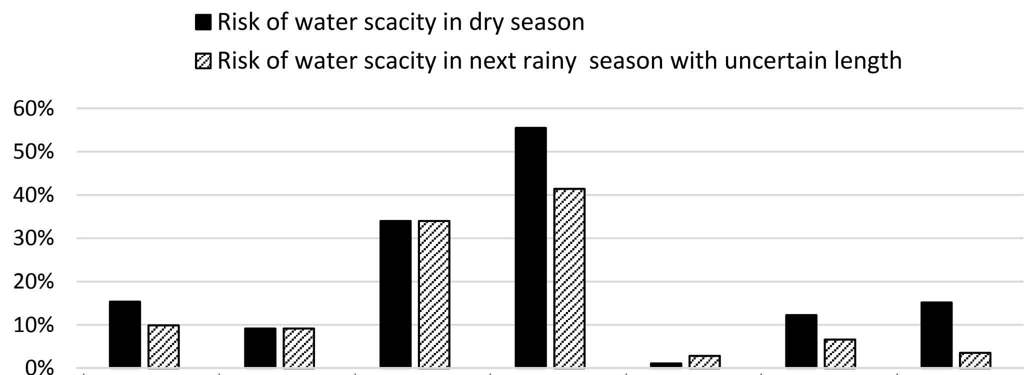


Figure 15: Water quality in rainy season (RainyS) and dry season (dryS) based on Asare (2004); supported by experts.

Quantitative water provision

The total water potential was based on the annual runoff coefficient, which was estimated by four scientists based on different soil water storage capacities and rainfall intensity. In the current situation, there is 89% probability that the runoff coefficient is between 0.1 and 0.15, which means that 10-15% of the total rainfall is runoff as surface water and groundwater and 85-90% as evaporation. However, the water potential is not equal to the water access (and therefore, not equal to the water use), since an economic water scarcity exists in Africa (IWMI, 2007). Also, eight interviewed field officers reported that, with 10-60% probability, communities could suffer from water scarcity in the dry season. This could be due to low rainfall during the previous rainy season but mainly due to an insufficient number of boreholes or to the unfavorable location of the boreholes, e.g. on top of a hill, the field officers said. It is still unclear how much of the total water potential can be accessed. One expert assumed that a maximum of 2% of the total water potential can be accessed in the UER. Assuming that the rural population can access 1-2% of the total water potential, the BBN shows a likelihood of water scarcity of max. 19% in the dry season with a weather scenario of low rainfall and a short rainy season. There was almost no risk of water scarcity in the following rainy season. A short rainy season means a long dry season, and, therefore, a higher risk of water scarcity in the dry season due to higher water demand. When the access of the total water potential is reduced to 0.5-1%, water scarcity occurs with 29% probability in the dry season and 19% in the following rainy season. The results shown in Figure 16 were calculated based on an equal chance (50:50) of 0.5-1% and 1-2% water access due to high uncertainty of real water access. Under weather uncertainty, there is a probability of 15% for the dry season to experience water scarcity and a 10% probability for the following rainy season. In scenarios M and L1, the risk in both, the dry season and the rainy season is the same, due to the fact that a smaller population size (due to migration) in a dry season of 185-244 days has the same water demand (of 7-8 million m^3) as a larger population with an uncertain length of the following rainy season. Furthermore, the risk of water scarcity is not increasing in the rainy season because water consumption in the dry season does not affect water consumption in the rainy season as the potential water provision is not the limiting factor but rather water access. The lowest risk of water scarcity is for high rainfall, a long rainy season and low rainfall intensity (scenario H1). The highest risk of water scarcity is in scenario L2, which has a low rainfall, a short rainy season (consequently a long dry season) and a low rainfall intensity. In scenario H1, the risk of water scarcity is lower for the dry season, because the dry season was regarded to be short and the length of the following rainy season uncertain. A population increase of 3.5-4% in scenario U would increase the risk of water scarcity by 6.1% for the dry season and 5.5% for the rainy season. An increase in the water demand of 20-30 l/capita/day in addition to a larger population, e.g. due to rising living standards, would increase the risk by 13% for the dry season.



	U	M	L1	L2	H1	H2	H3
Rainfall	Uncertain	Medium	Low	Low	High	High	High
Length of rainy season	Uncertain	Medium	Medium	Short	Long	Short	Short
Rainfall intensity	Uncertain	Uncertain	High	Low	High	High	Low

Figure 16: Risk of water scarcity under different climate scenarios for the dry and rainy season in the Upper East Region; assuming a water demand with max. 7-8 million m^3 in dry season with medium length rainy season; water demand with max. 9-10 million m^3 in the dry season with short rainy season (higher due to longer dry season). The water demand in the following rainy season was uncertain and resulted in max. 7-8 million m^3.

3.2.3 Sensitivity of quantitative water balance

Water access has the highest influence on the accessible water at the end of the rainy season (Table 8). Furthermore, the total water potential and rainfall have also strong influence.

Table 8: Mutual information of the accessible water end of the rainy season shown in bits. Values smaller than 0.00003 bits are not shown.

Accessible water end of rainy season	Mutual information in bits
Water access (to the total water potential)	0.32189
Total water potential	0.27525
Rainfall	0.10095
Usable Soil Water Storage Capacity	0.00078
Rainfall intensity	0.00062
Soil type	0.00041
Soil erosion	0.00003

3.2.4 Trade-offs and/or synergies between ecosystem services

The analysis of trade-offs and/or synergies between food and water was limited because it was not the focus of this study. But it was possible to start a basic analysis which could be further developed. Trade-offs and/or synergies between ES are related to the provision of ES (Rodríguez et al., 2006). Therefore, Figure 17 shows only nodes that are directly linked to ES provision and that are overlapping nodes, i.e. nodes that are indicators for food provision as well as for water provision:

- Soil erosion, and therefore soil erosion control and tree and shrub density on fallow,
- Total rainfall and rainfall intensity,
- and the runoff coefficient.

The manageable node in the rainy season which is relevant for food and water provision in the model would be soil erosion control (yellow input node on top on the right in Figure 17). Soil erosion control is also an ES because it occurs as shrubs, roots and stones, which retain soil against wind erosion in the Harmattan season and against heavy rainfall during rainy season (Dietz et al., 2004). However, it has to be noted that only soil erosion by water was considered in this study due to a stronger emphasis of regional relevance by experts. Natural hazard protection, where soil erosion control is a part, was of high importance as ES on regional level in the online survey with the WASCAL community (Figure 8). Furthermore, soil erosion control belongs to the techniques of conservation agriculture (Kombiok et al., 2012). Conservation agriculture reflects a potential synergy between food and water provision (also see Table 5). However, conservation agriculture had a low confidence level in the analysis of important drivers of LULCC (see Table 4, Table 5 and paper II).

The results of the sensitivity analysis (Table 9) show that soil erosion is more sensitive to soil erosion control than to tree and shrub density, which makes, for example, the management of stone bonding more important. In the BBN, also seen in Figure 17, soil erosion directly affects crop yields and indirectly affects the runoff-coefficient by the usable soil water storage capacity, which is also a factor for the accessible water. In addition, the runoff coefficient determines the available reservoir water for dry-season irrigation. Therefore, soil erosion can also affect food provision in the dry season. The degree of soil erosion is determined by tree and shrub cover, rainfall intensity and soil erosion control (Figure 18, marked in red). In the current situation, there is a 21.6% probability of severe soil erosion in the UER (Figure 19) - if there is a 32% probability of soil erosion control based on the average value estimated by 33 field officers. Soil erosion control can reduce severe soil erosion by 16% against missing soil erosion control if the likelihood of rainfall intensity and tree cover is the same as in the current situation. If there is an event of high rainfall intensity, soil erosion control can reduce soil erosion by about 33% against a scenario without soil erosion control. If there is bare land and high rainfall intensity, there is a 79% probability of severe soil erosion. In this case, soil erosion control can reduce the probability of severe soil erosion by 42%.

Table 9: Mutual information of soil erosion (only a factor in the rainy season because only soil erosion by water is considered) shown in bits. Values below 0.00003 bits are not shown. The sensitivity analysis was conducted by using Netica (Norsys Software Corporation, 2016b).

Soil erosion	Mutual information in bits
Soil erosion control	0.02764
Tree and shrub density on fallow t1	0.01290
Tree and shrub density on fallow t0	0.01158
Rainfall intensity in mm/h	0.01017

Soil erosion control would improve food provision by about 3% for the dry season and by 2% for the following rainy season in comparison to the business as usual scenario (Figure 20). Missing soil erosion control would slightly reduce food provision by 1% for both seasons. However, Figure 20 also illustrates that soil erosion control has no impact on water provision. Therefore, soil erosion control has a marginal synergy with food provision but neither a synergy nor trade-off with water provision in the model.

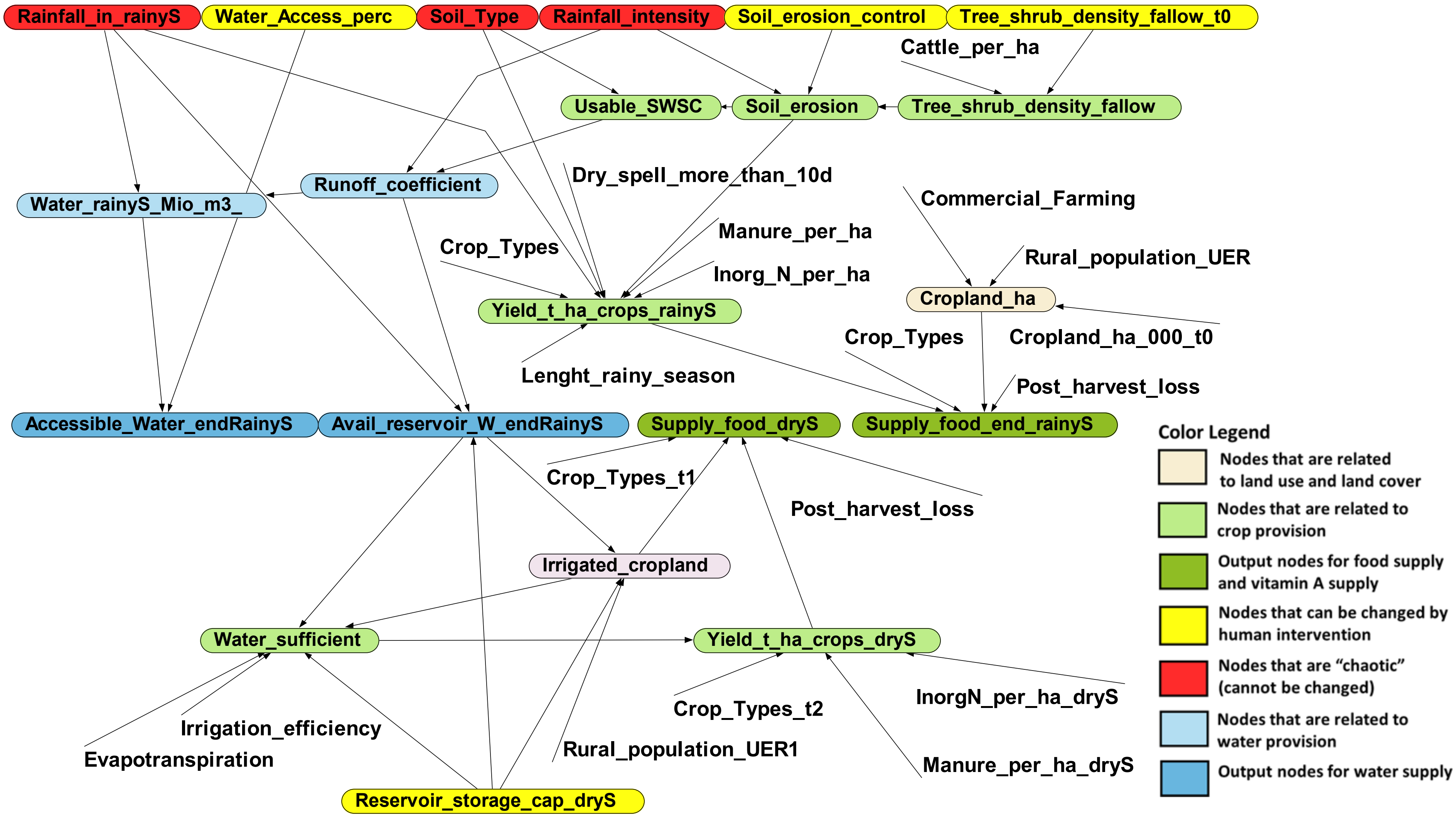


Figure 17: Extract of the Bayesian Belief Network showing relevant nodes for water and food provision; SWSC= Soil water storage capacity, dryS= dry season; rainyS= rainy season; UER = Upper East Region

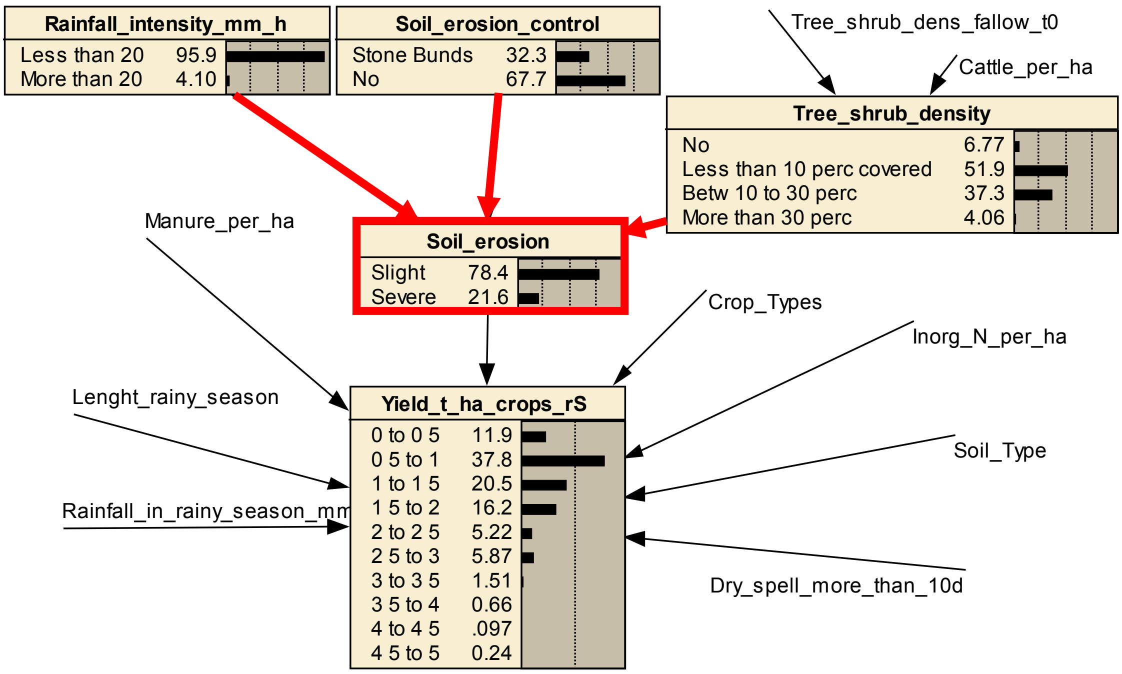


Figure 18: Extract of soil erosion part in the rainy season BBN.

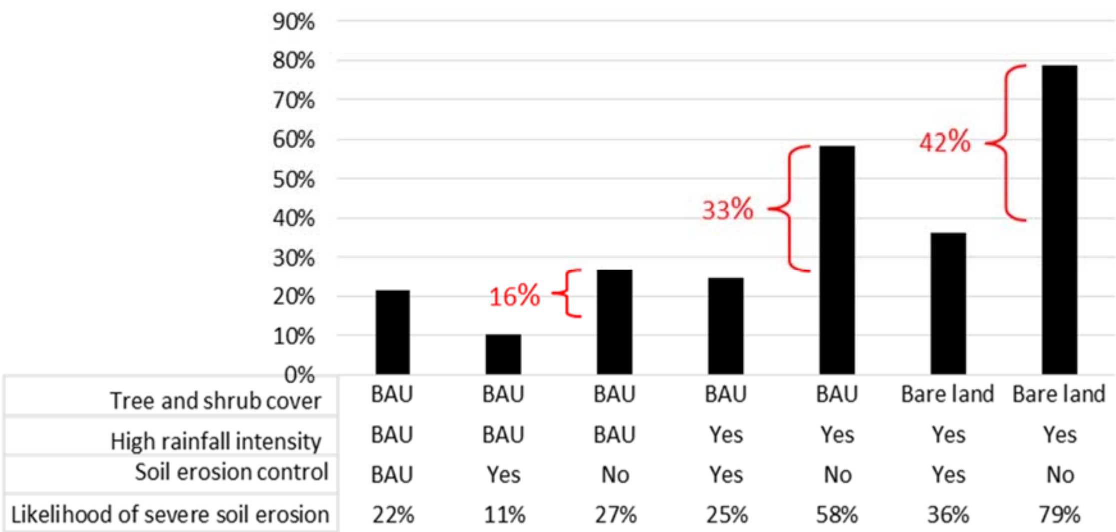


Figure 19: Likelihood of severe soil erosion; BAU= business as usual/with current probabilities. Values in red show difference between scenario with and without soil erosion control.

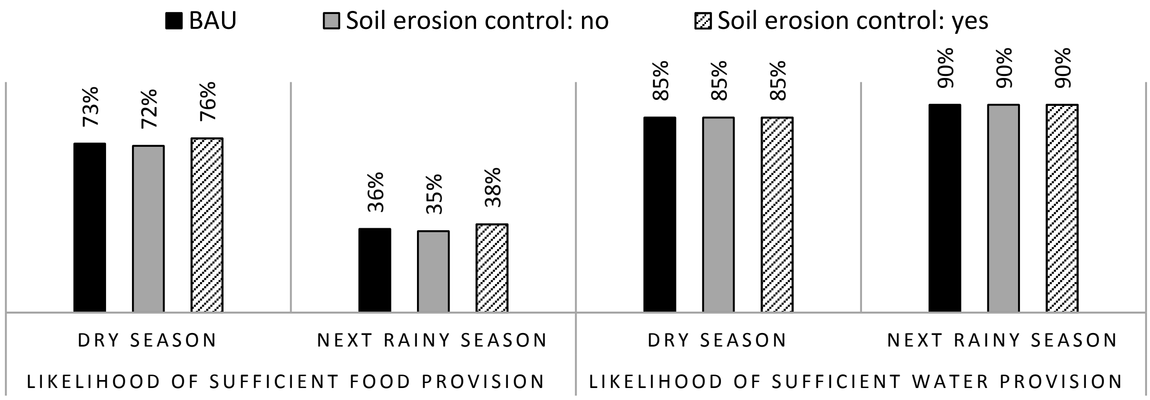


Figure 20: Analysis of trade-offs and/or synergies between food and water provision for soil erosion control; BAU= business as usual/as current probability.

3.2.5 Contributions from the papers to chapter 3.2 (Bayesian Belief Network of food and water provision)

Table 10: Overview of the contribution by the respective paper to chapter 3.2. BBN= Bayesian Belief Network, ES= Ecosystem Service, CPTs= Conditional Probability Tables, LULCC= Land use and land cover change, UER = Upper East Region, WASCAL= West African Science Service Center on Climate Change and Adapted Land Use.

Paper	General contribution
Paper I and II: Rural and urban drivers of LULCC in the UER	**Interactions between parameters, development of the BBN:** • The selection of the most important drivers of LULCC served as input for the BBN. • Causal relations between the main drivers of LULCC, ES and land use types were identified.
Paper III: Food provision under LULCC and climate scenarios in the UER	**BBN development and ES assessment:** • Causal relations between the main drivers of LULCC, ES and land use types in the BBN were further specified with WASCAL scientists in Germany and discussed with WASCAL scientists at the Competence Center. Furthermore, experts filled in the Conditional Probability Tables where information from other sources (e.g. literature) were missing. • The focus was set on food provision from subsistence crops as most important ES in order to keep the paper structure simple and clear. • A sensitivity analysis of food provision in dry and rainy season was conducted which showed that food supply was most sensitive to crop yield per hectare in both seasons. • The BBN showed that farmer income might be more effective than agricultural programs with respect to food security under weather uncertainty, provided that income is partly spent on fertilizer. The same is true under increasing population and decreasing total cropland.

4. DISCUSSION

4.1 Discussion of the results

4.1.1 Food provision

As seen from chapter 3.1.2 and 3.1.3, population growth, especially rural population growth, is currently the main driver of LULCC and remains the most relevant driver in future, causing a threat to the provision of ecosystem services. The growth rate of 1.2% for the UER between 2000 and 2010 is lower than the national average of 2.5% (GSS, 2012). However, the population density of the UER of 118 p/km² (including urban areas) is higher than the national average of 103 p/km² (GSS, 2010).

Future LULCC, projected by experts (chapter 3.1.4), shows that there might be a link between increasing population and LULCC due to the expected increase in urban area, increase in cropland and decrease in savannah. Therefore, it is very likely that land pressure will increase in the future. Experts also see a trend that the share of maize cultivation will increase. This was also mentioned by the field officers and literature (Angelucci, 2012; Millar et al., 2004; MOFA, 2011). Six scientists and field officers said that maize varieties with short duration now exist, which are becoming popular in the UER. In addition, new varieties are more drought tolerant (Ragasa et al., 2013). In contrast, new maize varieties can be hardly reproduced and increase the dependency of farmers on seed companies (mentioned by scientists in Ghana).

With regard to millet, in some areas of the UER, farmers use an old variety, which is exhausted and, therefore, lower yielding than in the past (interview with field officers). Farmers are gradually changing to maize cultivation even though millet remains “the crop of the poor” since maize needs some levels of fertilizer (González-Estrada et al., 2008; Vanlauwe et al., 2011), which cannot be purchased by poor people (interviews with scientists in Ghana and field officers). In addition, the BBN shows a link between commercial farming and maize. If a higher probability for commercial farming in the BBN was used, the share of maize (and rice) also increases, which indicates the better marketability of maize and rice, especially within Ghana (Cudjoe et al., 2010; Ellis-Jones et al., 2012).

The vitamin A demand could not be covered in any scenario, which indicates a high risk of malnutrition if no additional food sources can be identified. Vitamin A sources are fruits collected from trees (e.g. shea) and fruits and vegetables bought at the market (e.g. carrots, papaya, and plantain). However, poor households have a low purchasing power, and available money would rather be used for clothes and medicine than for additional food if there is no food shortage (interviews with scientists in Ghana). Moreover, the share of income that would be spent on fertilizer is questionable.

The BBN shows that increasing income would be the most promising measure for food security, which is also supported by Asmah (2011). I therefore recommend that policy makers focus on different income opportunities for farmers. Livelihood diversification and off-farm income are already adaptive measures to cope with food shortage and other risks (Asmah, 2011; GLSS6, 2014). Furthermore, an increase in off-farm income could reduce land pressure, because off-farm jobs are more likely in urban areas (Kolavalli et al., 2012). People already tend to migrate to southern Ghana (Van der Geest et al., 2010). In contrast, Yaro et al. (2016) showed in a study with 530 farmers in northern Ghana that the wealth of a farmer was not the main explanation for fertilizer application but rather the village, education, age and gender.

The services sector is further increasing in Ghana at the cost of the agricultural share of the GDP (Kolavalli et al., 2012). In 2012, 42% of Ghana´s population was employed by the services sector (World Bank, 2015). A high share of the subsector is related to public and governmental services, e.g. administration, health, education. In addition, Ghana is in a phase of informal employment (Kingdon et al., 2006). Most employment is located in the informal sector with a high employment insecurity (Kolavalli et al., 2012). Due to the fact that economic transformation in Ghana is mainly consumption driven, production linkages are weakened. Potential domestic markets for agriculture are currently met through imports.

Kolavalli et al. (2012) sees that the agricultural sector could have played a stronger role in reducing poverty by developing large-scale commercial agriculture and irrigation schemes. However, this study revealed that the development of any medium or large-scale agricultural investments is unlikely in the UER due to the customary land tenure system (see paper I and II). Furthermore, irrigation schemes had the lowest impact among the measures in the BBN to increase food security. On the one hand, the expansion of irrigated areas was not represented to its maximum extent in the model. On the other hand, the minority of people in the UER benefit from this measure, and mainly only those with higher incomes (GSS, 2008; Hjelm and Dasori, 2012). If the majority of farmers should also benefit, considerable efforts need to be taken by the government, which is also challenging in view of weak governmental structures. In addition, Dinye (2013) showed that farmers in irrigated areas in Tono and Vea could not increase their income due to high production costs.

Furthermore, functioning agricultural programs are very uncertain. Agricultural programs, such as fertilizer subsidies, and development aid are already existent in the UER for some time but the experts in Ghana said that nothing has changed, which is supported by Blench (2006). Even though the impact of supportive measures for food security show an increase in the likelihood of food provision (Figure 13), its implementation in the UER is missing. Many improvements are suggested by the experts but not adopted by the local people, e.g. collecting rainwater for water provision and by using crop residues to feed livestock instead of burning the residues. The results also show that experts give lower importance to current supportive measures for food provision (positive drivers of LULCC) than to drivers with negative effects on food provision. One of the scientists said that farmers would be able to help themselves, but if development aid and governmental support were confirmed, they could wait for years until something was done, e.g. a broken or silted dam repaired (supported by Blench, 2006; Namara et al., 2011). Corruption, lacking law enforcement, or low financial capacities/misbalance in distribution hinder development (see paper I and II). Consequently, the government as well as the farmer is responsible for the slow or lacking process of livelihood improvement. A comprehensive discussion on the context is provided in paper I-III.

4.1.2 Water provision

Comparing food with water provision, the model output reflects the differences in provision. Food is a limiting source, and food consumption during the dry season reduces the total food stock while water consumption does not affect total water provision because potential water provision is not a limiting factor but rather water access. The risk of food insecurity is higher in the rainy season before the harvest, while the risk of water scarcity is in generally slightly higher in the dry season. This is due to the fact that the dry season is longer than the rainy season, which leads to a higher total water demand.

A scenario with a lower rainfall intensity shows a slightly higher risk of water scarcity (Figure 16). This can be explained by the fact that a lower rainfall intensity leads to a lower runoff coefficient and also causes less soil erosion (Fraser et al., 1999; Kowal and Kassam, 1978; Lal, 1998). Therefore, more water is evaporating. Also, literature shows that higher permeable and also well vegetated areas have a lower runoff coefficient (CWT, 2011). However, the scientists in WASCAL who developed this part of the model assigned a direct impact of the soil water storage capacity on the runoff coefficient, while in literature also the land cover (vegetation) plays a direct role (Ibid.); scientists in Ghana supported the findings provided in literature. The water balance for the rainy season has a high sensitivity to water access (Table 8). Since the real water access is highly uncertain, results from the water provision should be contested.

The probability of a better water quality is higher from boreholes than from rivers, ponds, dugouts and dams (Birner et al., 2005), which was confirmed by field officers. However, Zango et al. (2014) mentioned exceeding nitrate values through infiltrating water from agricultural areas in Bawku District, which was against my expectation since fertilizer input is in general low. Anku et al. (2008) showed very selective nitrate concentrations in the water, which could also indicate poor sanitary conditions of the boreholes where animal feces could drop into the borehole. Furthermore, it can happen that, on a very local scale, water pollution appears due to the collection of animal feces over years near the household compound in the kraal system, which is in general without roofing. Consequently, nitrate leaching could occur during the rainy season (Fening et al., 2010).

4.1.3 Trade-offs and/or synergies between ecosystem services

Trade-offs and synergies exist between different levels of food and water provision. For example, a trade-off would be the impact of fertilizer on water quality as described above which was, unfortunately, not included in the BBN. High nitrate values are common in high-income countries but were not assumed for countries with generally low-input agriculture (Mueller et al., 2014; Smaling and Toulmin, 2000). Furthermore, flood control could reduce the total available agricultural area if agricultural plots are potentially used as water retention basins (Bennett et al., 2009). In contrast, intensified river or dam irrigation could reduce water availability for fishing, hydropower and domestic use in a catchment area (Rodríguez et al., 2006).

The use of stone bunds for soil erosion control as an example for increasing crop yields by nutrient, soil and water retention (Bennett et al., 2009) could have a possible impact on water provision. However, the BBN showed that water provision did not change with increasing soil erosion control in the UER. Among the management scenarios, soil erosion control was not the best measure in the BBN to increase food security since it only contributed indirectly by maintaining soil cover and avoiding soil erosion.

There was a potential synergy between food and water for soil erosion control (Table 5) if soil erosion control is considered as a measure in conservation agriculture (Kombiok et al., 2012). But this synergy could not be discovered in the BBN because there was no change in water provision. However, the missing evidence of the influence of soil erosion and soil erosion control on water provision in the BBN does not mean that there is no influence. The analysis only covered the impact of soil erosion on water quantity but soil erosion also affects water quality through sediment load in the rivers and the transport of chemicals to water bodies (Lal, 1998). Changes in soil erosion control only affected the runoff coefficient by 0.1% in the model and did not change the probability of the accessible water. In addition, the relation between soil water storage capacity and runoff coefficient was only based on information from four experts with divergent opinions. Therefore, there is high uncertainty for this node.

4.2 Discussion of the methodological approach

4.2.1 Food provision

The integration of expected crop yields under different weather conditions from crop models improved the BBN. However, only optimal land management (e.g. fertilizer application, sowing time) could be reflected in the crop models. Therefore, results represent optimal yields. Furthermore, nutrient depletion from the preceding years or crop rotation were not included in the crop models. In addition, the economic value of crops was considered in a very reductionist way because it was not the focus of this study. The mean monthly market price at Bongo Soe in 2012 was taken as input to estimate the economic value of crops, which might be outdated. Further, crops in the dry season are expected to be cash crops but were calculated as crops for subsistence. However, since the regional aspect was studied, food from irrigated crops might have been sold by one farmer and consumed by another farmer within the UER, which allows this assumption.

Malnutrition was only a minor aspect in the modeling exercise. For specific scenarios with a focus on vitamin A provision, it would have been necessary to consider crop types with a high vitamin A content. This could have been sweet potato, carrot, papaya and plantain (Stadlmayr et al., 2010). However, these vegetables and fruits are either not or rarely produced in the UER (Jalloh et al., 2013).

In addition, the loss of crops as consequence of pests and diseases was not considered. Irrigated crops are especially prone to nematodes (Al-Hassan, 2015). For example, nematodes in tomato production pose a high risk at the Vea and Tono dams (Robinson and Kolavalli, 2010). A comprehensive methodological discussion on food provision is provided in paper III.

4.2.2 Water provision

A few inconsistencies were also accepted for water provision due to data scarcity and modeling challenges. Even though the share of crop types, irrigated area and irrigation efficiency were taken from statistics for Tono and Vea dam, the dam storage capacity was taken from all dams in the UER. However, Tono and Vea are the biggest dams in the UER, and the influence of small dams might be marginal. Furthermore, the results from water provision are questionable since any inflow or outflow of water (e.g. fluctuations of groundwater table or dam water level) or spatial differences (e.g. water logging conditions) could not be considered due to modeling challenges and complexity. And due to the fact that the runoff represents the water which is available for people, the assumption that bare land leads to higher water availability – because of higher runoff – might be misleading. In addition, a high surface runoff might represent flooding, which was not considered in the model.

4.2.3 Summary of methodological strengths and weaknesses

BBNs have the advantage to address uncertainty and variability, but they have the same limitation of a reduced display of reality like other modeling approaches (McCann et al., 2006). In complex human-environmental interactions, assumptions and over-simplification need to be recognized in a modeling approach (Banks, 1999). Even though epistemic uncertainty was reduced by including expert knowledge, the modeler still had to deal with other sources of uncertainty. Methodological weaknesses are accumulated by using various methods (Amaratunga et al., 2002; Todd, 1979). Predictions for the future are also difficult to validate (Rounsevell et al., 2006; Woodside et al., 2007). Data was often provided in different spatial and temporal scales. For example, agricultural drivers of LULCC were analyzed by remote sensing between 2001 and 2013 while the analysis of urban drivers of LULCC was based on data between 2007 and 2013 which makes a direct comparison difficult. In addition, some data and information sources from literature seemed to be outdated but more recent data was not available. For example, the population census needed to be taken from 2010.

Despite its challenges, the BBN is regarded as a tool to provide a visual overview of complex system relationships and, therefore, can be used for participatory approaches (McCann et al., 2006). The modeling exercise facilitated inter- and transdisciplinary teamwork by knowledge exchange and offered a discussion basis for further research needs. The model can be transferred to other areas with similar socio-ecological system, i.e. in the Sudan/Guinea Savanna Zone, distinct dry and rainy season and similar driving forces. The Upper East Region is special regarding its focus on food crops for subsistence. For example, in Burkina Faso, cotton as cash crop for small-scale subsistence farmers is much more emphasized (Paré et al., 2008) and would need to be considered in a modeling approach. Main strengths and weaknesses of the study are illustrated in Table 11 (specific strengths and weaknesses in paper I-IV). In addition, knowing about weaknesses is the starting point for further improvements (see chapter 6).

Table 11: Main strengths and weaknesses of the study. Details are provided in paper I-IV.

Strengths	Weaknesses
New insights were provided on driving forces, interactions in a socio-ecological system and ecosystem service demand and supply under seasonality and different scenarios for the study area, which was not done before in this context.	The socio-ecological system had to be modeled as a closed system without inflow or outflow of energy. But this unrealistic assumption (Wohl et al., 2014) was necessary due to technical limitations (e.g. no feedback loops in the BBN) and to reduce complexity.
A huge amount of actors were involved and a great variety of methods was applied to explicitly allow inter- and transdisciplinarity.	Not all critiques could be equally considered since a specific focus needed to be maintained.
A new process was described on how to develop a BBN and to validate data (table of confidence).	Most of the data generation, even though from experts, was subjective.
The BBN was developed to be used at the WASCAL Competence Center and, therefore, oriented towards applicability.	Due to the required reduction of complexity of the BBN, among others, expectations of all participants could not be met. Consequently, the BBN is only for some of the WASCAL scientists of interest and modifications should be made.
A BBN was developed which considered seasonality for the first time.	Different temporal and spatial scales had to be used in this study due to data gaps which increased inconsistency in dada.
Objectives and spatial boundaries were clearly defined.	Due to the consideration of multiple methods (e.g. mixed-method approach), inherent methodological problems accumulated.
Uncertainty, validity, reliability and applicability were specifically considered, which allowed a qualitative, transparent, critical and also quantifiable reflection on the model and its results.	Different thresholds for methods in the table of confidence had to be used to enable the comparison between methods. However, this measure increased the risk of imbalance.

4.2.4 Contributions from the papers to chapter 4 (Discussion)

Table 12: Overview of the contribution by the respective paper to chapter 4. BBN= Bayesian Belief Network, LULCC= Land use and land cover change, LUP= Land use planning, WASCAL= West African Science Service Center on Climate Change and Adapted Land Use.

Paper	General contribution
Paper I: Peri-/urban drivers of LULCC and LUP in Ghana/UER	**Discussion of urban drivers of LULCC, the mixed-method approach and individual methods:** • The investigation of opportunities and challenges of land use planning in the UER through expert interviews helped to develop the discussion part. • Remote sensing analysis could show the compliance or the ignorance of legal land use planning which was mentioned by expert interviews and provided in literature.
Paper II: Rural drivers of LULCC in the UER	**Discussion of rural drivers of LULCC, the mixed-method approach and individual methods:** • Strengths and weaknesses of individual methods and the mixed-method approach were discussed. • Expert interviews and literature analysis described also indirect drivers of LULCC. Furthermore, the literature analysis questioned some of the experts' statements and supported a critical reflection of the findings. • All advantages and disadvantages of each method are accumulated in a mixed-method approach which could have an influence on the degree of evidence. However, the consideration of four different methods for analyzing drivers of LULCC has the advantage that information can be directly compared.
Paper III: Food provision under LULCC and climate scenarios in the UER	**Discussion of the drivers of food security and the BBN development:** • The paper provided a contextual and methodological discussion of the findings, the BBN and its components. • Main limitations of the BBN were due to the attempt of reducing complexity. • The participation of researchers from different disciplinary and cultural backgrounds as well as the involvement of local representatives provided the advantage of encompassing the diversity of knowledge and, therefore, giving also attention to contradictory findings, and to an increase in the maximum likelihood of available information on the research topic. • An outlook was provided for improving the model.

Paper IV: Validation of the BBN	**Presentation of different validation approaches for the BBN:** • The reliability of the BBN structure, the Conditional Probability Tables and the BBN output was analyzed by using qualitative (e.g. critical feedback from experts, literature) and quantitative validation approaches (e.g. statistical analysis, extreme-condition test). • Model applicability was identified by scientists at the WASCAL Competence Center. The majority of the scientists acknowledged the BBN as a potential contribution to their scientific research after some adaptations. • The extreme-condition test demonstrated that the BBN works according to the assumed system understanding that food provision decreases under floods, droughts, land pressure and poverty. • Validation approaches showed that structural model uncertainties are still high and reliability of input data is low. • The BBN can provide general trends for output nodes but lacks reliability if detailed results of single system components are required.

5. CONCLUSIONS

An expert-based model was developed which allows the assessment of selected ecosystem services, with a focus on food and water provision, under different management, land cover/land use and climate scenarios. In addition, trade-offs and/or synergies between food and water provision by soil erosion control were assessed. The BBN is a useful tool under data-scarce conditions. Furthermore, the here presented model considered seasonality for the first time in a BBN.

Key lessons learned from the results:

- Population growth is the most important direct agricultural and urban driver of LULCC in the UER. Customary land tenure drives indirectly LULCC.
- The UER is highly vulnerable to food crises due to a high probability of food shortage, especially in the rainy season before the harvest.
- The vitamin A demand could not be covered in any of the scenarios which hints to a high vulnerability of malnutrition.
- The sensitivity analysis showed that focus should be laid on the application of inorganic fertilizer in order to increase the probability of food security.
- Higher income levels increase the probability that more fertilizer can be purchased and applied to the crops. But for this scenario, also changes in LULCC have to be expected because income levels were also an important indirect driver of LULCC in the agricultural context.
- By comparing food and water provision, food provision has different patterns of provision than water provision. The risk of water scarcity is much lower than the risk of food insecurity and is rather related to technical water access (economic water scarcity) than to physical water scarcity.
- No trade-off or synergy could be identified between soil erosion control and water provision, but a minor synergy was detected between soil erosion control and food provision.

Key lessons learned from the modeling approach:

- The BBN is a flexible tool which visualizes complex interrelationships and facilitates inter- and transdisciplinary collaboration.
- The dry and rainy season in the UER can be regarded as different socio-ecological systems and should be considered in a modeling approach.
- Data quality: Due to data scarcity, different temporal and spatial scales had to be used, which increased the uncertainty of the validity of the results.
- Robustness: In an extreme-condition test, the BBN behaved according to the general system understanding. However, other validation approaches revealed that the model is not robust if specific details are required as results.
- Applicability: Scientists at the WASCAL Competence Center are interested to use the BBN further if model adaptations are made.
- Transferability: The BBN can be adapted to areas with similar climatic and socio-ecological context (with distinct dry and rainy season and similar driving forces).

6. OUTLOOK: FUTURE USE AND SUGGESTIONS FOR IMPROVING THE BBN

Due to the fact that the BBN was developed in cooperation with the WASCAL Competence Center, it could be used by scientists in the Competence Center in order to inform policy makers at regional administrative level in West Africa. The model could support decisions on food security under future changing weather conditions and different land cover and land use options. If further fine-tuned, it could contribute to a forecasting system on the likelihood of food insecurity under specific weather conditions and land pressure. If the risk of food insecurity is high, measures could be taken in advance of an event, e.g. the provision of supplementary food by the government. The effects of the most likely scenarios, e.g. population growth and increasing poverty, can be assessed or used to inform policy makers to start counteractions. Management options could be more differentiated in combination with farmer decisions (agent-based modeling), e.g. to analyze whether improved crop varieties are more efficient than fertilizer subsidies, out-grower schemes or irrigation schemes. In addition, it could be assessed if the adoption of different management options is dependent on the donor, e.g. if it is a governmental program or NGO. Also, more trade-offs between ecosystem services, especially between wood use and crop cultivation, could be analyzed.

If the BBN is used by the WASCAL Competence Center, adaptations to the needs of scientists and policy makers would be required (see paper IV for the applicability of the BBN). Following improvements are suggested:

- Rework on recommendations from experts who have not yet been considered in the model, e.g. by follow-up interviews or the development of two different BBNs (e.g. one developed only by scientists and one developed only by field officers) and comparison of the BBNs.
- Test other settings, e.g. adapt and differentiate between calorific demand per person (e.g. age, gender, workload), increase the irrigated area, include other crop types, e.g. those that provide vitamin A.
- Couple the BBN with a programming interface with a crop model or hydrological model to fine-tune the BBN output.
- Couple the BBN with an agent-based model to include farm level and farmer decisions.
- Couple the BBN with GIS and make it spatially explicit.
- Separate temporal processes in the BBN to annual time steps and decades.
- Focus more on trade-offs between ecosystem services, e.g. the impact of commercial farming on food and water provision.
- Include more ecosystem services, e.g. extend the model to wood provision, which was also mentioned as important ecosystem service in the WASCAL survey.
- Focus more on economic values by an economic model, e.g. including the market price of crop types as an influence on farm income; differentiate income into farm, livestock and off-farm income; include price volatility and/or economic discounting.
- Compare the regional BBN output with BBN output at district level to analyze applicability of the BBN at local level.
- Compare the BBN with other models in the UER, e.g. GISCAME (Fürst et al., 2010).
- Transfer the BBN to other study areas with similar research context, e.g. northern Benin.

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ANNEX A: SUPPLEMENTARY TO DISSERTATION

Table A1: Description of the potential positive and negative impact of driving forces of land use and land cover change (LULCC) on food and water provision; in alphabetical order. ES= Ecosystem services, UER= Upper East Region

Driving forces of LULCC	Description (references in paper II)	
	Food	Water
Agricultural extensification	**Positive:** Food increase due to more land use. **Negative:** -	**Positive: -** **Negative:** Increase in water use. Land conversion could decrease water availability.
Agricultural intensification: traditional	**Positive:** If there is low population density, it is a sustainable land use because the bush-follow practice allows regeneration but this is unrealistic in the UER. **Negative:** Exhaustion of soils due to no or low fertilizer input, removal of trees, slash and burn practice, and almost no fallow under high population pressure.	**Positive:** Low nitrate infiltration from crops; no irrigation and, therefore, no overuse of water. **Positive/negative:** Removal of trees/bare land increases surface-runoff. **Negative:** -
Agricultural medium-scale investments	**Positive:** Improved agricultural practices and cropland expansion increases food provision and/or income. **Negative:** Cash crops are normally highly intensified (mono crops, high need of fertilizer to make the business profitable; see commercial agriculture). Agricultural expansion decreases savanna and other ES.	**Positive:** See water provision in commercial agriculture. **Negative:** See water provision in commercial agriculture.
Bush fires	**(Positive:** Ash contains nutrients for crops but annual bush burning exhausts the soil.) **Negative:** Destruction of forests and crops. Soil erosion if land is bare.	**Positive/negative:** Bare land increases surface-runoff (more surface water, less groundwater; changes in local water availability). **Negative:** Large-scale vegetation changes influence the micro-climate and could reduce moisture.
Changes in religious patterns	**Positive:** - **Negative:** Due to the advent of Christianity and Islam, traditional believes and local knowledge is decreasing. Natural features could be affected, e.g. the appreciation of sacred groves and holy places. Environmental awareness is diminished.	**Positive:** - **Negative:** See food provision.
Commercial agriculture	**Positive:** Increase in crop yields and intensifies land use (less land have to be used for agriculture). **Negative:** Risk of mono-cropping, removal of trees, use of genetically-modified organisms (GMOs) or crop varieties (hybrids) which have to be purchased every year (increases the dependence of farmer on agri-businesses).	**Positive:** Potentially higher water efficiency due to improved agricultural practices. **Negative:** Higher fertilizer and pesticide use would have an effect on water quality, e.g. pollution. Potentially higher water use.
Conservation agriculture	**Positive:** It contributes to sustainable land use, e.g. zaii method, keeping residues as soil cover. **Negative:** Potentially lower yields in comparison to intensified agriculture with high fertilizer input.	**Positive:** Sustainable agricultural methods support water retention. **Negative: -**

Credits by family, bank, government or NGO	**Positive:** Allows the purchase of fertilizer and other agricultural inputs to increase yields**.** **Negative:** Intensification could have effects on the environment (see commercial agriculture and agricultural extensification).	**Positive:** Potentially higher water efficiency and better water access. **Negative:** Potentially higher water demand.
Customary land tenure	**Positive:** Control of the land by the Tendana (earth priest) that not everybody is allowed to expand farms and housing. **Negative:** Communal land as "tragedy of the commons" (overuse and non-responsibility) and land insecurity is not an incentive to invest in land.	**Positive/Negative:** Unknown.
Dry season gardening	**Positive:** Possibility of food supply in dry season. **Negative:** -	**Positive: -** **Negative:** If intensified, it could cause local water shortage.
Fertilizer subsidies	**Positive:** A chance to increase yields. **Negative:** Fertilizer subsidy is ineffective/ not functioning (corruption).	**Positive:** - **Negative:** Too much fertilizer could lead to water pollution (e.g. nitrogen percolation into groundwater).
Financial capital of rural farmers	**Positive:** A higher income could contribute to more and/or improved agricultural inputs to reach higher yields; to buy additional food would reduce land pressure. **Negative:** Poverty contributes to low-input agriculture and exhausted soils.	**Positive:** If income increases: improved water access, also to bottled water, and higher sanitation standards (less water pollution). Potentially higher water efficiency. **Negative:** Potential increase of water demand. Poverty forces farmers to drink from rivers with low water quality.
Governmental laws	**Positive:** Control and legal protection of nature and resources, e.g. laws against bush fires, laws for the protection of riverine forest. **Negative:** Law enforcement/implementation is a general problem in Ghana.	**Positive:** The same as for food provision. **Negative:** The same as for food provision.
Improved crop varieties	**Positive:** Potentially increase yields and reduce risks of crop failure because of drought-adapted plant species and plants with short maturing periods. **Negative:** The impact of hybrids and/or GMOs on human body in the long-term unknown. Negative effects on biodiversity and other ES. Some crop varieties are not tested in long-term and could have other disadvantages, e.g. bland flavor, difficult processing.	**Positive:** Potentially higher water efficiency. **Negative:** Water demand of some new crop varieties are not tested yet. Early maturing varieties will be harvested earlier and leaves land bare, which causes soil erosion.
Improved roads	**Positive**: Complementary or substitutional food provision by delivery could reduce pressure on local food production. **Positive/Negative:** Improved access to remote areas could increase agricultural expansion but increases also the risk of deforestation. **Negative:** Land destruction; the density of roads increase land fragmentation. Higher pollution rates.	**Positive: -** **Negative:** Soil sealing does not allow water infiltration; higher surface runoff.
International funding/ development aid	**Positive:** Funding source of projects for agricultural improvements (see pro/con for commercial agriculture). **Negative:** Depends on the scope of the project if harmful to the environment; e.g. if rather economic development is in the focus.	**Positive:** Potentially improved sanitation (less water pollution), higher water efficiency and better water access. **Negative:** Potentially higher water demand.

Irrigation with dams and rivers	**Positive:** Independent from rainfall, potential yield improvement (with additional fertilizer). **Negative:** Could lead to further agricultural expansion - in the extreme case leads to water scarcity.	**Positive:** - **Negative:** Could cause water scarcity.
Labour shortage	**Positive:** - **Negative:** Missing labour delays the harvest and increases the risk of reduced harvest because of overripe grains.	**Positive:** - **Negative: -**
Level of education	**Positive:** Improved knowledge could increases environmental awareness and allows livelihood diversification. **Negative:** A low level of education does not allow the farmer to change his/her business.	**Positive:** - **Negative: -**
Livestock	**Positive:** The use of manure increases yields if manure is collected. **Negative:** Destruction of crops by livestock; overgrazing in the UER.	**Positive:** - **Negative:** Nitrate infiltration, e.g. if droppings are in the borehole. Reduction in water quality.
Migration	**Positive:** Reduction of land pressure if people leave the UER. **Positive/negative:** Changes in food demand. **Negative:** Demographic change because mainly the youth are migrating**;** missing labor in the UER to work on the crops.	**Positive/negative:** Changes in water demand.
Mining	**Positive: -** **Negative:** Destruction of (agricultural) land and pollution.	**Positive: -** **Negative:** Pollution decreases water quality.
National agricultural programs	**Positive:** Out-grower schemes, fertilizer subsidies and irrigation schemes are a precondition for improvements in yield. **Negative:** Also GMOs, hybrids could be supported, the promotion of agriculture could lead to further agricultural expansion; non-functioning programs due to corruption, missing financial capacities**.**	**Positive:** - **Negative:** Potentially higher water demand due to the promotion of irrigation and agricultural expansion. Higher risk of water pollution due to fertilizer subsidies and pesticides.
Population growth rural	**Positive:** - **Negative:** Intensification of land use, land pressure, destruction of potential agricultural area. Higher food demand.	**Positive:** - **Negative:** Higher water demand.
Population growth urban (urbanization)	**Positive:** - **Negative:** Destruction of potential agricultural area. Higher food demand.	**Positive:** - **Negative:** Soil sealing does not allow water infiltration; higher surface runoff. Higher water demand.
Rainfall variability	**Positive: -** **Negative:** The increase in weather extremes, i.e. floods and droughts, destroy crops.	**Positive/negative:** Changes in potential water provision.
Research	**Positive:** Development of new strategies of sustainable land use practice, and new value chains to increase yield. **Negative:** Could contribute to the promotion of GMOs.	**Positive:** Development of tools for improved water use, water access and water quality. **Negative:** Improved tools could support higher water use.
Rising living standard	**Positive:** Improved and potentially more sustainable agricultural technologies could be applied.	**Positive:** Improved water access, also to bottled water, and higher sanitation standards. Potentially higher water efficiency.

	Negative: Often correlated with urbanization, intensification and increasing food demand.	**Negative:** Potential increase of water demand and water use.
Temperature variability	**Positive:** - **Negative**: Too high or too low temperatures increase the risk of crop failure or reduce yields; higher water demand for high temperatures	**Positive/negative:** Changes in potential water provision.
Topography	**Positive/Negative:** The UER is mainly a flat area. However, the area is prone to soil erosion because of high rainfall intensities. **Negative:** A flat area is exposed to wind erosion without soil cover and increases the likelihood of lower crop yields.	**Positive/Negative:** Changes in local water availability.
Research	**Positive:** Development of new strategies of sustainable land use practice, and new value chains to increase yield. **Negative:** Could contribute to the promotion of GMOs.	**Positive:** Development of tools for improved water use, water access and water quality. **Negative:** Improved tools could also promote more water use.
Service by extension officers	**Positive:** Support for rural farmers, e.g. training programs on sustainable land use practices, could contribute to environmental awareness. **Negative:** Often, human and financial capacities are limited in the UER to provide effective support. In addition, field officers could support the use of GMOs.	**Positive:** Potential promotion of higher water efficiency. **Negative:** Potential promotion of higher water use, e.g. irrigation, agricultural expansion.
Soil type and fertility	**Positive/negative:** Highly vulnerable soils. Lowland and river beds are still fertile but land pressure causes a risk of land degradation. **Negative:** Highly weathered soil type is dominating; thin humus layer have a lower capacity for nutrient storage and they are more prone to soil degradation. Soils with iron pan cannot be used for agriculture.	**Positive: -** **Negative:** Land degradation increases with vulnerable soils.
Use of wood (especially fuel wood)	**Positive:** More direct sunlight for crops. **Negative:** Overuse leads to bare land and soil erosion, reduced availability of fodder for livestock, destruction of forests: loss of micro-climate, loss of higher moisture content, loss of fruits and medicinal plants.	**Positive:** - **Negative:** Less groundwater (changes in local water availability); long-term changes of less water due to changes in micro-climate.
Wind intensity	**Positive: -** **Negative:** High wind intensities could destroy crops.	**Positive: -** **Negative: -**

Table A2: Conditional Probability Tables (CPTs) of the rainy season with its unit and source, including the joint nodes from rainy and dry season (paper III); UER= Upper East Region

Conditional Probability Tables of input nodes		
Node Specification	**Division of unit**	**Source**
Rural population in the UER	800 000 – 830 000 830 000 – 860 000 860 000 – 890 000	GSS (2010)
Rainfall in rainy season in mm	650-750 (low) 750 – 950 950 – 1100 1100 – 1400 (high)	Navrongo 1977-1997 and Bolgatanga weather station 1998-2013 (38 events)
Rainfall intensity in mm/hour	> 20 < 20	Definition from Kowal and Kassam (1978) "all storms of over 20 mm/hour rain produced some run off"; only daily precipitation of the Navrongo and Bolgatanga weather station was available; ≥ 35 mm rainfall per day assumes a high likelihood of an event with ≥ 20mm/h rainfall (relation between high rainfall per rain and high rainfall intensity also described in Yengoh et al. (2010)
Dry spell more than 10 days	Between 1st June to 30th July No	Navrongo 1977-1997 and Bolgatanga weather station 1998-2013; critical time span mentioned by WASCAL agronomists and studies on dry spells effects on crops growth (Barron et al., 2003; Sivakumar, 1992) show that dry spells become harmful to crops when they last more than seven days
Length of rainy season in days	90-120 (short) 121-180 181-220 (long)	Navrongo 1977-1997 and Bolgatanga weather station 1998-2013; agronomic definition: "the rainy season starts after the first of April with a 3-days-cumulative rainfall amount higher than 20 mm and not followed by a dry spell of more than 7 days. The rainy season end of this method is marked by the last rainfall higher than 5 mm/day after the first September with any rainfall higher than 5 mm/day during the twenty following days" (p.1289 in Ibrahim et al., 2012); average length of rainy season: 160 days (FAO, 2005b)
Length of the following rainy season in days	90-120 (short) 121-180 181-220 (long)	The food demand in the next rainy season is dependent on the next length of the rainy season which is uncertain.
Crop Types of the previous year (t0)	Sorghum + millet Maize Legumes Rice	Agro-Maps FAO (2015) data from UER; average values from 2000 to 2011
Used cropland of the previous year (t0) in hectares	300 000 – 350 000 350 000 – 400 000 400 000 – 450 000	Agro-Maps FAO (2015) data from UER from 1997 to 2011 (sweet potato excluded)
Income per household in Cedi per year	<1000 1000 – 2000 > 2000	MOFA (2007): vulnerable group and poor group counted as "<1000"
Soil type	Lixisols + Leptosols Fluvisols Luvisols	GLOWA Volta project; soil map from the UER
Tree and shrub density on fallow in the previous year (t0) in %	No cover < 10 10 – 30 > 30	Remote sensing data from 2013 with ArcGIS 10.1 from WASCAL for the UER

Water type	Hand dug well Borehole River close River far away	32 field officers from the UER
Market demand	Yes No	Scientists stated that there is hardly any crop in the UER which has a good market (only for crops in the dry season) and people have a low purchasing power. Therefore, the prior probability for market demand was assumed to be 1% and 100% as possible scenario.
Agricultural programs	Yes No	Four researchers from Ghana and WASCAL mentioned that there are no functioning agricultural programs. Also here, the probability was taken with 1% and 100% for the possible scenario.
Soil erosion control	Yes (stones bunds) No	33 field officers from the UER
Conditional Probability Tables of intermediate nodes		
Node Specification	**Division of unit**	**Source**
Tropical Livestock Unit (TLU) per household under different income levels	<0.5 0.6-3 3-15	31 field officers from the Upper East Region
TLU per ha	0-0.5 0.5-3	Calculation based on population, household size (5.8 people in UER), cattle per household, surface for grazing of UER: 884200 ha (total) minus 3408 ha surface water bodies (Liebe, 2002) minus 270157 ha urban/bare land (Adanu et al., 2013)= 610 635 ha
Water use per capita per day in liters with different water types	20 – 30 30 – 40 40 – 50	8 researchers from Ghana and WASCAL; on average: 24 liters (Asare, 2004)
Water supply (rainfall) rainy season million m^3	500 – 1000 1000 – 1500 […] 3500 – 4000	Calculation based on runoff coefficient and total rainfall
Yield of crops in kg per ha	0 – 500 500 – 1000 […] 2000 – 2500	Crop model APSIM; modeling with Navrongo 1977-1997 and Bolgatanga weather station 1998-2013 for each crop type; planting dates were taken from Bamler (2016)
Post-harvest loss in %	1 – 7 7 – 16	Egyir et al. (2008) per crop type
Tree and shrub density of fallow change under livestock grazing (t1)	No <10% covered 10-30% covered >30% covered	9 researchers from Ghana and WASCAL
Soil erosion under different tree and shrub density, rainfall intensity and soil erosion control (focus on erosion from water)	No or slight Severe	15 researchers from Ghana and WASCAL
Commercial farming under impact of agricultural programs, market demand and income per household	Yes No	31 field officers from the UER

Inorganic fertilizer per ha in kg under different soil types and agricultural programs	No or max. 5 18 36	36 field officers from the UER
Manure per ha in kg under different soil types and amount of livestock per household	No or max. 10 250 2500	30 field officers from the UER
Cropland change in hectare under previous cropland, population and commercial farming (t1)	250 000 – 300 000 300 000 – 350 000 […] 450 000 – 500 000	17 researchers from Ghana and WASCAL
Crop type change under previous crop type and commercial farming (t1)	Millet and Sorghum Maize Legumes Rice	20 researchers from Ghana and WASCAL
Soil Water Storage Capacity (SWSC) in mm under soil erosion and different soil types	< 20 20-40 40-80	5 researchers from Ghana and WASCAL
Runoff-coefficient under different SWSC and rainfall intensity	0.1 – 0.15 0.16 – 0.3	4 researchers from Ghana and WASCAL; the runoff-coefficient is an indicator with annual time step (also accounts for the dry season)
Cedi per kg	0.5 – 1 1 – 1.5 1.5 – 6	Average monthly market prices for crop types from Bongo Soe market in 2014 in Cedi
Conditional Probability Tables of the output nodes		
Node Specification	**Division of unit**	**Source**
Accessible water end of the rainy season in million m^3	2 – 3 3 – 4 4 – 5 […] 11 and more	Calculation based on water access in % and water in rainy season (rainfall) in million m^3
Demand of water in in million m^3 in the following rainy season	1 – 2 […] 9 – 10	Calculation based on water use per capita per day, population, and length of next rainy season
Demand of food in the following rainy season in billion kcal	100 – 150 […] 400 – 450	Calculation based on population, length of next rainy season, food demand/day/person average: 2118 kcal/capita (FAO Ghana, 2009)
Total food supply end of the rainy season in billion kcal	0 – 100 100 – 150 […] 450 – 500 500 – 800 800 – 1000 1000 – 1500 3000 – 3500	Calculation based on yield per hectare, post-harvest loss, available cropland, and crop type: kcal of boiled crop products (FAO, 2010)
Supply of food from crops in *1000 tones (for economic value)	0 – 100 100 – 150 […] 450 – 500 500 – 800 800 – 1000 1000 – 1500 3000 – 3500	Calculation based on yield per hectare, available cropland and post-harvest loss

Economic value of food from crops in million dollar	0 – 50 50 – 100 100 – 200 200 – 500 500 – 1000 1000 – 1500 […] 3000 – 3700 (max.)	Supply of food from crops in *1000 tones, Cedi per kg, and exchange rate from Cedi to dollar
Demand of vitamin A in the following rainy season in billion mcg	45-70 70-90 90-110 110-130 130-150 150-170	Calculation based on population, length of next rainy season, average vitamin A need: 800 mcg/day (NIH, 2013)
Supply from crops of vitamin A in billion mcg	0 0-1 1-5 5-10 […] 30-40 40-70 70-90	Calculation based on yield kg, crop type, available cropland, vitamin A per crop type if boiled (FAO, 2010)
Water quality	Low Medium High	Dependent on water type; Asare (2004)
Joint nodes of rainy and dry season		
Node Specification	**Division of unit**	**Source**
Vitamin A balance of the following rainy season in billion mcg	0 0-1 1-5 5-10 10-20 20-30 30-40	Calculation based on supply of vitamin A end of the dry season, the supply of vitamin A end of the rainy season and the demand of vitamin A in the dry season (opposed to the vitamin A demand in the rainy season)
Food balance of the following rainy season in billion kcal	-500 to -200 -200-0 0-150 150-200 […] 800-1000 1000-1500 […] 3000-3500	Calculation based on the total food supply end of the rainy season, the food supply end of the dry season
Water balance of the following rainy season in million m^3	1 and less 1 – 2 […] 10 and more	Calculation based on accessible water end of the rainy season in million m^3 and use of people in dry season in million m^3
Available reservoir water end of rainy season (for irrigation in the dry season) in million m^3	100 – 140 140 – 180 180 – 200 and more	Calculation based on reservoir storage capacity and potential water from rainfall

Table A3: Conditional Probability Tables (CPTs) of the dry season with its unit and source

Conditional Probability Tables of input nodes		
Node specification dry season BBN	**Division of unit**	**Source**
Rural Population in the UER	700 000 – 730 000 730 000 – 760 000 760 000 – 790 000	Ghana Statistical Service (2010) and Van der Geest et al. (2010): up to 100 000 people are migrating in dry season
Water type	Hand dug well Borehole River close River far away	32 field officers from the UER
Water access (used water potential)	0.5 – 1 1 – 2	One scientist; with annual time step (also accounts for the rainy season)
Irrigation efficiency in %	15 – 30 30 – 50	Ofosu (2011)
Crop types t0	Rice Vegetables	GIDA-MOFA (2008)
Length of dry season	245 – 285 185 – 244 145 – 184	Coordinated with the length of the rainy season
Income per household in Cedi	1000 – 2000 > 2000	MOFA (2007): vulnerable group counted to poor; poor excluded because they do not cultivate crops in the dry season
Reservoir storage capacity in million m^3	100-140 (lower) 140-180 180-200 (higher)	Total storage capacity of 185 million m^3 (Liebe, 2002); all water reservoirs in the UER counted together
Conditional Probability Tables of interim nodes		
Node specification dry season BBN	**Division of unit**	**Source**
Inorganic fertilizer (NPK) in kg per ha	No or max. 5 kg 18 36	36 field officers from the Upper East Region
Manure in kg per ha	No 250 2500	30 field officers from the Upper East Region
Post-harvest loss in %	1 – 10 10 – 25	Egyir et al. (2008) per crop type
Water sufficiency	Yes No	Calculation based on irrigated area, crop type (ET), available reservoir water, irrigation efficiency; 10 million m3 water taken as threshold (as minimum water) in the reservoir because if there is only low water table there is sedimentation and low water supply for irrigation
Water use per capita per day in liters with different water types	20 – 30 30 – 40 40 – 50	8 researchers from Ghana and WASCAL; on average: 22.7 liters (Asare, 2004)
Tropical Livestock Unit (TLU) per household	Max. 0.5 0.5 – 3 3 – 15	31 field officers from the Upper East Region

Irrigated cropland change in hectare under previous cropland, population and dam storage capacity (t1)	1000 – 1500 1500 – 2000 2000 – 2500	Tono: 245 ha used, Vea: 468 ha used = 713 ha used plus 895 ha from small dams = 1608 ha in total (GIDA-MOFA 2008); 8 researchers from Ghana and WASCAL
Irrigated crop type change under previous irrigated crop type and available irrigate cropland (t1)	Rice Vegetables	15 researchers from Ghana and WASCAL
Inorganic fertilizer per ha in kg under different soil types and agricultural programs	No or max. 5 18 36	36 field officers from the UER
Manure per ha in kg under different soil types and amount of livestock per HH	No or max. 10 250 2500	30 field officers from the UER
Yield per ha in tons	0 – 1 1 – 2 2 – 3 4 – 5 6 – 7 7 – 10 10 – 15 15 – 20	Rice modeling: APSIM; Vegetables modeling: DSSAT; Planting dates: Bamler (2016); applications and management from MOFA (2011)
Evapotranspiration in mm per crop type in the cropping period (if water from reservoir is sufficient)	350 – 500 500 – 650 650 – 800	Based on water needs of crop types (FAO, 1986)
Cedi per kg	0.5 – 1.5 1.5 – 2.5 2.5 – 3.5	Average monthly market prices for crop types from Bongo Soe market in 2014 in Cedi
Supply of food from crops in *1000 tones (for economic value)	0 – 5 5 – 10 10 – 15 […] 35 – 40	Calculation based on yield per hectare, irrigated cropland and post-harvest loss
Conditional Probability Tables of output nodes		
Node specification dry season BBN	**Division of unit**	**Source**
Demand of food dry season in billion kcal	150 – 200 200 –250 250 –300 300 –350 350 –400 400 –450	Population, length of dry season, and food demand/day/person average (calculated with 2000 kcal/capita)
Supply of food in dry season in billion kcal	0 – 5 5 – 10 10 – 30 30 – 65	Yield per hectare, post-harvest loss, available irrigated cropland, and crop type: kcal of boiled crop products (FAO, 2010)
Demand of vitamin A in billion mcg	70 – 90 90 – 110 110 – 130 130 – 150 150 – 170	Population, length of rainy season, average vitamin A need: 800 mcg/day (NIH, 2013)

Supply of vitamin A in billion mcg	0 0 – 1 1 – 5 5 – 10 10 – 20 20 – 30 30 – 40	Yield tons per ha, crop type, irrigated cropland, post-harvest loss; vitamin A content of different crop types (FAO, 2010)
Demand of water in in million m^3 in the dry season	2 – 3 […] 10 – 11	Calculation based on water use per capita per day, population, and length of dry season
Water quality	Low Medium High	Dependent on water type; Asare (2004)
Economic value of food from crops in million dollar	0 – 1 1 – 5 5 – 10 […] 30 – 35	Supply of food from crops in *1000 tones, Cedi per kg, and exchange rate from Cedi to dollar

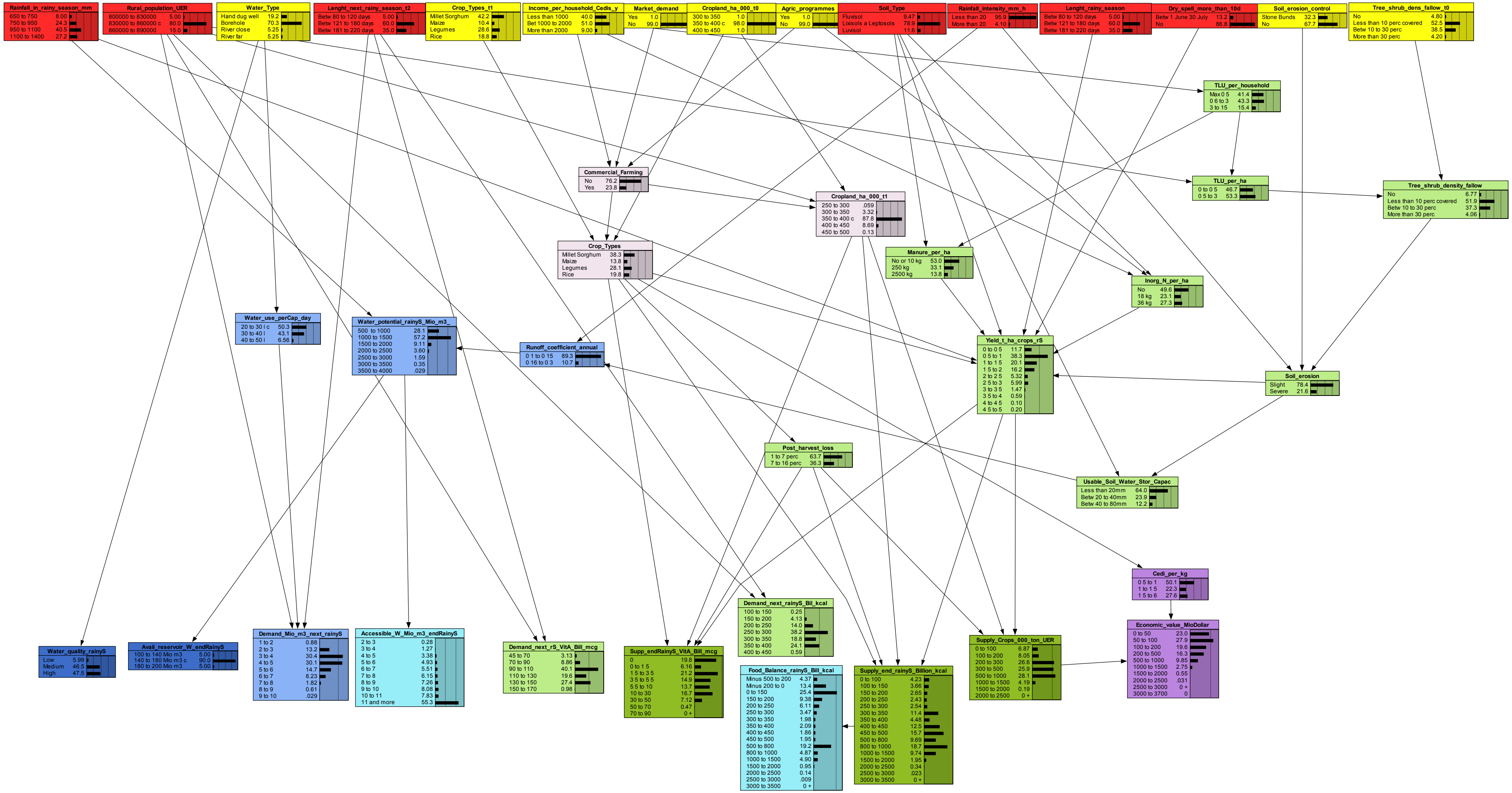

Figure A1: Rainy season-part of the BBN including the joint nodes

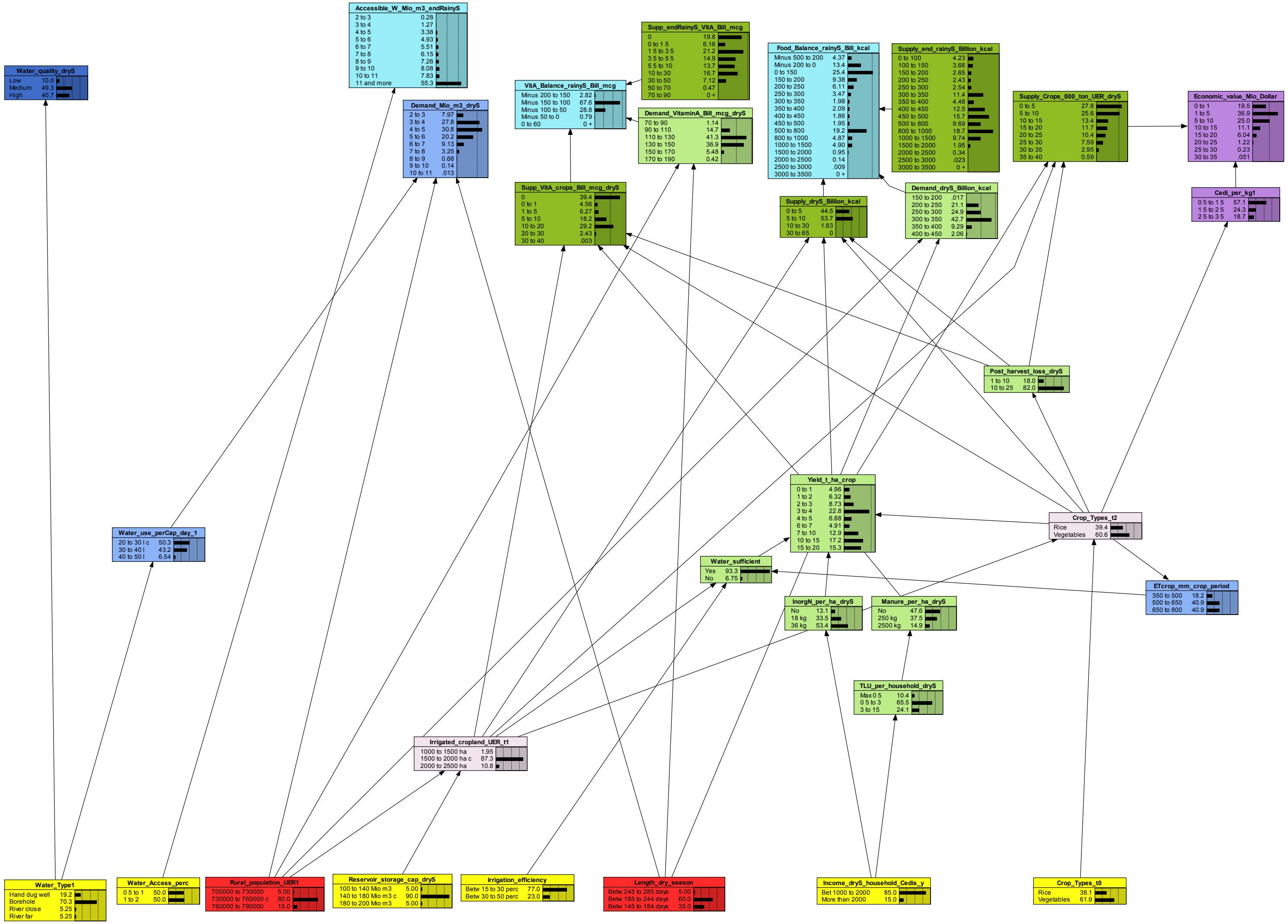

Figure A2: Dry season-part of the BBN including the joint nodes

ANNEX B: PUBLICATIONS

Kleemann, J., Inkoom, J.N., Thiel, M., Shankar, S., Lautenbach, S., and Fürst, C. (2017) Peri-urban land use pattern and its relation to land use planning in Ghana, West Africa. Landscape and Urban Planning, 165:280-294. http://dx.doi.org/10.1016/j.landurbplan.2017.02.004

Kleemann*, J., Baysal, G., Bulley, H.N.N., and Fürst, C. (2017) Assessing driving forces of land use and land cover change by a mixed-method approach in north-eastern Ghana, West Africa. Environmental Management, 196:411-442. http://dx.doi.org/10.1016/j.jenvman.2017.01.053

Kleemann*, J., Celio, E., Nyarko, B., Jimenez-Martinez, M., and Fürst, C. (2017) Assessing the risk of seasonal food insecurity with an expert-based Bayesian Belief Network approach in northern Ghana, West Africa. Ecological Complexity, 32:53-73. http://dx.doi.org/10.1016/j.ecocom.2017.09.002

Kleemann*, J., Celio, E., and Fürst, C. (2017) Validation approaches of an expert-based Bayesian Belief Network in northern Ghana, West Africa. Ecological Modelling, 365:10-29. https://doi.org/10.1016/j.ecolmodel.2017.09.018

Additional publications:

Callo-Concha, D., Sommer, J.H., **Kleemann**, J., Gatzweiler, F.W. and Denich, M. (2014) Marginality from a Socio-ecological Perspective. In: von Braun, J. and F. W. Gatzweiler (eds.) Marginality - Addressing the Nexus of Poverty, Exclusion and Ecology. Springer, pp. 57-65.

Opdam, P., Albert, C., Fürst, C., Grêt-Regamey, A., **Kleemann**, J., Parker, D., La Rosa, D., Schmidt, K., Villamor, G.B., and Walz, A. (2015) Ecosystem services for connecting actors – lessons from a symposium. Change and Adaptation in Socio-Ecological Systems, 2:1-7.

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Kleemann, J., Baysal, G., Bulley, H.N.N., and Fürst, C. (2017) Assessing driving forces of land use and land cover change by a mixed-method approach in north-eastern Ghana, West Africa. Environmental Management, 196:411-442. http://dx.doi.org/10.1016/j.jenvman.2017.01.053

Abstract
Land use and land cover change (LULCC) is the result of complex human-environmental interactions. The high interdependencies in social-ecological systems make it difficult to identify the main drivers. However, knowledge of key drivers of LULCC, including indirect (underlying) drivers which cannot be easily determined by spatial or economic analyses, is essential for land use planning and especially important in developing countries. We used a mixed-method approach in order to detect drivers of LULCC in the Upper East Region of northern Ghana by different qualitative and quantitative methods which were compared in a confidence level analysis. Viewpoints from experts help to answer *why* the land use is changing, since many triggering effects, especially non-spatial and indirect drivers of LULCC, are not measurable by other methodological approaches. Geo-statistical or economic analyses add to validate the relevance of the expert-based results. First, we conducted in-depth interviews and developed a list of 34 direct and indirect drivers of LULCC. Subsequently, a group of experts was asked in a questionnaire to select the most important drivers by using a Likert scale. This information was complemented by remote sensing analysis. Finally, the driver analysis was compared to information from literature. Based on these analyses there is a very high confidence that population growth, especially in rural areas, is a major driver of LULCC. Further, current farming practice, bush fires, livestock, the road network and climate variability were the main direct drivers while the financial capital of farmers and customary norms regarding land tenure were listed as important indirect drivers with high confidence. Many of these driving forces, such as labour scarcity and migration, are furthermore interdependent. Governmental laws, credits, the service by extension officers, conservational agriculture and foreign agricultural medium-scale investments are currently not driving land use changes. We conclude that the mixed-method approach improves the confidence of findings and the selection of most important drivers for modelling LULCC, especially in developing countries.

Highlights

- A combined qualitative and quantitative analysis for assessing drivers of LULCC
- Rural population growth is with very high confidence the main driver of LULCC
- Technological and political parameters are currently not driving LULCC
- The confidence table is a useful tool to compare results of a mixed-method approach

Key words: Land degradation, population pressure, remote sensing, expert interviews, agriculture, Upper East Region

Kleemann, J., Celio, E., Nyarko, B., Jimenez-Martinez, M., and Fürst, C. (2017) Assessing the risk of seasonal food insecurity with an expert-based Bayesian Belief Network approach in northern Ghana, West Africa. Ecological Complexity, 32:53-73. http://dx.doi.org/10.1016/j.ecocom.2017.09.002

Abstract

Food insecurity is still a major global concern. Population growth, poverty, climate variability, and low agricultural productivity, among others, are threatening food provision. Rural areas in West Africa are particularly vulnerable due to low financial and physical capacity and high dependency on agriculture. Programs to support food provision exist, but their effects bear uncertainties under different weather and land use scenarios. Our study focuses on the regional assessment of food provision in the Upper East Region in northern Ghana under land use changes and different weather scenarios by using a Bayesian Belief Network. Especially in the beginning of the rainy season, there is a high risk of food insecurity. Therefore, seasonality needs to be considered in a modeling approach. In addition, we estimated the Vitamin A supply indicating the risk of malnutrition. Improving agricultural programs, increasing income by off-farm activities, reducing post-harvest loss, reducing soil erosion, expanding irrigated areas in the dry season and increasing market demand were assessed in order to support food security. The Bayesian Belief Network specifically handles uncertainty and different data types and allows the visualization of complex socio-ecological interactions to communicate to different expert groups, mainly scientists and field officers. A combination of literature, calculations and expert knowledge was required to fill the knowledge gaps in the West African context. About 95 experts were involved in the Bayesian Belief Network development process. An important finding was that an increase in household income, for example by off-farm income, might be better support for people than agricultural programs for providing a contribution to food security under weather uncertainty, provided that income is partly spent on fertilizer. The same is true under increasing population and decreasing total cropland. The likelihood of food provision in the following rainy season was 15% to 55% lower than in the dry season. In addition, the vitamin A provision was far below the demand in all scenarios.

Keywords: Climate variability, driving forces, expert interviews, participatory approaches, population growth

Highlights

- A Bayesian Belief Network (BBN) considering the seasonal dimension.
- We combined scenarios of weather and land use with measures of food security.
- Scenarios with high rainfall showed higher risk of food insecurity than those with low rainfall.
- Increasing income could be a better contribution to food security than agricultural programs.
- The vitamin A provision was far below the demand in all scenarios.

Kleemann, J., Celio, E., and Fürst, C. (2017) Validation approaches of an expert-based Bayesian Belief Network in northern Ghana, West Africa. Ecological Modelling, 365:10-29.
https://doi.org/10.1016/j.ecolmodel.2017.09.018

Abstract
Model validation is a precondition for credibility and acceptance of a model. However, it appears that there is no scientific standard for validation of Bayesian Belief Networks (BBNs). In this paper, we present a novel combination of BBN validation approaches. A set of qualitative and quantitative validation approaches for the BBN structure, the Conditional Probability Tables and the BBN output is presented and discussed. The validation approaches were tested for a BBN on food provision under land use and land cover changes and different weather scenarios in rural northern Ghana. Experts played an important role in developing and validating the BBN due to data scarcity. Furthermore, selected nodes and the BBN output were compared to existing data. A sensitivity analysis was conducted. Validation approaches show that structural model uncertainties are still high and reliability of input data is low. However, the extreme-condition test shows that the BBN works according to the assumed system understanding that food provision decreases under floods, droughts, land pressure and poverty. Therefore, the BBN can provide general trends for output nodes but lacks reliability if detailed results of single system components are required.

Key words: Conditional probabilities, expert knowledge, extreme-condition test, uncertainty, predictive power, sensitivity analysis

Highlights

- A novel combination of validation approaches for Bayesian Belief Networks (BBNs).
- A mixture of qualitative and quantitative validation approaches enhances the understanding of model uncertainties.
- Validation approaches showed that structural model uncertainties are still high.

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Peri-urban land use pattern and its relation to land use planning in Ghana, West Africa

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HIGHLIGHTS

- Patterns of peri-urban development differ between northern and southern Ghana.
- Population growth is an important driver of urban development in both study areas.
- Land inheritance contributes to urban sprawl in Bolgatanga.
- The oil boom increases competition for land use in Takoradi.
- Land tenure and lacking law enforcement challenge land use planning in both areas.

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ABSTRACT

Population growth, economic development, and rural migration to urban areas have caused rapid expansion of urban centres in Ghana. One reason is that spatial planning and in particular urban planning face different social, economic and political challenges which hinder a structured and planned urban development, therefore causing urban sprawl. We hypothesise that different peri-urban patterns are driven by geographical, historical, cultural and economic discrepancies between southern and northern Ghana, and reflect the effectiveness of land use planning instruments. We tested our hypothesis by comparing patterns of urban development in two case study regions: Takoradi in southern Ghana and Bolgatanga in northern Ghana, representing an economically vibrant and a non-vibrant region, respectively. This paper provides new insights for the study sites based on a mixed-method approach. We applied an interdisciplinary approach combining expert interviews, a literature review, and a bi-temporal change analysis based on remote sensing/geo-information systems. We assigned confidence levels of the findings from the respective methods based on their plausibility and sensitivity. Expert opinion indicated that land use planning fails due to the lack of implementation of legal regulations, to the customary land tenure and lack of participation of local citizens in the planning process. The remote sensing analysis revealed that urban development was stronger in Takoradi (7.1% increase between 2007 and 2013) than in Bolgatanga (1.1% increase between 2007 and 2013). Urban development patterns differ with a dominance of small-scale scattered settlement units (SUs) in Bolgatanga and a mixture of small- and large-scale SUs

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in Takoradi. Besides population growth, markets and industry are identified as major drivers of urban development in the Takoradi area (large SUs) and customary land tenure in the Bolgatanga area (small SUs).

1. Introduction

Worldwide, urban sprawl is one of the key drivers of unsustainable development (Camagni, Gibelli, & Rigamonti, 2002; Jabareen, 2006; Næss, 2001). Its negative impacts are particularly visible and crucial in developing countries such as the West African countries, where unplanned land use change obstructs sustainable management efforts (Anderson, Okereke, Rudd, & Parnell, 2013; Buhaug & Urdal, 2013). Some of the current migration from Africa to Europe and across the world could be better managed by a comprehensive development of urban areas, particularly in the poor countries in West Africa (Bakewell, 2008; ESPON, 2015; Hummel & Liehr, 2015).

Urban population in West Africa is particularly fast growing in the coastal areas (Hitimana, Allen, Heinrigs, & Tremolières, 2011). During colonial times, commercial activities concentrated strategically along the sea coast (Kuper, 1965). In the 1960s and 70s, after the colonial rule, new bureaucracies, infrastructure, and companies provided employment in coastal urban centres. This led to rapid immigration to urban areas in Anglophone Africa (Okpala, 2009), which became attractive because of the opportunities to reduce dependency on agriculture and diversify household income. Other factors were improved social care and/or escape from armed conflicts (AfDB, 2005). Today, changing lifestyles and globalisation effects (e.g. land grabbing) push urban development forward (Cohen, 2006). Additional reasons for informal processes of urban development in Anglophone West Africa are governments' low levels of financial capacity, ineffective administrative systems, poor governance, mismanagement of resources, and corruption (Okpala, 2009).

Ghana can be seen as an example for trends in urban development in Anglophone West Africa (Otoo, Whyatt, & Ite, 2006). Population densities along the coastline, but also in traditional inland trading centres such as Tamale and Kumasi, grew considerably during colonial times and through European investments. Between 1960 and 1984, Ghana's population doubled (12.3 million in 1984; GSS, 1989) with an annual growth rate of 2.7%. For urban areas, migration from rural areas remained the main source of growth (Frazier, 1961; Liebenow, 1986), resulting in an annual growth rate of 4.7%. This led to a strong increase in the urban population, which reached 50.9% of the total population in 2012 (GSS, 2012). This population growth was higher than the growth of the total West African population, which increased by about 40% between 1960 and 1980. The share of urban population is also higher in Ghana than in West Africa, where in 2010 about 42% of the West African population lived in urban areas (OECD, 2015). This higher population pressure in Ghana has led to extreme pressure on natural resources. For example, between 1975 and 2000, urban expansion in Ghana triggered deforestation processes resulting in a more than 22% loss in forest area (USGS, 2013). Land use planning is key to meeting increasing demands for human needs and at the same time maintaining the natural environment.

Regional development in Ghana is spatially heterogeneous with a clear distinction between the northern and the southern part of the country. The coastal region in southern Ghana has long been the focus of national investments for economy and trading (Bukari, Aabeyir, & Basommi, 2014; Plange, 1979). In addition to the ports, the area is rich in natural resources such as minerals, oil and timber, which are the main drivers of Ghana's economic development (Alfsen, Bye, Glomsrod, & Wiig, 1997). Northern Ghana used to be seen mainly as a source of labour for the export-oriented sectors of mining and cocoa in the south (Plange, 1979). At the end of the 1950s, the north lagged behind the south in terms of economy, sanitation, level of education, and general infrastructure. However, Ghana is struggling to develop the north, where about half of the population lives in extreme poverty (MDG Ghana, 2012). The three northern regions are the regions with the highest share of people living in poverty (GSS, 2014a). In the Upper East Region, 44.4% (2013) of the people live in poverty, and 20.9% in the Western Region (absolute poverty line: US$1.83 per day, GSS 2014).

1.1. Historical background of land use planning in Ghana

Like in most of the Anglophone West African countries, urban land use planning in Ghana is oriented on British town planning legislation. The British Town and Country Planning Act of 1947 specified procedures for controlling urban sprawl, for example, by seeking permission from the local council, and by slum clearance (Okpala, 2009; UK Parliament, 2016). All areas of the country were requested to have a development plan. During independence, informal urban sprawl increased considerably, and public hygiene as well as environmental quality declined. Before 1993, urban citizens were not informed about compulsory land acquisition for water, electricity, roads and other land use priorities by the centralised Town and Country Planning Department. This led to the displacement of affected citizens and to increasing poverty (Kasanga & Kotey, 2001). Between 1992 and 1994, Ghana restructured its urban and land use planning system into a decentralised form where more political, planning and administrative power was transferred to the district level in order to facilitate an increase in exchange between governmental and public concerns. The district assemblies have legislative, executive and deliberative powers. For example, they have the right to change local taxes and laws, and to implement projects on improving rural incomes and general welfare (Botchie, 2000). Expectations with respect to local participation, acceptance, and effective use and management of local resources have been high, even though participation is still limited to public consultation (Okpala, 2009).

The declared goal to become a middle-income country by 2020 has accelerated ambitious land use plans and development in Ghana (NDPC, 1995). Ghana has improved public infrastructure such as schools, hospitals and roads in the country (Kasanga & Kotey, 2001). The Land Administration Project from 2003 to 2010 pushed land use planning in Ghana forward (TCPD, 2014). The project aimed to provide spatial solutions for reaching defined social, economic and environmental policies while considering the spatial impact from any form of development. Information pertaining to land, such as location, size, improvements, ownership and value, was documented. The project identified people who were interested in land as real estate, and collected information concerning the type and duration of land use and owner rights (Karikari, 2006). A change in land use planning could be triggered by the Land Use and Spatial Planning Bill, which was ratified in July 2016 and aims at harmonising existing land use laws, construction laws and regulations, while lending more power to the Town and Country

Planning Department in order to ensure conformity and compliance with spatial plans and planning standards at the national, regional and district levels (Parliament of Ghana, 2016).

The northern and southern parts of Ghana differ in their customary land tenure system. In the Upper West and Upper East Region, the allodial titleholder is the Tendamba. The Tendamba is like an earth priest, and is a descendant of the early settlers of the villages (Kotey, 1993). He has a moral role, for example, in land dispute resolution, annual sacrifices for peace and prosperity, sanctions for violations, and allocation of vacant land to "strangers" (Kasanga & Kotey, 2001). In addition, local chiefs control the traditional land and give the plots to titleholders in order to administer an area (Tonah, 2005). Growing population pressure and commercialisation of land in the north led to conflicts between the Tendamba and local chiefs claiming allodial land titles (Kotey, 1993). Historically, southern Ghana has always been more densely populated than northern Ghana. Local institutions are therefore more experienced with respect to land agreements, particularly land rents for people outside the community.

About 78% of the land in Ghana is under customary land ownership (Kasanga & Kotey, 2001). However, in urban areas, statutory tenure predominates and, particularly in the centres of big cities such as Accra and Kumasi, settlement development is better controlled (Kasanga & Kotey, 2001; Konadu-Agyemang, 1991). However, in peri-urban areas, where land tenure is in transition to customary land tenure, user rights are not clearly defined and cause conflicts. Problems arise from undocumented informal agreements under the customary land tenure system. The majority of owned land is not formally registered, leading to existence insecurity (Twerefou, Osei-Assibey, & Agyire- Tettey, 2011). Formal registration processes are part of the national framework of land use planning. However, statutory land entitlement demands the registration of only one person, which is in most cases the group leader, e.g. family head, and decisions are taken without consulting the other group members (Kasanga & Kotey, 2001). Kasanga & Kotey (2001) pronounced the statutory and customary land tenure system "on collision course" even though customary land tenure is legally acknowledged by statutory land tenure (in reference to Article 36(8) of the 1992 Constitution). Statutory land tenure is characterised by written and registered records of land entitlement and, therefore, should promote investments in land property. Furthermore, it should contribute to the public good or national interest (Kasanga & Kotey, 2001). However, the statutory system is often perceived by the local population as part of the colonial heritage (Deininger, 2003) imposed from top-down. For example, in 1897, the government tried to enforce a regulation through the Lands Bill that all unoccupied land in the Crown belonged to the government. This led to strong resistance from the land chiefs. Land ownership and land use are still a sensitive issue in Ghana (Konadu-Agyemang, 1991), and for this reason the government refuses to nationalise land. A detailed description of land use planning in Ghana is provided in Annex A.

1.2. Monitoring and modelling urban development – a plea for an interdisciplinary perspective

Patterns and processes of urban development can be best observed in the peri-urban fringe where urban land uses are in transition to rural land uses and where dynamics between urban and other land uses are most visible (Tacoli, 1998). We refer to "urban development" as a spatial expansion of urban area in the periphery. We use the term "urban sprawl" to describe a special type of urban development where the development occurs scattered and uneven on new (non-urban) lots, leading to inefficient resource utilisation, i.e. land fragmentation (Camagni, Gibelli, & Rigamonti, 2002). Often, urban sprawl indicates poorly planned and poorly managed urban growth (Siedentop & Fina, 2012). Development is patchy, scattered, and with a tendency towards discontinuity (EEA, 2006). Especially in developing countries, urban sprawl occurs as a result of illegal house construction not conforming to land use planning.

Extreme uncertainties exist with respect to the assessment of complex real life problems related to urban development, such as land use conflicts, which requires the collaboration of multiple disciplines (Brewer, 1995; Miller, 1985; Rolen, 1996). Single disciplines comprise deep but fragmented knowledge (Stern, 1986). Spatial patterns and dynamics of urban sprawl over time can be analysed, for example, based on multi-temporal remote sensing data (Bhatta, 2010; Brinkmann, Schumacher, Dittrich, Kadaore, & Buerkert, 2012; Griffiths, Hostert, Gruebner, & Van Der, 2010; Oloukoi, Oyinloye, & Yadjemi, 2014; Tewolde & Cabral, 2011), but the underlying determinants of these patterns would require an understanding of the political, administrative and social driving forces (Lambin & Geist, 2006). From our perspective, such analysis is best done in an interdisciplinary framework.

The objective of the presented study is twofold. We provide new insights for a specific study site and test the applicability of a transparent framework to compare and contrast information from different scientific disciplines in a mixed-method approach. We hypothesise that regional and cultural differences together with different land tenure systems and economic settings in southern and northern Ghana have led to different patterns of urban development. We expect that urban development takes place faster but in a more regulated way in southern Ghana than in northern. We hypothesise that urban development in northern Ghana is more fragmented and on a small scale due to less supervision by land use planners and to the tenure system practised there. Furthermore, we provide insights into how the national land use planning framework is approached in practice under different spatial contexts. And finally, we prove that our mixed-method approach is applicable for land use planning research in West Africa despite some challenges.

We selected Takoradi as a representative urban area for the south of Ghana and Bolgatanga representing an urban area in the north of Ghana. Both study areas are experiencing urban growth, but this differs in drivers and patterns. This study is important because it shows the inherent challenges in the blueprint implementation of the existing land use planning laws in Ghana. The study also demonstrates the relative importance of considering regional differences in the implementation of these laws. The drivers, character and consequences of urban expansion in Ghana are still poorly understood (Doan & Oduro, 2012), and according to our knowledge, there is no study that compares urban development between the northern and southern part of Ghana with a comprehensive approach comparing a literature review with remote sensing data and expert interviews. For example, Poku-Boansi & Amoako (2015) compared spatial inequalities of cities within Ghana, including Takoradi and Bolgatanga, using statistics (secondary data) without consulting experts or comparing urban development with the aid of remote sensing data.

The specific research questions are:

- What are the patterns of peri-urban development and differences between northern and southern Ghana, using Bolgatanga as an example for the north and Takoradi as an example for the south?
- What are the determinants of urban development for both study areas?
- Which conclusions can be drawn for land use planning? What are the current opportunities and challenges of land use planning and how can they be linked to urban sprawl?
- What are the (dis-)advantages of a mixed method approach to analyse peri-urban land use patterns?

The analysis of the dynamics of urban and peri-urban areas from a social science perspective introduces reasoning of human behaviour and provides a background of historical, cultural and social development (e.g. Beauchemin & Bocquier, 2004; Gough & Yankson, 2000; Oteng-Ababio & Agyemang, 2012). In-depth interviews provide qualitative data where, for example, the value and management of different land use types can be identified. But studies focusing solely on interviews often lack an understanding of interdependencies between human behaviour and spatial configuration, such as the effect of the distance to roads, irrigation systems, markets or the suitability of a location for house construction. Consequently, a link between remote sensing observations and human behaviour is needed to understand the complexity of human-environment interactions (Campbell, Lusch, Smucker, & Wangui, 2005; Liverman & Cuesta, 2009; Rindfuss & Stern, 1998). Today, census and household data are often combined with remote sensing to analyse patterns of land use change (Cardille & Foley, 2003; Doan & Oduro, 2012; Martinuzzi, Gould, & Gonzalez, 2007). The combination of in-depth interviews and remote sensing is uncommon, because the integration of qualitative and quantitative data is still challenging (Gobin, Campling, Deckers, & Feyen, 2001; Haregeweyn, Fikadu, Tsunekawa, Tsubo, & Meshesha, 2012; Rindfuss et al., 2003a, 2003b). We advocate a mixed analysis using remote sensing, expert interviews and a literature review, and contrast the information in a confidence table.

2. Study areas and methods

2.1. Study areas: Takoradi (in the south) and Bolgatanga (in the north)

We selected Takoradi and Bolgatanga as representatives of urban areas in the south and north, respectively, because they are characterised as having similar urban populations with similar population pressure, but they differ in their past economic and political relevance. Takoradi is part of the twin city Sekondi-Takoradi (merged in 1946) with roughly 170,000 inhabitants. The city is located in the coastal zone of the Atlantic Ocean (see Fig. 1) within the formal rainforest zone in the south of Ghana. Recognised by the state as a highly prioritised area for fast development and growth, it was the first region in Ghana selected for the regional spatial development framework in 2012 to officially coordinate multiple spatial demands and to regulate the trade-offs of urban development (TCPD, 2012). The beneficial strategic location close to the Atlantic Ocean as a connection to the international market and the discovery of off-shore oil have drawn attention to Sekondi-Takoradi at the national level. The city has been declared as a free trade zone and an industrial core region in order to attract foreign investment, thus aiming to accelerate the rate of economic growth and pushing Ghana's decentralisation (Ghana Free Zones Board, 1997). Rural communities surrounding the urban area are characterised by agriculture and fisheries along the coast.

Bolgatanga, with 66,000 inhabitants, is the capital of the Upper East Region, and is located close to the border to Burkina Faso and Togo (GSS, 2012). It lies in the Guinea Savannah Zone in transition to the Sudanian Savannah Zone, which is characterised by mosaics of trees, open grassland and crops on a relatively flat terrain (Fig. 3). The main source of income in this region is small-scale subsistence farming of maize, sorghum, and millet intercropped with groundnuts or beans on compound and bush farms (Birner, Schiffer, Asante, Gyasi, & McCarthy, 2005) as well as small-scale gold mining. The income of the urban population is based on petty trading, house rents or indirectly on agriculture where labour is paid for livestock rearing and commercial farming outside the city. The contribution of the region to the country's gross domestic product is much lower compared to Sekondi-Takoradi (GSS, 2012). The region is experiencing high population pressure with a population density of 118 people/km^2, which is higher than the national average of 103 people/km^2 (GSS, 2013). One reason for the high population density is the high fertility rate of 4.7 children per woman. In addition, there is immigration from other districts and Burkina Faso coming to Bolgatanga for trading and to escape from conflict regions, e.g. Bawku (Ampofo, Kumi, & Ampadu, 2015). The share of urban population in the region increased from 3.9% in 1960 to 21% in 2010 (GSS, 2014a) due to infrastructural development since 1990 (e.g. schools, hospitals and electricity), especially in Bolgatanga (Bolgatanga District Assembly, 2002). The high population pressure has resulted in land fragmentation and land degradation. An overview of the two regions is provided in Table 1.

The spatial extent of the remote sensing analysis needed to focus on subsets of the region due to the processing effort for delineating small-scale buildings as a proxy-indicator for informal urban sprawl. We therefore focused the remote sensing analysis on areas with particularly fast urban development in 2007 – 2012. For the focus area in the north, we chose an area towards Bongo, which is the closest settlement to Bolgatanga – settlement structures expand towards Bongo along the road. Bolgatanga itself is situated in a region with nearly no geographical constraints such as mountains or large waterbodies. Therefore, urban development in Bolgatanga can potentially spread in all directions. Sekondi-Takoradi shows a different environmental configuration. Due to its location along the Atlantic coast, the urbanised zone is located in the south and east of the city (Fig. 1). Thus, settlement development occurs mainly to the north and west. In this study, the area to the west of Takoradi in closest proximity to Agona was chosen as the focus region for the remote sensing analysis.

2.2. Methods

Our analyses considered patterns of urban development, and driving forces of urban development as well as opportunities and challenges of urban and peri-urban land use planning. Patterns of urban development are the spatial and temporal traces of urban development (Lasuén, 1973), for example land fragmentation and settlement configuration. We combined three different methodological approaches: expert interviews, remote sensing/GIS and literature review. We started our analysis with expert interviews to assess perceived patterns and drivers of urban development in the study areas. In addition, experts were interviewed about strengths and weaknesses of land use planning, since informal rules in addition to formal regulations were expected to shape the land use pattern (Fig. 2). This was followed by a remote sensing analysis to validate how reliable these perceived patterns and drivers were, using the number, size, and density of scattered buildings. This analysis was used as a proxy indicator for informal urban development. A literature review was performed before the field work to get an idea of the topic, but in a reduced way in order to remain unbiased for the interviews. An extensive literature review on district and local levels was carried out complementarily to the remote sensing analysis in order to validate the findings. Based on the consistency of the results of the three methods, we assigned confidence levels (Table 6a and 6b).

Urban sprawl is difficult to detect without comparing spatial land use plans with existing urban housing. We can identify urban sprawl through the use of different methods with the following characteristics: a land use and land cover change with low but scattered building density, uneven building sizes, mixed land uses, and their negative effect on the environment and people (Chin, 2002). "Bolgatanga area" refers to the city of Bolgatanga and its surrounding area including Bongo, while "Takoradi area" refers to the city of

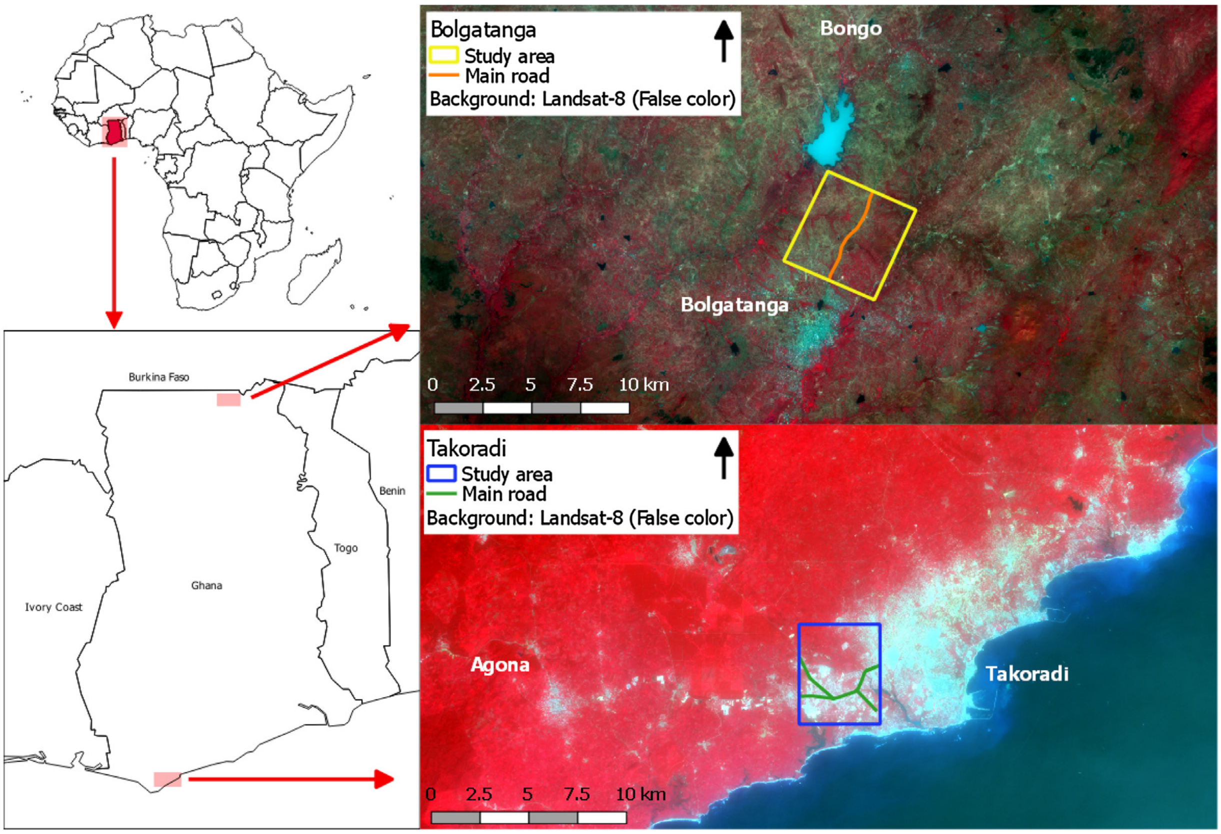

Fig. 1. Location of the study areas in Ghana, West Africa. National and administrative boundaries from OpenStreetMap (http://www.openstreetmap.org). Right maps: location of the northern study area: Bolgatanga towards Bongo; location of the southern study area: Takoradi towards Agona. The 5 km × 5 km focus areas were selected for the remote sensing analysis (see Section 2.2.2).

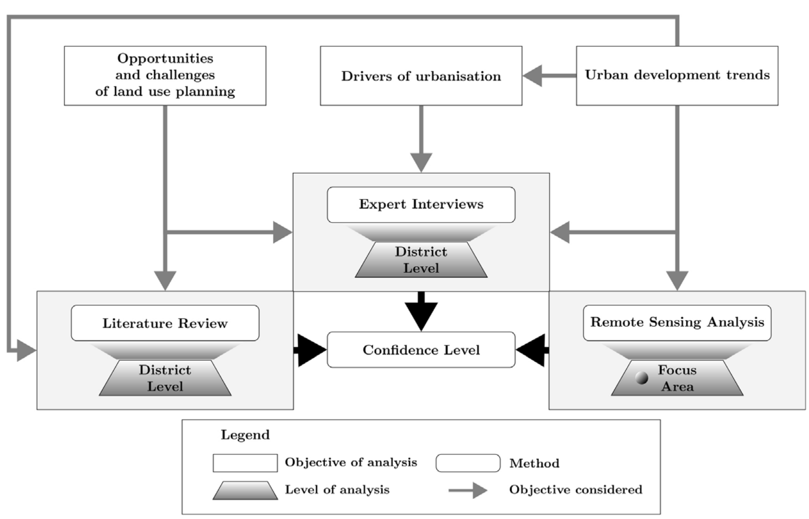

Fig. 2. Methodological framework and analysis scales.

Takoradi (often known as Sekondi-Takoradi) and the surrounding area including Agona located in the Ahanta West District.

2.2.1. *Expert interviews*

In both regions, we started by forming regional focus groups consisting of a few, but highly relevant experts. We define "experts" as people with extensive knowledge and experience regarding land use planning in the study regions or residents who have lived there for more than 20 years, who were included as key knowledge holders. In total, we conducted in-depth interviews with 14 experts, 9 in the Takoradi area, 4 in the Bolgatanga area, and one expert at the national level who knew both study areas. The experts were also chosen according to availability and willingness to contribute to our study.

Our focus group consisted of two groups: (1) land use planning experts at the district level to obtain a clear understanding of urban development in the context of the process of formal and informal land use planning, and (2) representatives of organisations with legal and cultural mandates in land use planning at different levels of statutory planning. Examples are public authorities on

Fig. 3. Examples from the focus areas in Bolgatanga (right) and Takoradi (left). The small-scale structures and the small building cluster in the Bolgatanga subset can be clearly identified. The Takoradi subset shows a mix of large and medium-sized building clusters.

Table 1
Characteristics of the study areas Takoradi (as part of Sekondi-Takoradi), Bolgatanga and Ghana; data from 2010 where no year is indicated.

Study areas	Takoradi	Bolgatanga	Ghana
Administrative Region	Western Region	Upper East Region	In total, 10 Regions
Regional population	2,376,021	1,046,545	Total population: 24,658,823
Urban population[a]	Sekondi: 70,361 Takoradi: 97,352	Bolgatanga: 65,549	Total urban population: 12,545,229
Share of urban population in the region	42.4%	21%	Share of urban population: 50.9%
Average household size (persons)	3.6	4.9	4.4
Mean annual per capita income in US$	363 (2008)	115 (2008)	400 (2008)
Share of population in poverty in the region[b]	20.9% (2013) In extreme poverty: 5.5%	44.4% (2013) In extreme poverty: 21.3%	Total poverty: 24.2% (2013) In extreme poverty: 8.4%
Regional population growth rate	2.0%	1.2%	National population growth rate: 2.5%
Trading opportunities	Harbour located on the Atlantic (international)	Border with Burkina Faso and Togo	Border trade with Burkina Faso, Togo and Ivory Coast; harbours
Main economic sectors of the region	Oil, gas, rubber; mining of: gold, bauxite, iron and diamonds	Agriculture; small-scale gold mining	Services: 51.4% (mainly transport and public administration) Industry: 18.6% (mainly construction and manufacturing) Agriculture: 29.9% (mainly crops)
Climate zones of the region	Deciduous Forest and Coast Savannah; 1500 mm mean annual rainfall	Guinea and Sudanian Savannah; 1000 mm mean annual rainfall	Guinea Savannah, Sudanian Savannah, Transition Zone, Deciduous Forest, Rain Forest and Coast Savannah; 1200 mm mean annual rainfall

Source: GSS (2008); GSS (2012); GSS (2014a); Rainfall data: FAO (2005).

[a] Counted as people living in the urban area.

[b] Absolute poverty line: U$1.83 per day; extreme poverty line: U$1.10; equivalent adult per year in the January 2013 prices of Greater Accra Region; extreme poverty line = even if a household spends its entire budget on food, it still would not meet the minimum calorie requirement (2,900 cal per adult equivalent of food per day) GSS (2014a).

different levels, non-governmental organisations, traditional heads and long-term residents (Table 2). The largest number of experts belonged to the Town and Country Planning Department, which is the leading institution for the planning and management of urban and rural development at national, regional, and district levels. Hεn Mpoano is a regional non-governmental organisation providing support in mapping and collaborating with rural coastal communities. Spatial Solution is a small company specialised in urban design and spatial planning. Both organisations were not working in northern Ghana.

After a general introduction to our research, the interviewees were requested to present their understanding of land use planning and urban development in the focus areas, the different stages of the planning process, the roles of different institutions, how land use priorities were considered in the planning process, the spatially explicit key determinants of spatial growth in the districts, and the internal and external obstacles to sustainable development. Other questions addressed participatory land use planning and suggestions for future land use planning. Each interview took 30–75 min. The questionnaire is provided in Annex B.

We focused on individual interviews rather than on group discussions (Potter, 2011), as it turned out to be impossible to gather all experts at the same time. Internet-based consultation and other SoftGIS methodologies (Kyttä & Kahila, 2011) were also not applicable because the internet access of the participants was rather limited. We employed in-depth interviews to obtain comprehensive knowledge about the variation in land use planning processes and to allow respondents to express their knowledge of and expe-

Table 2
Interviewed governmental and non-governmental experts at the different levels for the two study areas; TCPD = Town and Country Planning Department, EPA = Environmental Protection Agency; NGO = Non-Governmental Organisation.

Level	Experts on governmental level	Experts on non-governmental level
	Representatives for the north (Bolgatanga area)	
National	TCPD Technical Director of Ghana	–
Regional	EPA staff Upper East Region	–
District	TCPD planner Bongo District	Chief of Bongo District
Local (city)	–	Resident living in Bolgatanga for more than 30 years
	Representatives for the south (Takoradi area)	
National	TCPD Technical Director of Ghana	–
Regional	Regional director of TCPD and staff of EPA Western Region	Staff of Hɛn Mpoano and Spatial Solution
District	TCPD Planner of Ahanta West District	Community development officer of Ahanta West District
Local (city)	TCPD planner of Sekondi-Takoradi Metropolitan Area	Residents living in Takoradi for more than 30 years and for more than 20 years in Agona

rience with the issue under discussion. We applied open-ended questions to gain a profound insight into the regional spatial differences and perceived development processes (Bradburn, Sudman, & Wansink, 2004).

Interviews were transcribed and analysed in a content analysis. After a first text analysis, we conducted a coding to conceptually validate and/or extend our hypothesis (Hsieh & Shannon, 2005; Mayring, 2000). The codes were further refined after the first reading and resulted in 14 codes, for example, determinants of urban development, land use priorities, and challenges of land use planning. The interviews were analysed in the qualitative analysis software ATLAS.ti, which simplifies the content analysis of interviews and improves transparency by providing support in managing, shaping and analysing qualitative data (ATLAS.ti, 2015). The hermeneutic unit holds all data sources, quotations, codes, conceptual linkages (families, networks), memos, etc., and therefore helps to organise the complexity of the content.

2.2.2. Remote sensing/GIS analysis

In our study, remote sensing data were exclusively used to identify patterns of urban development, but not for interpreting further drivers, such as distance to roads or markets. Single buildings in the study areas can only be identified on very high-resolution satellite images. Access to such data is very limited and expensive, and available data sets lack the benefit of multi-spectral images.

Consequently, and due to difficulties in discriminating buildings from bare soil in remote sensing data using classic classification algorithms, we decided to perform a manual digitalisation of each building. However, it was the most time-consuming method. For this reason, we decided to monitor urban development between 2007 and 2013 within two 5 km x 5 km focus areas in the peri-urban zones of the two cities. When selecting the focus areas, we kept a 2.5-km distance to the main road from Takoradi to Agona and from Bolgatanga to Bongo (Fig. 3). Clusters of buildings with a distance of less than 25 m to the next building were defined as building cluster and digitised as one unit. In the following, the term "settlement unit" (SU) is used for compounds of the digitised buildings and building clusters. The subsequent analyses of urban sprawl were based on parameters like number and size of SU, total size of the built-up area, built-up density, and the average size of SU. High resolution data were taken from DigitalGlobe via GoogleEarth without cloud cover; reference dates of the data for Bolgatanga are 01/10/2007 and 06/01/2013, while data for Takoradi refers to 02/15/2007 and 06/01/2013.

2.2.3. Literature review

For the literature review, we used databases such as Science Direct and Google Scholar, and added grey literature from free web searches to collate information on customary norms and experience. Land use planning in Ghana is mainly conducted by national and international non-governmental organisations and thus not published in peer-review journals (Cohen, 2006). The literature review was conducted over three weeks between December 2015 and January 2016. Our search terms are provided in Table 6a and 6b. In total, 72 publications were identified as relevant for our research objectives.

2.2.4. Confidence level

To express the reliability of our results, we followed the approach of confidence levels provided by Jacobs, Burkhard, Van Daele, Staes, & Schneiders (2015), which is based on Mastrandrea, Mach, Plattner, Edenhofe, & Stocker (2011) for the IPCC Fifth Assessment Report and the Millennium Ecosystem Assessment (MA, 2005). They used a combination of agreement and evidence levels to evaluate confidence in the validity of a finding. The reason for developing a confidence table for the IPCC Report was the inconsistent interpretation of the degree of certainty between the working groups (Mastrandrea, Mach, Plattner, Edenhofe, & Stocker (2011). Part of the evidence level is its type, amount, quality, and consistency, but further specifications on measuring those parameters are not described in the report. The agreement level is based on the consensus across the scientific community. The author teams agreed on the final confidence level, as it is the case in our study, too. We transformed the matrix model from Mastrandrea, Mach, Plattner, Edenhofe, & Stocker (2011) and Jacobs, Burkhard, Van Daele, Staes, & Schneiders (2015) by specifying the level of agreement and level of evidence by defined thresholds for the respective methods.

In our case, the level of evidence is defined by the number of methods which can provide information. Thus, we have robust evidence if three methods, medium evidence if two methods, and limited evidence if only one method can provide evidential information (Table 3).

The level of agreement is defined differently for the respective methods (Table 3). We have high agreement if all or more than 60% of the interviewees or more than two sources of literature confirm the argument. For remote sensing, a high agreement between different data is not applicable, since we used one study site per location. Medium agreement is defined if 25–60% of the interviewees, one or two references, or remote sensing analyses confirm the argument. Low agreement is provided if less than 25% of the interviewees and if the number of confirmations and rejections is the same in literature. For expert interviews and literature, the number

Table 3
Combinations between agreement and evidence levels for a finding. Each level is defined for the respective method (RS = remote sensing; expert interviews: literature review). For the agreement levels for literature and expert interviews, the number of confirmations is reduced by the fraction of rejections.

Symbol	Level of agreement	Explanation
XX	High agreement	Statement was confirmed within one method - for interviews: > 60% of interviewees confirmed - for literature: more than two sources confirmed - for RS: not applicable (only one location)
X	Medium agreement	Statement was confirmed but limited data within one method - for interviews: 25–60% of interviewees confirmed - for literature: one or two sources confirmed - for RS: confirmed
?	Low agreement	Confirmation and rejection within one method - for interviews: <25% of interviewees confirmed - for literature: confirmation and rejection balanced - for RS: rejection
–		No data or no evidence

Level of Evidence	Explanation
High evidence	All three methods can provide information
Medium evidence	Two methods can provide information
Low evidence	One method can provide information

of confirmations is reduced by the fraction of rejections. For remote sensing, we have low agreement if the argument is not supported by the remote sensing analysis.

The confidence levels used (Table 4) were very high, high, medium, low and very low. Very high confidence is given if we have enough data and results from all three methods, e.g. enough literature as reference (robust evidence) with a high level of accordance between remote sensing and expert interviews (all methods support the hypothesis). High confidence is provided if we have medium evidence (data from two methods) and still high accordance between their results. We also have high confidence if all three methods provide enough data but statements are slightly diverging (medium agreement) or data are limited but results are in high accordance. Conversely, we have low confidence if we have contradictory results from only two methods, e.g. literature and expert interviews. Furthermore, low confidence in findings occurs if only one method on the topic is accessible with limited information to serve as evidence for the argument.

3. Results: integrative analysis of interviews, remote sensing/GIS and literature

In the following, we present a comparative and integrative analysis of our three different data sets. Table 6a and 6b, to which we refer throughout the text, provides information on the level of confidence in the findings to assess how reliable the observed or assumed trends and patterns of urban development are.

3.1. Patterns of urban development

Considerable urban development rates and land fragmentation trends were observed in both areas. This trend was confirmed by all three methods (very high confidence, Table 6a). Analysis of the remote sensing data (Fig. 4) shows that in the Bolgatanga area, the built-up area increased in the period between 2007 and 2013 from 3.6% to 4.7%, equivalent to an increase from 91 ha to 118 ha (+30.4%). In the same period, the number of settlement units (SUs) increased from 873 to 1156 (+32.4%). The number of SUs smaller than 500 m^2 increased by two thirds from 371 to 548 SUs within the analysed period. These change rates together with the decreasing average SU size (Table 5) indicate that urban expansion was mainly based on smaller SUs, thus indicating informal urban sprawl.

The histogram of the SU sizes in the two study areas (Fig. 5) shows that the frequency of SUs of nearly all size ranges increased from 2007 to 2013. Nevertheless, the highest increase can be observed for the smaller SU sizes, which already dominated in both study sites. SUs bigger than 1 ha were only present in the Takoradi area. Similar to very small buildings (<100 m^2), the frequency of such large SUs did not increase considerably between 2007 and 2012.

In the Takoradi area, the remote sensing/GIS analysis identified an increase in the built-up area from 12.5% (312 ha) in 2007–19.6% (490 ha) in 2013. The number of SUs grew from 201 to 381. Though the number of SUs smaller than 500 m^2 was much lower than in the Bolgatanga area, it increased from 70 to 155. This SU size distribution is well in line with the perceptions of the experts, who reported fast growing informal urban sprawl areas located side by side with huge industrial compounds. While the largest five SUs of the entire built-up area in Bolgatanga covered only 13% in 2007 and 11% in 2013, the largest five SU in Takoradi covered 52% and 49%, respectively. Half of the growth of the built-up area in Takoradi between 2007 and 2013 was due to two SUs in the west. The literature supports the observed trend that large buildings are a typical pattern of urban development in the Takoradi area (e.g. Awuah & Hammond, 2014; Somiah, Osei-Poku, & Aidoo, 2015; STMA, 2013). However, the trend of large buildings was only reported by one expert for the Bolgatanga area (very low confidence).

Urban development in the Takoradi area was proceeding much faster than the small-scale scattered development in the Bolgatanga area. However, negative consequences for individuals were much more immediate in the Bolgatanga area due to the higher dependence on land for food provision through subsistence farming. Currently, based on expert statements, land parcels for agriculture are too small to feed the increasing household size of the families, and individual food crises are triggered. Local markets are poorly developed, and financial resources of farmers are very limited. Coping capacities were therefore assumed to be lower for the Bolgatanga area, which could lead to local food crises provoked by urban sprawl where land becomes useless for agriculture.

3.2. Driving forces of urban development

Our three data sets show at a high confidence level that population growth is a driving force of urban development in both study areas (Table 6a). More than 60% of the experts and more than two sources of literature confirmed this fact and provided many statements with high agreement. Expert interviews and literature analysis indicate that natural population growth and migration from rural areas due to poverty and land conflicts are the main reasons for increasing population in the Bolgatanga area, while in the Takoradi area, population growth is mainly based on migration due to employment opportunities in the industry and the servicing sectors.

In general, industry development was identified as a strong driver of urban development in the Takoradi area, particularly the oil and gas industry along the coast of Cape Three Point. This has resulted in increasing demand for settlement areas for industrial employees and workers (confirmed by >60% of the experts and more than two literature sources). Competition between industry and residential/agricultural land use was identified for the Takoradi area by both experts and literature. Zoning regulation was reported to be less strict, leading to mixed land uses, which were considered less desirable than separated land uses. Within the region, spill-overs from already congested areas were assumed to drive

Table 4
The table of confidence of findings from interviews, remote sensing and literature (Table 6a and 6b).

Level of confidence	Limited evidence	Medium evidence	Robust evidence
High Agreement	Medium	High	Very High
Medium Agreement	Low	Medium	High
Low Agreement	Very Low	Low	Medium

Adapted from Jacobs, Burkhard, Van Daele, Staes, & Schneiders (2015) based on Mastrandrea, Mach, Plattner, Edenhofe, & Stocker (2011) and MA (2005).

Fig. 4. Settlement expansion in a Bolgatanga subset (right) and Takoradi (left). Grey and black areas show expansion in 2007 and 2013, respectively.

Table 5
Comparison of the development of settlement pattern of Bolgatanga and Takoradi study area between 2007 and 2013.

Built-up area on the 5 km × 5 km focus areas	Bolgatanga		Takoradi	
Year	2007	2013	2007	2013
Area [ha]	91	118	312	490
Area [%]	3.6	4.7	12.5	19.6
Settlement units [No.]	873	1156	201	381
Average settlement unit size in m^2	1036	1021	15,554	12,868
SU <500m^2	371	548	70	155
SU <100 m^2	42	83	19	34

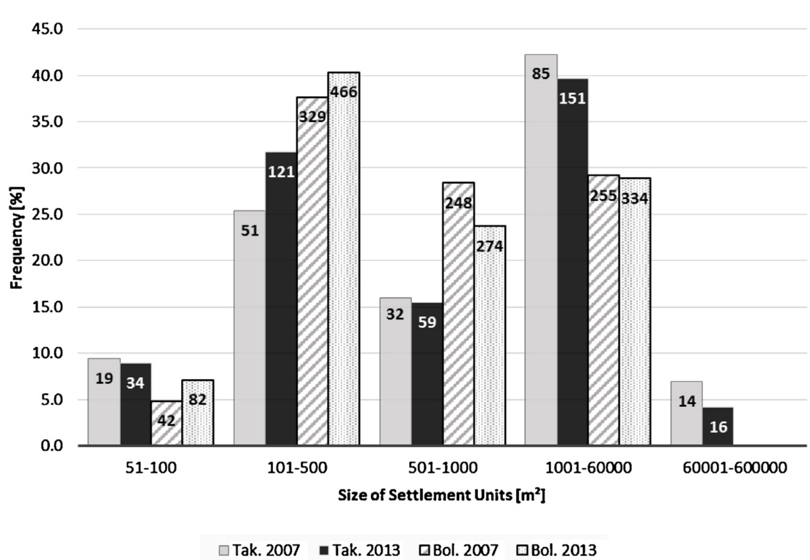

Fig. 5. Histogram of the Settlement Unit (SU) sizes in study areas for years 2007 and 2013. Overall number of SUs in the Bolgatanga area (Bol.) is much higher than in the Takoradi area (Tak.). On the other hand, large SUs can only be found in the Takoradi area.

Table 6a
Confidence of findings of patterns and drivers of urban development for the Bolgatanga area (B) and Takoradi area (T). References from literature review in Annex C; references of expert interviews in Annex D and E. For methodology see Chapter 2.2. RS = Remote sensing; B = Bolgatanga and the surrounding area including Bongo; T = Takoradi and the surrounding area including Agona; XX = high agreement; X = medium agreement; ? = low agreement; – = no data or no evidence.

Analysed topic	Keywords	Interviews		RS analysis		Literature		Confidence	
		B	T	B	T	B	T	B	T
Patterns of urban development	Urban sprawl (unstructured urban expansion)	XX	XX	X	X	X	XX	Very High	Very High
	Land fragmentation	XX	XX	X	X	X	X	Very High	Very High
	Scattered small settlement units (for RS: < 500 m²)	X	XX	X	X	X	XX	Very High	Very High
	Scattered large settlement units (for RS: > 10.000 m²)	?	XX	-	X	-	XX	Very Low	Very High
Drivers of urban development	Population growth (housing)	XX	XX	-	-	XX	XX	High	High
	Roads	?	X	-	-	X	X	Low	Medium
	Markets (trade and economy)	X	XX	-	-	XX	XX	Medium	High
	Mining of gold, stones or sand	-	-	-	-	X	X	Low	Low
	Agriculture	XX	?	-	-	X	?	Medium	Very Low
	Governmental buildings and staff accommodations (decentralisation processes)	?	?	-	-	?	X	Very Low	Low
	Customary land tenure	XX	X	-	-	XX	-	High	Low
	Educational facilities	XX	?	-	-	?	XX	Medium	Medium
	Heavy industry and worker´s accommodations	-	XX	-	-	-	XX	No	High
	Real estate and hotels	?	X	-	-	-	XX	Very Low	Medium
	Infrastructural development in general (electricity, piped water, hospitals)	?	?	-	-	?	?	Very Low	Very Low
	Changing lifestyle	-	?	-	-	-	X	No	Low

Table 6b
Confidence of findings of challenges and opportunities of urban and peri-urban land use planning for the Bolgatanga area (B) and Takoradi area (T). References from literature review in Annex C; references of expert interviews in Annex D and E. Methodology in Chapter 2.2.; NGO = Non-governmental organisation; B = Bolgatanga and the surrounding area including Bongo; T = Takoradi and the surrounding area including Agona; XX = high agreement; X = medium agreement; ? = low agreement; – = no data or no evidence.

Analysed topics	Keywords	Interviews		RS analysis		Literature		Confidence	
		B	T	B	T	B	T	B	T
Challenges for urban and peri-urban land use planning (LUP)	Customary land tenure	XX	XX	-	-	XX	XX	High	High
	Lack of participation by people	?	?	-	-	?	X	Very Low	Low
	Lack of communication between industry & government	-	?	-	-	-	XX	No	Medium
	Distrust in government	X	X	-	-	X	X	Medium	Medium
	Governmental decentralisation	?	?	-	-	?	?	Very Low	Very Low
	Joint planning across district borders	?	?	-	-	X	X	Low	Low
	Lack of law enforcement	X	XX	-	-	X	X	Medium	Medium
	Lack of financial capacity	X	X	-	-	X	?	Medium	Low
	Funding for urban LUP from NGOs and/or industry (biased)	-	X	-	-	-	X	No	Medium
Opport-unities of urban and peri-urban LUP	Land Administration Project	X	?	-	-	?	?	Low	Very Low
	Land Use Bill	-	?	-	-	-	X	No	Low
	National and Regional Spatial Development Framework	X	X	-	-	-	X	Low	Medium
	Public-Private-Partnerships (private = industry)	-	X	-	-	-	?	No	Low
	Awareness raising and local participation	XX	XX	-	-	X	?	Medium	Medium
	Tendency towards multi-storey structures	-	X	-	-	-	X	No	Medium

migration and informal urban sprawl. Real estate property and hotels were booming (medium confidence for the Takoradi area). Experts also reported the tendency to live outside the main cities due to increasing rents, pollution and traffic loads. A new town concept is evolving in Takoradi, where workers and residents are encouraged to settle outside completely built-up areas by constructing affordable, public housing in the peri-urban areas (Owusu & Oteng-Ababio, 2015).

Roads as drivers of urban development were rated with low confidence level for the Bolgatanga area and with medium confidence for the Takoradi area. For the Takoradi area, an expert reported that individuals buy parcels of land in remote areas, but have not settled there yet because most of them are waiting until access roads are constructed. For example, vacant lands towards the north of Takoradi, although unused, have been considered for industrial development once basic infrastructure such as roads and electricity are made available. In Takoradi, agricultural land area competes with industrial and residential land uses (very low confidence of agriculture as driver of urban development). Conversely, displacement was reported as an issue in the Bolgatanga area, where small-scale farmers preferred to settle close to their farmland. This activity increases land fragmentation and urban development. However, we have medium confidence that agriculture is a driver of urban development because some comments from experts and interviews were only related to land fragmentation, which does not directly lead to urban development.

An expert in the Bolgatanga area mentioned the increase in governmental buildings in the course of the decentralisation process as a factor contributing to urban development. He highlighted that the administrative role of Bolgatanga as the regional capital had increased and that new districts, such as the Bongo district, had been established. As a consequence, new accommodations for administrative staff were needed. The Ghana Statistical Service showed that splitting-up of land is also taking place on the administration level. Between 2004 and 2008, 60 new districts were created in Ghana (GSS, 2013). However, a direct link between governmental decentralisation and urban development was not confirmed by the literature (Codjoe, Badasu, & Kwankye, 2014; Lund, 2006; Owusu & Oteng-Ababio, 2015). Consequently, governmental decentralisation as a driver for urban development connotes a very low confidence level in the Bolgatanga area and a low confidence level in the Takoradi area.

Apart from roads, other infrastructural development such as electricity, schools, hospitals and water provision appears uncorrelated with urban development. Poku-Boansi & Amoako (2015) showed that in the past, the government had focused infrastructural development on fast growing urban areas, which in turn caused immigration from rural areas where public services are non-existent. They identified that in 2000, 35.4% of the population in Sekondi-Takoradi had access to hospitals within their localities, while this was reported for only 0.6% of the population of Bolgatanga. Furthermore, Poku-Boansi & Amoako (2015) argued that the scattered urban development in northern Ghana poses a challenge to infrastructure planning, since the provision of social services in localities with few residents makes the service economically inefficient. However, infrastructure for sanitation and waste management is also a general problem in cities of Ghana, including Takoradi (Owusu & Afutu-Kotey, 2010). Experts provided conflicting statements as evidence. Therefore, infrastructural development (excluding roads) has a very low confidence level as a driver for urban development in both study areas.

Even though it was not mentioned by the experts, sand, stone and gold mining form an additional driving force of urban development. Mining was mentioned several times in the literature as a driver of urban development for both study areas (for the Bolgatanga area: Agyemang, 2010; Owusu, 2009; for the Takoradi area: AWDA, 2014; Rocha, 2012), but it appeared irrelevant from the point of view of the experts interviewed. Due to a lack of more complete information, mining as a driver had a low confidence level.

Based on the expert interviews (> 60% confirmed), the customary land tenure system was identified as an indirect driver of urban development with high confidence for the Bolgatanga area. The customary land tenure system, particularly for those lands which are based on inheritance rights, provides the entry point for urban development. Splitting-up of land into smaller parcels leads to land fragmentation, as the small parcels are not suitable for agriculture and local planning (parcel by parcel planning), but suitable for settlements (Tonah, 2005). Statutory land tenure could terminate the process of land fragmentation. In addition, chiefs and families are gradually interpreting common land as private ownership, which facilitates the selling of land for house construction (Dietz, Geest, & Obeng, 2013). However, fragmented small-scale land ownership is hard to manage by large-scale investors, since these have to convince many different owners of small parcels.

In contrast to the customary land tenure in the Bolgatanga area, individuals in southern Ghana own vast parcels of land. As it is easy for private investors to purchase large tracts of land, they are motivated to convince the few affluent people in the community. Instead of contacting the municipal authority, investors directly approach the land owners. As a result, existing land use plans contradict investors' development plans. Nevertheless, about 50% of the experts mentioned customary land tenure as a driver of urban development in the Takoradi area, a finding that could not be confirmed through literature (low confidence level).

3.3. Opportunities and challenges for urban and peri-urban land use planning

The experts named several challenges for land use planning in the study areas. Literature and experts identified customary land tenure system, distrust in the government, and lack of law enforcement as main reasons. Especially for the customary land tenure system, we have high confidence that it is not only a driver of urban development but also a challenge to land use planning as such (Table 6b). People insist on their customary land use rights, which complicates statutory planning. Poor communication and misunderstandings between government and population have led to an increase in informal settlements. Involvement of the local population in land use planning decisions is often limited to chiefs or selected representatives. However, statements from experts and literature were diverse, so that a lack of participation by people led to a very low confidence level for the Bolgatanga area and low confidence for the Takoradi area.

Challenges in the Takoradi area are the influence of non-governmental organisations or industry on urban land use planning, and the lack of communication between industry and government (medium confidence). For example, four experts of the Takoradi area pointed out that the KOICA (Korea International Cooperation Agency) and the business community (e.g. Tullow Oil) have a strong influence on the decisions of planners and town council in relation to land use priority and rezoning channelled through funding. Governmental decentralisation was contested as a challenge of land use planning by the experts and literature for both study areas. A higher financial burden as well as more governmental power and proximity to the people was transferred to district assemblies.

To counteract the challenges, the experts and literature suggested an improvement in communication channels such as radio announcements and information boards with development plans. Only when land owners are sensitised and educated regarding land use planning, and adequately compensated in the case of compulsory land acquisition, will they understand the necessity for national land use planning (medium confidence). Especially for the Takoradi area, land use plans need to be developed before industries emerge, and cooperation with private companies should be enforced. Public-Private-Partnerships (PPP) were named by three experts as an opportunity for attracting investors for prospective development and covering the costs of basic infrastructure. However, literature gives contradictory statements if PPPs are conducted in the Takoradi area (Ayee & Crook, 2003; Owusu & Afutu-Kotey, 2010). The World Bank Group (2015) stated that PPPs in Ghana are generally weak due to limited fiscal and technical capacity, a missing legal framework and, consequently, a lack of interest of the private sector. Therefore, we have low confidence for this area. For the Bolgatanga area, PPPs were not mentioned by the experts and were proposed by literature only for agricultural areas.

Another opportunity for the Takoradi area is the building of multi-storey structures for residences in order to efficiently utilise the limited space in the city centre (reflecting medium confidence). This would imply a change from individual ownership to statutory land ownership in order to prevent one-storey buildings of former farming communities in the city centre or to prevent uncompleted constructions due to individual financial problems. Historically, individuals (families, clans) own the land in the city centre, but they do not have the capacity to develop the land profitably.

Land use planning regulations and guidelines, for example the Land Administration Project, the National and Regional Spatial Development Framework, and the upcoming Land Use Bill were considered as opportunities for land use planning but with low confidence (apart from the National and Regional Spatial Development Framework for Takoradi with medium confidence) due to the abovementioned lack of law enforcement, inequalities and financial gaps. Similarly, decentralisation is contested as a challenge. On the one hand, it is seen as a challenge because of lacking financial capacities of local assemblies, lacking synchronisation of activities between local and regional units, and delays in the implementation of frameworks, because every district is supposed to prepare a district development framework. On the other hand, decentralisation is an opportunity because of the increased power of local assemblies.

4. Discussion

4.1. Discussion of findings

The results show that regional differences in urban development and spatial planning exist which can be traced back to colonial times and are continued by ineffective post-colonial institutions and poor governance. This finding is confirmed by Poku-Boansi & Amoako (2015) and the UN-Habitat (2008). But also customary land tenure and ignorance of people played a role. Ineffective land use planning can contribute to an increase in land fragmentation resulting in loss of land for food provision. Land use planning is the key to maintaining resources. For example, Asare-Kyei, Kloos, & Renaud (2015) studied indicators for climate change risk in northern Ghana where land use planning was seen as a national indicator for climate change risk by experts. These experts also believed that areas with effective land use plans could contribute to meeting the needs of the people whilst protecting natural resources.

Road network was less obvious as a driver of urban development, even though the general trend for West Africa is the increase in cities in the hinterlands due to the expanding road network (UN-Habitat, 2014). In the case of Ghana, that statement might be true for Kumasi as expanding city in the hinterlands, but not for Bolgatanga. Furthermore, the general infrastructural development of electricity and hospitals, for example, as drivers of urban development could not be confirmed. Even though infrastructural improvements in the 1990s were named as the centre of attraction for Bolgatanga (Bolgatanga District Assembly, 2002), this driver can be questioned based on our findings. For example, Poku-Boansi & Amoako (2015) and also the Ghana Statistical Service (GSS, 2014b) mentioned the poor infrastructure in Bolgatanga.

4.2. Discussion of the mixed-method approach

Our approach combined three different methods to characterise processes and key drivers of urban development in two representative areas. An advantage was that we were able to compare the information provided with the three methods and thus assign confidence levels. Expert interviews and literature analysis described patterns of urban development and helped to connect those patterns with legal, socio-cultural and environmental drivers. The benefit of utilising remote sensing data consists of an objective characterisation of the physical consequences of formal and informal agreements. Furthermore, the remote sensing analysis can show either the compliance or the ignorance of legal land use planning mentioned by expert interviews and literature analysis by using small-scale buildings as a proxy-indicator for informal urban sprawl. In both areas, perceived patterns of urban development matched well with the results from interpreted remote sensing data. The extended literature review provided important sources of information for the purpose of estimating the level of confidence. Though not considered by expert knowledge, the literature reviewed that sand, stone and gold mining were drivers of urban development in both study areas. Furthermore, it questioned some of the experts' statements and supported a critical reflection of the findings. The reason for not mentioning mining as a driver could be that it is more likely taking place in rural areas, which were not in the focus of the experts.

However, the information provided by expert opinion and literature has some weaknesses. The most important weakness is the limited number of experts available for the interviews and their composition in the focus groups. Though we strived to identify the most important and relevant persons, their opinion and perceptions do not cover all potential aspects. The lower number of experts for Bolgatanga was due to non-availability of land use planners and local organisations working on land use planning. A response by the regional planner of the Upper East Region would have given us the opportunity to contextualise the regional level planning variations. The literature research was based on the keywords that we identified when analysing the interviews (Table 6a and 6b). This might have thematically limited the selection of literature. Furthermore, peer-reviewed literature was rare for the study areas. Therefore, grey literature was also used where quality could not be assessed. A single method approach might be the better choice when a lot of data and certainty exists. But even though there are weaknesses, a mixed-method approach allows us to obtain a clearer picture of an uncertain issue.

Considering the remote sensing/GIS analysis, our data set allowed a very detailed manual classification of buildings. However, the lack of the near-infrared band reduced the accuracy of classification processors, specifically in arid areas such as the Bolgatanga area where open soil features hinder a discrimination of settlement areas. The availability of a very high resolution satellite dataset including infrared or a time series with high temporal resolution could provide further details and better support a comparative overview of urban development trends for the areas under study. Furthermore, it would allow the assessment of single buildings within building clusters. Additional statistical analysis, for example of spatially explicit population census data, could have strengthened our analysis. In addition, we would have appreciated access to local land use plans to compare zoning variations with the urban development seen in the remote sensing/GIS data. Furthermore, by developing datasets with the requisite data structures, we could use additional landscape indices to reveal further information about the spatial arrangement and heterogeneity of urban development, and to further discriminate levels of landscape fragmentation and/or aggregation over time.

We adapted the confidence level approach of Jacobs, Burkhard, Van Daele, Staes, & Schneiders (2015) to a general assessment of findings from a mixed-method approach. Our intention was to increase transparency through defined thresholds for the agreement levels as well as evidence levels. Mastrandrea, Mach, Plattner, Edenhofe, & Stocker (2011) and Jacobs, Burkhard, Van Daele, Staes, & Schneiders (2015) used the evidence levels for assessing the output from models while we focused on the amount of methods which provided information. In our case, it was necessary to adapt evidence levels to data availability and applicability. For example, we had only one set of data per location for remote sensing, for experts we had a limited number, and for literature we had a potentially limited data set due to the possible combinations and terms used for the search. It can be concluded that even the change of one statement within a method could have changed the agreement level. Considering this fact, there is still high uncertainty in our findings. As a next step in combining information from diverse methods, we suggest consideration of type and quality of methods for confidence levels.

5. Conclusions and outlook

Urban expansion, particularly informal urban expansion with small settlement units, is one of the key processes that we observed in both study areas, while particularities in land tenure, customary norms, historical development, strategic-geographical location and related economic priorities led to a different speed and pattern of urban development. For the Takoradi area, the expansion was faster than in the Bolgatanga area, which is with high confidence due to its economic vibrancy and markets. The expansion of scattered large settlement units in the Takoradi area was due to the rise of the oil and gas industry. In the Bolgatanga area, especially customary land tenure was a driver of urban development. Population growth remains an important driver of urban development with high confidence in both areas. We recommend that national land use planning needs to be adapted to respective local conditions.

The development-related separation between northern and southern Ghana has been prominent in the past and might continue in the future even though urban development in the hinterland is gaining momentum through newly developed trade and road connections (UN-Habitat, 2014). Projections of urban population in Ghana show a share of urban population of 72.3% in 2050, which would be above the average of 65.7% for all West African countries (UNDESA, 2011). Owusu & Oteng-Ababio (2015) assume that urban growth will concentrate on large cities such as Accra. In the Western Region, oil production, mineral extraction and cash cropping will further attract work migrants. By implication, agricultural activity will decline in favour of the servicing sector (Owusu & Oteng-Ababio, 2015). The government needs to provide job opportunities and affordable housing facilities while intensifying planning laws and regulations, otherwise informal urban sprawl will continue (Yeboah & Obeng-Odoom, 2010) and poverty might increase again.

Also considering the challenges of land use planning revealed by our study, customary land tenure should be one of the focal points in spatial planning. Great efforts to improve local participation and law enforcement are necessary. A key step towards this achievement is the adoption of participatory land use planning with critical adaptation to and emphasis on sectoral planning. Such a bottom-up approach for planning with adequate compensation of compulsory acquired land could facilitate the incorporation of the development of local plans at the district and municipal levels into the respective regional spatial development frameworks. Furthermore, we see a need for an improved dialogue between district and municipal assemblies, private organisations, and civil society organisations for collaboration with regard to technical know-how and funding. The Land Use Planning Bill could help to unify laws and regulations and to support the decentralisation process, but it is just starting and must prove itself.

The flexibility in the use of confidence level analysis presents a promising approach to improve interdisciplinary research as exemplified in this study. In evaluating different data sources for a specific theme, researchers from different disciplines are confronted with having to communicate and deal with unfamiliar methods and approaches. The confidence level provides a qualitative synthesis of a team's judgement on the validity of a finding. A low confidence level depicts either data gaps or contradictory statements from the research findings, and thus helps to detect needs for refined research and data analyses before giving political recommendations for taking action.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.landurbplan.2017.02.004.

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Chapter 4
Marginality from a Socio-ecological Perspective

Daniel Callo-Concha, Jan Henning Sommer, Janina Kleemann, Franz W. Gatzweiler, and Manfred Denich

Abstract The authors analyze the concept of marginality from an ecological perspective and provide examples of some mechanisms of marginalization. Marginalization cannot solely be described as an ecological phenomenon, but rather occurs via the interplay of ecological and social aspects of complex arrangements. Hence the use of socio-ecological systems as a conceptual unit is proposed. One way to combat marginalization is to increase the resilience and adaptability of these systems. However, multiple needs must be considered simultaneously, including: food security, income generation, or ecosystem services. Research on marginality in the context of interlinked socio-ecological, complex, and dynamic systems demands paradigm shifts in scientific disciplines that are beginning to merge.

Keywords Socio-ecological systems • Carrying capacity • Competition • Resilience • Adaptability

4.1 Marginality in Ecology

The term marginality has become a buzzword across various disciplines and contexts (Cullen and Pretes 2000). Marginality can only be properly defined in a specific reference context. In social systems, marginalized people are often defined as subgroups that differ from the core or mainstream. The core group in this respect is the reference group that the outlier subgroups are marginal to. In ecological systems the designation of any of its components as marginalized is a more challenging

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exercise. This is because ecosystems consist of manifold interdependent components that are under the influence of a variety of biophysical factors.

In ecology marginality has been applied to describe phenomena that occur at biophysical limits of any kind. These may be geophysical boundaries, environmental thresholds, or habitats that are not well suited for particular species or populations (Odum and Barrett 1971; Cassel-Ginz et al. 1997; Leimgruber 2004). Since the diversity of nature provides a great variety of conditions, margins and marginal conditions are innumerable. Marginal areas may be environments that pose extreme challenges to the survival of certain species such as deserts, high altitude areas, ephemeral water bodies, or sites with heavy metal soils. Stochastic dynamics or disturbances such as volcanic eruptions, floods, or droughts also create temporary marginal conditions in ecological terms. The 'limits' of ecosystems in most cases merge into gradients rather than forming sharp boundaries, creating 'ecotones,' which are zones of transition between adjacent ecosystems (Holland 1988) where distinctions are blurred (Odum and Barrett 1971).

To comprehensively describe marginality with respect to an ecosystem requires the analysis of each of its components and their interactions. Each species has optimal conditions under which it can best survive and reproduce. The most extreme conditions would be lethal to a species, while less extreme conditions would prevent or limit growth and development and thus be considered marginal (Begon et al. 2006). For example, tree growth is determined by different factors such as temperature, soil conditions, humidity, etc. To determine whether marginality exists in the context of a forest requires an evaluation of the conditions of individual tree species. Changes in the status of one species affect the status of other species (positive/negative feedback). For instance, when resources are shared between competing species the superior competitors profit at the cost of inferior ones (Araujo and Pearson 2005; Soberon 2007).

At the species level, Liebig's law of the minimum states that the scarcest required resource determines the overall suitability of living conditions in a given area. With respect to the occurrence and abundance of plant or animal species, population growth and size are limited by the availability of the scarcest required resource or 'limiting factor.' Therefore it makes sense to describe marginalization in relation to the carrying capacity of the ecosystem, which is the maximum population size of a species that can be sustained indefinitely in a given area. In addition, the carrying capacity for one species is strongly influenced by the presence and relative abundance of other species that compete for the same resources. For example, nutrient availability limits the growth and size of populations of two species of phytoplankton in a pond. The population size of either species will depend on both nutrient availability and the ability of each competing species to procure these nutrients. If one species can access the scarcest nutrient more proficiently it will out-compete the other species in the long run if conditions and nutrient availability are constant over space and time (provided that population growth of the better competitor does not change with increases in population size, i.e., their increased abundance does not increase mortality via greater incidence of disease or predation rate). Therefore a species can be marginalized by the presence of a competing species despite the overall availability of required resources in an ecosystem.

Ecosystems can also be classified by the limiting biophysical factors at different hierarchical levels. For instance, edaphic conditions are more relevant at fine scales, while climatic and orographic factors are more relevant at broader scales (Pearson and Dawson 2003). A translation of this relationship directly to social systems would describe social marginalization as a result of overexploitation of a system's resources, often due to either high human population density or else decreased resource availability. Hence a relevant way of equating the concept of ecosystems to social marginality is that they are analogous to social systems in which marginality occurs when certain groups have only limited access to resources.

A direct link between marginality in ecological and social systems can be made when considering the concept of biological value and life regulation in living systems (Damasio 2010). The primitive of biological value (Damasio 2010, 2011) is the physiological state of living tissue within a homeostatic range that is necessary for normal function (i.e., health). Extremes of homeostatic ranges have low biological value to them, whereas more central conditions along homeostatic ranges have higher biological values. Thereby biological value is directly linked to need, and need is linked to life. The productive capacity of organisms can be reached in healthy organisms and environments, whereas it will always be underperforming in marginal environments with low biological value.

The propensity of humans to attach values to virtually everything around them relative to their desired living conditions can be perceived as a process which aims at achieving ideal homeostatic conditions. Humans formulate values that regulate the processes (economic and social) within their homeostatic range and thereby contribute to their well-being. Staying alive requires processes of transforming nutrients into energy, disposal of waste, and making use of energy for biological processes under particular biophysical conditions. Departures from homeostatic ranges are detected by the brain, which can stimulate corrective actions. The process of cognition (in simple organisms such as earthworms) and consciousness (in more complex organisms such as humans) is used to monitor and detect whether the body is operating within this range or else in danger—within or outside the homeostatic range (Parvizi and Damasio 2001). A situation where an organism is in danger due to homeostatic imbalance can be conceived as being analogous to organisms living in marginal conditions.

4.2 Socio-ecological Systems and Marginality

Evidently humans have decoupled themselves from purely physiological and competition-related ecological limitations due to technological developments that prop broad adaptive strategies. As a result humans are able to survive in areas that are otherwise unsuitable for them from an ecological point of view. This may, however, put populations that live close to (or beyond) the margins of ecological suitability at risk and make them dependent on inputs from external sources. Extreme examples are human settlements under completely hostile conditions such as polar or space stations that depend entirely on external inputs and modern technologies.

A couple of assumptions can be made regarding how ecological factors may determine social marginality and how boundaries in ecological marginality are similar to those in social marginality. We assume that marginalized people often lack access to resources due to unfavorable (geographical) location or generally restrictive local biophysical conditions (Gatzweiler et al. 2011). For instance, remoteness in the sense of living far away from economic centers may result in social marginality by limiting access to work, education, and health care (Leimgruber 2004). From an anthropocentric point of view, ecological systems provide goods and services that their inhabitants use to ensure their well-being. Constraints in resource procurement determine the extent of marginalization. Examples are farming in isolated areas, in areas with limited access to water, or where soils or other conditions are of limited suitability. Complementarily, people may become marginalized as the result of ecological degradation such as desertification, acidification, or salinization of soils, and air or water pollution, etc. In these cases marginalization is the result of a gradual process.

Assuming that unfavorable ecological conditions contribute to the general marginality of a human settlement, there may also be privileged individuals who are able to increase their resilience and adaptive capabilities at the expense of less privileged individuals or of common resources. In environments with poor or depleted biophysical assets, forms of social exclusion often manifest (Winchester and White 1988; Gatzweiler et al. 2011). These considerations suggest that it is appropriate to enlarge the scope of analysis over a broader realm in order to understand ecological marginality and the 'socio-ecological systems' (SES) concept.

It is generally acknowledged that understanding complex phenomena requires insights from multiple scientific disciplines, but not until the 1970s in the context of greater awareness of the global environmental crisis did an appropriate conceptual framework for considering 'mingled phenomena' emerge (Vayda and McCay 1975). It was during this period that the concepts such as 'lifescape,' 'livelihood,' 'coupled human-environmental,' and 'human-natural systems' were first proposed (Howorth 1999; Marschke and Berkes 2006). Recently SES has emerged as a concept integrating human-natural interrelationships that is used to harmonize social development and conservation goals. By asserting that many complex phenomena include both social and ecological systems simultaneously and inseparably (Gallopin 2006), and therefore any demarcation is artificial and arbitrary (Folke 2006), the application of crosscutting and integrated approaches such as the concept of marginality are advocated for the consideration of complex issues.

Based on this concept it is worth identifying situations where social marginalization occurs due to ecological variables or ecosystem settings. People can be marginalized due to environmental factors that inhibit their well-being. These factors generally act on distinct spatial and temporal scales due to variation in the physical and chemical characteristics of ecosystems (degraded soils, salinity, toxic pollutants, etc.). All of these factors may be used to describe the degree of marginality to which the inhabitants of an ecosystem are subject. For example, many tropical areas of Africa are affected by sleeping sickness/animal trypanosomiasis, which is transmitted by tsetse flies, making them marginal areas to inhabit and raise cattle: pastoralists who only have access to these areas are marginalized by environmental factors.

People can be marginalized by limited access to natural resources due to inherent variability of the amount and quality of the natural resources in a particular ecosystem (Landres et al. 1999). Constraints on an ecosystem that limit the amount of resources available to residents after having passed a physiological threshold (e.g., due to high human population density), can result in the marginalization of the inhabitants. Resource depletion can also occur due to the degradation of ecosystems by overexploitation (e.g., soil erosion, deforestation, extirpation of wildlife, etc.) or other means and lead to degradation-induced marginality.

Marginalization also occurs in SES through competition. This may occur directly, as when one actor takes land or resources from another, or through indirect mechanisms such as the appropriation of land by central governments (Cotula et al. 2009). Marginalization in a SES may occur consensually, for example the resettlement of populations for the construction of hydroelectric dams that contribute to the general well-being in a society.

The cases above reveal how marginality can be complex and often deal with SES that are subject to risk and uncertainty (Leach et al. 2007). Moreover the drivers of marginalization respond to changing socio-ecological factors and are often uncontrollable by the affected people, as the inherent causal mechanisms emerge on spatial, temporal, or administrative scales that the affected people have limited control over. Strengthening the resilience and adaptability of SES, however, helps to prevent the marginalization of its inhabitants.

4.3 Addressing Marginality in Socio-ecological Systems via Resilience and Adaptability

It has been found that human communities, particularly when overpopulated, often overuse local natural resources, thus aggravating poverty through natural resource depletion (Dasgupta and Mäler 1994). This feedback loop contributes actively to the marginalization of the poor by limiting their resource options (UNCCD 2003). This has been documented in the case of West African savannah agricultural systems that are constrained by limited soil productivity and highly variable precipitation patterns (Sanchez 2002; Sanchez et al. 2002; Challinor et al. 2007), in the case of slash-and-burn agriculture in rainforests at historically high population densities leading to deforestation and the exhaustion of soils (Palm et al. 2005), and in the case of the migration of Andean farmers to less productive, higher altitude areas due to reduced local availability of agricultural land at more favorable altitudes (Mayer 2002).

The difficulties of escaping such poverty/natural-resource-depletion feedback loops are aggravated by global drivers such as human population growth, habitat degradation and destruction, climate change, the global economic crisis, and their combined impacts. In this context the sustainable performance of a SES requires a dynamic configuration that can adjust to progressive or sudden changes (Adger 2006). Therefore considering marginality in SES requires taking into account

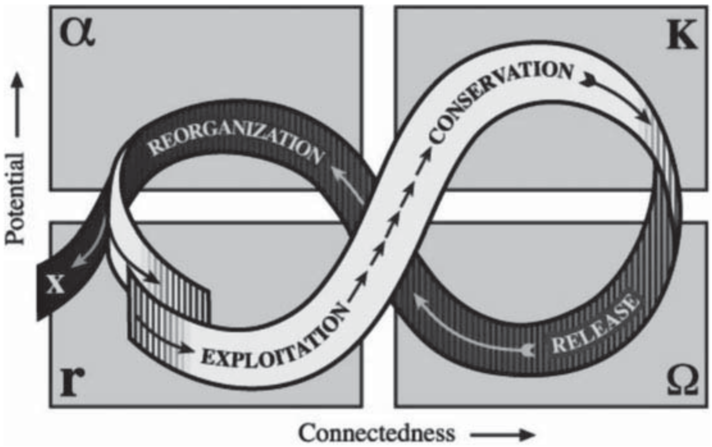

Fig. 4.1 The adaptive cycle: successive phases of response of a complex system to changing conditions (Gunderson and Holling 2002, 34; Reproduced by permission of Island Press, Washington, DC)

change and disturbance as the principal constraints that can be considered using the concepts of resilience and adaptability (Dilley and Boudreau 2001; Vogel et al. 2007).

Resilience was originally coined in ecology to describe the capacity of ecosystems to recover functionality after shocks (Holling 1973), and may be used to refer to the capacity for renewal and reorganization of a SES (Gunderson and Holling 2002; Berkes et al. 2003). It is conceived of as a system's capacity to maintain its identity, structure and function in response to a disturbance event (Walker and Meyers 2004). Adaptability is the capacity to adjust to change (Smit and Wandel 2006) or in other words the ability to remain in a stable configuration despite changes to internal or external factors over time (Denevan 1983; Andresen and Gronau 2005).

Despite coming from ecology, the concepts of resilience and adaptability have started to be used in interdisciplinary contexts (Janssen and Ostrom 2006; Vogel 2006) due to their utility for portraying the drivers of sustainability and long-term functionality of complex systems (Callo-Concha and Ewert 2011). In this framework a marginal SES is a system with limited or no resilience. Marginal systems are vulnerable in the sense that their stability is menaced by events that push them towards a threshold after which the system must either reach a new homeostasis under different conditions or else become unstable.

The adaptive cycle (Fig. 4.1) is a conceptual tool that portrays the successive stages of systems in response to changing conditions (Gunderson and Holling 2002). In the case of poverty and natural-resource-depletion feedback loops, the adaptive cycle can help to identify 'poverty traps' or situations where system diversity, connectivity, and resilience are reduced to the extent that system performance cannot be regained or is destabilizing. Gunderson and Holling (2002) provide examples of a productive savannah that became degraded due to drought and over-grazing fueled by economic incentives for maintaining high stocking densities. Other examples of system collapse are societies traumatized by civil war, where social and cultural cohesion and adaptive abilities have been lost, preventing the rebuilding of society (Volkan 2000). In the case of 'rigidity traps,' decision circuits are highly interconnected, reinforcing themselves and making the system inflexible (Gunderson and Holling 2002). A good example is an old forest where larger, well-established trees inhibit the growth of saplings, impeding the renewal of the forest as a whole and increasing vulnerability to disturbances such as wildfire (Carpenter and Brock 2008). A corresponding social example would be the case of authoritarian governments where vertical decision-making structures impede innovation and adaptation, that tend to collapse when the overall settings such as democratic values become gradually hegemonic.

Preventing the marginalization of a human community by increasing its resilience and adaptive capacity cannot be achieved by concentrating on a single component without considering other interlinked components of the SES. Contrarily it must fulfill various complementary and successive goals (e.g., guaranteeing food security, creating income generating opportunities, and maintaining ecosystem services)—goals which aim at improving the conditions for living systems, either social or ecological. In consequence any intervention to prevent and eventually reduce marginality should consider the functionality of the components of the SES and the involved processes. Moreover these efforts need to acknowledge the complexity of SES and therefore adopt systemic principles that allow the identification and characterization of the components, and consideration of the context, boundaries, connectedness, feedback, inflows and outflows as proposed by the 'Ecosystem Approach' (Waltner-Toews et al. 2008), and further elaborated by Gatzweiler et al. (2011) in the context of social marginality.

4.4 Outlook

We have discussed basic biological, ecological, and social dimensions of marginality from a systems perspective. We support the assertion that understanding human-environmental interrelationships demands a broader conceptualization such as the SES concept. Furthermore, marginalization appears difficult to reverse once complex systems have produced states which are far outside of normal homeostatic ranges. One way to combat marginalization is to increase the resilience and adaptability of the SES. This can be done (e.g., by valuation, feedback, and monitoring), however, multiple needs must be considered at the same time that refer to the ideal condition for human and non-human life to prevail, mainly: food security, income generation, energy provision, and the maintenance of diversity. Research on marginality in the context of interlinked, complex, and dynamic socio-ecological systems demand paradigm shifts in scientific disciplines that are beginning to merge. New research networks and funding policies should address marginality by promoting interdisciplinary, systems-based, and practical (problem-solving) approaches to provide better decision-making arguments.

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Communication **Open Access**

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Ecosystem services for connecting actors – lessons from a symposium

Abstract: This paper is a communication from the corresponding symposium at the Global Land Project Open Science Meeting, Berlin, March 2014. We explored the assumption that the ecosystem services-(ES) concept has the potential to support communication and collaboration between actors in land use planning. If true, the concept could facilitate collaborative planning processes. We analyse how to evolve a planning context in which governance networks at the local landscape level gain importance in decision making, while the central government delegates power. From case studies presented during the symposium we learned that the ES-concept has been explored for application in local land use planning around the world. However, whether ES are recognized as a useful planning concept depends on individual actor preferences and cultural and contextual factors, such as the actual nature-human relationship and gender differences. Also, successful application requires the support of novel assessment, design and visualization tools, which are designed to foster collaboration and social learning. The potential of the concept to contribute to collaborative relationships needs further investigation.

Keywords: Local land use planning, community-based learning, governance networks, market mechanism, individual and cultural variation, perception of value

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1 Introduction

The concept of ecosystem services (ES) has the potential to develop as a basis for integrative assessment approaches that foster a shared focus on common values provided by ecosystems [1,2]. Beyond its usefulness for assessing values of natural assets in land use systems, the ES-concept (as well as the related landscape service concept as proposed by Termorshuizen & Opdam [3] has the potential to be used as a reference for collective action. Therefore it may support decision-making about balancing landscape values and vision building in social-ecological systems [4,5]. Ruckelshaus et al. [6] have analysed the use of the ES-concept in a series of spatial planning cases in which decisions were primarily made by governments. Although they conclude that the ES-concept definitely has potential to influence investments and development around the globe, our insights into how the use of ES affects decision-making are still in its early days.

In this paper, we draw upon a session held during the Open Science Meeting of the Global Land Project in Berlin, March 2014. In this session, "Ecosystem services for connecting actors", we explored possible answers to the question: How do ES connect people in land change processes and facilitate collaborative action for common values? We recognized that although most land-use planning approaches make use of target systems that show parallels to the ES-concept [7], the concept as such is not yet widely applied in planning practice [5,8]. Possible reasons for this lack of acceptance, such as differences in terminology, the emphasis on existing assessment methods and economic values, and the dominant scale of application, have been suggested [3,9], or explored in interviews with practitioners [10].

Several authors have suggested that the ES-concept has a potential to facilitate land-use planning and landscape governance. Arguments have been based on assumptions that the concept would facilitate knowledge exchange between actors, connect actors at different levels of spatial and governance scale, help to balance between private and common needs or build consensus about planning objectives [11, 12]. Also, the added value of using ES in land-use planning has been associated with revealing multiple benefits and trade-offs of land change decisions at the micro-scale and macro-scale [13,14]. Due to the fact that most ES depend on the spatial configuration of landscape elements and land-use patterns, the concept may help individual actors to understand how actions on their properties may contribute to common landscape level benefits ([3,15]. Because of these benefits, the ES-concept has a potential advantage in collaborative approaches for common goal-setting and finding acceptable and effective solutions that match the local landscape context. These new planning approaches require scientific tools that foster integration of disciplinary knowledge, the development of social networks, collaboration at the landscape level, use of local knowledge and social learning [16,17]. Such steps towards operationalising the ES-concept are addressed as part of recent research undertakings, e.g. OPERAs (http://operas-project.eu) and OPENNESS http://www.openness-project.eu)

Fifty to sixty people attended the symposium, where 10 short talks were presented addressing new challenges in ecosystem service research. In order to take full benefit of the potential for the ES-concept to connect actors and facilitate collective action, it is essential to learn from cases where this concept was used. We first summarize the symposium planning context. We developed the symposium starting with basic topics regarding use and awareness of ES, then focusing on the required level of knowledge to apply ES in collaborative planning and the availability of adequate frameworks and tools, and finally discussing the role of the ES-concept in fostering collaborative relations. The reason for this sequence is the assumption that the ES-concept needs to be understood and adequately supported by scientific tools in order to facilitate collaboration between different actor groups.

2 The planning context for using the ES-concept is changing

The audience acknowledged that most ES research to date is focussed on conservation issues and application at the international and national policy level. One popular current topic concerns mapping the actual provisioning of services, while others consider impact or policy assessment methods and economic valuation. Such work is reported to have an impact on policy agendas and policy planning [18,19]. This impact cannot be regarded as independent of how scientists are engaged in the policy processes. Based on a comparative analysis of cases, Ruckelshaus et al. [6] concluded that the way how scientists interact with policy makers is often of greater importance than the quality of information and tools brought to the interactions.

However, the planning context for applying ES information is changing. Policy is shifting from hierarchical implementation with the government as a powerful actor towards multi-actor governance modes [20]. As governments identify the need to decentralize their power and responsibilities to lower governance levels (e.g. EU Water Framework Directive; [21]), the mandate to more intensively involve local actors in planning to increase acceptance and support grows. For example, in the participatory democracy of Switzerland, an ES-based tool has recently been developed to support a collaborative planning processes for implementing a revision of their spatial regulation law (www.palm.ethz.ch). Governance concepts such as adaptive management, adaptive co-management and community-based environmental planning [22,23,16] advocate active roles for local land owners and users in decision-making about preferred future landscapes and measures to develop these roles.

For the application of scientific information about ES, this shift in planning means a change of end users from governmental administrators towards land owners, managers and a wide range of potential users. Also, it means a change of the character of the planning process the information has to contribute to, and of the level of spatial scale of planning [17]. Cooperation between a variety of actors involved in land management, including citizens, farmers' collectives, municipalities and enterprises, becomes a key issue. This governance change brings up questions about the added value of using the ES-concept as a conceptual model in land use planning [24].

A German case study (presented by Albert) showed that a differentiated analysis of provided cultural ES, recreational infrastructure and the actual use of cultural ES delivers information complementary to what the standard methods of land use planning tend to provide. Innovative aspects are, for example, an eased identification of places in need for planning interventions, the introduction of benchmarks in the planning process, and an approach for trade-offs between planning alternatives. These aspects are a potential advantage from the point of view of developing a shared vision of priorities to adapt the landscape to future needs. La Rosa's presentation focused on experiences of the use of ES in Italian urban planning processes, highlighting the limited integration of ES. According to a web-based review of land-use plans in Italy, ES have been integrated in a few Strategic Environmental Assessments for local land-use planning and in a couple of regional planning laws, but without relevant and tangible examples. He suggested that particular issues for these urban landscapes, such as the high pressure from private land owners, the limited financial resources by local municipalities and the need of fine scale decisions about land-use assets, might make the use of ES-concept more challenging. He called for a more wide inclusion of the ES-concept in regional planning laws and the integration of different land-use planning tools (e.g. Transfer of Development Rights, Incentive-based approaches for managing urban growth and/or protect open spaces as ES providers) to achieve more efficient results in urban planning contexts [25].

3 Awareness and understanding of ES

The use of the ES-concept in collaborative land use planning is still in its early days. A case study in Waterloo Region, Ontario, Canada, reported by Parker, highlights the potential for the ES-concept to enhance communication and increase support for measures that protect green infrastructure and the provision of ES. The Region has designed policies to address several management challenges: storm water management fees and incentives programs, tree removal to control tree canopy damage from the Emerald Ash Borer, protection of agricultural land and endangered species, and land-use planning and growth controls to protect ground-water recharge. Although these programs protect ES, the concept is not invoked. Lively public debates around these programs centres on how to evaluate trade-offs between these competing goals to allocate increasingly scarce budget resources. Although scientifically grounded information enters these debates, a clear voice for the public good aspects of ES values is absent. Use of the ES concept might well enhance the perception of stakeholders value of the protected resources and provide a conceptual framework for evaluating trade-offs between them. The concept is increasingly used at the provincial level at the Ministry of Natural Resources, with staff reporting that its use enhances their ability to argue for resource protection.

Various factors may inhibit the introduction of ES in land use planning. One reason for not actively demanding ES was suggested by Termorshuizen and Opdam [3], who argued that the term ES was associated with conservation and protected nature. They suggested the term landscape services for use in collaborative planning. The terminology used in local applications needs to be adapted to the context, and the language must be chosen carefully to pick-up the stakeholders starting from their socio-cultural context. During the symposium, Schmidt and Walz reported that values differed notably whether visitors to the Pentland Hills Regional Park in Scotland were asked about their personal values of ES or shared values for society. Local actors were well aware that the landscape provides specific regulating, provisioning and cultural ES and valued all these services highly when asked for the shared/societal value. Local actors gave lower values to regulating and provisioning services, when they were asked about personal values and the benefits they obtained from the Pentland Hills. Benefits received through cultural ES for the near-by citizens of Edinburgh distinctly dominated the overall valuation, with a clear emphasis on services that supported both well-being through physical exercise and nature experience.

Whether potential services are recognized as important may also depend on the cultural background and economic development of a community. Explorative research in West Africa, reported by Kleemann and Fürst at the symposium, about the recognition of the concept among planners, agricultural consultants, scientists and policy makers raised a lively discussion about the use of the ES-concept as such and how it is operationalized in land use planning. It was questioned whether the absence of the recognition of cultural services was due to the way the concept was introduced or due to limitations to recognize the concept as legitimite by a society that suffers from sincere daily survival pressures. By contrast, in the Pentland Hills Scottish community reported on by Schmidt and Walz, the personal value attributed to cultural ES was high, not only among regional experts but also among the local population. This reflects very well the actual use of the Regional Park and the benefits it provides for the city of Edinburgh and its surroundings.

Another aspect to consider when organizing collaborative stakeholder processes is that the recognition of and preferences for ecosystem services are dependent on personal characteristics. A study presented by Villamor in South-East Asia and West-Africa revealed in particular the impact of gender differences. Such gender specificity in response to land-use options, agents and desirable goods or services has so far received little attention [26].

These examples show that the recognition of and preferences for ES in collaborative planning processes depend on how the information is framed in relation to the variable mind sets of actors. The formulation and terminology used is conditional on the role which the ES-concept plays in connecting actors. While this seems to be pivotal to the application of the ES-concept, little is known about how ES-based information is understood by actors with different background and interests.

4 Frameworks and tools

Evidently, the current focus in ES-research is on its application in policy and conservation planning [27]. Recent publications have advocated the development of ES-knowledge and tools towards application in multi-stakeholder communities at the local landscape level [17]. For example, von Haaren et al. [28] discussed the suitability of current ES approaches in environmental planning and decision contexts at the local and regional scale and proposed an adapted ES cascade for improved application. It was also recognized that, while socio-cultural services are rated as highly important in enquiries among landscape users, this category of services only recently became better represented in scientific analysis [29,30,31].

With respect to tools that support such market based planning processes, the diagnosis and valuation tools which are produced in the mainstream of ES research [6] need to be scaled down and specified to individual stakeholder perceptions of value. Liu and Opdam [32] argue that the perception of values is created through a social process, which means that valuation tools have to be flexible enough to foster the evolution of value perception in the course of the planning process and thereby facilitate collective learning. The need for novel methods that foster social interaction in multi-actor groups is not limited to assessments, but should also consider different phases in the planning process in which common vision building and problem-solving approaches are important. An example of such an approach was given at the symposium by Grêt-Regamey in the frame of a collaborative planning process for rehabilitating the Ciliwung River in Jakarta, Indonesia [33]. In a first step, preferences of location and water-related ES values were assessed in a discrete choice experiment. The expressed ES-preferences were linked to computational parametric design methods with hydrodynamic models providing design outputs that were readily accessible to stakeholders and members of the public.

5 Enhancing collaboration

Does the ES-concept enhance collaboration if information about ES is understood as relevant and legitimate by local actors, and application is supported by participatory methods? Does it serve as an umbrella for people with widely different interests to discover shared interests of the functioning of the landscape to foster communication and collaboration? This potential power of the concept in social interactions has not yet been investigated systematically.

A possible issue to explore is the role the concept could play as a boundary object [34,35], because it can be given different meanings by actors with different backgrounds and mind-sets, but still serve as a common ground in discussions and negotiations. Such a role was found in an analysis of three Dutch case studies by Opdam et al. [36], a role supposedly accentuated by linking the ES-concept to a second concept “Green infrastructure”. Green infrastructure is the network of (semi-)natural landscape elements, which serve as a common object of physical landscape adaptation. Collaboration was observed in the various phases of the planning process: problem analysis, goal setting, developing solutions and implementation. The study also concluded that the application of the ES-concept was linked to the participatory approach and tools that researchers have applied. At the symposium, this dependency on the way the information is presented and integrated in collaborative planning activities was highlighted by Grêt-Regamey. 3D visualizations were integrated into interactive collaborative platforms and assisted in making urban ecosystem services trade-offs explicit for sustainable urban planning [37].

During the symposium, Opdam presented a conceptual model for analysing collaborative relationships in local communities involved in landscape adaptation, suggesting that such a model can be used as the basis of a role-playing game to support the planning process.

This model is based on the assumption that actors consider the landscape as a social-ecological system that can be managed to supply ES in response to a demand

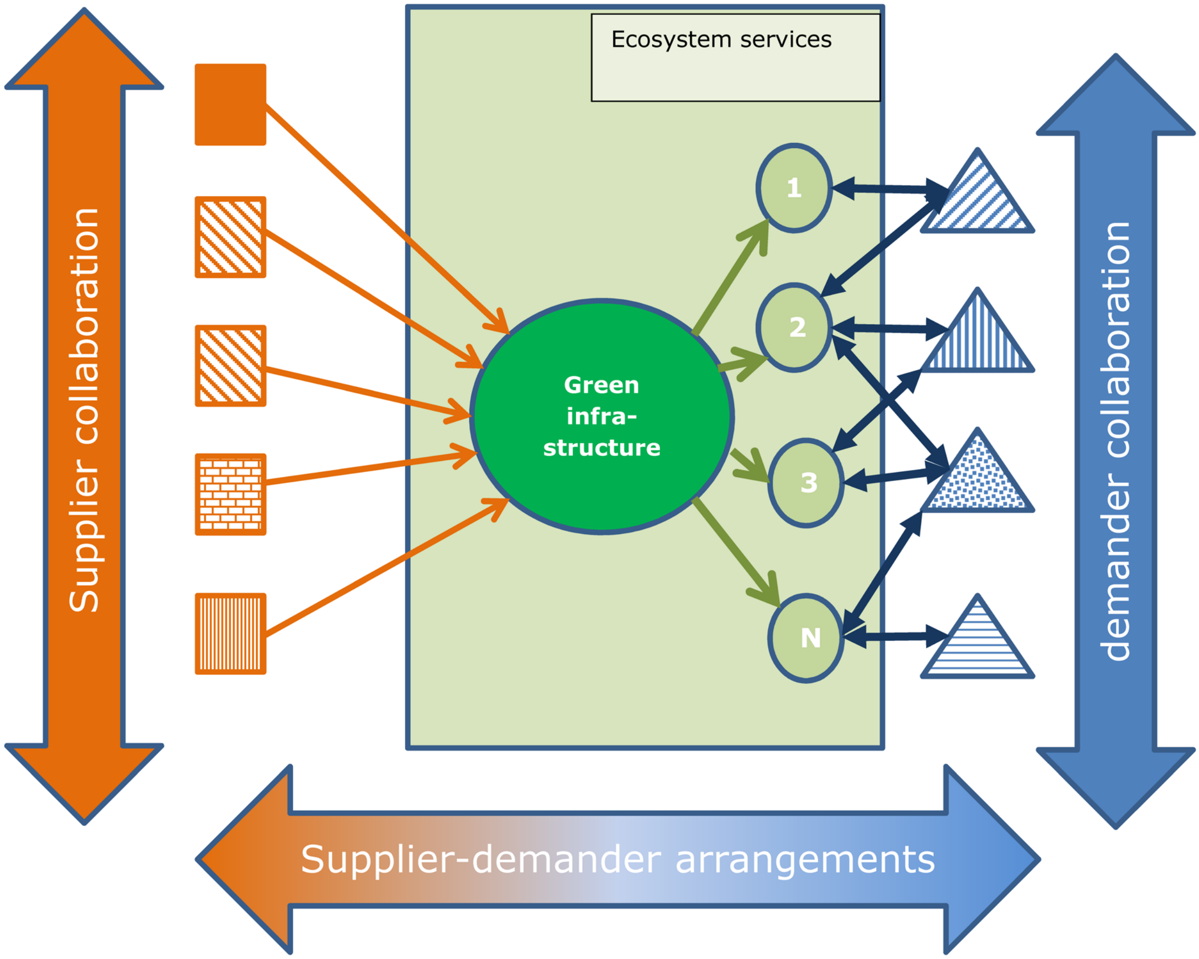

Figure 1: Representation of a virtual social-ecological governance network. Ecosystem services (represented by circles with numbers) link the physical network (green infrastructure) to the values preferred by different demanders (sometimes called beneficiaries), which are the users of the landscape (represented by triangles on the right hand side). Demanders may make arrangements with suppliers of services (land owners, represented by rectangles on the left hand side) to adapt the green infrastructure of the landscape in order to enhance the provision of demanded services. Demander and supplier are roles that actors play. Sometimes one actor plays two roles simultaneously, for example if a farmer demands an increase in pollination service.

for ES-benefits, thus creating a market mechanism of demand and supply. This means that in the social network two roles are to be distinguished: to benefit from using services (demander) and to manage and adapt the provision of services to the demand (supplier) (figure 1). Based on this view, three types of ES-driven collaborative interactions may be established within the social network: firstly, interactions between demanders and suppliers, including negotiations about payments for delivering ES. Secondly, a collective demand for ES. If demanders discover they all benefit from adapting the green infrastructure, their collaboration creates a stronger and economically more promising pull factor for land owners to respond to the demand and adapt the landscape. For example, developing green infrastructure to produce biomass for energy production in a local industry might become economically more profitable if the green infrastructure also ensures a more reliable pollination service (e.g. for growing better strawberries) and improves the attractiveness of the landscape for visitors. A third type of interaction follows from the need to manage ES from a landscape perspective. Raising the level of service provision in response to a demand often requires that land owners coordinate the management of their properties at the landscape scale. For example, the level of species diversity required for a reliable pollination service can only be established in landscape wide areas.

6 Conclusions

The reports presented at the symposium suggest that the added value of applying ES in collaborative planning processes can only be understood in relation to the context of the planning case and the methods applied in the planning process. We summarize the insights from the symposium by the following four conclusions.

– Ecosystem services as such have reached the perception of planners and policy makers in most world regions. However, an unexplored potential of the concept is its role in collaborative land use planning where decisions about landscape development are primarily made in multiple-stakeholder governance networks.
– The role of the ES-concept in multiple-actor planning processes depends on the framing of the information in connection to actors' cultural backgrounds and personal characteristics.
– Using the ES-concept in planning reveals the connection between personal values and public goods (see also [24]) and highlights roles that actors play in the planning process.
– Developing the role of ES in land use planning requires new insights in how actors understand the concept and respond to perceived benefits, and how the concept bridges different mind-frames of actors to facilitate collaboration and social-network building. New interactive methods, for example for valuation and design, may help in developing such insights.

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