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A stakeholder-based modeling approach for assessing the impact of land-use scenarios on ecosystem services in northern Ghana, West Africa

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Executive summary

Background and motivation

The concept of ecosystem services (ES), which characterizes goods and services provided by nature and utilized by people, is appropriate for an examination of the linkages between land-use systems and their multifaceted effects associated with human benefits. Identification of spatial distribution of ES, as well as trade-offs and synergies between ES under different land-use scenarios, can, in particular, provide useful knowledge for developing effective future alternatives. ES approaches for assessing land-use impacts are useful in West Africa, where the majority of the population is highly dependent on natural resources and rain-fed agriculture. Intensifying climate variability increases uncertainty about the sustainable supply of food and raw materials, thereby escalating the vulnerability of the region. Besides, the rapid population growth raises land-use pressures by causing a shortage of arable land and diversification of land-use demand. Although the potential of ES assessments in land-use management and planning to respond to such risks and growing land-use demand has been considered, there are still many challenges to adapt this foreign concept to the regional or local contexts. In addition, compared to other continents, ES related studies are thus far scarce in West Africa. Against this background, this PhD study has explored the potential of the ES concept for understanding land-use systems in northern Ghana. The specific methods and findings were published in peer-reviewed scientific journals (Koo et al., 2018, 2019, 2020), and the contents of this dissertation are based on the three articles as a cumulative format.

Aim, objectives, research hypotheses and research questions

This study aims to propose an integrative ES assessment approach to an analysis of the impact of various land-use scenarios and identification of future recommendations in a local context, through a case study of two adjoining districts, Bolgatanga and Bongo, in northern Ghana. A participatory method and spatial land-use modeling were combined in order to consider locally specific land-use conditions and perspectives, as well as to provide useful information for spatial planning. Specifically, this study focused on 1) identifying ES and indicators for understanding the status of land-use systems in the local context, 2) developing land-use and management scenarios and assessing their impact considering local conditions, and 3) determining future recommendations based on the assessment results and stakeholder feedback. Research hypotheses tested in this study are: i) different future scenarios lead to dissimilar effects presented as trade-offs or synergies between ES; ii) local preferences and perceptions and land-use characteristics influence the district capacity of ES provision. Main research questions addressed in this study are as follows:

- What ES and indicators are most relevant to land-use systems in the study area?
- What are the locally applicable land-use and management scenarios?
- How do future scenarios influence the current land-use system and the status of ES provision?
- What are the effective scenarios for enhancing ES provision and what are the recommended future alternatives for each district?

Data and methods

Two types of data were collected and used in this study. Firstly, local knowledge and perspectives were obtained through stakeholder surveys and reflected in the selection of ES and indicators, in the development of future scenarios, and in the feasibility check of assessment results. Considering the level of influence and interest in agricultural land-use decisions at district level, agricultural extension officers of the Ministry of Food and Agriculture (MOFA) were selected as the most legitimate stakeholder group and involved in the data collection process. Secondly, spatial data such as land-use maps, soil, climate, and topographical data were applied as environmental conditions that influence the status and patterns of ES at district level. The impact of developed scenarios was simulated and assessed using a modeling platform GISCAME that combines Geographic Information System (GIS) and Cellular Automaton (CA) modules, and an ES assessment matrix. Future land-use patterns according to land-use and management scenarios were generated using the CA module that reassigns land-use types to all cells in the district land-use maps according to transition rule-sets. The rule-sets comprised transitional probabilities, and neighboring and environmental conditions provided by the GIS module were elaborated based on stakeholder surveys. Generated future land-use patterns were combined with an assessment matrix that presents the relationship between ES provisioning level and land-use types for an evaluation of the district capacity to provide ES. The results were presented in a spider chart and an ES balance table, which enabled visual comparison of the potential impact of various scenarios indicating synergies or trade-offs between different ES. Based on the modeled results, effective scenarios for enhancing ES for each district were determined. The evaluation results of land-use strategies, in particular, were checked by the local stakeholders regarding their feasibility in the local context, which was used as grounds for identifying future recommendations.

Results

As locally relevant ES related to agricultural activities, the provision of food, fodder, energy (fuel for household usage), construction materials, marketable products, water, and erosion control were determined. Three types of land-use scenarios were developed and assessed: land-use change scenarios, land management scenarios, and land-use strategies as a combination of land management scenarios. First, regarding urbanization and deforestation as land-use change scenarios, the two districts showed similar patterns of influence on ES provision. Urbanization led to a decrease in the provision of most ES except water. Food provision and erosion control, in particular, were largely reduced. As the impact of deforestation, the provision of food, fodder and marketable products was increased or remained constant, while the provision of energy, construction materials, water and erosion control were reduced, as a trade-off. Bongo was slightly more influenced by urbanization than Bolgatanga, while the impact upon deforestation was bigger in Bolgatanga than in Bongo. As land management scenarios, 15 scenarios related to crop intercropping, afforestation, agroforestry and soil conservation were developed and evaluated. Cereal-related scenarios showed the biggest increase in food provision and erosion control, while maize-related management scenarios led to relatively minor impact on the provision of overall ES in both districts. Intercropping cereals/maize with mango as agroforestry management scenarios were assumed to bring negative impact on food provision in Bolgatanga, whereas they were expected to increase the ES in Bongo. Water provision was declined by most land management scenarios in both districts. In terms of land-use strategies which combined different agricultural management practices, 75 land-use strategies were elaborated and assessed. As the cumulative impact of management options comprising each strategy was assumed, greater synergies and trade-offs between different ES were derived by land-use strategies compared to a single land management scenario. According to the assessment results, 14 best strategies in Bolgatanga and 8 best strategies in Bongo were identified, which can provide more than three different ES with the highest potential. Among the best land-use strategies, future recommendations were determined considering their feasibility based on feedback from the stakeholders. For instance, strategy 61 (a combination of windbreak on cereals, crop intercropping on maize and legumes, and afforestation on grassland and mixed vegetation) in Bolgatanga and strategy 46 (a combination of soil or stone bunds on cereals, crop intercropping on maize and legumes, and afforestation on grassland and mixed vegetation) in Bongo were identified as locally-tailored recommendations.

Discussion

The selected ES and indicators based on the local perception facilitated reflection on the multifunctionality of the actual land-use systems. However, there is a limit when addressing some ES that are crucial but difficult regarding the perception of their status, such as climate regulating service. The characteristics of land-use patterns and local perceptions led to similarity and dissimilarity in the land-use change impacts between the districts. Specifically, Bongo which has scattered patterns of bare/artificial surfaces was more influenced by urbanization than Bolgatanga, which has a concentrated pattern due to the proximity effect of the conversion. As cereals are most largely cultivated among staple crops in both districts, the types of scenarios applied to cereal fields were highly influential in the district capacity of ES provision, e.g. cereal-dominant intercropping significantly enhanced food provision, whereas agroforestry scenarios applied in cereals were less effective. The discrepancy in preferred scenarios for enhancing ES between the districts, e.g., cereal-dominant intercropping in Bolgatanga and leucaena agroforestry in Bongo for the better provision of fodder and erosion control, resulted in different scenario impacts at district level. Water provision decreased noticeably in most land management scenarios and land-use strategies as a trade-off with the increase of other ES. This can be attributed to the definition of water provision focusing on the competition for water availability between land cover types and human uses. However, the contribution of woody and crop fields with high surface water demand to atmospheric moisture, which positively affects water provision in the long run, should also be considered, especially in semi-arid West Africa. The applied participatory approach has advantages in terms of identifying and developing locally pertinent ES and future scenarios, which can increase the acceptability of assessment results. On the other hand, subjective data based on local perceptions could be criticized for their reliability. The spatially-explicit modeling approach applied in this study enabled to integrate local perceptions with the spatial peculiarity of ES provision. Quantified and visualized results enhanced the understanding of the impacts of different land-use decisions. However, the dynamics of interactions between land-use decisions and ES status were simplified due to the limited field data and modeling capacity. In addition, multi-scale interactions, e.g., the influence of district level decisions on farm level conditions were not considered in this study.

Conclusions

This study integrated local knowledge into a land-use modeling approach for assessing and comparing the impact of various land-use scenarios on ES provision in two districts, Bolgatanga and Bongo in northern Ghana. Key findings of this study are: i) participation of the local stakeholders allowed identification of locally relevant ES and indicators, and development of future scenarios and simulation conditions in reference to local preferences and land-use characteristics; ii) developed scenarios led to synergies or trade-offs between ES, and such scenario impacts showed similarity and dissimilarity between the districts due to local perceptions and spatial characteristics of land-use activities; iii) dissimilar future recommendations between the districts emphasized the importance of local conditions and perspectives in land-use management. The findings of this study provide insight into how to design a locally tailored decision-supporting framework for future land-use planning from a transdisciplinary perspective. For better use of ES assessment in actual land-use planning in the context of West Africa and Ghana, further researches should be conducted to identify the types of ES relevant information required by decision-makers, and to establish ES evaluation standards harmonized with existing decision-making structures.

Zusammenfassung

Hintergrund und Motivation

Das Konzept der Ökosystemleistungen (ES), das die von der Natur bereitgestellten und vom Menschen genutzten Güter und Leistungen charakterisiert, ist geeignet die Zusammenhänge zwischen Landnutzungssystemen und ihren vielfältigen Auswirkungen im Zusammenhang mit dem menschlichen Nutzen zu untersuchen. Insbesondere die Identifizierung der räumlichen Verteilung von ES sowie von Kompromissen und Synergien zwischen ES unter verschiedenen Landnutzungsszenarien kann nützliches Wissen für die Entwicklung effektiver künftiger Alternativen liefern. ES-Ansätze zur Bewertung von Landnutzungsauswirkungen sind in Westafrika sinnvoll, wo die Mehrheit der Bevölkerung in hohem Maße von natürlichen Ressourcen und Regenfeldbau abhängig ist. Die zunehmende Klimavariabilität erhöht die Unsicherheit über die nachhaltige Versorgung mit Nahrungsmitteln und Rohstoffen und steigert damit die Verwundbarkeit der Region. Außerdem erhöht das schnelle Bevölkerungswachstum den Druck auf die Landnutzung, indem es zu einer Verknappung von Ackerland und einer Diversifizierung der Landnachfrage führt. Obwohl das Potenzial von ES-Bewertungen im Landnutzungsmanagement und in der Planung berücksichtigt wurde, um auf solche Risiken und den wachsenden Landnutzungsbedarf zu reagieren, gibt es immer noch viele Herausforderungen bei der Anpassung dieses ausländischen Konzepts an die regionalen oder lokalen Gegebenheiten. Darüber hinaus gibt es in Westafrika im Vergleich zu anderen Kontinenten bisher nur wenige Studien zu ES. Vor diesem Hintergrund untersuchte diese PhD-Studie das Potenzial des ES-Konzepts für das Verständnis des Landnutzungssystems im Norden Ghanas. Die spezifischen Methoden und Ergebnisse wurden in wissenschaftlichen Fachzeitschriften mit Peer-Review veröffentlicht (Koo et al., 2018, 2019, 2020), und der Inhalt dieser Dissertation basiert auf den drei Artikeln als kumulatives Format.

Zielsetzung und Forschungsfragen

Diese Studie zielt darauf ab, einen integrativen ES-Bewertungsansatz vorzuschlagen, um die Auswirkungen verschiedener Landnutzungsszenarien zu analysieren und künftige Empfehlungen in einem lokalen Kontext zu identifizieren, und zwar anhand einer Fallstudie von zwei benachbarten Distrikten, Bolgatanga und Bongo, im Norden Ghanas. Eine partizipative Methode und räumliche Landnutzungsmodellierung wurden kombiniert, um lokal spezifische Landnutzungsbedingungen und -perspektiven zu berücksichtigen sowie nützliche Informationen für die Raumplanung zu liefern. Konkret konzentrierte sich diese Studie auf 1) die Identifizierung von ES und Indikatoren für das Verständnis des Status von Landnutzungssystemen im lokalen Kontext, 2) die Entwicklung von Landnutzungs- und Managementszenarien und die Bewertung ihrer Auswirkungen unter Berücksichtigung der lokalen Bedingungen und 3) die Festlegung zukünftiger Empfehlungen auf der Grundlage der Bewertungsergebnisse und des Feedbacks der Interessenvertreter. Die in dieser Studie getesteten Forschungshypothesen sind: i) verschiedene Zukunftsszenarien führen zu unterschiedlichen Effekten, die als Kompromisse oder Synergien zwischen ES dargestellt werden; ii) lokale Präferenzen und Wahrnehmungen sowie Landnutzungsmerkmale beeinflussen die Bezirkskapazität der ES-Bereitstellung. Die wichtigsten Forschungsfragen, die in dieser Studie behandelt werden, sind die folgenden:

- Welche ES und Indikatoren sind für die Landnutzungssysteme im Untersuchungsgebiet am wichtigsten?
- Was sind die lokal anwendbaren Landnutzungs- und Managementszenarien?
- Wie beeinflussen die Zukunftsszenarien das aktuelle Landnutzungssystem und den Status der ES-Versorgung?

- Was sind die effektiven Szenarien zur Verbesserung der ES-Versorgung und was sind die empfohlenen zukünftigen Alternativen für jeden Distrikt?

Daten und Methoden

In dieser Studie wurden zwei Arten von Daten gesammelt und verwendet. Erstens wurden lokales Wissen und Perspektiven durch Befragungen von Interessenvertretern gewonnen und bei der Auswahl von ES und Indikatoren, der Entwicklung von Zukunftsszenarien und der Machbarkeitsprüfung der Bewertungsergebnisse berücksichtigt. In Anbetracht des Einflusses und des Interesses an landwirtschaftlichen Landnutzungsentscheidungen auf Distrikt-Ebene wurden die landwirtschaftlichen Berater des Ministeriums für Ernährung und Landwirtschaft (MOFA) als die legitimste Stakeholder-Gruppe ausgewählt und in den Datenerhebungsprozess einbezogen. Zweitens wurden räumliche Daten wie Landnutzungskarten, Boden-, Klima- und topografische Daten als Umweltbedingungen verwendet, die den Status und die Muster von ES auf Distrikt-Ebene beeinflussen. Die Auswirkungen der entwickelten Szenarien wurden mit Hilfe der Modellierungsplattform GISCAME simuliert und bewertet, die Module des Geographischen Informationssystems (GIS) und des Zellulären Automaten (CA) sowie eine ES-Bewertungsmatrix kombiniert. Künftige Landnutzungsmuster gemäß Landnutzungs- und Managementszenarien wurden mit dem CA-Modul generiert, das allen Zellen in den Landnutzungskarten des Distrikts gemäß Übergangsregelsätzen Landnutzungstypen neu zuordnet. Die Regelsätze, die sich aus Übergangswahrscheinlichkeiten und Nachbarschafts- und Umweltbedingungen zusammensetzen, die vom GIS-Modul zur Verfügung gestellt werden, wurden auf der Grundlage von Befragungen von Interessengruppen ausgearbeitet. Die generierten künftigen Landnutzungsmuster wurden mit einer Bewertungsmatrix kombiniert, die die Beziehung zwischen der ES-Versorgung und den Landnutzungsarten darstellt, um die Kapazität des Distrikts zur ES-Versorgung zu bewerten. Die Ergebnisse wurden in einem Spinnendiagramm und einer ES-Bilanztabelle dargestellt, die es ermöglichten, die potenziellen Auswirkungen verschiedener Szenarien visuell zu vergleichen und Synergien oder Kompromisse zwischen verschiedenen ES aufzuzeigen. Basierend auf den modellierten Ergebnissen wurden effektive Szenarien zur Verbesserung der ES für jeden Distrikt bestimmt. Insbesondere die Bewertungsergebnisse der Landnutzungsstrategien wurden von den lokalen Interessenvertretern hinsichtlich ihrer Machbarkeit im lokalen Kontext überprüft, was als Grundlage für die Identifizierung künftiger Empfehlungen diente.

Ergebnisse

Als lokal relevante ES im Zusammenhang mit landwirtschaftlichen Aktivitäten wurden die Bereitstellung von Nahrung, Futter, Energie (Brennstoff für den Hausgebrauch), Baumaterialien, marktfähigen Produkten, Wasser und Erosionsschutz ermittelt. Es wurden drei Arten von Landnutzungsszenarien entwickelt und bewertet: Landnutzungsänderungsszenarien, Landmanagementszenarien und Landnutzungsstrategien als Kombination von Landmanagementszenarien. Erstens zeigten die beiden Distrikte in Bezug auf Urbanisierung und Entwaldung als Szenarien der Landnutzungsänderung ähnliche Muster des Einflusses auf die Bereitstellung von ES. Die Urbanisierung führte zu einem Rückgang der Bereitstellung der meisten ES außer Wasser. Vor allem die Bereitstellung von Nahrung und der Erosionsschutz wurden weitgehend zurückgenommen. Als Auswirkung der Abholzung wurde die Bereitstellung von Nahrungsmitteln, Futtermitteln und marktfähigen Produkten erhöht oder blieb konstant, während die Bereitstellung von Energie, Baumaterialien, Wasser und Erosionsschutz als Kompromiss zurückging. Bongo war etwas stärker von der Urbanisierung beeinflusst als Bolgatanga, während die Auswirkungen der Entwaldung in Bolgatanga größer waren als in Bongo. Als Landmanagementszenarien wurden 15

Szenarien in Bezug auf Zwischenfruchtanbau, Aufforstung, Agroforstwirtschaft und Bodenschutz entwickelt und bewertet. Getreidebezogene Szenarien, z. B. getreidedominanter Zwischenfruchtanbau und Erd- oder Steinböschung auf Getreide, zeigten die größte Steigerung der Nahrungsversorgung und des Erosionsschutzes, während maisbezogene Bewirtschaftungsszenarien zu relativ geringen Auswirkungen auf die Bereitstellung von ES insgesamt in beiden Distrikten führten. Der Zwischenfruchtanbau von Getreide/Mais mit Mango als Agroforst-Management-Szenario sollte in Bolgatanga negative Auswirkungen auf die Nahrungsmittelversorgung haben, während in Bongo eine Erhöhung der ES erwartet wurde. Die Wasserversorgung wurde durch die meisten Landmanagementszenarien in beiden Distrikten verschlechtert. In Bezug auf Landnutzungsstrategien, die verschiedene landwirtschaftliche Bewirtschaftungsmethoden kombinierten, wurden 75 Landnutzungsstrategien ausgearbeitet und bewertet. Da die kumulative Wirkung von Managementoptionen, die jede Strategie umfassen, erwartet wurde, wurden größere Synergien und Kompromisse zwischen verschiedenen ES durch Landnutzungsstrategien im Vergleich zur Anwendung eines einzelnen Landmanagementszenarios abgeleitet. Gemäß den Bewertungsergebnissen wurden 14 beste Strategien in Bolgatanga und 8 beste Strategien in Bongo identifiziert, die mehr als drei verschiedene ES mit dem höchsten Potenzial bieten können. Unter den besten Landnutzungsstrategien wurden künftige Empfehlungen unter Berücksichtigung ihrer Machbarkeit auf der Grundlage des Feedbacks der Interessenvertreter festgelegt. So wurden beispielsweise Strategie 61 (eine Kombination aus Windschutz bei Getreide, Zwischenfruchtanbau bei Mais und Leguminosen und Aufforstung von Grasland und Mischvegetation) in Bolgatanga und Strategie 46 (eine Kombination aus Erd- oder Steinböschung bei Getreide, Zwischenfruchtanbau bei Mais und Leguminosen und Aufforstung von Grasland und Mischvegetation) in Bongo als lokal zugeschnittene Empfehlungen identifiziert.

Diskussionen

Die ausgewählten ES und Indikatoren, die auf der lokalen Wahrnehmung basieren, ermöglichten es, die Multifunktionalität der tatsächlichen Landnutzungssysteme widerzuspiegeln. Es gibt jedoch eine Einschränkung bei der Berücksichtigung einiger ES, die zwar wichtig sind, deren Status aber von den Interessenvertretern nur schwer wahrgenommen werden kann, wie z. B. klimaregulierende Leistungen. Die Charakteristika der Landnutzungsmuster und die lokalen Wahrnehmungen führten zu Ähnlichkeiten und Unterschieden in den Auswirkungen von Landnutzungsänderungen zwischen den Distrikten. Insbesondere Bongo, das verstreute Muster von kahlen/künstlichen Flächen aufweist, wurde durch die Urbanisierung stärker beeinflusst als Bolgatanga, das ein konzentriertes Muster aufweist, was auf den Näheffekt der Umwandlung zurückzuführen ist. Da Getreide unter den Grundnahrungsmitteln in beiden Distrikten am meisten angebaut wird, hatten die Arten von Szenarien, die auf Getreidefeldern angewandt wurden, einen großen Einfluss auf die Fähigkeit des Distrikts zur ES-Versorgung; der getreidedominierte Zwischenfruchtanbau z.B. verbesserte die Nahrungsversorgung signifikant, während Agroforstszenarien, die auf Getreidefeldern angewandt wurden, weniger effektiv waren. Die Diskrepanz in den bevorzugten Szenarien zur Verbesserung der ES zwischen den Distrikten, z.B. getreidedominanter Zwischenfruchtanbau in Bolgatanga und Leucaena-Agroforstwirtschaft in Bongo zur besseren Versorgung mit Futter und Erosionsschutz, führte zu unterschiedlichen Auswirkungen der Szenarien auf Distriktebene. Die Wasserversorgung wurde durch die meisten Landmanagementszenarien und Landnutzungsstrategien erheblich verringert, was mit einer Zunahme anderer ES einherging. Dies kann auf die Definition der Wasserversorgung zurückgeführt werden, die sich auf die Konkurrenz um die Wasserverfügbarkeit zwischen Landbedeckungstypen und menschlichen Nutzungen konzentriert. Allerdings sollte auch der Beitrag von Wald- und Ackerflächen mit hohem Oberflächenwasserbedarf zur atmosphärischen Feuchtigkeit berücksichtigt werden, der sich langfristig positiv auf die Wasserbereitstellung auswirkt, insbesondere im semi-ariden Westafrika. Der angewandte partizipative Ansatz hat Vorteile in Bezug auf die Identifizierung und Entwicklung lokal relevanter ES und Zukunftsszenarien, was die Akzeptanz der Bewertungsergebnisse erhöhen kann. Auf der anderen Seite könnten subjektive Daten, die auf lokalen Wahrnehmungen basieren, hinsichtlich ihrer Zuverlässigkeit kritisiert werden. Der in dieser Studie angewandte räumlich-explizite Modellierungsansatz ermöglichte es, lokale Wahrnehmungen mit der räumlichen Besonderheit der ES-Versorgung zu integrieren. Quantifizierte und visualisierte Ergebnisse verbesserten das Verständnis für die Auswirkungen verschiedener Landnutzungsentscheidungen. Die Dynamik der Wechselwirkungen zwischen Landnutzungsentscheidungen und dem ES-Status wurde jedoch aufgrund der begrenzten Felddaten und Modellierungskapazität vereinfacht. Darüber hinaus wurden Wechselwirkungen auf mehreren Ebenen, z. B. der Einfluss von Entscheidungen auf Distrikt-Ebene auf die Bedingungen auf Betriebsebene, in dieser Studie nicht berücksichtigt.

Schlussfolgerungen

Diese Studie integrierte lokales Wissen in einen Landnutzungsmodellierungsansatz, um die Auswirkungen verschiedener Landnutzungsszenarien auf die ES-Versorgung in zwei Distrikten, Bolgatanga und Bongo im Norden Ghanas, zu bewerten und zu vergleichen. Die wichtigsten Ergebnisse dieser Studie sind: i) Die Beteiligung der lokalen Interessenvertreter ermöglichte es, lokal relevante ES und Indikatoren zu identifizieren und Zukunftsszenarien und Simulationsbedingungen unter Berücksichtigung lokaler Präferenzen und Landnutzungsmerkmale zu entwickeln; ii) Die entwickelten Szenarien führten zu Synergien oder Kompromissen zwischen ES, und solche Szenarioauswirkungen zeigten Ähnlichkeiten und Unterschiede zwischen den Distrikten aufgrund lokaler Wahrnehmungen und räumlicher Merkmale der Landnutzungsaktivitäten; iii) Unterschiedliche Zukunftsempfehlungen zwischen den Distrikten betonten die Bedeutung lokaler Bedingungen und Perspektiven im Landnutzungsmanagement. Die Ergebnisse dieser Studie geben einen Einblick, wie ein lokal zugeschnittener entscheidungsunterstützender Rahmen für die künftige Landnutzungsplanung aus transdisziplinärer Perspektive gestaltet werden kann. Für eine bessere Nutzung der ES-Bewertung in der tatsächlichen Landnutzungsplanung im Kontext von Westafrika und Ghana sollten weitere Untersuchungen durchgeführt werden, um die Arten von ES-relevanten Informationen zu identifizieren, die von Entscheidungsträgern benötigt werden, und ES-Bewertungsstandards zu etablieren, die mit der bestehenden Entscheidungsstruktur harmonisiert sind.

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BMBF	German Federal Ministry of Education and Research
CA	Cellular Automaton
ES	Ecosystem Services
GIS	Geographic Information System
LUT	Land Use Type
MOFA	Ministry of Food and Agriculture of Ghana
SC	Scenario
TRMM	Tropical Rainfall Measuring Mission
UER	Upper East Region
USGS	The United States Geological Survey
WASCAL	West African Science Service Center on Climate Change and Adapted Land Use

1. Introduction

1.1. Background and motivation

'Land' is one of the representative social-ecological systems which are characterized by the interactions and mutual adaptation between human components and environmental components (DeClerck et al., 2016; Kelly et al., 2015). Land-use and management decisions alter the conditions of ecosystems and environment, thereby affecting the benefits for humans who live within the system (Koellner et al., 2013; Mensah et al., 2017; Polasky et al., 2011; Rega et al., 2019). In addition, land-use change can be a result of people's actions to cope with a lack of essential resources or a decrease in the provision of important ecological goods and services related to their interests (Lambin and Meyfroidt, 2010; Pennington et al., 2017). The concept of ecosystem services (ES) has been emphasized in addressing such reciprocal relationships between the status of land systems and human benefits (Martín-López et al., 2017; Mastrangelo et al., 2015; Norton et al., 2016). The spatial linkage of land-use types with ES provision, in particular, has been used as a key approach to evaluate land-use conditions and further explore future land-use alternatives (Burkhard et al., 2014; Koschke et al., 2012; Spake et al., 2017). For example, the assessment of the impact of past and current land-use changes on ES provision was conducted in order to provide guidelines for future land-use schemes and policies (e.g., Huq et al., 2019; Salata et al., 2017). The changing status of multiple ES provision according to future land-use patterns, which were presented as ES trade-offs was quantified and used to determine optimal or suboptimal future scenarios (e.g., Barnett et al., 2016; Clerici et al., 2019; Rimal et al., 2018). ES assessments applied in a spatially explicit way can facilitate integration of the ES concept into land-use planning by providing useful information, e.g., ES hotspots, potential ES mismatches between supply and demand, and optimization of land-use for efficient ES provision (e.g., Bennett et al., 2015; Gómez-Baggethun and Barton, 2013; Lawler et al., 2014; Sumarga and Hein, 2014).

Changes in the conditions of ES suppliers, i.e. land-use systems, affect the well-being and the satisfaction of ES beneficiaries, i.e. land-users, while ES status may vary depending on the perspectives and valuation of ES beneficiaries for ES suppliers (Bagstad et al., 2014; García-Nieto et al., 2013; Spyra et al., 2019; Vallecillo et al., 2018). In addition, local stakeholders as ES beneficiaries hold rich and practical information regarding their environment intimately connected to daily activities, which includes how they actually obtain ES from land-use activities (Mialhe et al., 2015; Mukul et al., 2017; Norton et al., 2016; Reilly et al., 2018; Sanon et al., 2012). Such local knowledge is especially useful to understand the multifunctionality of land-use and landscape systems that provide multiple benefits (Geneletti et al., 2018; Willcock et al., 2016). For instance, agroforestry which combines crops and trees as an inter- or mixed-cropping practice can supply various ES including food, raw materials for fuel and construction, soil erosion control, pest control, and climate regulation (Kumar, 2016; Santos et al., 2019). The level of ES expected to be obtained from specific land-use practice and the utilization patterns of the obtained ES might be different depending on the preferences and experiences of stakeholders, even between communities with similar environmental conditions. In this light, the participation of stakeholders in ES assessments is crucial in order to identify the heterogeneous demands on multifunctional land-use systems and explore efficient ways of providing multiple ES in the specific context (Boumans et al., 2015; Sutherland et al., 2014). Another important aspect of stakeholder participation relates to the generation of ES knowledge pertinent to supporting real-world land-use decisions by sharing the assessment process and findings (Fürst et al., 2014; Kusters et al., 2018; Mastrangelo et al., 2015). Practical solutions to land-use problems associated with specific localities need to be based on the social and natural peculiarity of the region, and the perspectives of people who have been adapting to the changing environment (Norton et al., 2016). Land-use scenarios aiming to elicit solutions or recommendations should consider stakeholders' own foreseeable futures and their desire and ability to adopt new land-use practices (Chowdhury et al., 2016; DeClerck et al., 2016; Lambin and Meyfroidt, 2010). Sharing with stakeholders about potential changes in the quality and quantity of ES as a result of future land-use decisions can raise their awareness of the need for land management to improve the supply of valuable ES (Mastrangelo et al., 2015; Rounsevell and Robinson, 2012). Furthermore, such a stakeholder-based and context-specific result enables the introduction of socially and institutionally feasible land-use policies (Abson et al., 2014; Opdam et al., 2013).

Analysis of land-use impacts using an ES assessment is especially required in West Africa, where the majority of the population is reliant on natural resources and economically active in the agricultural sector. Approximately 70% of the land is utilized for cultivation, which is primarily for rain-fed agriculture (Emmanuel et al., 2016; Jalloh et al., 2013; Sultan and Gaetani, 2016). High reliance on climate-sensitive farming increases vulnerability to climate variability and uncertainty in sustainable food and raw material production (Connolly-Boutin and Smit, 2016; Kleemann et al., 2017). What's more, rapid population growth raises pressures on land-use systems and promotes overuse of natural resources, thereby negatively affecting land productivity in the long run (Douxchamps et al., 2016; Rukundo et al., 2018). This implies that reducing risk and addressing increased land-use demand through adapted and coordinated land-use and resource management is urgent in this region. However, a lack of regional economic and institutional capabilities makes it challenging to appropriately respond to the situation (Sultan and Gaetani, 2016). The possibility of using ES assessments in land-use planning has been raised in the West African context, however, there are still many challenges, such as a lack of awareness and understanding of the ES concept, low public participation, limited access to land resource-related information for proper planning, and a lack of tools and approaches to support practical implementation (Adekola et al., 2015; Inkoom et al., 2017). Compared to Europe, Asia and America, where ES concept and assessment have been applied in various ways for land-use evaluation and planning (e.g., Barnett et al., 2016; Clerici et al., 2019; Huq et al., 2019; Karner et al., 2019; Rimal et al., 2018; Saito et al., 2019; Salata et al., 2017), researches related to ES assessments for understanding land-use conditions and exploring future options are still scarce in West Africa (Boumans et al., 2015). Even the existing ES studies did not consider locally-specific perspectives in the assessment process (e.g., Ahmed et al., 2016; Leh et al., 2013; Salack et al., 2015) or the spatial interlinkage between land-use systems and the status of ES provision (e.g.,Kleemann et al., 2017; Laux et al., 2010; Roudier et al., 2011). Against this background, understanding the status and conditions of land-use system using a locally-tailored ES approach is helpful to provide insight into future pathways in the West African context. Detailed information on the analysis of land-use impact on ES provision is described in the attached papers I, II and III.

This study was conducted as a part of the West African Science Service Center on Climate Change and Adapted Land-use (WASCAL) program funded by the German Federal Ministry of Education and Research (BMBF). Starting as a large-scale West African-German scientific collaboration, WASCAL was designed to tackle climate change-driven issues and enhance the resilience of human-environmental systems vis-à-vis climate variability (https://wascal.org). The result of this study contributed to the output of work package 6.1. Land-use Impact Modeling.

1.2. Objectives, scope and the structure of the thesis

This study aims to suggest an integrative ES assessment approach involving the combination of a participatory method with spatial land-use modeling for analysis of the impact of land-use scenarios and identification of future recommendations in the agricultural context of northern Ghana, West Africa. The main objectives are:

1) Understanding the local context: to identify ES and indicators in order to understand the status of land-use systems in the local context
2) Exploring potential pathways: to develop future scenarios related to land-use change and land management, and assess their impact on land-use patterns and ES provision
3) Implications for future land-use: to determine locally-tailored future recommendations based on the assessment results and stakeholder feedback.

In order to understand the effect of different local perception on land-use decisions, this study was conducted in two adjoining districts located in northern Ghana, which have similar environmental conditions but individual decision-making processes, and compared assessment results between the districts. The following research hypotheses were tested through this study:

RH1) Different future scenarios lead to dissimilar effects presented as trade-offs or synergies between ES.

RH2) Local preferences and perceptions and land-use characteristics influence the district capacity of ES provision.

The specific research questions that were focused on are:

RQ1) What ES and indicators are most relevant to the primary land-use activities in the study area?
RQ2) What are the locally applicable land-use and management scenarios?
RQ3) How do future scenarios influence the current land-use system and the status of ES provision?
RQ4) What are the main factors that lead to different scenario impacts?
RQ5) What are the effective scenarios for enhancing ES provision?
RQ6) What are the recommended future alternatives for each district?
RQ7) What are the advantages and challenges of the applied integrated assessment approach?

The research questions were addressed by the papers published in peer-reviewed scientific journals:

I. **Koo, H**., Kleemann, J., Fürst, C., 2018. Land-use scenario modeling based on local knowledge for the provision of ecosystem services in Northern Ghana, *Land*, 7:59. https://doi.org/10.3390/land7020059

II. **Koo, H**., Kleemann, J., Fürst, C., 2019. Impact assessment of land-use changes using local knowledge for the provision of ecosystem services in Northern Ghana, West Africa, *Ecological Indicators*, 103: 156-172. https://doi.org/10.1016/j.ecolind.2019.04.002

III. **Koo, H**., Kleemann, J., Fürst, C., 2020. Integrating ecosystem services into land-use modeling to assess the effects of future land-use strategies in Northern Ghana, *Land*, 9:379. http://doi.10.3390/land9100379

Paper I focused on assessing the potential impact of locally adapted land management scenarios on the provision of ES. In particular, it clarified the process of selecting ES and indicators which were suitable for interpreting land-use impact (RQ1). Land management scenarios in the agricultural context were elaborated (RQ2) and their potential impacts were spatially assessed and analyzed while taking the local characteristics in to consideration (RQ3 and RQ4). Effective land management scenarios for increasing a specific ES were identified based on the evaluation results (RQ5). In paper II, the impact of urbanization and deforestation as major land-use changes in West Africa on the current status of ES was assessed. The selection process of a legitimate stakeholder group in the study context was described. Transition conditions for simulating the intensification of the land-use changes were elaborated (RQ2), and their impacts on the spatial distribution of land-use types and the consequent changes in ES provision were evaluated (RQ3 and RQ4). Paper III identified future land-use recommendations that are highly feasible in practice while effectively improving multiple ES. Future land-use strategies were elaborated based on the land management scenarios developed in paper I (RQ2), and their impact on ES provision was spatially evaluated and effective strategies for enhancing multiple ES were identified (RQ3 and RQ4). Recommended strategies were determined based on the modeled results and stakeholder feedback (RQ5 and RQ6). Furthermore, a methodological discussion regarding the advantages and challenges of applied methods was addressed in paper III (RQ7).

The following chapters consist of four parts. In the chapter of materials and methods, the methodological framework, the study area, and two key methods of this study which are a participatory approach and a land-use modeling approach are described. The chapter of results includes locally relevant ES, their indicator values and the impact of various future scenarios corresponding to the publications. Since the results of paper I are closely related to the evaluation process of paper III, the results of the papers are presented in the order of paper II, paper I and paper III. Discussions on the findings and the applied methods follow. In the chapter of conclusions and outlook, the summary of the key findings and the follow-up action for increasing the applicability of the ES concept in West Africa are elaborated.

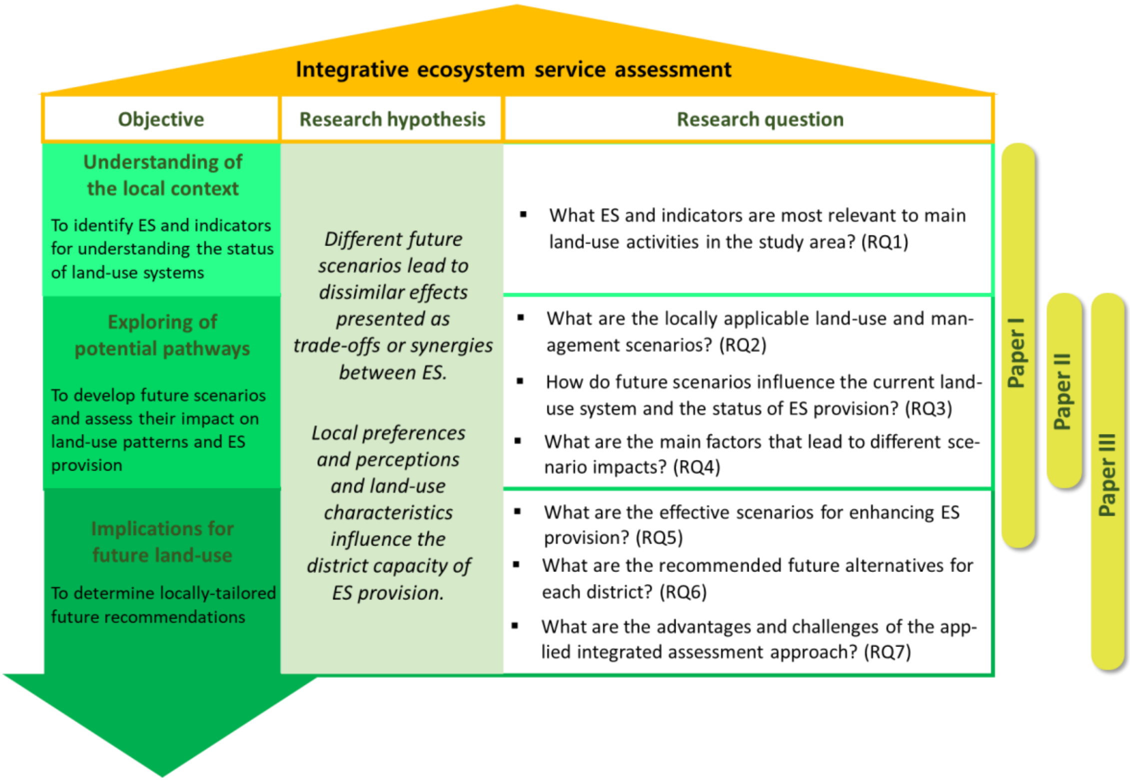


Figure 1. Developmental process of the doctoral thesis and the contributions of publications to address objectives, research hypotheses and research questions.

2. Materials and methods

2.2. Methodological framework

Figure 2 presents the methodological process of this study. Two types of data were collected and applied in this study: local knowledge regarding land-use and management practices, and spatial variables related to environmental characteristics of the case study areas. Local knowledge and perception identified through stakeholder surveys facilitated the determination of ES and indicators relevant to agricultural land-use, future scenarios on land-use change and management, a potential change in ES status depending on different future land-use types, and the feasibility check of assessment results. Spatial data such as land-use maps, climate, soil, and topographical data were used as environmental factors that influence ES status and patterns at district level. A land-use modeling approach was applied to evaluate and visualize the impact of future scenarios on land-use patterns and resultant ES capacity at district level. As assessment results, the impact of various future scenarios (land management scenarios, land-use change scenarios and land-use strategies) on ES provision such as trade-offs and synergies and future recommendations for each district were identified.

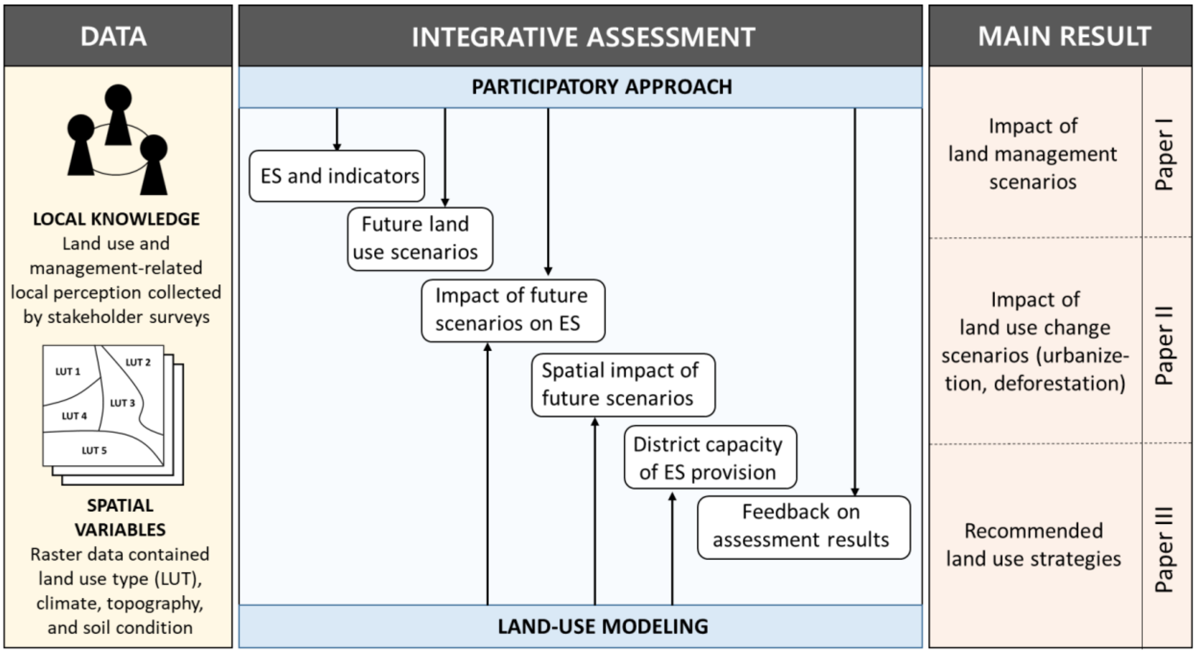


Figure 2. Methodological framework of this study.

2.1. Study area

The study area is located in the Upper East Region (UER) of northern Ghana, which includes two districts called Bolgatanga Municipal (hereafter Bolgatanga) and Bongo (Figure 3). Bolgatanga, as the capital of the UER, is located in the center of the UER, covering a total area of 729km^2. Bongo is bordered by Bolgatanga to the south and Burkina Faso to the north, with a total area of 456 km^2 (Ghana Statistical Service, 2010a, b). These two adjoining districts have similar environmental conditions sharing the Vea watershed. This area belongs to the Guinea Savannah Ecological Zone and has two distinct seasons: a rainy season from April/May to September/early of October and a dry season spanning from October to early April. The average annual rainfall ranges from 645mm to 1,250mm with peaks occurring in late August or early September (Issahaku et al., 2016). However, erratic rainfall patterns in terms of time of onset, duration, and quantity render sufficient and consistent provision of amounts of water for various uses unstable (Antwi-Agyei et al., 2014). Most of the soil types in this area, which has coarse texture and low organic matter, are prone to surface runoff (Agyemang et al., 2007; Wossen and Berger, 2015). Notwithstanding the adverse conditions for climate-sensitive farming, both districts are highly dependent on agriculture: approximately 60% of households in Bolgatanga and 96% of households in Bongo are engaged in agriculture (Ghana Statistical Service, 2010a, b). Each district has an individual political and administrative system due to Ghana's decentralization reforms (Fiankor and Akussah, 2012). Thus, the decision-making process related to agricultural land-use is heavily influenced by the respective agricultural extension services within each district, which could lead to different land-use preferences despite the similar environmental and land-use conditions.

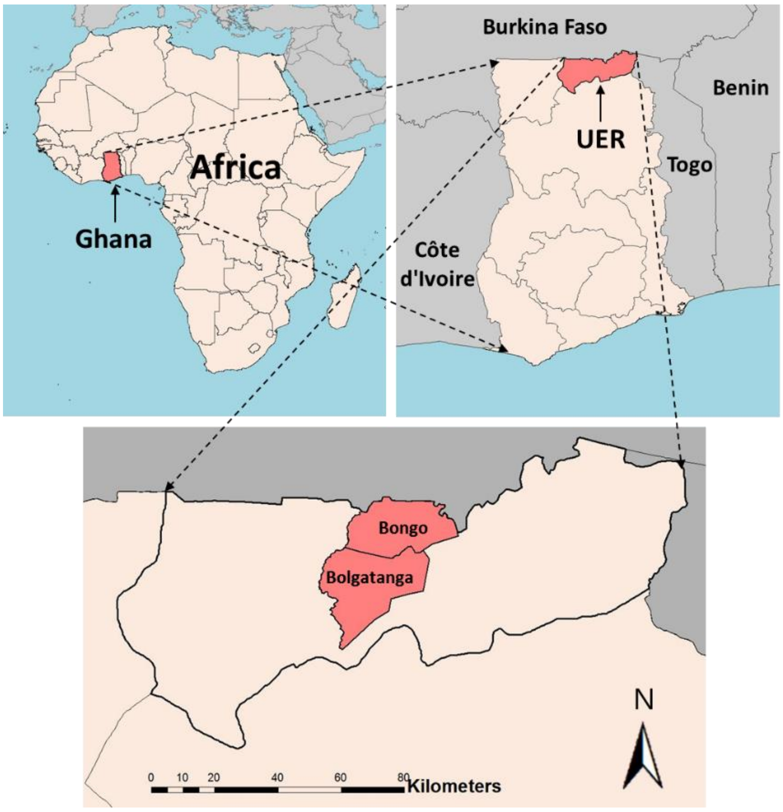


Figure 3. The location of two districts in northern Ghana as the study area.

2.3. Participatory approach

2.3.1. Selection of stakeholders

Since local knowledge is characterized by the engaged stakeholders, selection of stakeholders is decisive in a participatory approach (Lamarque et al., 2011; Pérez-Soba et al., 2018). A legitimate stakeholder group for this study was determined according to their level of influence and interest in agricultural land-use decisions at district level. Based on interviews with various actors in the agricultural sectors and existing studies (Bonye et al., 2012; Emmanuel et al., 2016), diverse stakeholders were classified in an 'interest-influence' matrix (Figure 4). Farmers play a crucial role in determining the

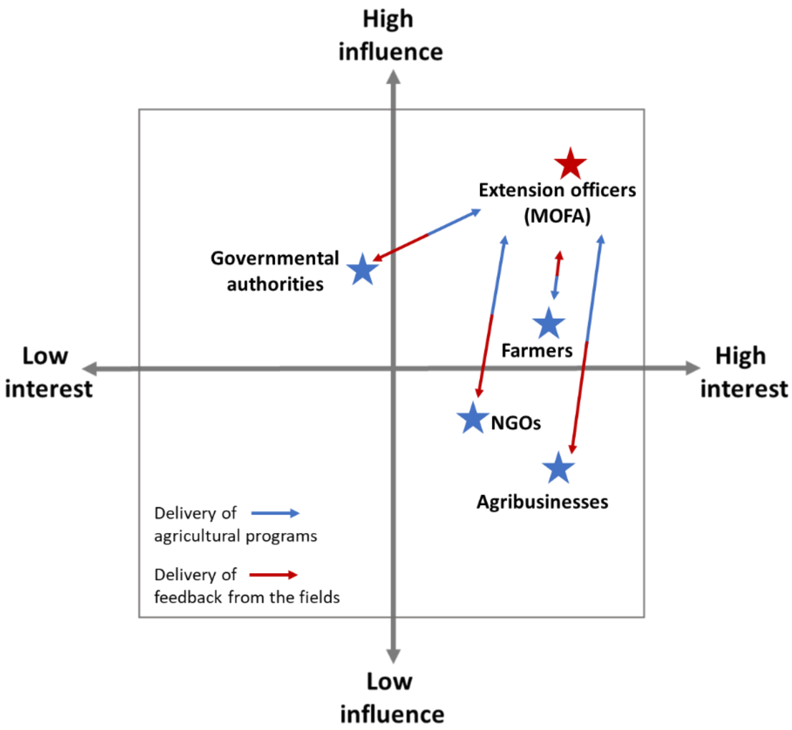


Figure 4. Interest-influence matrix (after Reed et al., 2009) for stakeholder identification and interrelationships between different stakeholder groups adapted to actors in agricultural programs in northern Ghana (modified from Koo et al., 2019). Extension offers of MOFA are placed in a high influence-interest section in the matrix, who are preferred in the stakeholder selection process.

conditions of agricultural land by selecting and allocating crop types and farming practices. However, their decisions primarily affect land-use activities at plot and farm level and indirectly influence agriculture-related decision-making at district level. Governmental authorities such as the Water Resources Commission and the Forestry Commission do not prioritize agricultural issues, but they indirectly affect agricultural land-use decisions through regulations and support programs associated with water and forest management. NGOs (e.g., Farmer training Center, Spring Ghana, Trias) and agribusinesses who focus on the introduction of new crop varieties and farming technologies are highly interested in agricultural conditions, while their activities are governed by approvals and plans of the Ministry of Food and Agriculture (MOFA) of Ghana. Agricultural extension agents of MOFA (hereafter, "extension officers" or "stakeholders") play a pivotal role in linking these stakeholders. One of their main tasks is to provide technical advice and introduce new technologies and policies to farmers. The extension officers are also responsible for regular monitoring of the performance of cultivation systems and reporting the monitoring results to a district office of MOFA. Thus, their opinions considerably influence land-use decisions of farmers and the implementation of agricultural strategies and policies of MOFA. In light of their knowledge, field experience and relationships with farmers and MOFA, cooperation with the extension officers is essential for other stakeholders to initialize and monitor a new agricultural program. Feedback from farmers regarding farming programs is collected by the extension officers and delivered to supervising NGOs or governmental authorities. In consideration of interest and influence on agricultural land-use decisions and policies at district level, the extension officers can be the most appropriate and legitimate stakeholder group. All extension officers who are in charge of Bolgatanga (15 officers) and Bongo (11 officers) participated as stakeholders for this study.

2.3.2. Collection of local knowledge

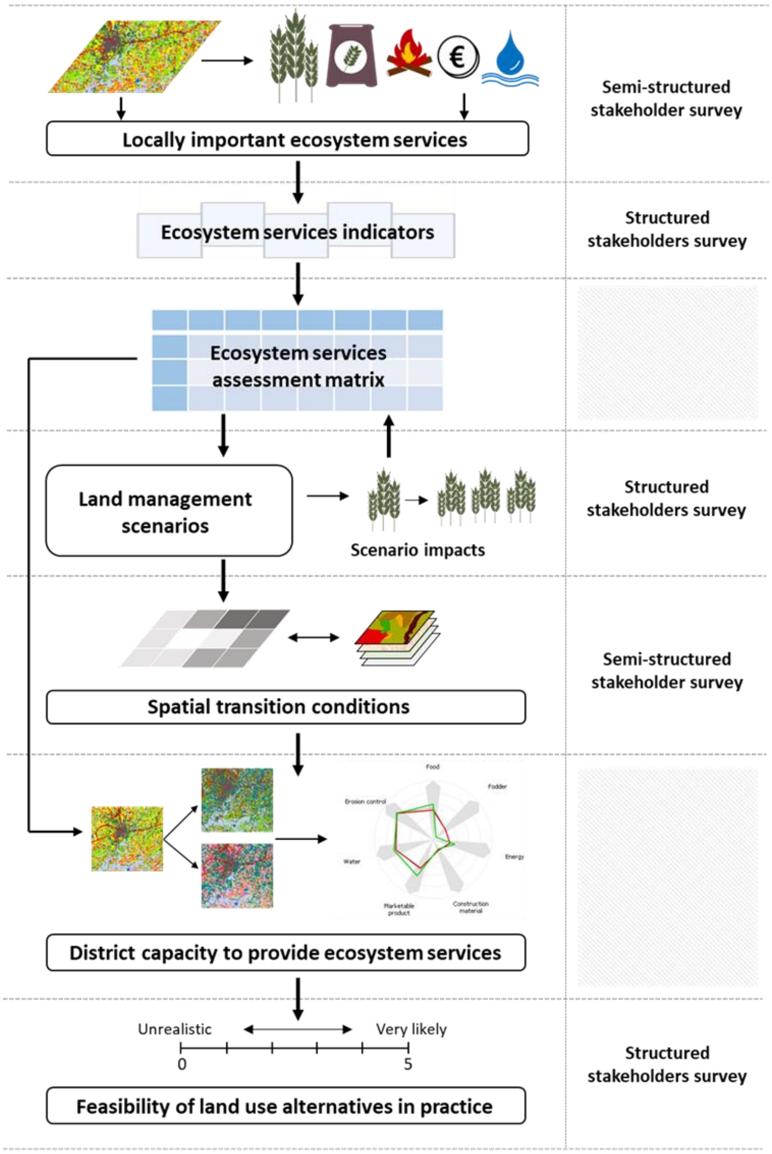


Figure 5. Application of local knowledge generated by stakeholder surveys to each assessment step.

Local knowledge regarding ES values and future scenarios was obtained through semi-structured and structure surveys with the selected stakeholders. The collected information was used as input data for each assessment step (Figure 5).

2.3.2.1. Ecosystem services-related local knowledge

Considering the fact that local stakeholders are usually unacquainted with the ES concept, the establishment of a common knowledge base with stakeholders using their language is necessary (Fürst et al., 2014). Here, ES indicate human benefits obtained from agricultural land-use activities. In order to identify relevant ES from the local perspective, a semi-structured stakeholder survey was conducted. Firstly, a preliminary list of ES was generated based on existing ES studies (Chen et al., 2009; de Groot et al., 2002; Egoh et al., 2011; Haines-Young and Potschin, 2011; Hein et al., 2006; Kandziora et al., 2013; Koschke et al., 2012; Leh et al., 2013; MA, 2005; Martín-López et al., 2014).(Table A 1, Annex A). A specific set of ES to be applied in this study was then identified from the preliminary ES list based on a semi-structured stakeholder survey results. The criteria of the selection were: i) the importance of the benefits in the local agricultural context and ii) the comparability of the differences between land-use types regarding the status of ES provision (e.g., higher food provisioning level of legumes than maize). Indicators to assess the selected ES were focused on measuring the multifunctionality of local land-use patterns in practice. Specifically, cereals are not only consumed by humans for food, but also as feed for livestock, domestic fuel and construction materials using grains, stalks and leaves. Thus, assuming the entirety of products from one land-use type as 100%, a proportion to be utilized for different benefits was identified as ES indicator values (e.g., the percentage used as feed for livestock out of all the maize products signifies the fodder provisioning value of maize). In terms of ES that are not suitable to be calculated by such consumption patterns of land-use products (e.g., erosion control), proxy indicators employed in existing studies were used.

2.3.2.2. Future scenario-related local knowledge

Local knowledge was applied in scenario development and evaluation from four aspects: development of locally applicable scenarios, potential impact of future land-use types on ES values, spatially explicit simulation conditions of the scenarios, and feedback on evaluation results.

Regarding locally applicable scenarios, firstly, the definitions of urbanization and deforestation as major land-use changes were identified. Urbanization in this region is closely related to the relocation of rural labor to non-farm sectors due to the difficulty to maintain a subsistence level by farming (Güneralp et al., 2017; IFPRI, 2005; Njoh, 2003). Urban areas grow rapidly associated with increased demand for access to infrastructure and various economic activities (Fox, 2012; Tiffen, 2003). Accordingly, urbanization in this study was defined as the spatial expansion of current urban/artificial surfaces into the surrounding neighborhood. Deforestation as another major land-use change in this region is caused by the penetration of crop land into forests due to the lack of arable land and an increase in land demand for housing and infrastructure (Braimoh, 2004; Dimobe et al., 2015; Lambin et al., 2001; Pouliot et al., 2012). In this light, deforestation here was characterized as the conversion of tree/forest cover and mixed vegetation into crop fields and artificial areas. Secondly, land management scenarios were formulated for five agriculture-related land-use types—cereals, maize, legumes, grassland, and mixed vegetation—considering their high likelihood of conversion in the local context (Kleemann et al., 2017). Since rice has high value in the local market as well as restricted farming conditions associated with water demand and soil types, its probability of transitioning into other land use types in the local context is low. Besides, forest cover is largely influenced by statutory land-use planning of the Town and Country Planning Department and the Forest Commission, which makes land-use change in forest cover less likely (Ubink, 2008). Therefore, these two land use types were excluded in developing land management scenarios. Land management scenarios as newly introduced land-use types were first identified based on literature and field observation, considering their potential to mitigate negative climate change impacts on agricultural land, e.g., a decrease in land productivity or an increase in surface erosion. The perspectives of the local stakeholders on the applicability of the potential land management scenarios in the study area were then reflected via a structured stakeholder survey. Land management scenarios in which more than 90% of the respondents agreed on the applicability in practice were included in the final set of scenarios tested in this study. Lastly, future land-use strategies that signify comprehensive alternatives for the efficient and effective land-use to supply multiple ES at district level were elaborated. Application of various management options as a land-use strategy is expected to be more suitable to improve multiple ES than a single management practice by virtue of the cumulative positive effects of the management options that compose each strategy. In this respect, future land-use strategies were developed as combinations of different land management scenarios.

Impact of land-use scenarios should be assessed in consideration of what benefits can replace those provided by previous (current) land-use types (Sanon et al., 2012). In terms of urbanization and deforestation that simulate the conversion between existing land-use types (e.g., from legumes to artificial surface by urbanization or from forest to cereals by deforestation), their potential impacts can be evaluated by differences of indicator values between the existing land-use types. However, land management scenarios simulating the introduction of new land-use types should be evaluated by reflecting the potential impact of future land-use types to current ES indicator values. A structured-survey was conducted to ask the stakeholders if they expect any changes in ES provision (increase/decrease/constant) for each land management scenario, and how much change would be specifically anticipated as percentages compared to the current ES provisioning level (e.g., 10% potential increase in fodder provision by agroforestry management). The indicator values of future land use types according to land management scenarios were calculated reflecting the extent of changes in ES status. The indicator values of future land-use types were also applied for evaluating the impact of land-use strategies.

In order to simulate the identified future scenarios considering locally specific characteristics, local knowledge regarding spatial transitional conditions of different scenarios was collected through semi-structured surveys. For instance, the stakeholders were asked about urbanization respecting the likelihood (%) of a change from crop fields (current state) to artificial surfaces (future state) under which kind of neighboring conditions (neighboring land use types) and environmental attributes.

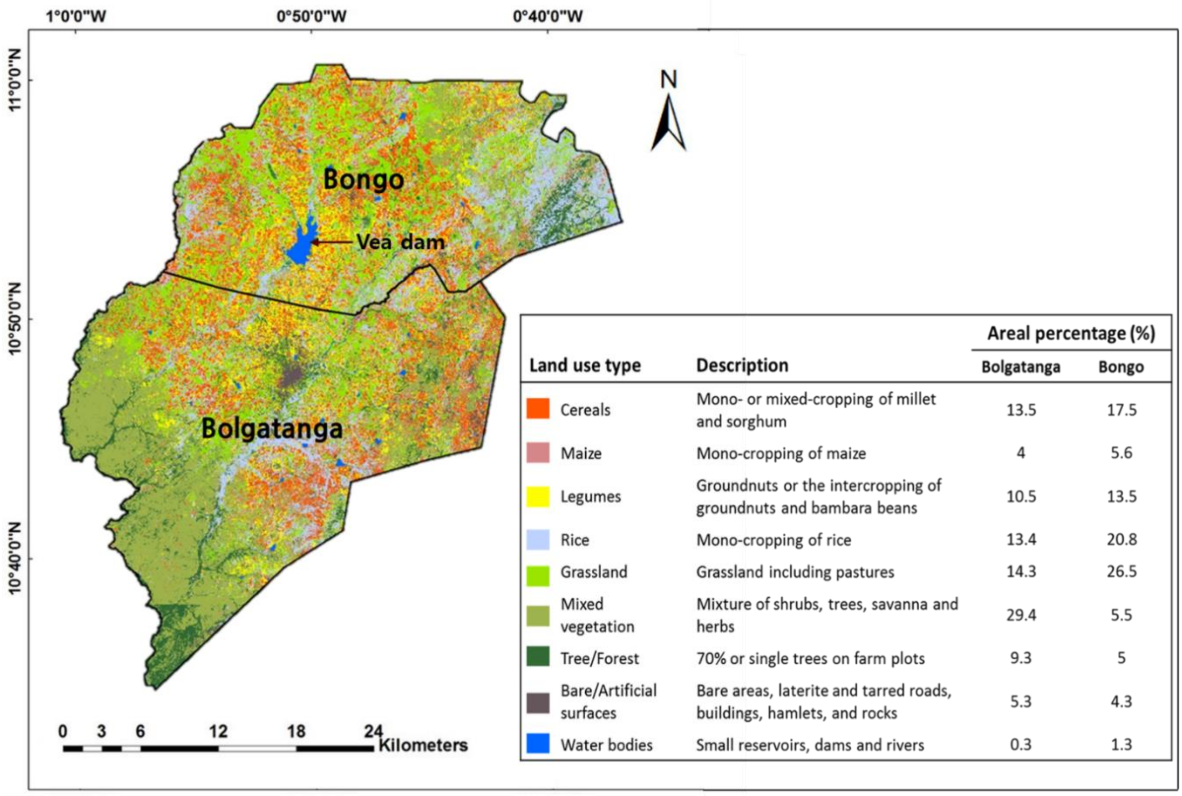
Despite the effectiveness of a certain land-use alternative to improve ES according to the simulation results, the future strategy might not be practicable without the consent of stakeholders. Thus, local perspectives are crucial for determining feasible future alternatives in a specific context (Bezák et al., 2020; Lord et al., 2016). Future land-use strategies which were assumed to be effective for enhancing multiple ES based on assessment results were checked by the local stakeholders. A structured survey using a Likert-scale (from 0 = unrealistic to 5 = very likely) was conducted to investigate how the local stakeholders perceive the feasibility of the effective land-use strategies.

2.4. Land-use modeling approach

2.4.1. Spatial data

As this study adopted a spatially explicit assessment, application of a land-use map with a relevant spatial scale is essential. In northern Ghana, only limited areas are available for dry season irrigation farming due to a lack of accessibility to dams, technical constraints, and credit availability of farmers to use the irrigation system and mineral fertilizer (Callo-concha et al., 2012; Forkuor, 2014; Hjelm and Dasori, 2012). Thus, this study dealt with a land-use pattern of the rainy season, which was classified by Forkuor (2014) as nine land-use types based on RapidEye images of 2013 and field reference data with an average accuracy rate of 82% (Figure 6). In consideration of the potential use of grassland for herbaceous forage crop cultivation in practice (Schindler, 2009), more than 65% of the land in Bolgatanga and 88% of the land in Bongo are estimated to be utilized for agricultural purposes (the sum of the cropland and grassland areas in the table in Figure 6). Grassland and mixed vegetation are composed of short deciduous and indigenous tree species and shrubs, which are normally located on communal land. A large-scale tree/forest cover in this area is mainly established as forest reserve for protecting headwaters and their catchments, timber production and biodiversity conservation (Derkyi et al., 2013; Masozera et al., 2006). Single trees that are scattered around farm plots and houses are mostly fruit trees such as mango. Bolgatanga as an administrative capital of the UER is more urbanized than Bongo (Ghana Statistical Service, 2010a). Granite outcrops that are especially dispersed throughout Bongo are also defined as bare/artificial surfaces (Forkuor, 2014). The Vea dam as the main surface water body of the study area is located in Bongo. It covers 4km^2 of surface area and 136km^2 of catchment area including nine communities in Bolgatanga and Bongo (Adongo et al., 2014; Ampadu et al., 2015).

In addition to the land-use map, spatial data such as precipitation and topographical data were employed for two purposes: the evaluation of ES that are difficult to measure by local knowledge-based indicators, thereby requiring proxy indicators based on existing studies (e.g., surface erosion control), and the generation of locally specific environmental conditions for spatial transitional rule-sets applied to the simulation of future scenarios. Precipitation data (2013) was obtained from the Tropical Rainfall Measuring Mission (TRMM) of NASA, a soil map (2008) was from the Soil Research Institute of Ghana, and the Digital Elevation Model (2013) was downloaded from the United States Geological Survey (USGS). More recent data for district scale, which can match the land-use map, was not available or not accessible. All spatial data was generated by raster format with resolution of 25 × 25 m^2.



Land use type	Description	Areal percentage (%) Bolgatanga	Areal percentage (%) Bongo
Cereals	Mono- or mixed-cropping of millet and sorghum	13.5	17.5
Maize	Mono-cropping of maize	4	5.6
Legumes	Groundnuts or the intercropping of groundnuts and bambara beans	10.5	13.5
Rice	Mono-cropping of rice	13.4	20.8
Grassland	Grassland including pastures	14.3	26.5
Mixed vegetation	Mixture of shrubs, trees, savanna and herbs	29.4	5.5
Tree/Forest	70% or single trees on farm plots	9.3	5
Bare/Artificial surfaces	Bare areas, laterite and tarred roads, buildings, hamlets, and rocks	5.3	4.3
Water bodies	Small reservoirs, dams and rivers	0.3	1.3

Figure 6. Land-use map of the study area. The description and the share of each land-use type in the study area are in the table (right).

2.4.2. Scenario simulation using spatially explicit modeling

The potential impact of land-use and management scenarios were simulated and evaluated considering the spatial peculiarity of ES provision, whose values and distribution are affected by land-use patterns (Burkhard et al., 2012; Swetnam et al., 2011; Wissen Hayek et al., 2016; Zhang et al., 2017). This study adopted a web-based modeling platform called GISCAME that combines Geographic Information System (GIS) and Cellular Automaton (CA) modules, and an assessment matrix which defines the potential ES values assigned to different land-use types (Fürst et al., 2013). Simulation and assessment of this study were conducted in the GISCAME platform which is used exclusively for the WASCAL program (https://apps.giscame.com/wascal2), and access to the system is only granted upon approval.

2.4.2.1. Future land-use patterns

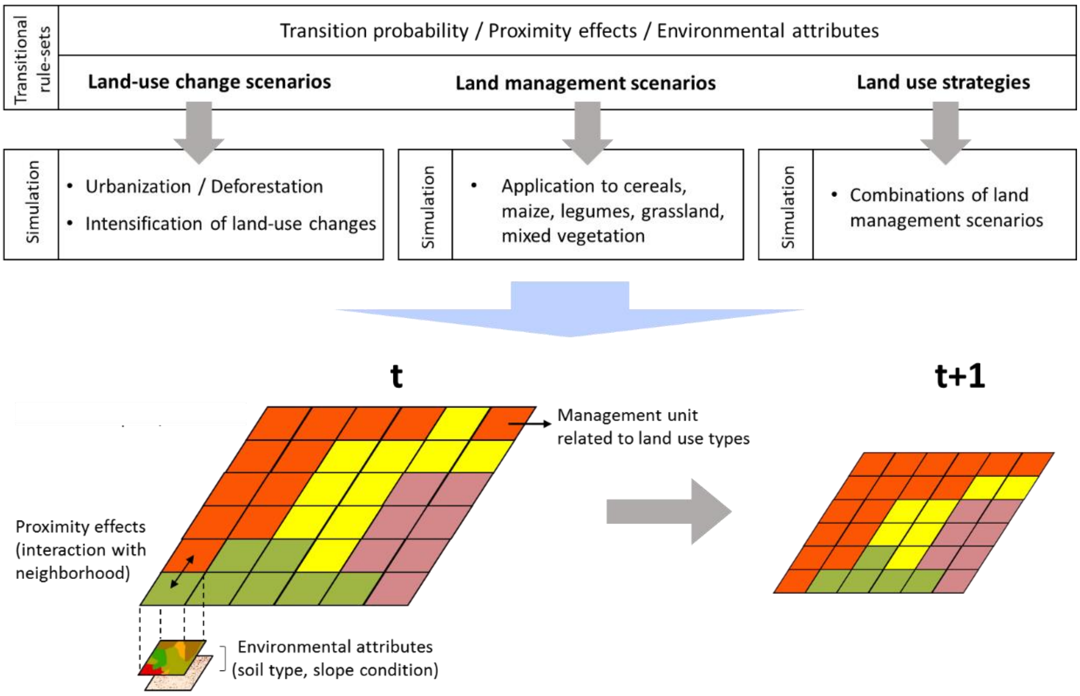


Figure 7. Simulation of land-use patterns influenced by future scenarios using a Cellular Automata module. A cell is considered to be a basic management unit whose transition is realized only according to its spatial conditions (interactions with neighboring cells and environmental attributes). The application of spatial conditions, i.e., rule-sets lead to a change of land-use patterns from time t to time t+1.

The GIS module of the modeling platform allows one to integrate available digital information on land-use and environmental conditions such as soil, topographical and climate features and visualize geographic spaces that overlap various local characteristics (Fürst et al., 2013). The CA module supports the simulation of cell-wise land-use changes within a certain spatial boundary (ibid.). CA is a spatially discrete dynamic gridded system in which the development of the state of individual cells at the time t +1 depends primarily on their own state and neighboring conditions at the time t (de Noronha Vaz et al., 2012; Shafizadeh-Moghadam et al., 2017; Shiffman, 2012). Accordingly, CA was used in this study for reassigning land-use types to all cells in a current district land-use map depending on synchronized transitional rule-sets that consist of transitional probability, neighboring land-use types and environmental attributes, i.e., spatial conditions provided by the GIS module, thereby creating new land-use patterns influenced by future scenarios. The rule-set for individual scenarios was elaborated based on consulted information with the stakeholders (see chapter 2.3.2.2). The conversion of cells in the current map (t) through application of transition probability, neighboring land-use types which perform as proximity effects, and environmental attributes (e.g., soil and slope characteristics) generated future land-use patterns (t+1) (Figure 7). Regarding land-use change scenarios, an iterative application of the rule-sets allowed simulation of intensifying urbanization and deforestation. An one-time application was defined together with the stakeholders as a probable change in five years, presenting a change in 25 years by a five-time iterative simulation. Transitional rule-sets for testing land management scenarios such as a change from monocropping to intercropping or to an agroforestry practice were applied to the current cereals, maize, legumes, grassland and mixed vegetation. Conforming to the definition of a future land-use strategy as a combination of various land management options, land-use patterns influenced by land-use strategies were created by the simultaneous application of transitional rule-sets of land management scenarios that compose each land-use strategy.

2.4.2.2. Relationship between ecosystem service provision and land-use types

In order to compare a changing capacity in the provision of various ES depending on future scenarios, all indicator values assigned to land-use types should be calculated with the same value range and unit (Koschke et al., 2012). Thus, all final indicator values were transformed to a relative scale from 0 (the minimum potential for the land-use type to provide the specific ES) to 100 (the maximum potential for the land-use type to provide the specific ES) by standardization. The ES values of newly introduced land-use types by land management scenarios were firstly calculated by applying their potential impact on the current ES provision (% of increase or decrease) identified through a stakeholder survey (see chapter 2.3.2.2), then standardized. All standardized ES values comprised an assessment matrix which bundles information on the potential of land-use types for ES provision and displays the relationship between land-use types and ES values.

2.4.2.3. Assessment of district capacity for the provision of ecosystem services

The district capacity for ES provision was evaluated and visualized as a result of integrating future land-use patterns and an assessment matrix. The ES values of the whole district area were calculated as mean ES values of each land-use type in rearranged land-use patterns according to future scenarios. Thus, the final assessment score signified the mean capacity of the district to provide ES. The capacity of a district to provide ES was displayed in a spider chart and an ES balance table. This representation of results allowed a visual comparison of the expected impact of future land-use scenarios, which could be interpreted as trade-offs or synergies between different ES. Trade-offs indicated an increase in a certain ES and a concurrent decrease in another ES, and synergies meant simultaneous improvement (positive synergies) or simultaneous decline (negative synergies) of multiple ES. By comparing the assessed ES values between the districts, the impact of different local perception on ES provision was also identified. Regarding future land-use strategies, the ES values at district level were used as grounds for determining best future land-use strategies which could effectively supply multiple ES.

2.5. Contributions from papers to the methods

Table 1. Overview of the key contribution from the respective papers regrading chapter 2. Materials and methods.

<table>
<tr><th>Paper</th><th>Key contribution</th></tr>
<tr><td>Paper I: Land management scenarios and their potential impact on ES provision in the local context</td><td>Establishment of locally tailored ES assessment basis
The local stakeholders participated in selecting locally relevant ES considering their importance related to agricultural land-use in the local context.
Indicators/proxies for assessing ES were designed to capture the potential of each land-use type to provide multiple ES. The selected ES and indicators were also applied in conducting studies for paper II and paper III.
Development and assessment of land management scenarios
Locally applicable land management scenarios were firstly identified based on literature and field observation, then specified based on the perspective of the local stakeholders.
Structured and semi-structured surveys were conducted to identify the local perception on the impact of land management scenarios on the current ES provision and simulation conditions of the developed scenarios.
ES indicator values of land-use types were integrated with future land-use patterns in the modeling platform, GISCAME, for assessing and visualizing the changes in the capacity of the two districts to provide ES depending on scenarios.</td></tr>
<tr><td>Paper II: Impact assessment of land-use changes on ES provision based local knowledge</td><td>Selection process of locally legitimate stakeholder group
An ‘Interest-influence’ matrix was generated based on interviews with various potential stakeholder groups and literature, and stakeholders who categorized in the high interest-influence group regarding agricultural land-use at district level were selected as a stakeholder group of this study.
Assessment of land-use change scenarios
Simulating conditions of urbanization and deforestation as major land-use changes in this region were identified based on a stakeholder survey.
ES indicator values of land-use type were integrated with future land-use patterns by land-use change scenarios for assessment and visualization of the impact of urbanization and deforestation on ES provision at district level.</td></tr>
<tr><td>Paper III: Future land-use recommendations based on the impact assessment of land-use strategies</td><td>Development and assessment of land-use strategies
According to the assumption that the application of multiple management options is more effective to enhance different ES than a single option, land-use strategies were delineated as combinations of land management options that developed in Paper I.
Future land-use patterns were generated by the simultaneous application of simulating conditions of land-management scenarios. ES indicator values of land-use types were integrated with the future land-use patterns for assessment and visualization of the impact of land-use strategies on ES provision at district level.
Identification of future recommendations
Best strategies which could effectively enhance multiple ES were identified based on the assessment result. A stakeholder survey was conducted to obtain feedback on the assessment results focusing on the feasibility of the best strategies. Effective and highly feasible land-use strategies in each district were determined as future recommendations.</td></tr>
</table>

3. Results

3.1. Locally relevant ecosystem services and indicator values

As locally relevant ES in the agricultural context, food provision, fodder provision, energy provision, construction material provision, marketable (agricultural) product provision, water provision, and erosion control were determined (Table 2). Indicators for ES that are directly obtained from land-use activities such as the provision of food, fodder, energy, construction materials, and marketable products were designed to reflect local consumptive patterns of land-use products (e.g., grains, stalks, fruits, branches and leaves of crops and trees). The status of water provision and erosion control as indirect benefits that are concomitant with farming activities were difficult to be identified by such a localized perception. Therefore, proxy indicators applied in existing studies were used, which signified the obtainable quantity of surface water for direct use by households and the extent of potential surface run-off caused by each land-use type. ES indicator values of each land-use type are presented in the Annex (Table A 2, Annex A). They were standardized ranging from 0 to 100 for integration with land use maps and assessment of district capacity to provide ES (Table A 3, Annex A).

Table 2. Locally relevant ecosystem services (direct benefit and indirect benefit), indicators and proxies for evaluation of the ecosystem services, and data generation methods for the indicator values (modified from Koo et al., 2018).

Ecosystem services		Description	Indicator and proxy	Data creation
Direct benefit	Food	Benefit of agricultural land-use related to food for households	Proportion of land-use products consumed for food (%)	Stakeholder survey
	Fodder	Benefit of agricultural land-use related to livestock feed	Proportion of land-use products consumed for livestock feed (%)	Stakeholder survey
	Energy	Benefit of agricultural land-use related to fuel for households	Proportion of land-use products consumed for fuel (cooking and heating) (%)	Stakeholder survey
	Construction material	Benefit of agricultural land-use related to construction materials for households	Proportion of land-use products consumed for construction purposes (roofs, pillars, fence, etc.) (%)	Stakeholder survey
	Marketable product	Benefit of agricultural land-use related to economic value for households	Proportion of land-use products consumed for household income by selling in the market (%)	Stakeholder survey
Indirect benefit	Water	The amount of surface water for direct household consumption	Potential water yield based on the difference between precipitation and evapotranspiration (mm $cell^{-1}a^{-1}$)	Water yield equation (a, b)
	Erosion control	The level of surface run-off prevention	Potential extent of soil loss calculated by the RUSLE model (t $ha^{-1}a^{-1}$)	RUSLE equation (c, d, e)

(a) Zhang et al.(2001) (b) Leh et al. (2013) (c) Renard et al. (1991) (d) Millward and Mersey (1999) (e) Angima et al. (2003).

3.2. Impact of land-use changes

3.2.1. Impact of urbanization on the provision of ecosystem services

Regarding a rule-set for simulating urbanization, the local stakeholders considered environmental attributes such as soil and slope conditions as inconsequential in leading urbanization in this region, whereas proximity effects performed as a decisive driver of the land-use change. Thus, the future land-use pattern by urbanization was generated according to the probability of a change from each land-use type to bare/artificial surfaces, and neighboring cell types (Table A 4, Annex A). For example, legumes can be converted to bare/artificial surfaces with 80% of probability when the neighboring cells are artificial surfaces, while rice considered as a valuable income source for households presented lower likelihood of transition to bare/artificial surfaces. Tree/forest which is largely affected by management policies and planning of the Forestry Commission also showed lower transition probability to bare/artificial surfaces compared to other land-use types. The application of the rule-set in CA induced a decrease in most land use types that were converted to bare/artificial surfaces, and iterative simulation (urbanization 5 and urbanization 10) which signified the intensification of urbanization showed more noticeable spatial impacts of the land-use change (the expansion of grey areas presented in (a) in Figure 8). Their consequential impacts on ES provision also became more apparent as the red areas in the food provisioning maps indicating low capacity of the ES were expanded ((b) in Figure 8). Urbanization resulted in a decrease in overall ES except water provision in both districts as shown in the spider chart and the ES balance table ((c) in Figure 8). A decrease in the provision of food, fodder, energy, construction materials, marketable products and erosion control, i.e., a negative synergy, can be attributed to the local perception regarding the missing capacity of the expanded bare/artificial surfaces to supply such agricultural land-use benefits (Table A 3, Annex A). Especially, a noticeable decline in food provision in both districts is related to a decrease in cereal and legume fields that were regarded to have high potential for food provision. A decrease in grassland due to urbanization is related to the negative influence on erosion control. Conversely, water provision was increased according to the expansion of bare/artificial surfaces as a trade-off. Since the indicator for assessing water provision was calculated as the potential amount of surface water utilized for direct human use, the level of water demand by land-use types was critical to determine water provision for household. The spread of bare/artificial surfaces by urbanization that required less surface water compared to other crop and tree-covered land-use types, thus, can enhance the capacity of water provision at district level. Comparing the simulated results of the two districts (the extent of increase or decrease in ES provision compared to current (reference) ES values in the ES balance table), it was noteworthy that Bongo was slightly more influenced by urbanization than Bolgatanga which, as the regional capital, has a bigger downtown area.

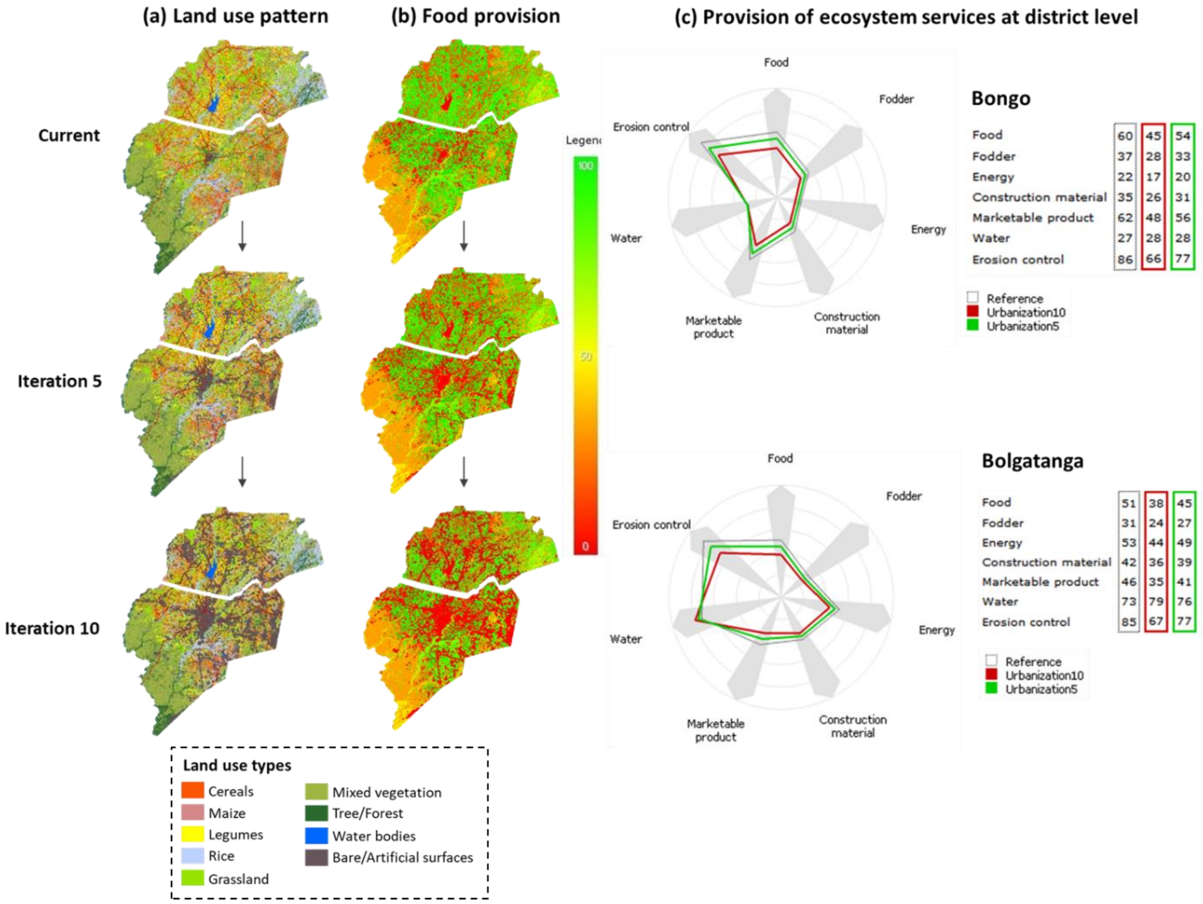


Figure 8. Impact of urbanization on land-use patterns and ecosystem service provision in Bolgatanga (lower region in the map) and Bongo (upper region in the map). Provisioning maps for food show the impact of urbanization on the spatial distribution of the ecosystem services (b). The spider chart presents the change in the current provision of ecosystem services (reference) according to intensifying urbanization (a five-time iterative simulation: Urbanization 5, a ten-time iterative simulation: Urbanization 10). The capacity of the districts to provide ecosystem services depending on the simulation results is displayed in the balance tables, which correspond to the spider charts (c). The images were captured from the GISCAME platform for the WASCAL program.

3.2.2. Impact of deforestation on the provision of ecosystem services

The simulation of deforestation, which signifies the transition from tree/forest and mixed vegetation to cereals, maize, legumes, grassland, and bare/artificial surfaces, led to distributional changes in land-use types, and their resultant impacts on the capacity of ES provision at district level (Figure 9). The conversion conditions of deforestation were also affected by proximity effects (Table A 4, Annex A). For instance, tree/forest cover can be converted to maize with 70% probability if maize cells already exist as neighboring land-use types. Since rice has restricted cultivation conditions in term of water demand and soil characteristics, which means the low likelihood of conversion from tree/forest and mixed vegetation to rice paddy, rice was excluded from the target land-use types. The application of the rule-set led to the expansion of agricultural land ((a) in Figure 9). As deforestation was intensified, the high capacity areas of energy provision decreased, which is expressed as the green areas in the ES provisioning maps ((b) in Figure 9). Compared to urbanization, deforestation was less influential on the

ES status ((c) in Figure 9). The provision of food and marketable products in Bolgatanga was slightly enhanced in Bolgatanga, which can be explained by the expansion of legumes perceived to have a high potential to provide the ES. On the other hand, the provision of energy and construction materials, and erosion control that were mainly delivered by tree/forest and mixed vegetation were negatively influenced by deforestation in both districts. The extent of impacts was slightly higher in Bolgatanga than in Bongo, in contrast to the impact of urbanization.

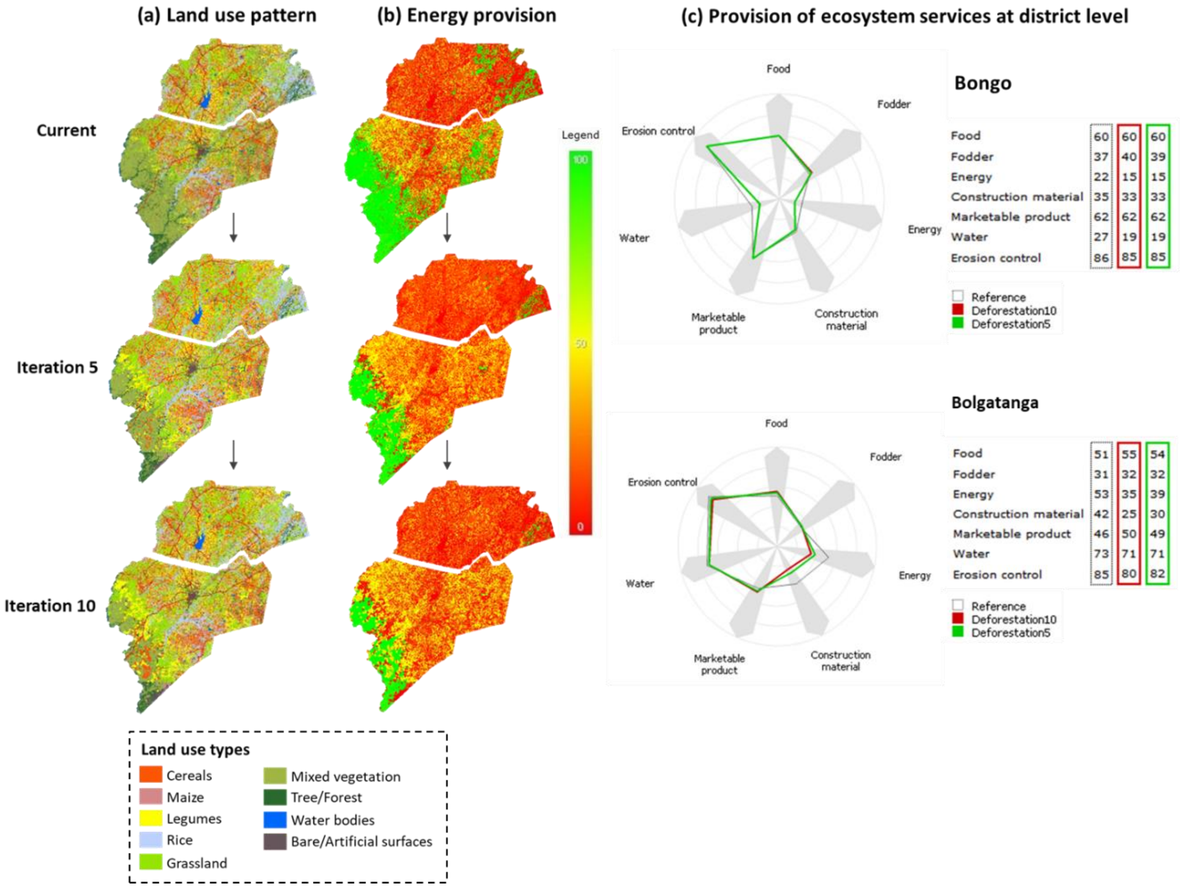


Figure 9. Impact of deforestation on land-use patterns and ecosystem service provision in Bolgatanga (lower region in the map) and Bono (upper region in the map). Provisioning maps for energy shows the impact of deforestation on the spatial distribution of the ecosystem services (b). The spider chart presents the change in the current provision of ecosystem services (reference) according to intensifying deforestation (a five-time iterative simulation: Deforestation 5, a ten-time iterative simulation: Deforestation 10). The capacity of the districts to provide ecosystem services depending on the simulation results is displayed in the balance tables, which correspond to the spider charts (c). The images were captured from the GISCAME platform for the WASCAL program.

3.3. Impact of land management scenarios

3.3.1. Relationship between future land-use types and the provision of ecosystem services

	Land management scenario		Description
Crop intercropping	1	Cereal-dominant intercropping	Conversion of cereal fields into cereal-legume intercropping fields
	2	Maize-dominant intercropping	Conversion of maize fields into maize-legume intercropping fields
	3	Legume-dominant intercropping	Conversion of legume fields into legume-cereal/maize intercropping fields
Afforestation and agroforestry	4	Grassland afforestation	Conversion of grassland into forest
	5	Mixed vegetation afforestation	Conversion of mixed vegetation into forest
	6	Cereal intercropping with mango (fruit tree)	Introduction of mango trees into cereal fields
	7	Maize intercropping with mango (fruit tree)	Introduction of mango trees into maize fields
	8	Legume intercropping with mango (fruit tree)	Introduction of mango trees into legume field
	9	Cereal intercropping with leucaena (fodder tree)	Introduction of leucaena to cereal fields
	10	Maize intercropping with leucaena (fodder tree)	Introduction of leucaena to maize fields
	11	Legume intercropping with leucaena (fodder tree)	Introduction of leucaena to legume field
Soil conservation	12	Soil or stone bunds on cereals	Introduction of bunds to cereal fields with the possibility of soil loss
	13	Soil or stone bunds on maize	Introduction of bunds to maize fields with the possibility of soil loss
	14	Windbreak on cereals	Establishment of wind break though planting trees in cereal fields
	15	Windbreak on maize	Establishment of wind break though planting trees in maize fields

↔	Food	Fodder	Energy	Construction materials	Marketable products	Water	Erosion control
Food	▪	1,2,3,5,6,7,8,9,10,11,12,13,14,15	1,2,3,4,5,8,9,10,11,12,13,14,15	1,2,3,4,5,8,9,10,11,12,13,14,15	1,2,3,4,5,8,9,10,11,12,13,14,15	6,7	1,2,3,4,5,8,9,10,11,12,13,14,15
Fodder		▪	1,2,3,5,8,9,10,11,12,13,14,15	1,2,3,5,8,9,10,11,12,13,14,15	1,2,3,5,8,9,10,11,12,13,14,15	6,7	1,2,3,5,8,9,10,11,12,13,14,15
Energy	6,7	6,7	▪	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15		1,2,3,4,5,6,7,8,9,10,11,12,13,14,15
Construction materials	6,7	6,7		▪	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15		1,2,3,4,5,6,7,8,9,10,11,12,13,14,15
Marketable products	6,7	6,7			▪		1,2,3,4,5,6,7,8,9,10,11,12,13,14,15
Water	1,2,3,4,5,8,9,10,11,12,13,14,15	1,2,3,4,5,8,9,10,11,12,13,14,15	1,2,3,4,5,8,9,10,11,12,13,14,15	1,2,3,4,5,8,9,10,11,12,13,14,15	1,2,3,4,5,8,9,10,11,12,13,14,15	▪	
Erosion control	6,7	6,7				1,2,3,4,5,6,7,8,9,10,11,12,13,14,15	▪

Synergy

Trade-off

Figure 10. Land management scenarios and their potential impact on ecosystem services based on the local perception in Bolgatanga.

Table 3. Assessment matrix to display the relationship between current (first nine land-use types) and future land-use types and their capacity to provide ecosystem services within a scale from 0 (no provision, in white) to 100 (highest level of provision, in dark green) (modified from Koo et al., 2018).

	Bolgatanga							Bongo						
Land-use type	Food	Fodder	Energy	Construction materials	Marketable products	Water	Erosion control	Food	Fodder	Energy	Construction materials	Marketable products	Water	Erosion control
Cereals	58	7	29	4	30	97	60	63	6	28	6	42	88	71
Maize	52	12	7	4	43	98	62	56	11	6	6	60	89	63
Legumes	60	4	3	4	65	97	95	53	16	0	5	71	88	96
Rice	44	1	3	0	70	83	88	51	15	0	0	69	92	92
Grassland	1	100	32	37	11	95	98	11	97	11	65	20	89	99
Mixed vegetation	19	47	63	63	12	98	100	21	53	68	68	20	94	100
Tree/Forest	28	7	57	31	54	97	100	33	13	62	24	60	94	100
Bare/Artificial surfaces	0	0	0	0	0	100	0	0	0	0	0	0	89	0
Water body	0	0	0	0	0	100	100	0	0	0	0	0	100	100
Cereal-dominant intercropping	96	12	34	4	46	30	90	100	9	32	6	65	94	85
Maize-dominant intercropping	89	19	8	4	71	31	86	90	15	6	6	92	100	78
Legume-dominant intercropping	100	6	4	4	100	28	97	75	19	0	5	100	14	97
Grassland afforestation	2	100	53	60	18	20	99	15	100	17	99	30	0	100
Mixed vegetation afforestation	27	49	100	100	17	31	100	29	70	100	100	27	15	100
Cereal intercropping with mango	51	7	32	4	36	0	77	79	7	32	7	61	0	79
Maize intercropping with mango	46	11	8	4	52	1	78	70	13	7	7	86	0	73
Legume intercropping with mango	86	5	4	4	95	6	97	76	20	0	6	94	30	97
Cereal intercropping with leucaena	71	11	39	4	38	8	83	75	10	37	7	52	19	83
Maize intercropping with leucaena	64	19	10	4	55	9	84	67	16	8	7	73	20	78
Legume intercropping with leucaena	70	7	4	4	85	20	98	69	25	0	6	90	3	97
Soil or stone bunds on cereals	94	11	42	4	52	20	87	99	10	38	8	63	28	91
Soil or stone bunds on maize	85	18	11	4	75	7	87	88	16	8	8	89	28	88
Windbreak on cereals	89	11	43	4	44	32	84	88	9	39	9	55	28	84
Windbreak on maize	80	18	11	4	63	33	85	78	15	9	9	78	28	80

As land management scenarios that were assumed to be effective to mitigate negative climate change impacts on agricultural field and highly applicable in practice, 15 options categorized as crop intercropping, afforestation/agroforestry, and soil conservation were determined and assessed (the upper side in Figure 10). According to the local perception, the selected scenarios were expected to bring synergies or trade-offs between ES (the lower side in Figure 10). For instance, the stakeholders in Bolgatanga were of the opinion that cereal and maize intercropping with mango (land management scenario 6 and 7) can bring negative effect on food provision; this is because the presence of mango trees is regarded to be an obstacle to the growth of cereals and maize due to shade and nutrient competition. On the other hand, the provision of energy, construction materials and marketable products can be enhanced by virtue of additional products from mango trees (trade-offs). Such a change in the provision of ES (increase/decrease/constant) was numerically identified as percentages based on the result of a stakeholder survey (Table A 5, Annex A). The ES capacity of current (first nine land-use types) and future land-use types reflecting such local perception on scenario impacts was presented as value ranges between 0 and 100 (Table 3). Legume-dominant intercropping was identified to be most effective for food provision in Bolgatanga, while cereal-dominant intercropping presented the highest capacity for the ES in Bongo. In both districts, grassland afforestation scored the highest value for fodder provision, and mixed vegetation afforestation was assumed to be most effective for the provision of energy and construction materials. Legume-related future land use types scored relatively higher for the provision of marketable products than other land use types, and afforestation-related land use types were effective for erosion control in both districts.

3.3.2. Impact of land management scenarios at district level

ES capacity of the districts depending on the 15 land management scenarios was identified as a result of integrating the assessment matrix in Table 3 and future land-use patterns (an example in Figure A 1, Annex A) which were generated by transitional rule-sets based on local perception (Table A 6, Annex A). The transitional rule-sets included transition probabilities and neighboring land-use types, as well as soil condition (sandy loamy/sandy/clay) and slope characteristics closely related to risk of surface runoff (t ha−1yr −1). The modeling output that referred the district ES capacity according to all 15 land management scenarios was presented in Table 4 based on spider charts and ES balance tables (an example in Figure A 1, Annex A). In both districts, cereal-dominant intercropping (Scenario 1) and soil or stone bunds on cereals (Scenario 12) were most effective for the provision of food. None of the management options affected the status of fodder provision in Bolgatanga, whereas all management options were assumed to increase the ES in Bongo. Mixed vegetation afforestation (scenario 5) was most effective for the provision of construction materials in Bolgatanga while grassland afforestation (scenario 4) showed the higher ES value in Bongo. In association with the potential of future land use types to provide ES (Table 3), water provision was negatively influenced by all scenarios, while most ES were either increased or steady in Bolgatanga. In Bongo, all scenarios except cereal-dominant intercropping and maize-dominant intercropping (scenario 1 and 2) decreased water provision.

There are similarity and dissimilarity between the districts regarding the effects of land management scenarios, which can be attributed to spatial distribution of land-use types and local perception. Cereals are most widely cultivated in both districts according to the current land-use map (Figure 6). Thus, land management scenarios applied to cereals were assumed to have considerable effect on the ES provision, such as cereal-dominant intercropping and soil or stone bunds on cereals (scenario 1 and 12) that showed the biggest improvement in the provision food and erosion control. On the other hand, land management scenarios related to maize, which occupied the low share of the land in both districts, were expected to induce relatively minor impact on the provision of overall ES. The different impact of afforestation scenarios between the districts, which mainly contributed to the provision of construction materials, can also be explained by the spatial distribution of land-use types. Afforestation applied to mixed vegetation (scenario 5) that occupies the biggest area in Bolgatanga was expected to provide the highest level of construction materials. Contrarily, grassland afforestation (scenario 4) was identified to be more effective for the ES in Bongo since the area of grassland is nearly twice the area of mixed vegetation in this district. The stakeholders in both districts perceived positive impacts of intercropping between staple crops regarding the provision of diversified land-use products, efficient land-use and the stabilization of root and land surface systems. Intercropping cereals/maize with mango trees (scenario 6 and 7), however, was perceived differently by the stakeholders between the district. Unlike the stakeholders in Bolgatanga who recognized the negative role of mango trees for the growth of cereals, the stakeholders in Bongo appreciated mango trees for increasing food provision in the household. Water provision was decreased by most land management scenarios, which was defined as the potential amount of surface water for direct human use. As explained in the impact of urbanization, the level of surface water requirement by land-use types was decisive to determine the values of water provision of different land-use types and management scenarios. The stakeholders assumed that intercropping scenarios could increase surface water demand due to the varied water requirements of different intercropped crop species. Afforestation and agroforestry management scenarios were also assumed to cause water stress considering the high-water demand of additionally planted trees. The establishment of bunds as a soil conservation measure was regarded to improve water absorption efficiency of crops, thereby decreasing surface water availability.

Table 4. Fifteen land-use management scenarios and their potential impacts on the provision of ecosystem services at district level. Comparing to the current status of ecosystem services (gray color), the increase from the current status is indicated by blue color, while the decreased is expressed by red color. No change in the provision of ecosystem services compared to current status is indicated by white color (modified from Koo et al., 2018).

District		Land management scenario	Food	Fodder	Energy	Construction materials	Marketable products	Water	Erosion control
Bolgatanga		Current status	30	31	33	28	32	95	85
	1	Cereal-dominant intercropping	35	31	34	28	34	87	89
	2	Maize-dominant intercropping	32	31	33	28	33	93	86
	3	Legume-dominant intercropping	34	31	33	28	36	88	86
	4	Grassland afforestation	31	31	36	30	33	85	85
	5	Mixed vegetation afforestation	33	31	44	37	34	76	85
	6	Cereal intercropping with mango	30	31	34	28	33	83	88
	7	Maize intercropping with mango	30	31	33	28	32	92	86
	8	Legume intercropping with mango	33	31	33	28	35	86	86
	9	Cereal intercropping with leucaena	32	31	35	28	33	84	88
	10	Maize intercropping with leucaena	31	31	33	28	32	92	86
	11	Legume intercropping with leucaena	31	31	33	28	34	88	86
	12	Soil or stone bunds on cereals	35	31	35	28	35	85	89
	13	Soil or stone bunds on maize	32	31	33	28	33	92	86
	14	Windbreak on cereals	34	31	35	28	34	87	88
	15	Windbreak on maize	31	31	33	28	33	93	86
Bongo		Current status	38	36	15	24	44	90	86
	1	Cereal-dominant intercropping	44	37	16	24	48	91	88
	2	Maize-dominant intercropping	39	36	15	24	46	90	87
	3	Legume-dominant intercropping	40	37	15	24	48	80	86
	4	Grassland afforestation	39	37	16	33	46	67	86
	5	Mixed vegetation afforestation	38	37	17	26	44	86	86
	6	Cereal intercropping with mango	40	36	16	24	47	75	87
	7	Maize intercropping with mango	38	36	15	24	45	86	86
	8	Legume intercropping with mango	40	37	15	24	47	82	86
	9	Cereal intercropping with leucaena	40	37	16	24	46	78	88
	10	Maize intercropping with leucaena	38	36	15	24	45	87	87
	11	Legume intercropping with leucaena	40	37	15	24	46	79	86
	12	Soil or stone bunds on cereals	44	37	17	25	47	80	89
	13	Soil or stone bunds on maize	39	36	15	24	45	87	87
	14	Windbreak on cereals	42	37	17	25	46	79	88
	15	Windbreak on maize	39	36	15	24	45	87	87

3.4. Impact of land-use strategies as future recommendations

3.4.1. Impact of future land-use strategies

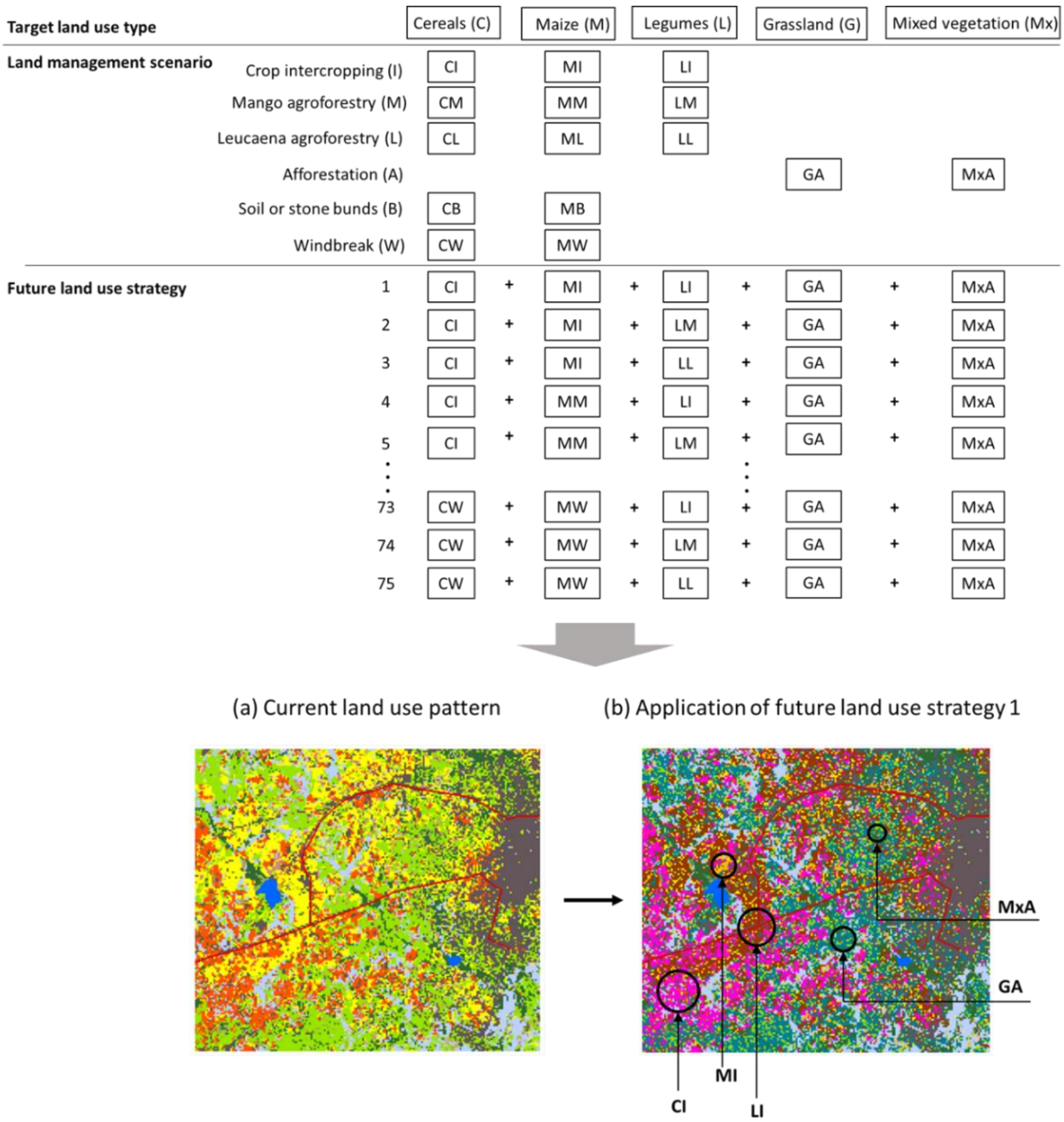


Figure 11. Development and application of future land-use strategies. Future land-use strategies are defined as combinations of land management scenarios applied to cereals, maize, legumes, grassland and mixed vegetation as target land-use types. Each box signifies which land management scenario applies to which target land-use type, e.g., “CI” indicates cereal-dominant intercropping. The impact of future land-use strategy 1 on land-use patterns (from (a) to (b) in the lower part), for example, is expressed as simultaneous application of cereal-dominant intercropping (CI), maize-dominant intercropping (MI), Legume-dominant intercropping (LI), grassland afforestation (GA), and mixed vegetation afforestation (MxA).

As combinations of different land management scenarios, 75 future land-use strategies were elaborated (Figure 11 and Table A 7, Annex A). The integration of rearranged land-use patterns by land-use strategies and an assessment matrix for ES values of different future land use types resulted in different

ES capacities of the districts (Table A 8 and Table A 9, Annex A). Land-use strategies that contained cereal-dominant intercropping (e.g., land-use strategies 1, 2, 10 and 11) were considered to be more effective in providing food, while land-use strategies that included agroforestry management options on cereals (e.g., land-use strategies 19-24, 33-39) presented lower provisioning levels of food than other strategies in both districts. This can be ascribed to the fact that cereals are the main staple crops in the study area, and the provision of food thereby was largely influenced by which kind of land management scenarios was applied in cereal fields, as shown in the simulation results of land-management scenarios. Regarding the provision of marketable products, land-use strategies that incorporated legume-dominant intercropping (e.g., land-use strategies 1, 4, 46, 55 and 58) were effective in increasing the ES in both districts. Future land-use strategies that included leucaena agroforestry on legumes (e.g. land-use strategies 33, 39, 42, 45, 48, 54, 57, and 60) were specifically identified to be more effective to enhance fodder provision in Bongo, whereas most land-use strategies brought about similar impacts on the ES in Bolgatanga. In addition, land-use strategies with the establishment of soil or stone bunds on cereals as a land management scenario (e.g., land-use strategies 51-60) led to higher capacity of erosion control in Bongo, dissimilar to Bolgatanga where land-use strategies with cereal-dominant intercropping seemed to be more effective in increasing the ES. Water provision was prominently decreased by all land-use strategies as a trade-off to the increase in other ES. As each land management scenario was expected to increase surface water demand as analyzed in the chapter 3.3.2, land-use strategies that were composed of different management options could potentially intensify the negative impact on water provision at district level.

3.4.2. Feasibility of land-use strategies

The quantified ES values facilitated a comparison of the potential impacts depending on land-use strategies. Best land-use strategies that can provide more than three different ES with the highest capacity were determined based on the ES values of land-use strategies (yellow color in Table A 8 and Table A 9, Annex A), resulting in identification of 14 best land-use strategies in Bolgatanga and 8 best land-use strategies in Bongo. Conforming to the local perspectives, feasibility of the best strategies was evaluated (Table 5). Most of the best land-use strategies were presented above the moderate level of feasibility (mean value ≥ 3) in both districts. In particular, land-use strategy 1 (a combination of cereal-dominant intercropping, maize-dominant intercropping, legume-dominant intercropping, grassland afforestation and mixed vegetation afforestation) and land-use strategy 61 (a combination of windbreak on cereals, maize-dominant intercropping, legume-dominant intercropping, grassland afforestation and mixed vegetation afforestation) showed higher feasibility than other best strategies in Bolgatanga considering their mean values and coefficient of variation. In Bongo, land-use strategy 2 (a combination of cereal-dominant intercropping, maize-dominant intercropping, legume intercropping with mango, grassland afforestation and mixed vegetation afforestation) and land-use strategy 46 (a combination of soil or stone bunds on cereals, maize-dominant intercropping, legume-dominant intercropping, grassland afforestation and mixed vegetation afforestation) particularly presented higher mean values and lower coefficients of variation than other best strategies. These land-use strategies can be regarded as locally recommended options which can effectively increase multiple ES and have high feasibility in the local context. Figure 12 displays visualized impact of the future recommendations (Bolgatanga: strategy 61, Bongo: strategy 46) on land-use patterns and the ES provisioning level. According to the changes in the land-use patterns, the green areas (high capacity to provide ES) in the food provisioning maps were enlarged ((b) in Figure 12), and the trade-offs between water provision and the remaining ES were noticeable ((c) in Figure 12).

Table 5. Feasibility of best land-use strategies based on the local perception. Mean values and the coefficient of variation (CV) of a Likert-scale survey result (from 0 = unrealistic to 5 = very likely) are used as ground to determine the most feasible land-use strategies in the local context (modified from Koo et al., 2020).

			Feasibility	
District	**Land-use strategy**		**Mean**	**CV**
Bolgatanga	1	CI + MI + LI + GA + MxA	3.78	0.12
	10	CI + MB + LI + GA + MxA	4	0.25
	13	CI + MW + LI + GA + MxA	3.78	0.26
	46	CB + MI + LI + GA + MxA	3.56	0.25
	55	CB + MB + LI + GA + MxA	3.67	0.14
	57	CB + MB + LL + GA +MxA	3.78	0.22
	58	CB + MW + LI + GA + MxA	3.22	0.21
	61	CW + MI + LI + GA + MxA	4.22	0.16
	63	CW + MI + LL + GA + MxA	3.56	0.25
	64	CW + MM + LI + GA +MxA	2.56	0.21
	67	CW + ML +LI +GA + MxA	3.44	0.29
	70	CW + MB + LI + GA + MxA	3.67	0.19
	73	CW + MW + LI + GA + MxA	3.22	0.37
	75	CW + MW + LL + GA +MxA	3.11	0.30
Bongo	1	CI + MI + LI + GA + MxA	3.78	0.18
	2	CI + MI + LM + GA + MxA	4.10	0.18
	46	CB + MI + LI + GA + MxA	4.11	0.15
	47	CB + MI + LM + GA + MxA	3.78	0.18
	48	CB + MI + LL + GA + MxA	3.56	0.20
	54	CB + ML + LL + GA + MxA	3.78	0.26
	57	CB + MB + LL + GA +MxA	3.89	0.15
	60	CB + MW + LL + GA +MxA	3.44	0.29

* CI: Cereal-dominant intercropping; MI: Maize-dominant intercropping; LI: Legume-dominant intercropping; GA: Grassland afforestation; MxA: Mixed vegetation afforestation; CM: Cereal intercropping with mango; MM: Maize intercropping with mango; LM: Legume intercropping with mango; CL: Cereal intercropping with leucaena; ML: Maize intercropping with leucaena; LL: Legume intercropping with leucaena; CB: Soil or stone bunds on cereals; MB: Soil or stone bunds on maize; CW: Windbreak on cereals; MW: Windbreak on maize

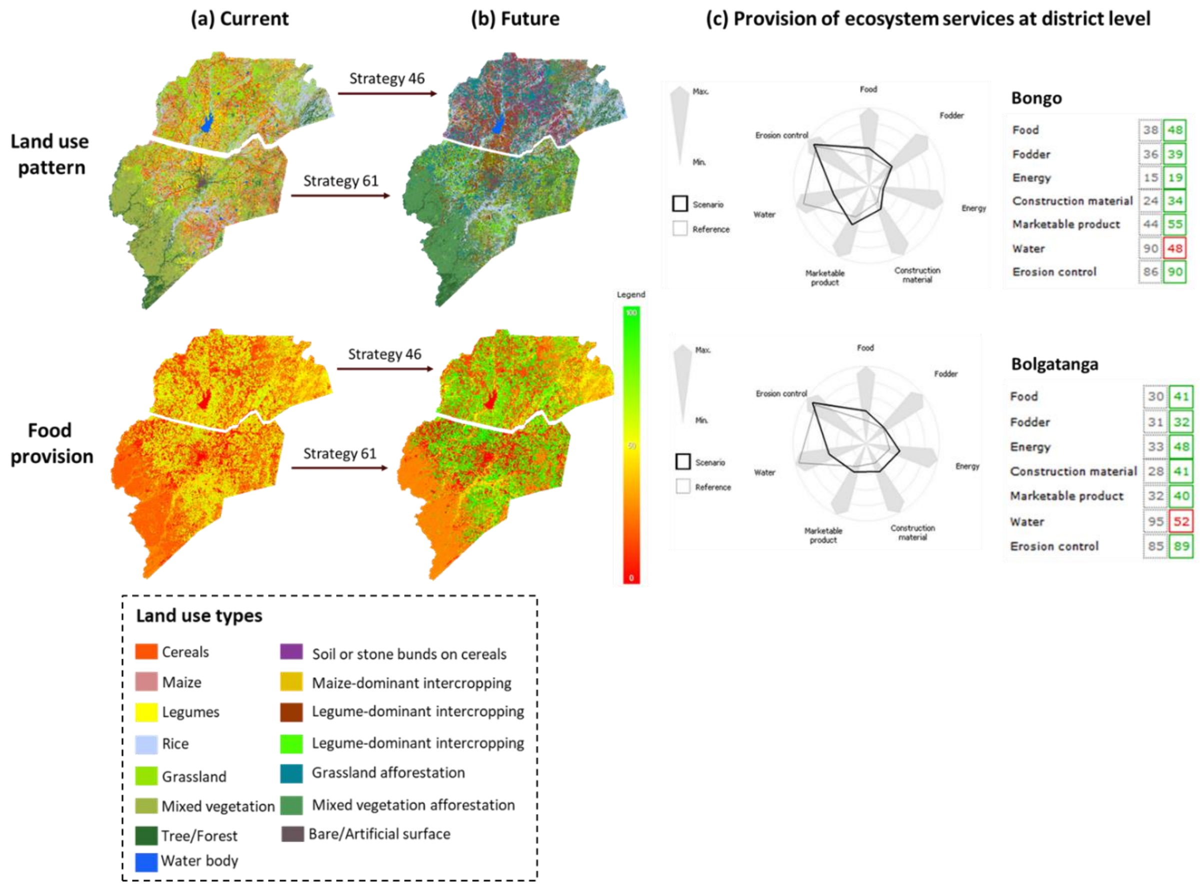


Figure 12. Future land-use patterns and changes in the provision of ecosystem services through the application of locally recommended land-use strategies in Bolgatanga (lower region in the map) and Bongo (upper region in the map). Future land-use strategies convert land-use patterns from (a) to (b) and the spatial distribution of ecosystem services (e.g., food provision) is affected by the newly generated land-use patterns. The spider chart and the ecosystem service balance tables display the changes in the provision of ecosystem services at district level compared to the current status (c). Green numbers signify an increase in the provisioning level while a red number indicates a decrease in the provisioning level. The images were captured from the GISCAME platform for the WASCAL program.

3.5. Contributions from papers to this chapter

Table 6. Overview of the key contributions from the respective papers regarding chapter 3. Results.

Paper	Key contribution
Paper I: Land management scenarios and their potential impact on ES provision in the local context	**Locally relevant ES and indicators/proxies** • The provision of food, fodder, energy, construction materials, marketable products, water and erosion control were determined as locally relevant ES in the agricultural context of the study area. Indicator values of ES related to direct benefits were obtained from on a stakeholder survey, and indicator values of ES concerning indirect benefits (water provision and erosion control) were calculated using geo-physical data. **Impact of land management scenarios on ES provision** • 15 land management scenarios regarding crop intercropping, agroforestry,

	afforestation, and soil conservation were developed as locally applicable future options. Future land-use patterns according to the management scenarios were generated by transitional rule-sets. Synergies and trade-offs between ES were identified as scenario impacts. Specifically, in both districts, the provision of food was most effectively increased by most scenarios, while water provision was noticeably decreased. • Spatial characteristics of land-use patterns and different local perceptions of scenarios, e.g., mango agroforestry, generated dissimilar impacts of the management options between the districts.
Paper II: Impact assessment of land-use changes on ES provision based local knowledge	**Impact of urbanization on ES provision** • Future land-use patterns caused by the intensification of urbanization were simulated according to transitional conditions focusing on the proximity effect (neighboring conditions). Food provision and erosion control were most negatively influenced by urbanization, whereas water provision was increased in both districts. Bongo was more affected by urbanization than Bolgatanga. **Impact of deforestation on ES provision** • Similar to the simulation of urbanization, the intensification of deforestation was simulated focusing on the proximity effect. The provision of energy, construction, water and erosion control were decreased by deforestation, while the provision of food, fodder and marketable products was slightly increased or consistent. Unlike the impact of urbanization, Bolgatanga tended to be more impacted by deforestation than Bongo.
Paper III: Future land-use recommendations based on the impact assessment of land-use strategies	**Impact of land-use strategies** • 75 land-use strategies as combinations of land management scenarios which developed in paper I were elaborated. Due to the cumulative effects of multiple management options, land-use strategies led to more notable impact on ES provision than a single management scenario. Most ES were effectively enhanced by all land-use strategies. On the contrary, water provision was declined considerably in both districts. **Recommended future strategies tailored to each district context** • As best land-use strategies which expect to increase more than 3 different ES with the highest value 14 best strategies in Bolgatanga and 8 best strategies were identified. In order to determine locally recommended strategies which can ensure their feasibility in practice, the local stakeholders were involved in the feedback process on the best strategies. As a result, strategy 61 (a combination of windbreak on cereals, maize-dominant intercropping, legume-dominant intercropping, grassland afforestation and mixed vegetation afforestation) in Bolgatanga, and strategy 46(a combination of soil or stone bunds on cereals, maize-dominant intercropping, legume-dominant intercropping, grassland afforestation and mixed vegetation afforestation) were finally determined as future recommendations.

4. Discussion

4.1. Discussion of the findings

4.1.1. Ecosystem services and indicators

As locally relevant ES, this study dealt with the benefits which the local stakeholders perceived as important related to agricultural land-use practices. Such an approach based on local knowledge and experience allows a better understanding of which ES and their status are influential in land-use decisions. However, there is a limitation to include some ES that are difficult for the stakeholders to perceive their status related to land-use practices. For example, carbon sequestration as climate regulation service and pollination as supporting service are regarded as important in terms of evaluating land-use change impacts in the West African context (Bayala et al., 2014; Leh et al., 2013; Nelson et al., 2010; Stein et al., 2017), but they were not addressed in this study since the local stakeholders had difficulty clearly distinguishing the impacts of different land-use types on these ES. Therefore, there should be further investigation into how such intangible but crucial ES can be incorporated using equivalent and understandable proxies in the local context.

Many of the existing ES studies employed yield per spatial unit for assessing the status of provisioning ES (e.g. Dunford et al., 2015; Koschke et al., 2012; Lawler et al., 2014; Paletto et al., 2017). The approaches identified only a single ES from one land-use type, e.g., food provision from crop field and fodder provision from pasture land, or merged all potential benefits as agricultural ES or forest ES. In contrast, the ES indicators adopted in this study considered the multifunctionality of land by reflecting the local perception regarding consumption of land-use products. Thus, multiple ES supplied by one land-use type can be identified without overlooking potential benefits (e.g., the stalks of maize used for roofing or fencing) or double-counting benefits (e.g. grains of legumes counted for food, fodder and marketable products simultaneously). Such an aspect is especially important in West Africa, where the social-ecological landscape presents its high multifunctionality (Malmborg et al., 2018).

4.1.2. Future scenarios and application conditions

Local stakeholders tend to avoid cultivation failure that could be potentially caused by a totally new farming method (OECD, 2012). Thus, farming practices that are unfamiliar to local stakeholders are likely to be less preferred in stakeholder-based scenario development, despite their effectiveness in increasing ES provision. In this light, land management scenarios and land-use strategies in this study were developed as modifications based on ongoing / existing farm practices, such as the application of the maize-dominant intercropping practice to maize monocropping field. “Being dominant” indicated that the corresponding land-use type occupies more than 50% of a spatial management unit, i.e., the area of a cell (25 x 25m^2). This detail allowed the local stakeholders to have a better perception of future consequences based on their understanding and experiences regarding the existing practices, as well as ensuring higher applicability of the scenario in the future land-use decisions. In addition, the future land management scenarios were elaborated considering their probability to be adopted in the local context. In light of the low probability of conversion due to the restricted land-use conditions and the preference of the local stakeholders, rice and forest were excluded from development process of the land management scenarios. Soil conservation related scenarios were not applied to legumes as a cover crop which is already assumed to have a high capacity to prevent surface run-off and to require no further action for erosion control conforming to the local perception.

Various existing studies employed CA-based land-use modeling for generating future land-use maps influenced by urban growth or understanding future behavior patterns of land-use systems (Liang et al., 2018; Omrani et al., 2017; Rimal et al., 2018). The transitional conditions and probability applied to these studies were generated based on pre-existing status or statistical relationships between historical land-use and driving factors. Assuming that past and present land-use patterns persist, such an approach is clearly limited in addressing the possibility of a change to a new land-use type that does not yet appear on existing land-use maps. On the other hand, this study elaborated the conversion conditions for land-use changes based on the perspectives of the stakeholders, which could be criticized in relation to verifiability. However, it is appropriate to consider the introduction of new land-use management and future strategies according to changing environments and preferences of the stakeholders.

4.1.3. Impact of future scenarios on ecosystem services

Potential impacts of future scenarios were characterized by rearranged land-use patterns and their cascading effects on the status of ES such as synergies or trade-offs between different ES. Accordingly, distributional patterns of land-use types along with local perception account for the assessment results of district capacity to provide ES.

Regarding the impact of land-use change scenarios, Bongo was more affected by urbanization than Bolgatanga as a regional capital. Since Bongo has more scattered patterns of bare/artificial surfaces than Bolgatanga that presented a concentration pattern of bare/artificial surfaces around the city center, Bongo has a larger area affected by the proximity effect of the transitional rule-set of urbanization. In contrast to the impact of urbanization, deforestation tended to be less influential in Bongo. This can be ascribed to the smaller areas of tree/forest and mixed vegetation in Bongo than in Bolgatanga, which were both affected by deforestation. In general, urbanization presented stronger impact than deforestation in both districts. This has to do with the remote and isolated locations of tree/forest as forest reserves, which have low proximity effect to activate the conversion of tree/forest to other land-use types by the deforestation scenario. Differences in ES values of land-use types before and after application of land-use change scenarios can also explain the lower impact of deforestation than urbanization at district level. Specifically, a change in food provisioning level according to the conversion between legumes and bare/artificial due to urbanization was much larger than the conversion between tree/forest and legumes owing to deforestation.

In terms of land management scenarios and land-use strategies, the types of scenarios applied to cereal fields were highly influential to determine the capacity of the districts to provide ES, since cereals are the main staple crops widely cultivated in both districts. For example, according to the local perception on the different effect of cereal-related options, future scenarios containing cereal-dominant intercropping were considered to be highly effective to increase food provision, whereas scenarios with agroforestry concerning cereals were assumed to deliver relatively lower improvement. Different local perception of the management scenarios led to the dissimilar impact of future strategies at district level. In Bongo, the stakeholders perceived the effectiveness of leucaena (fodder tree) agroforestry for fodder provision and soil or stone bunds for erosion control. Therefore, future strategies including the corresponding options contributed to better improvement of those ES. On the other hand, cereal-dominant intercropping was identified by the stakeholders in Bolgatanga as more effective for providing the ES. Since Bolgatanga hosts the main markets as a regional capital and has a higher purchasing power than Bongo, cereal-dominant practices as “bestsellers” have been preferred.

In addition, individual decision-making systems for each district by the decentralized program in Ghana (Fiankor and Akussah, 2012) influence such differences in favored agriculture practices between the districts. Different local perceptions between the districts can also be identified in the feasibility of land-use strategies. Land-use strategies containing 'establishment of bunds on cereals' in Bongo presented higher feasibility than in Bolgatanga, in particular, land-use strategy 46 (a combination of soil or stone bunds on cereals, maize-dominant intercropping, legume-dominant intercropping, grassland afforestation and mixed vegetation afforestation). This can be related to landscape characteristics of Bongo, where stone as materials for establishing bunds are easily obtained due to the scattered granite outcrops throughout the district.

When it comes to the impact on the provision of multiple ES, all future management scenarios and strategies commonly showed noticeable trade-offs between water provision and other services. As explained previously, this is attributed to the definition of water provision tailored to the recipients of the ES in this region, which indicates the potential amount of water available for direct household consumption. Thus, there is a competition perceived between human use and surface demand by land cover types, and most applied scenarios that focused on the expansion and intensification of woody vegetation and crop land were assumed to negatively influence water provision, whereas urbanization contributed to the increase in water provision. However, the impact of land-use changes and practices on water provision can be debatable depending on spatial scales. For example, in Africa, forest and tree covers are regarded as water consumers and competitors for water uses at local level, whereas they are expected to supply water to the atmosphere, thereby contributing to precipitation development at regional and global level (Ellison et al., 2012; Rockström and Falkenmark, 2015). Such interaction between land-use and land cover types and the provision of atmospheric moisture should also be thoroughly considered in semi-arid West Africa.

The integration of future scenarios and ES provision in a spatially explicit and quantified way can help to predict implications of changed land-use patterns and to explore future recommendations to enhance positive effects or cope with unfavorable effects (Bagstad et al., 2014; Fürst et al., 2013; Goldstein et al., 2012; Lawler et al., 2014). Based on the assessment results, for instance, the local stakeholders can contemplate soil conservation practices to prevent surface run-off or mixed-farming practices to offset the decrease in food provision, which can be caused by urbanization. Besides, the comparison between the impact of land-use strategies presented to the extent of synergies or trade-offs can be used for identifying suitable future alternatives. Although feasibility based on the stakeholder feedback on the modeled results was applied to determine future recommendations tailored to each district context, further criteria to understand local perception and preferences should be developed. For example, if stakeholders are risk-averse, they may choose options that minimize a trade-off regardless of high improvement of a certain ES, and if they prioritize food provision, future practices that increase food most effectively could be preferred despite the negative impact on another ES. Although weighting values of selected ES were not considered in this assessment as in other existing ES studies (e.g., Bagstad et al., 2016; Lu et al., 2015; Martin and Mazzotta, 2018), the application of different weight values to ES could allow one to reflect on such prioritization of ES. Accordingly, future land-use management and strategies for more efficient use of limited arable fields can be developed focusing on the provision of more preferred and important ES in the local context.

4.2. Discussion of the applied methods

The impact assessment of land-use systems in this study integrated a participatory method and spatially explicit simulation modeling as a transdisciplinary approach. The applied methods have advantages and challenges as presented in Figure 13. Participatory approaches support the use of information and knowledge of the local environment and the functions of land-use systems held by local stakeholders (Mialhe et al., 2015). Especially given the fact that the ES concept is completely unfamiliar to local stakeholders, the applied participatory method allowed the establishment of a common ES knowledge base intimately associated with their daily lives. As a result, a pertinent set of ES, indicators and future land-use scenarios in the local context were identified, reflecting local preferences and characteristics. Involvement of key local stakeholders from the data collection stage to feedback on the assessed results led to elaboration of more acceptable future land-use options in practice, which can ensure successful uptake of the ES concept. Sharing opportunities and constraints of ES management initiatives through a participatory approach is also helpful in guiding future land-use decisions (Urgenson et al., 2013). Such a stakeholder-oriented approach can complement existing statistical and biophysical data-oriented ES assessments in West Africa (e.g., Ahmed et al., 2016; Douxchamps et al., 2016; Salack et al., 2015). On the other hand, a reliability issue may arise in the quantification process of qualitative data based on subjective experiences and knowledge of individuals. It should be taken into account that the opinions of local stakeholders could be altered depending on the changing environmental conditions, policies, and their duties in the future. In a similar vein, participants sometimes show a limitation in linking their perceptions of environmental changes to specific places in reality (Escobedo et al., 2020; Reilly et al., 2018). As previously mentioned, important environmental aspects such as impacts on climate regulation service that the stakeholders could not consider in current land-use activities were excluded in determining ES and future scenarios. Although the most legitimate stakeholders were selected in terms of agricultural land-use at district level, the involvement of a specific group has a limitation in dealing with potential conflicts and trade-offs between the interests of different land-use actors (Dahik et al., 2018; Kusters et al., 2018; Labiosa et al., 2013).

In order to make a good use of local knowledge, efforts are required to combine local and scientific forms of knowledge, interpret them and produce insights arising from the combination (Mantyka-Pringle et al., 2017; Mialhe et al., 2015). GISCAME used as a spatially explicit modeling enabled to integrate stakeholder perspectives vis-à-vis the spatial peculiarity of ES provision in the assessment of future scenarios. As GISCAME can be run with simplified environmental data rather than an extensive dataset, it is easier to combine local details to test various future alternatives and translate the modeled results into decision-making related information. In this sense, this modeling approach has the potential to support a transdisciplinary planning approach, especially in West Africa where locally adapted methodological frameworks are still lacking (Inkoom et al., 2017). Quantified and visualized ES provision can improve the understanding of the stakeholders on the potential impact of land-use alternatives. It enables a better feedback from stakeholders and better communication between different land-use actors for building shared visions on future actions, which can therefore be used as an ex-ante assessment of future land-use decisions (Hermanns et al., 2015; Verburg et al., 2016). However, as a modeling approach deals with an abstract of the complex environment, dynamics of interactions between land-use decisions and ES status were inevitably simplified due to the limited modeling capacity and field data to address all possible feedback loops. Similarly, direct and indirect factors which could largely influence agricultural land-use decisions such as subsidy programs, labor availability, and market situation were not included in this study due to a lack of adequate data. Lastly, land-use systems are characterized as a nested multi-scale spatial hierarchy (Lyle, 2015), which means that land-use decisions at district level alter the land-use conditions at farm level and shape land management policies at regional and national level. Thus, future assessments should also consider such multi-scale interactions of land-use systems.

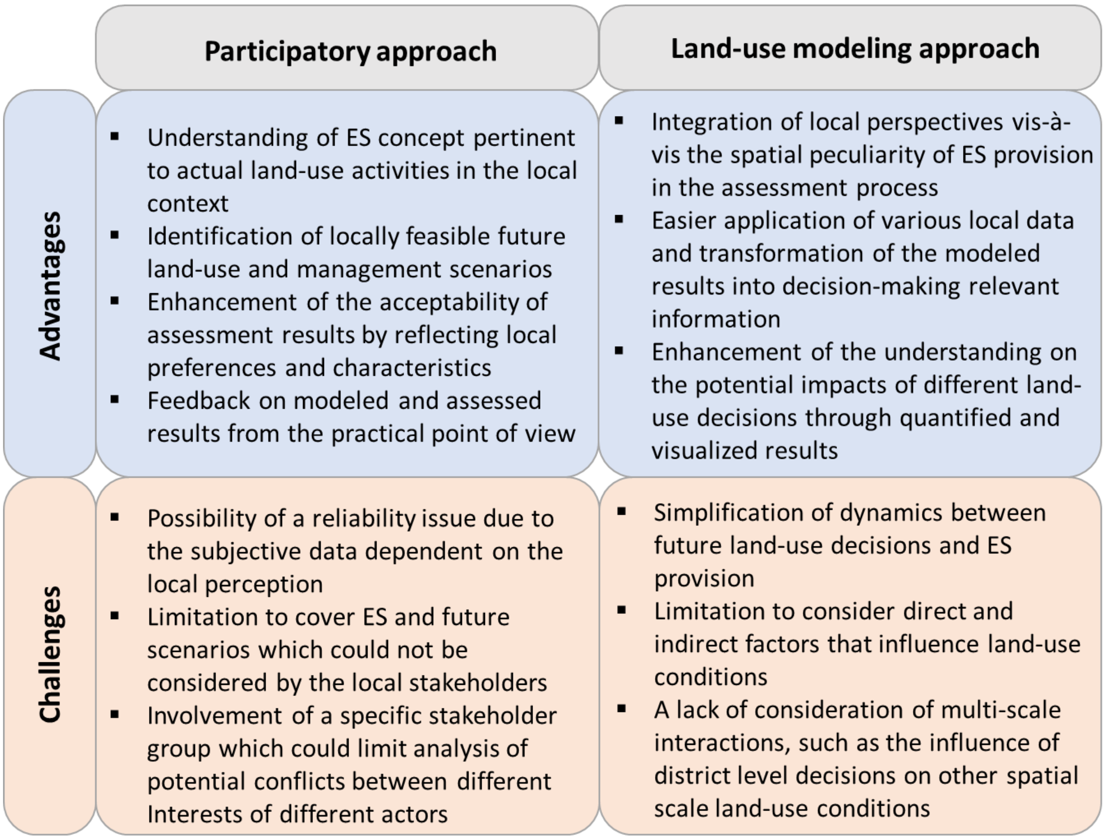


Figure 13. Advantages and challenges of applied approaches (modified from Koo et al., 2020)

4.3. Contributions from papers to this chapter

Table 7. Overview of the key contributions from the respective papers regarding chapter 4. Discussion

Paper	Key contribution
Paper I: Land management scenarios and their potential impact on ES provision in the local context	**Simulation of land management scenarios considering local characteristics** • Reflection of local perceptions allowed elaboration and evaluation of applicable future options in practice. Accordingly, the similarity and dissimilarity of scenario impacts on ES provision between the districts were understood, which were influenced by local perspectives and characteristics.
Paper II: Impact assessment of land-use changes on ES provision based local knowledge	**Local perception of the ES concept** • Participation of local stakeholders enabled to understand the locally pertinent ES concept related to actual land-use activities. In particular, ES indicators applied in this study allowed us to identify multiple ES supplied by a land-use type. However, some ES that are important in the West African context, but difficult for the stakeholders to recognize were excluded in this

	study. **Simulation of land-use change scenarios considering local characteristics** • Urbanization and deforestation were simulated according to different transition probabilities between land-use types and neighboring conditions, which were influenced by local preferences and land management/planning systems. However, there should be further consideration of applying various driving factors to the transition rule-sets.
Paper III: Future land-use recommendations based on the impact assessment of land-use strategies	**Locally-tailored future recommendations** • The integration of modeling results and feedback from the local stakeholders are useful for identification of future recommendations that are effective in enhancing multiple ES and highly feasible in the local context. The determination of different land-use strategies as future recommendations for each district emphasizes the necessity of considering local preferences on land-use and management systems. • A trade-off effect on water provision by future scenarios is due to the beneficiary-oriented definition. However, the potential of tested scenarios to contribute to atmospheric moisture at regional and global level should be further considered. **Synthesis of strengths and weaknesses of applied methods** • A participatory approach and spatially explicit modeling were integrated for assessment of the impact of various scenario in the local context. Advantages and challenges of the applied methods, which were also discussed in previous papers, were synthesized.

5. Conclusions and outlook

This study integrated local knowledge into land-use modeling for an assessment of the impact of various land-use and management scenarios on the provision of ES in the agricultural context of northern Ghana, West Africa. Local stakeholders who were selected as the most legitimate group regarding agricultural land-use decision at district level participated through surveys and interviews. Their perspectives were reflected in identification of locally relevant ES, indicator values, land management scenarios, scenario simulation conditions and recommended future strategies. Collected local knowledge for two districts, Bolgatanga and Bongo, was applied to a modeling platform GISCAME in order to evaluate spatial impacts of various scenarios and resultant effects on ES provision. Comparison of simulation results between the districts helped to understand how different local perception and characteristics can influence the level of district capacity to provide ES. Key findings of this study are as follows:

- As locally relevant ES in the agricultural context of northern Ghana, the provision of food, fodder, energy, construction materials, water and erosion control were selected. Indicators reflecting consumptive patterns of land-use products allowed consideration of the multifunctionality of agricultural land from the local perspective.
- Regarding the impact of land-use changes, urbanization was more influential than deforestation in both districts. Most ES were decreased by urbanization as a negative synergy, while water provision was increase as a trade-off. Deforestation led to a decrease in the provision of energy, construction materials and water, and erosion control, whereas the provision of food, fodder and marketable products was slightly increased or constant.
- As locally relevant land management scenarios, 15 scenarios concerned with intercropping, agroforestry, and soil conservation practices were developed. Cereal-dominant intercropping scenario and the establishment of soil or stone bunds on cereals scenario were presented as most effective to provide food, and legume-dominant intercropping showed the highest value of marketable product provision in both districts. Mixed vegetation afforestation was most effective for construction material provision in Bolgatanga while grassland afforestation presented the highest potential of the ES in Bongo. Most land management scenarios negatively influenced water provision in both districts.
- 75 land-use strategies as combinations of land management scenarios brought more prominent synergies and trade-offs between ES than the application of individual land management scenarios. As best strategies that can supply more than three different ES with the highest potential, 14 land-use strategies in Bolgatanga and 8 land-use strategies in Bongo were identified. Feedback from the stakeholders on the assessment results allowed determination of recommended land-use strategies which have high feasibility in practice as well as a high potential to enhance multiple ES.
- Water provision was negatively influenced by most land management scenarios and strategies, whereas other ES were either increased or consistent. This is due to the recipient-oriented definition of water provision that focused on the available amount of surface water for household consumption competing with water demand by crops and tree covers.
- Different local perceptions and preferences on land use practices, e.g., effects of agroforestry led to the dissimilar impact of future scenarios at district level. Spatial configuration of land use types such as the areas occupied by each land use type in the district and locational characteristics also contributed to different district capacity to supply ES, depending on scenarios.

Despite the potential of the applied approach in supporting locally-tailored land use management and planning, there should be further efforts to implement such ES evaluation in actual decision-making and planning in West Africa and Ghana. This study adapted the definition of ES and indicators to the local context considering the fact that local people are still unacquainted with this scientific term. Such a transdisciplinary attempt implies the possibility of involving various agriculture-related actors, e.g., farmers, NGOs, governmental bodies and experts, in assessment processes, allowing establishment of a shared understanding of ES. Different interests and benefits depending on actor groups, which are especially related to non-monetary ES values, can be compared and mediated by the shared and agreed ES definition. Consideration of various aspects of different groups can increase the acceptance of ES assessment results as well as the validity of findings, and further effectively support consensus building for future actions.

For better use of ES assessment in actual land-use planning, how ES information can be operated in a specific policy context should be further investigated. Since land-use stakeholders and decision-makers are interested in where new land-use practices and management are necessary, spatial distribution and peculiarity of ES closely linked to land-use patterns should be provided as key information for analyzing the current situation and exploring alternatives (Albert et al., 2014; Fürst et al., 2014). When and how the information can be integrated with actual planning processes should be investigated, e.g., applying in a preliminary step for identifying and classifying suitable land-use options for different purposes. In Ghana, although the majority of the land is still used for providing food and natural resources, land-use planning has mostly focused on managing physical growth and urban expansion. In addition, the ES concept has thus far been rarely reflected in any Ghanaian spatial development programs (Inkoom et al., 2017). Therefore, research on which types of ES-relevant information are required by planners and decision-makers and how to establish a new ES evaluation standard harmonized with existing decision-making structure, e.g., quantitative or monetary estimation of the impacts of policy options on ES provision, should be followed.

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Annex A: Supplementary to dissertation

Table A 1. Preliminary list of ecosystem services based on references (modified from Koo et al., 2019).

Ecosystem service		Potential indicator suggested by reference	Reference
Provisioning service	Subsistence crops	Harvested crops (t ha^{-1} a^{-1}, kJ ha^{-1} a^{-1}); Yield (dt ha^{-1} a^{-1})	a, b, c, d, e, g, h, j
	Cash crops	Contribution margin (€ ha^{-1} a^{-1})	e, g
	Fodder	Fodder plant harvest (t ha^{-1}, kJ ha^{-1} a^{-1})	a, c, h
	Biomass for fuel	Harvested plants for energy conversion (t ha^{-1} a^{-1}, kJ ha^{-1} a^{-1})	a, b, c, d, e, h
	Timber for construction	Harvested wood for construction purposes (t ha^{-1} a^{-1}, kJ ha^{-1} a^{-1})	a, b, c, d, e, g, h
	Fresh water	Withdrawal of freshwater (l ha^{-1} a^{-1}, m^3 ha^{-1} a^{-1}); N-export with infiltration water (kg N ha^{-1} a^{-1})	a, b, e, f, g, h, i
Regulating service	Erosion control	RUSLE value for probable landslide frequency (n ha^{-1} a^{-1}); Run-off coefficient (Ψ)	a, b, c, e, f, g, h, i, j
	Climate regulation	The amount of carbon stored and sequestered in surfaces (kg C ha^{-1} a^{-1})	a, b, c, e, g, h, I, j
	Pollination	Species numbers and number of pollinators (n ha^{-1})	a, b, c, h
Cultural service	Knowledge system for environmental education	Number of environmental educational-related facilities and/or events and number of their users (n ha^{-1} a^{-1})	a, b, c, e, h, j
	Preservation of traditions	Number of spiritual facilities (n ha^{-1}) Number of employees in traditional landscape (n ha^{-1})	a, b, c, e, h

(a) De Groot et al. (2002), (b) MA (2005), (c) Hein et al. (2006), (d) Chen et al. (2009), (e) CICES (2011), (f) Egoh et al. (2011), (g) Koschke et al. (2012), (h) Kandziora et al. (2013), (i) Leh et al. (2013) (j) Martín-López et al. (2014)

Table A 2. Indicator values of selected ecosystem services by land-use types (modified from Koo et al., 2019).

District	Land-use type	Food (%)	Fodder (%)	Energy (%)	Construction materials (%)	Marketable products (%)	Water (mm $cell^{-1}$ a^{-1})	Erosion control (t ha^{-1} a^{-1})
Bolgatanga	Cereals	66	5	9	0	20	800.43	13.88
	Maize	60	8	2	0	30	802.86	13.38
	Legumes	68	3	1	0	45	798.82	1.90
	Rice	50	1	1	0	48	763.70	4.21
	Grassland	1	71	10	10	8	795.42	0.77
	Mixed vegetation	22	33	20	17	8	801.67	0.28
	Trees/Forests	32	5	18	8	37	800.53	0.15
	Bare/Artificial surfaces	0	0	0	0	0	807.44	34.80
	Water bodies	0	0	0	0	0	800.88	0.22

(Continued)

District	Land-use type	Food (%)	Fodder (%)	Energy (%)	Construction materials (%)	Marketable products (%)	Water (mm cell^{-1} a^{-1})	Erosion control (t ha^{-1} a^{-1})
Bongo	Cereals	62	4	8	1	25	774.05	9.82
	Maize	55	7	2	1	35	776.06	12.37
	Legumes	52	10	0	0	38	774.64	1.51
	Rice	50	9	0	0	41	783.66	2.91
	Grassland	11	61	3	13	12	775.13	0.44
	Mixed vegetation	21	33	20	14	11	790.25	0.13
	Trees/Forests	33	8	19	5	35	790.97	0.16
	Bare/Artificial surfaces	0	0	0	0	0	777.40	33.63
	Water bodies	0	0	0	100	0	773.65	0.17

Table A 3. Standardized ecosystem service values ranging from 0 (lowest level of provision) to 100 (highest level of provision) (modified from Koo et al., 2019).

District	Land-use type	Food	Fodder	Energy	Construction materials	Marketable products	Water	Erosion control
Bolgatanga	Cereals	97	7	46	0	43	84	60
	Maize	87	12	11	0	62	90	62
	Legumes	100	4	5	0	94	80	95
	Rice	74	1	5	0	100	0	88
	Grassland	2	100	50	58	16	73	98
	Mixed vegetation	32	47	100	100	17	87	100
	Tree/Forest	47	7	90	49	78	84	100
	Bare/Artificial surfaces	0	0	0	0	0	99	0
	Water bodies	0	0	0	0	0	100	100
Bongo	Cereals	100	7	41	9	61	0	71
	Maize	89	11	9	9	86	12	63
	Legumes	84	17	0	0	94	3	96
	Rice	81	15	0	0	100	57	92
	Grassland	17	100	16	96	29	6	99
	Mixed vegetation	34	55	100	100	28	96	100
	Tree/Forest	54	14	91	36	86	100	100
	Bare/Artificial surfaces	0	0	0	0	0	20	0
	Water bodies	0	0	0	0	0	100	100

Table A 4. Transitional rule-sets for simulating land-use change scenarios. The rule-sets based on a stakeholder survey include transitional probabilities (in percentage) and neighboring conditions that induce urbanization and deforestation (modified from Koo et al., 2019).

Land-use change	Current land-use type	Future land-use type	Transition probability (%)	Neighboring land-use type
Urbanization	Cereals	Bare/artificial surfaces	70	Proximity of current land-use types to bare/artificial surfaces; more than three cells of bare/artificial surfaces located as neighboring cells around current cereals, maize, rice, grassland, mixed vegetation and tree/forest
	Maize	Bare/artificial surfaces	70	
	Legumes	Bare/artificial surfaces	80	
	Rice	Bare/artificial surfaces	60	
	Grassland	Bare/artificial surfaces	90	
	Mixed vegetation	Bare/artificial surfaces	90	
	Tree/Forest	Bare/artificial surfaces	60	
Deforestation	Tree/forest, mixed vegetation	Cereals	70	Proximity of initial land-use types to target land-use types; more than three cells of cereals or maize or legumes or grassland or bare/artificial surfaces located as neighboring cells around tree/forest and mixed vegetation
	Tree/forest, mixed vegetation	Maize	70	
	Tree/forest, mixed vegetation	Legumes	80	
	Tree/forest, mixed vegetation	Grassland	90	
	Tree/forest, mixed vegetation	Bare/artificial surfaces	60	

Table A 5. Impact of land management scenarios on the current status of ecosystem services based on a stakeholder survey. Each percentage implies the extent of potential increase or decrease in the capacity of ecosystem services according to the application of scenarios, compared to the current status of ecosystem services (modified from Koo et al., 2018).

District		Land management scenario	Change in ecosystem service provision (%)						
			Food	Fodder	Energy	Construction Material	Marketable Product	Water	Erosion Control
Bolgatanga	1	Cereal-dominant intercropping	67	64	18	9	56	−22	75
	2	Maize-dominant intercropping	71	63	15	12	63	−22	63
	3	Legume-dominant intercropping	67	38	34	17	53	−23	31
	4	Grassland afforestation	65	1	66	64	53	−25	38
	5	Mixed vegetation afforestation	43	6	59	58	41	−22	33
	6	Cereal intercropping with mango	−12	−5	12	9	21	−32	41
	7	Maize intercropping with mango	−12	−5	12	9	21	−32	41

(Continued)

		Land management scenario	Change in ecosystem service provision (%)						
			Food	Fodder	Energy	Construction Material	Marketable Product	Water	Erosion Control
Bolgatanga	8	Legume intercropping with mango	43	22	36	24	45	−30	41
	9	Cereal intercropping with leucaena	23	64	35	19	27	−29	57
	10	Maize intercropping with leucaena	23	64	35	19	27	−29	57
	11	Legume intercropping with leucaena	17	67	36	22	30	−25	59
	12	Soil or stone bunds on cereal	63	55	47	27	74	−25	66
	13	Soil or stone bunds on maize	63	55	47	27	74	−25	66
	14	Windbreak on cereal	54	51	49	47	46	−21	60
	15	Windbreak on maize	54	51	49	47	46	−21	60
Bongo	1	Cereal-dominant inter-cropping	60	45	14	−6	54	2	47
	2	Maize-dominant inter-cropping	62	41	−2	5	53	4	41
	3	Legume-dominant in-tercropping	43	17	19	12	54	−27	32
	4	Grassland afforestation	40	3	52	52	51	−32	46
	5	Mixed vegetation affor-estation	37	33	48	48	40	−28	42
	6	Cereal intercropping with mango	26	17	15	11	44	−32	26
	7	Maize intercropping with mango	26	17	15	11	44	−32	26
	8	Legume intercropping with mango	45	25	23	20	45	−21	36
	9	Cereal intercropping with leucaena	20	51	33	14	22	−25	41
	10	Maize intercropping with leucaena	20	51	33	14	22	−25	41
	11	Legume intercropping with leucaena	32	55	35	22	38	−31	39
	12	Soil or stone bunds on cereal	58	50	35	28	48	−22	67
	13	Soil or stone bunds on maize	58	50	35	28	48	−22	67
	14	Windbreak on cereal	40	40	39	40	30	−22	45
	15	Windbreak on maize	40	40	39	40	30	−22	45

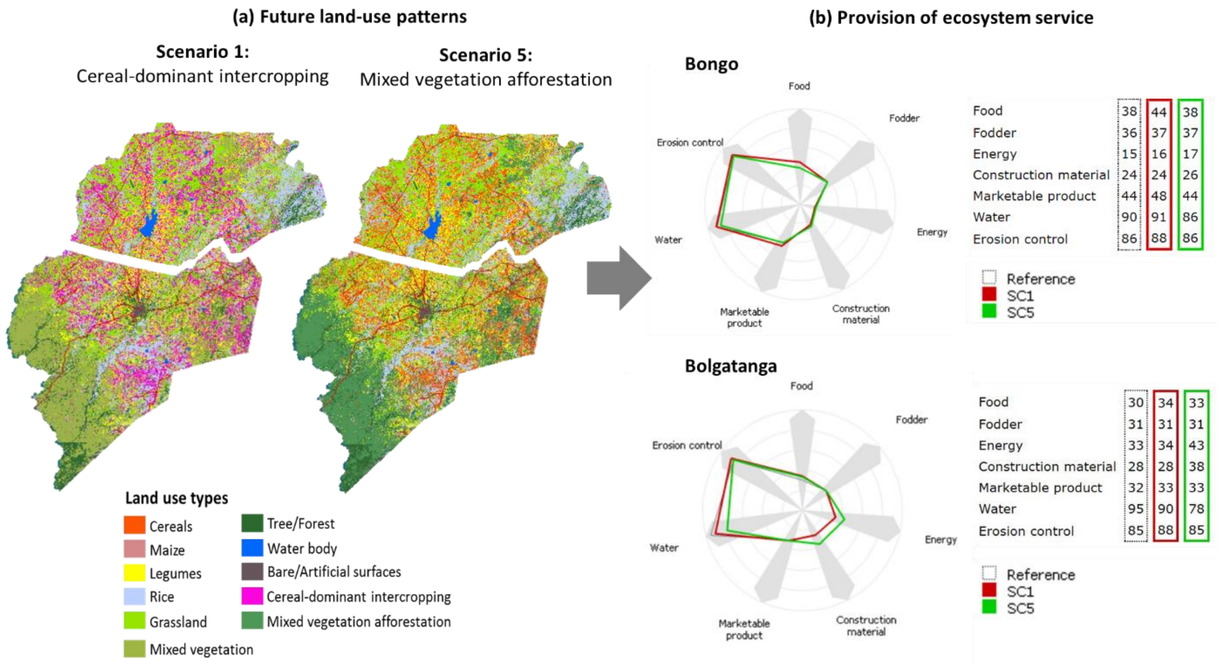

Figure A 1. Future land-use patterns and the ecosystem services balance according to land management scenarios. For example, the influence of cereal-dominant intercropping scenario (SC 1) and mixed vegetation afforestation scenario (SC 5) on the current land-use pattern were generated by cellular automaton (a). Changes in the provision of ecosystem services caused by SC1 and SC5 are displayed in the spider charts and the balance tables compared to the current provision of ecosystem services as reference (b). The images were captured from the GISCAME platform for the WASCAL program.

Table A 6. Simulation conditions for land management scenarios using cellular automaton, which are identified based on a stakeholder survey (modified from Koo et al., 2018).

Scenario	Current land-use type	Future land-use type	Transition probability (%)	Neighboring land-use type	Environmental attribute
1	Cereals	Cereal-dominant intercropping	90	Cereals, legume	Soil type, run-off
2	Maize	Maize-dominant intercropping	80	Maize, legume	Soil type, run-off
3	Legumes	Legume-dominant intercropping	85	Cereals, maize, legume	Soil type
4	Grassland	Grassland afforestation	75	Tree/forest, grassland	Soil type
5	Mixed vegetation	Mixed vegetation afforestation	80	Tree/forest, mixed vegetation	Soil type
6	Cereals	Cereal intercropping with mango	70	Cereals, bare/artificial surfaces	Soil type, run-off
7	Maize	Maize intercropping with mango	70	Maize, bare/artificial surfaces	Soil type, run-off
8	Legumes	Legume intercropping with mango	90	Legumes, bare/artificial surfaces	Soil type

(Continued)

Scenario	Current land-use type	Future land-use type	Transition probability (%)	Neighboring land-use type	Environmental attribute
9	Cereals	Cereal intercropping with leucaena	80	Cereals	Soil type, run-off
10	Maize	Maize intercropping with leucaena	70	Maize	Soil type, run-off
11	Legumes	Legume intercropping with leucaena	90	Legumes	Soil type
12	Cereals	Stone or soil bunds on cereals	80	Cereals	Soil type, run-off
13	Maize	Stone or soil bunds on maize	80	Maize	Soil type, run-off
14	Cereals	Windbreak on cereals	70	Cereals, legumes	Soil type, run-off
15	Maize	Windbreak on maize	70	Maize, legumes	Soil type, run-off

Table A 7. Future land-use strategies consisted of different land management options (modified from Koo et al., 2020).

Nº	Future land-use strategy	Nº	Future land-use strategy	Nº	Future land-use strategy
1	CI + MI + LI + GA + MxA	**2**	CI + MI + LM + GA + MxA	**3**	CI + MI + LL + GA + MxA
4	CI + MM + LI + GA +MxA	**5**	CI + MM+ LM + GA + MxA	**6**	CI +MM + LL +GA + MxA
7	CI + ML +LI +GA + MxA	**8**	CI + ML + LM + GA+ MxA	**9**	CI + ML + LL + GA + MxA
10	CI + MB + LI + GA + MxA	**11**	CI + MB + LM + GA +MxA	**12**	CI + MB + LL + GA +MxA
13	CI + MW + LI + GA + MxA	**14**	CI + MW + LM + GA +MxA	**15**	CI + MW + LL + GA +MxA
16	CM + MI + LI + GA + MxA	**17**	CM + MI + LM + GA + MxA	**18**	CM + MI + LL + GA + MxA
19	CM + MM + LI + GA +MxA	**20**	CM + MM+ LM + GA + MxA	**21**	CM +MM + LL +GA + MxA
22	CM + ML +LI +GA + MxA	**23**	CM + ML + LM + GA+ MxA	**24**	CM + ML + LL + GA + MxA
25	CM + MB + LI + GA + MxA	**26**	CM + MB + LM + GA +MxA	**27**	CM + MB + LL + GA +MxA
28	CM + MW + LI + GA + MxA	**29**	CM + MW + LM + GA +MxA	**30**	CM + MW + LL + GA +MxA
31	CL + MI + LI + GA + MxA	**32**	CL + MI + LM + GA + MxA	**33**	CL + MI + LL + GA + MxA
34	CL + MM + LI + GA +MxA	**35**	CL + MM+ LM + GA + MxA	**36**	CL +MM + LL +GA + MxA
37	CL + ML +LI +GA + MxA	**38**	CL + ML + LM + GA+ MxA	**39**	CL + ML + LL + GA + MxA
40	CL + MB + LI + GA + MxA	**41**	CL + MB + LM + GA +MxA	**42**	CL + MB + LL + GA +MxA
43	CL + MW + LI + GA + MxA	**44**	CL + MW + LM + GA +MxA	**45**	CL + MW + LL + GA +MxA
46	CB + MI + LI + GA + MxA	**47**	CB + MI + LM + GA + MxA	**48**	CB + MI + LL + GA + MxA
49	CB + MM + LI + GA +MxA	**50**	CB + MM+ LM + GA + MxA	**51**	CB +MM + LL +GA + MxA
52	CB + ML +LI +GA + MxA	**53**	CB + ML + LM + GA+ MxA	**54**	CB + ML + LL + GA + MxA

* CI: Cereal-dominant intercropping; MI: Maize-dominant intercropping; LI: Legume-dominant intercropping; GA: Grassland afforestation; MxA: Mixed vegetation afforestation; CM: Cereal intercropping with mango; MM: Maize intercropping with mango; LM: Legume intercropping with mango; CL: Cereal intercropping with leucaena; ML: Maize intercropping with leucaena; LL: Legume intercropping with leucaena; CB: Soil or stone bunds on cereals; MB: Soil or stone bunds on maize; CW: Windbreak on cereals; MW: Windbreak on maize

(Continued)

Nº	Future land-use strategy	Nº	Future land-use strategy	Nº	Future land-use strategy
55	CB + MB + LI + GA + MxA	**56**	CB + MB + LM + GA +MxA	**57**	CB + MB + LL + GA +MxA
58	CB + MW + LI + GA + MxA	**59**	CB + MW + LM + GA +MxA	**60**	CB + MW + LL + GA +MxA
61	CW + MI + LI + GA + MxA	**62**	CW + MI + LM + GA + MxA	**63**	CW + MI + LL + GA + MxA
64	CW + MM + LI + GA +MxA	**65**	CW + MM+ LM + GA + MxA	**66**	CW +MM + LL +GA + MxA
67	CW + ML +LI +GA + MxA	**68**	CW + ML + LM + GA+ MxA	**69**	CW + ML + LL + GA + MxA
70	CW + MB + LI + GA + MxA	**71**	CW + MB + LM + GA +MxA	**72**	CW + MB + LL + GA +MxA
73	CW + MW + LI + GA + MxA	**74**	CW + MW + LM + GA +MxA	**75**	CW + MW + LL + GA +MxA

* CI: Cereal-dominant intercropping; MI: Maize-dominant intercropping; LI: Legume-dominant intercropping; GA: Grassland afforestation; MxA: Mixed vegetation afforestation; CM: Cereal intercropping with mango; MM: Maize intercropping with mango; LM: Legume intercropping with mango; CL: Cereal intercropping with leucaena; ML: Maize intercropping with leucaena; LL: Legume intercropping with leucaena; CB: Soil or stone bunds on cereals; MB: Soil or stone bunds on maize; CW: Windbreak on cereals; MW: Windbreak on maize

Table A 8. Ecosystem service values of 75 land-use strategies in Bolgatanga. Current ecosystem service values are used as reference values (R), in grey color. The highest value of each ecosystem service is expressed in blue color (the provision of construction materials is excluded as it is equally increased by all land-use strategies). Best land-use strategies which have a potential to provide more than three different ecosystem services with the highest values are presented in orange color (modified from Koo et al., 2020).

		Future land-use strategy																								
Ecosystem services	**R**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
Food	30	42	41	39	41	40	38	41	40	39	42	41	39	42	41	37	35	34	35	34	33	36	35	33	37	37
Fodder	31	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	31	31	31	32	31	32	32	32
Energy	33	47	47	47	47	47	47	47	47	47	47	47	47	47	47	46	46	46	46	46	46	46	46	46	46	46
Construction material	28	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41
Marketable product	32	40	40	39	40	39	38	40	39	38	40	40	39	40	40	39	39	38	38	38	37	39	38	37	39	39
Water	95	52	50	51	51	49	50	51	49	51	51	49	50	52	50	48	46	48	48	46	47	48	46	48	48	48
Erosion control	85	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	88	88	88	88	88	88	88	88	88	88
		Future land-use strategy																								
Ecosystem services	**R**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**	**49**	**50**
Food	30	35	34	36	35	34	39	38	36	38	36	35	38	37	35	39	38	36	39	37	36	42	40	39	40	39
Fodder	31	31	32	32	31	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32
Energy	33	46	46	46	46	46	47	47	47	47	47	47	47	47	47	47	47	47	47	47	47	47	47	47	47	47
Construction material	28	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41
Marketable product	32	39	38	39	38	37	39	39	38	39	38	37	39	38	37	39	39	38	39	39	38	41	40	39	40	40
Water	95	46	47	49	47	48	49	47	49	49	47	48	49	47	48	49	47	48	50	48	49	51	49	50	50	48
Erosion control	85	88	88	88	88	88	89	89	89	89	89	89	89	89	89	89	89	89	89	89	89	89	89	90	89	89
		Future land-use strategy																								
Ecosystem services	**R**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**64**	**65**	**66**	**67**	**68**	**69**	**70**	**71**	**72**	**73**	**74**	**75**
Food	30	38	41	40	38	41	40	39	41	40	39	41	40	38	40	38	37	40	39	37	41	40	38	41	39	38
Fodder	31	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32
Energy	33	47	48	48	47	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48
Construction material	28	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41
Marketable product	32	39	40	40	39	41	40	40	41	40	39	40	39	39	39	39	38	39	39	38	40	40	39	40	39	38
Water	95	50	50	48	50	50	48	50	51	49	50	52	50	52	52	50	51	52	50	51	52	50	51	52	50	52
Erosion control	85	89	89	89	89	89	89	90	89	89	89	89	89	89	89	89	89	89	89	89	89	89	89	89	89	89

Table A 9. Ecosystem service values of 75 land-use strategies in Bongo. Current ecosystem service values are used as reference values (R), in grey color. The highest value of each ecosystem service is expressed in blue color. Best land-use strategies which have a potential to provide more than three different ecosystem services with the highest values are presented in orange color (modified from Koo et al., 2020).

		Future land-use strategy																								
Ecosystem services	**R**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
Food	38	49	49	48	48	48	47	48	48	47	48	49	48	48	48	48	45	45	45	44	45	44	44	44	44	45
Fodder	36	39	39	39	39	39	39	39	39	39	38	39	39	39	39	39	38	39	39	38	38	39	38	39	39	38
Energy	15	18	18	18	19	19	19	19	19	19	18	19	19	19	19	19	18	18	18	18	18	18	19	19	19	19
Construction material	24	34	34	34	34	34	34	34	34	34	32	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34
Marketable product	44	55	54	54	55	54	54	54	54	53	54	54	54	54	54	53	54	54	53	54	53	53	53	53	52	54
Water	90	58	60	57	54	56	53	55	56	54	60	57	54	55	57	54	44	46	43	40	42	39	41	43	40	41
Erosion control	86	89	89	89	89	89	89	89	89	89	89	89	89	89	89	89	88	88	88	88	88	88	88	88	88	88

		Future land-use strategy																								
Ecosystem services	**R**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**	**49**	**50**
Food	38	45	44	45	45	44	45	45	44	44	44	43	44	44	43	45	45	44	44	44	43	48	49	48	48	48
Fodder	36	39	39	38	39	39	39	39	40	39	39	39	39	39	40	39	39	40	39	39	40	39	39	40	39	39
Energy	15	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19
Construction material	24	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34
Marketable product	44	53	53	54	53	52	53	52	52	53	52	51	52	51	51	53	52	51	52	52	51	55	54	53	54	54
Water	90	43	40	41	43	40	47	49	46	43	45	41	43	45	42	44	46	43	44	46	43	48	50	47	44	46
Erosion control	86	88	88	88	88	88	89	89	89	88	88	88	89	89	89	89	89	89	89	89	89	90	90	90	90	90

		Future land-use strategy																								
Ecosystem services	**R**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**64**	**65**	**66**	**67**	**68**	**69**	**70**	**71**	**72**	**73**	**74**	**75**
Food	38	47	47	47	47	48	48	47	48	48	47	47	47	46	46	46	45	46	46	45	47	47	46	46	46	45
Fodder	36	39	39	39	40	39	39	40	39	39	40	39	39	39	39	39	39	39	39	39	39	39	39	39	39	39
Energy	15	19	19	19	19	19	19	19	19	19	19	19	19	19	20	20	20	20	20	20	20	20	20	20	20	20
Construction material	24	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34
Marketable product	44	53	54	53	52	54	54	53	54	53	53	53	53	52	53	52	52	53	52	51	53	52	52	53	52	51
Water	90	43	45	47	44	45	47	44	45	47	44	48	50	47	44	46	43	45	47	44	45	47	44	45	47	44
Erosion control	86	90	90	90	90	90	90	90	90	90	90	89	89	89	89	89	89	89	89	89	89	89	89	89	89	89

Annex B: Publications

Koo, H., Kleemann, J., Fürst, C., 2018. Land-use scenario modeling based on local knowledge for the provision of ecosystem services in Northern Ghana, *Land*, 7:59. https://doi.org/10.3390/land7020059

Abstract: The understanding of multiple effects by possible future development is essential for adapted land use planning. This study assessed the potential of land use scenarios for the provision of ecosystem services using local knowledge in two districts of northern Ghana. Local knowledge was gathered through surveys with extension officers, who are regarded as eligible knowledge holders for agricultural land use. Firstly, ecosystem services that were perceived as important by the stakeholders were identified, namely food, fodder, energy, construction materials, marketable products, water provision, and erosion control. Quantitative indicators were then determined to analyze the capacity of land use types to supply the ecosystem services. Land use scenarios were developed based on their applicability and capacity to mitigate climate change impacts. The perception of stakeholders was applied to evaluate changes in ecosystem services provision by the scenarios. A modeling approach for a spatially explicit simulation was used to assess the potential to provide ecosystem services at a district level. The results reflected the different trade-offs and synergies between ecosystem services of each scenario, depending on the district. Along with the local perception, characteristics of land use patterns also influenced the regional potential of ecosystem services provision.

Keywords: land use change; stakeholder; participation; planning; climate change impact; modeling; trade-off; synergy; transdisciplinarity; agriculture; West Africa

Koo, H., Kleemann, J., Fürst, C., 2019. Impact assessment of land-use changes using local knowledge for the provision of ecosystem services in Northern Ghana, West Africa, *Ecological Indicators*, 103: 156-172. https://doi.org/10.1016/j.ecolind.2019.04.002

Abstract: An integrative perspective on assessing land use impacts requires the understanding of relationships between land use and the provision of ecosystem services. This study presents a stakeholder-based modeling approach to assess the potential impact of land use patterns and land use changes on ecosystem services in two districts of northern Ghana. First, the most legitimate group of stakeholders considering their influence and interest in the agricultural sector was selected. Second, ecosystem services and quantitative indicators that are relevant to land uses were determined based on literature and a stakeholder survey. Future land use patterns were simulated considering land use changes caused by urbanization and deforestation in the local context. Subsequently, si- mulated land use patterns were integrated with the potential values of ecosystem services provided by different land use types to analyze the capacity of ecosystem services provision at district level in a modeling approach. The results showed the current status of ecosystem services supplied by each district, and trade-offs and sy- nergies between ecosystem services as effects of the land use changes. The similarity and dissimilarity of land use change impacts between the districts were identified, which were attributed to the different perception by stakeholders and specific characteristics of land use patterns.

Keywords: Stakeholder; Participatory assessment; Urbanization; Deforestation; Land use modeling; Trade-off; Synergy; Agriculture; Ghana

* Only the abstract of the original manuscript is included in the dissertation due to copyright restriction.

Koo, H., Kleemann, J., Fürst, C., 2020. Integrating ecosystem services into land-use modeling to assess the effects of future land-use strategies in Northern Ghana, *Land*, 9:379. http://doi.10.3390/land9100379

Abstract: In West Africa, where the majority of the population relies on natural resources and rain-fed agriculture, regionally adapted agricultural land-use planning is increasingly important to cope with growing demand for land-use products and intensifying climate variability. As an approach to identify effective future land-use strategies, this study applied spatially explicit modeling that addresses the spatial connectivity between the provision of ecosystem services and agricultural land-use systems. Considering that the status of ecosystem services varies with the perception of stakeholders, local knowledge, and characteristics of a case study area, two adjoining districts in northern Ghana were integrated into an assessment process of land-use strategies. Based on agricultural land-management options that were identified together with the local stakeholders, 75 future land-use strategies as combinations of multiple agricultural practices were elaborated. Potential impacts of the developed land-use strategies on ecosystem services and land-use patterns were assessed in a modeling platform that combines Geographic Information System (GIS) and Cellular Automaton (CA) modules. Modeled results were used to identify best land-use strategies that could deliver multiple ecosystem services most effectively. Then, local perception was applied to determine the feasibility of the best land-use strategies in practice. The results presented the different extent of trade-offs and synergies between ecosystem services delivered by future land-use strategies and their different feasibility depending on the district. Apart from the fact that findings were context-specific and scale-dependent, this study revealed that the integration of different local characteristics and local perceptions to spatially explicit ecosystem service assessment is beneficial for determining locally tailored recommendations for future agricultural land-use planning.

Keywords: land-use planning; scenario; agriculture; spatially explicit simulation; modeling; stakeholder; participatory assessment land

MDPI

Article

Land Use Scenario Modeling Based on Local Knowledge for the Provision of Ecosystem Services in Northern Ghana

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Abstract: The understanding of multiple effects by possible future development is essential for adapted land use planning. This study assessed the potential of land use scenarios for the provision of ecosystem services using local knowledge in two districts of northern Ghana. Local knowledge was gathered through surveys with extension officers, who are regarded as eligible knowledge holders for agricultural land use. Firstly, ecosystem services that were perceived as important by the stakeholders were identified, namely food, fodder, energy, construction materials, marketable products, water provision, and erosion control. Quantitative indicators were then determined to analyze the capacity of land use types to supply the ecosystem services. Land use scenarios were developed based on their applicability and capacity to mitigate climate change impacts. The perception of stakeholders was applied to evaluate changes in ecosystem services provision by the scenarios. A modeling approach for a spatially explicit simulation was used to assess the potential to provide ecosystem services at a district level. The results reflected the different trade-offs and synergies between ecosystem services of each scenario, depending on the district. Along with the local perception, characteristics of land use patterns also influenced the regional potential of ecosystem services provision.

Keywords: land use change; stakeholder; participation; planning; climate change impact; modeling; trade-off; synergy; transdisciplinarity; agriculture; West Africa

1. Introduction

In West Africa, the majority of farmers rely on small-scale subsistence farming that produces most of the staple crops through rain-fed agriculture [1–3]. The high dependence on climate-sensitive agriculture increases the vulnerability of poor communities to the consequences of increasing climate variability and extreme weather events, such as droughts and floods [4]. Therefore, adapted land use planning and resource management for avoiding unfavorable environmental conditions becomes important [5]. The Ghana Environmental Protection Council (1988) formerly expressed the necessity for coordinated and comprehensive land management and planning strategies [6]. It stipulated principles of land management as increasing crop yields while maintaining ecosystems and ecological processes, and encouraging public participation in decision-making, in order to address challenges in environmental and resource management due to land pressure. However, land use planning in Ghana is authorized and led by the local government as the basic administrative unit that has been criticized to implement overly general and haphazard schemes to solve pressing issues, rather than fostering proactive and adaptive planning [7–9]. The lack of public awareness of land management programs has also hampered the successful implementation of adapted land management strategies [10]. An approach is, thus, required to formulate land use schemes with a clear assessment component considering human–environmental relations, and applying participative processes tailored to regional conditions [11–13]. An instrument for assessing land use schemes should be particularly able to address impacts of human intervention (land use activities) on ecosystems, and the consequential changes in human benefits to which they are coupled. Incorporating the concept of ecosystem services (ES) into land use planning has received attention as a means to perform such an assessment [14–16]. An assessment approach also needs to deal with impacts of potential future land use options considering regional conditions. The integration of scenarios in planning is increasingly propagated to envisage different pathways of future landscapes, thereby allowing the exploration of options to reach specific targets [17,18]. The involvement of stakeholders in designing land use scenarios helps to identify acceptable land use alternatives by reflecting local preferences in land use decisions. It facilitates the understanding of the multifaceted nature of land use issues from the perspective of stakeholders who are directly affected by land use decisions, but limited to participate in science and policy discourses [19]. Scenarios that include the ES concept need to consider especially behaviors of ES beneficiaries (e.g., land users) and responses of ES providers (e.g., land use and landscape systems) [20,21]. Such attempts to determine the relationship between human activities and ES provision are, however, still scarce in many regions of West Africa [22]. Several studies in West Africa have so far focused on potential consequences of climate change scenarios on crop yield, rather than analyzing the influence of modified environmental conditions by human activities on land use-related human benefits (e.g., [4,23,24]). Stakeholder involvement was missing in the few studies that have assessed the impacts of land use patterns using the ES concept (e.g., [25,26]).

This study analyzes locally adapted and acceptable land use planning options based on the notion that human activities modify ecosystems and environmental conditions and, consequently, change the potential provision of ES. Specifically, this study aims at assessing the influence of future land use decisions on local ES provision using a participative approach in northern Ghana. By acknowledging local differences in perception, ES provision was analyzed separately for two adjoining districts. In the following sections, we describe the study areas, the land use types, the selection of local knowledge holders and ES, and the development of scenarios. The potential of the developed scenarios on the regional ES provision considering trade-offs and synergies between the ES are presented as results. In the discussion, differences between the districts in ES provision and limitations of this study are addressed.

2. Materials and Methods

2.1. Case Study Area

The study area is located in the Upper East Region (UER) of northern Ghana, and covers two districts, Bolgatanga Municipal (hereafter "Bolgatanga") and Bongo (Figure 1). Bolgatanga is located in the center of the UER, and covers a total area of 729 km^2. Bongo shares boundaries with Bolgatanga to the south, covering a total area of 460 km^2 [27]. Both districts belong to the Guinea Savannah Ecological Zone with two distinct seasons: a wet season from May to October, and a dry season from October to April. The average annual rainfall is approximately between 700 and 1010 mm, with a peak occurring in late August or early September [28,29]. The two districts are characterized by 1% to 5% of slopes, including granite rocky outcrops [30,31]. Their soil types are Lixisol, Leptosol, Luvisol, Gleysol, and Fluvisol, as classified by the Soil Research Institute of Ghana (2008). The two districts have similar environmental conditions and share the Vea watershed, whereas they have a different socio-political condition. Bolgatanga is more urbanized than Bongo, due to the fact that Bolgatanga is the administrative capital of the UER. About 55.4% of households in Bolgatanga are residents of urban areas, while only 7.5% of households in Bongo live in urban areas [27]. Each district has individual political, administrative, and developmental decision-making power, according to a decentralization program initiated in 1988 [32].

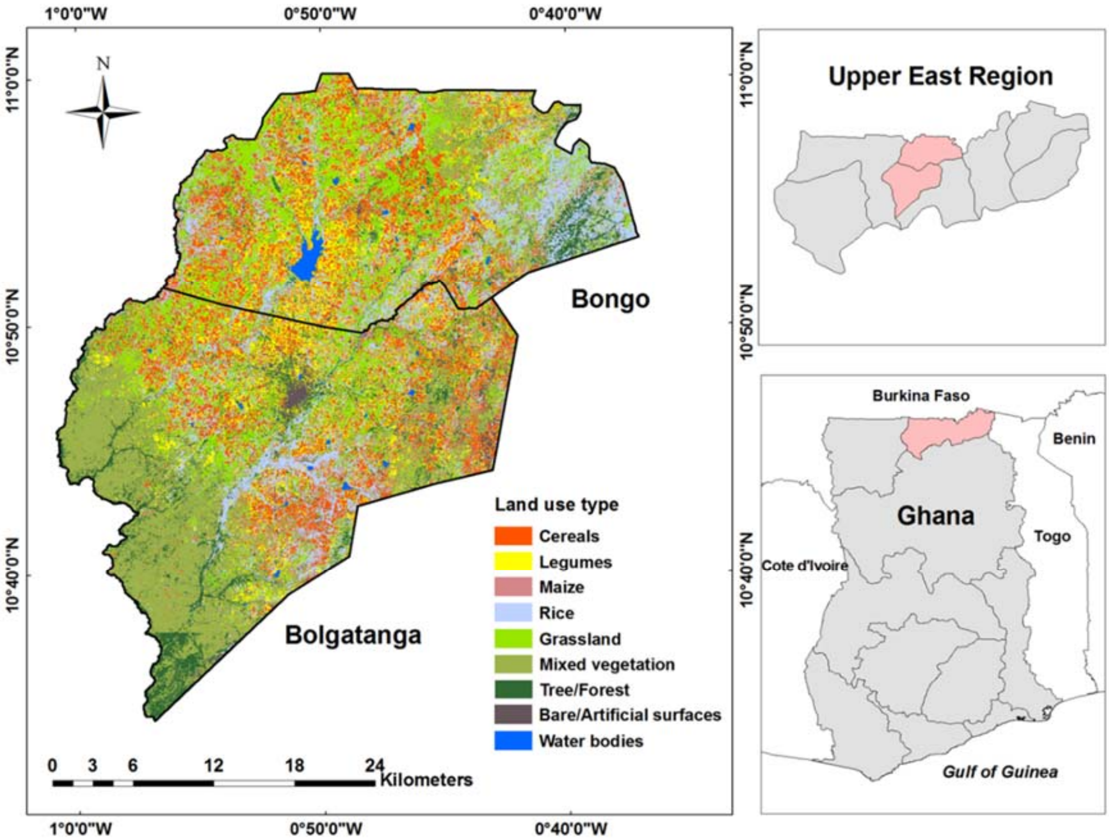

Figure 1. Location of Bolgatanga and Bongo districts and their land use patterns based on RapidEye images of 2013 and field calibration (25×25 m^2).

2.2. *Dataset for Ecosystem Service Assessment*

2.2.1. Land Use Pattern

In northern Ghana, only limited land is available for dry season irrigation farming, due to improper construction of small dams, technical constraints, and credit availability of farmers to use mineral fertilizer [33,34]. Furthermore, farmers with low income cannot afford the money for irrigated areas [35]. Therefore, this study only deals with land use patterns of the wet season. The study area is classified by nine land use types [33]. A definition of each land use type and its share in Bolgatanga and Bongo is shown in Table 1. Considering the potential use of grassland for the cultivation of herbaceous forage crops [31,36], more than 65% of the area in Bolgatanga and 88% of the area in Bongo is assumed to be utilized for agriculture. According to the classification of Forkuor (2014), artificially constructed areas and granite outcrops are defined as bare/artificial surfaces. Dense tree/forest cover on a large scale is mainly established as forest reserve. Scattered trees are mostly fruit trees, and often located around houses. Grassland and mixed vegetation is composed of short deciduous and indigenous trees and shrubs that are normally located on communal land. The Vea dam is considered as the main water body in the region. The dam is located in Bongo with 4 km^2 of surface area and 136 km^2 of catchment area covering nine communities in Bolgatanga and Bongo [37]. On the grounds that agriculture is the main land use activity in this region, we focused on the impact of agricultural land use scenarios on the distribution of land use types and the provision of ES.

Table 1. Definition of land use types for the wet season in the study area and the percentage of the area occupied by each land use type corresponding with the district land use map [33].

Land Use Type	Definition	Bolgatanga (%)	Bongo (%)
Cereals	Single or mixed cropping of millet and sorghum	13.5	17.5
Legumes	Groundnuts or the intercropping of groundnuts and bambara beans	10.5	13.5
Maize	Single cropping of maize	4	5.6
Rice	Single cropping of rice	13.4	20.8
Grassland	Grassland including pastures	14.3	26.5
Mixed vegetation	Mixture of shrubs, trees, savanna, and herbs	29.4	5.5
Tree/Forest	Tree cover ≥70% or single trees on farm plots	9.3	5
Bare/Artificial surfaces	Bare areas, laterite and tarred roads, buildings, hamlets, and rocks	5.3	4.3
Water bodies	Small reservoirs, dams, and rivers	0.3	1.3

Note: We regarded that one land use cell includes one land use type, i.e., all crop land use types were here defined as monoculture.

2.2.2. Local Knowledge

Local knowledge is shaped by the involved stakeholder group. The selection of the appropriate stakeholder group is therefore crucial in a participative approach [38,39]. Participants should be selected in light of representativeness of the broader stakeholder community, their capacity and willingness to constructively share their opinions, and ability to disseminate information and ideas to other relevant stakeholders [40]. Their relevance should be also considered by the level of influence and interest in land use decisions at a pertinent spatial scale [41]. Agricultural extension agents (hereafter, "extension officers" or "stakeholders") of the Ministry of Food and Agriculture of Ghana (MOFA) were selected among various stakeholder groups in this respect. They are highly decisive for the implementation of agricultural practices in this region [42,43]. Their main task is the provision of technical advice and the introduction of new farming techniques and policies to farmers. Each extension officer is assigned to specific communities and responsible to monitor and report field conditions and crop performance to the district office of MOFA [44]. All extension officers in this region meet and discuss agriculture-related issues, such as adjustment of farming schedules or a new cultivation practice through regular district meeting. As a liaison between farmers (direct land users) and policy makers (indirect land users), their opinions significantly influence the farmers' land use decisions and their role is crucial for the implementation of agricultural policies and strategies of MOFA. In consideration of extension officers' knowledge, field experience, and cooperation with farmers, they also play an important role in the initialization and monitoring of new agricultural programs that are supervised by NGOs, other governmental authorities, and agribusinesses [44]. Thus, the extension officers are considered as the most appropriate and representative knowledge holders regarding agricultural land use at district level, compared to other stakeholder groups who may have more specific knowledge and interest at plot or program level. There were fifteen extension officers in Bolgatanga and eleven in Bongo who are currently working in the study area and participated in data generation through stakeholder surveys. The following methodological chapters show the usage of collected local knowledge in terms of the selection of locally important ES, input data for ES indicators, the potential impact of individual land use scenarios, and the application conditions of land use scenarios in simulation.

2.2.3. Ecosystem Services and Indicators

A specific set of locally relevant ES for this study was identified together with the stakeholders among the suggested ES in previous studies (e.g., [45]). The ES selection criterion was based on its importance related to agricultural activities. The stakeholders were asked for their perception on the importance of suggested ES with a five-point Likert scale. ES with an average value of 4 or higher were selected (Table S1 in Supplementary). The perceptibility of the differences in the status of ES provision between land use types was regarded as the second selection criterion. The stakeholders were asked to compare the capacity of land use types to provide ES from 0 (no provision potential) to 10 (highest provision potential), in order to identify differences in ES provision by the respective land use type (Table S2 in Supplementary). The selected ES included the provision of food, fodder, energy, construction materials, marketable products, water, and erosion control (Table 2). Indicators to assess benefits that are directly obtained from land use activities, such as food, fodder, energy, construction materials, and marketable products, were determined to reflect the consumptive patterns of the stakeholders regarding land use products (e.g., grains, stalks, straws, branches, fruits, and leaves). For example, fodder provision delivered by legumes was identified as livestock feed in proportion to the entire products from legumes as perceived by the stakeholders. Data for the indicators were obtained by a stakeholder survey (details in [44], Table S3 in Supplementary). Such indicators allow the identification of multiple ES supplied by one land use type without ignoring or double-counting potential benefits (e.g., [46,47]). Water provision and erosion control as indirect benefits from land use activities were difficult to be determined by such a perception on the provision level. We adopted, thus, proxies applied in existing studies [26,48–51], which defined the quantity of surface water for direct use by households and the extent of surface run-off generated by each land use type.

Table 2. Selected ecosystem services, indicators, and data generation methods for indicator values.

Ecosystem Service	Definition	Proxy Indicator	Data Generation
Food provision	Benefits of agricultural land use related to food	Proportion of land use products consumed as food by households (%)	Stakeholder survey
Fodder provision	Benefits of agricultural land use related to livestock feed	Proportion of land use products used for animal feed (%)	Stakeholder survey
Energy provision	Benefits of agricultural land use related to fuel for households (biomass)	Proportion of land use products used for fuel (%)	Stakeholder survey
Construction material provision	Benefits of agricultural land use related to construction materials	Proportion of land use products used for construction purposes (e.g., roofs, pillars) (%)	Stakeholder survey
Marketable product provision	Benefits of agricultural land use related to economic value	Proportion of land use products sold on the market for income (%)	Stakeholder survey
Water provision	Surface water yield to contribute to water bodies for direct use	Potential water yields determined by subtracting evapotranspiration from precipitation (mm $cell^{-1}a^{-1}$)	Water yield equation (a, b)
Erosion control	Surface run-off prevention	Potential soil erosion level according to the RUSLE model $\left(t\ ha^{-1}a^{-1}\right)$	RUSLE equation (c, d, e)

Note: (a) [50], (b) [26], (c) [48], (d) [49], (e) [51].

2.3. Development of Land Use Scenarios

Scenarios combined with the ES concept need to handle assumptions which are manageable and comprehensible for stakeholders and decision-makers of land use associated with future ES provision [52,53]. In this study, land use scenarios were developed as potential change of land use activities and land use intensities in order to cope with climate change impacts on land use, which are adoptable by the stakeholders in the near future.

Among the current land use types shown in Table 1, the five agriculture-related land use—cereals, maize, legumes, grassland, and mixed vegetation—were used to formulate land use scenarios in consideration of their high likelihood of land use change [54]. Customary land use rights of local people and communities are mainly related to agricultural areas, while water bodies, urban areas, and tree/forest cover are largely influenced by statutory land use rights of the Town and Country Planning Department, whose likelihood of land use change is relatively low [8]. Rice, as an excluded agriculture-related land use type, has more restricted farming conditions associated with specific water demand and soil types than other staple crops, and is primarily cultivated in lowland valleys [55,56]. Besides that, the probability of converting a rice paddy is low, because rice is regarded as valuable income opportunity for households in this region [57]. Figure 2 shows the development process of locally feasible land use scenarios. At first, potential land use scenarios were generated based on literature and fieldwork in consideration of alleviating negative climate change impacts on agricultural land, such as the decline of land productivity and the increase of water erosion (Criterion 1 in Figure 2). The conversion of current crop monoculture to intercropping practices, for instance, can be one of the potential scenarios, because it diversifies land use products and improves surface stability due to a mixed rooting system [58,59]. An increase of tree cover through afforestation and agroforestry can be suggested in order to facilitate restoration of degraded land by protecting surface soil [60–62]. The potential land use scenarios of criterion 1 were examined by the local stakeholders, focusing on applicability (Criterion 2 in Figure 2). The stakeholders of each district were inquired regarding the feasibility of the scenarios in practice (yes or no). The result of the questionnaire was used as a basis for the determination of a final set of land use scenarios that could be feasible in the study area, whose applicability was perceived by more than 90% of the respondents.

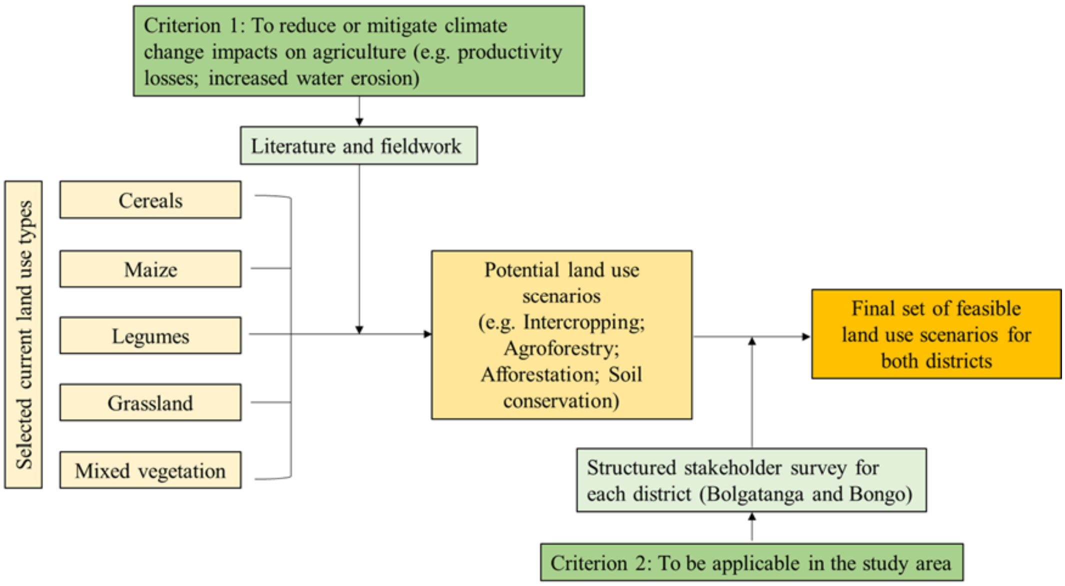

Figure 2. Development process of locally feasible land use scenarios.

2.4. Integration of Ecosystem Services and Land Use Scenarios

As the next step, locally relevant ES were coupled with the final set of feasible land use scenarios (Figure 3). A conversion of land use types could have positive and negative effects on ES on account of the linkage between ES and land use types [63,64]. Therefore, land use scenarios have to be assessed from the perspective of what benefits can replace those supplied by previous land use [65]. The integration of trees into crops as agroforestry, specifically, facilitates the provision of multiple benefits depending on the intercropped tree species (synergy). Mango intercropping provides fruit, firewood, poles, and fence material, and leucaena intercropping produces organic matter for soil fertility and forage. Both practices decrease surface run-off by the branched root system [62,66–68]. However, a negative effect of agroforestry could be the reduction of crop yield due to the competition for space, soil nutrients, and water (trade-off) [66,69].

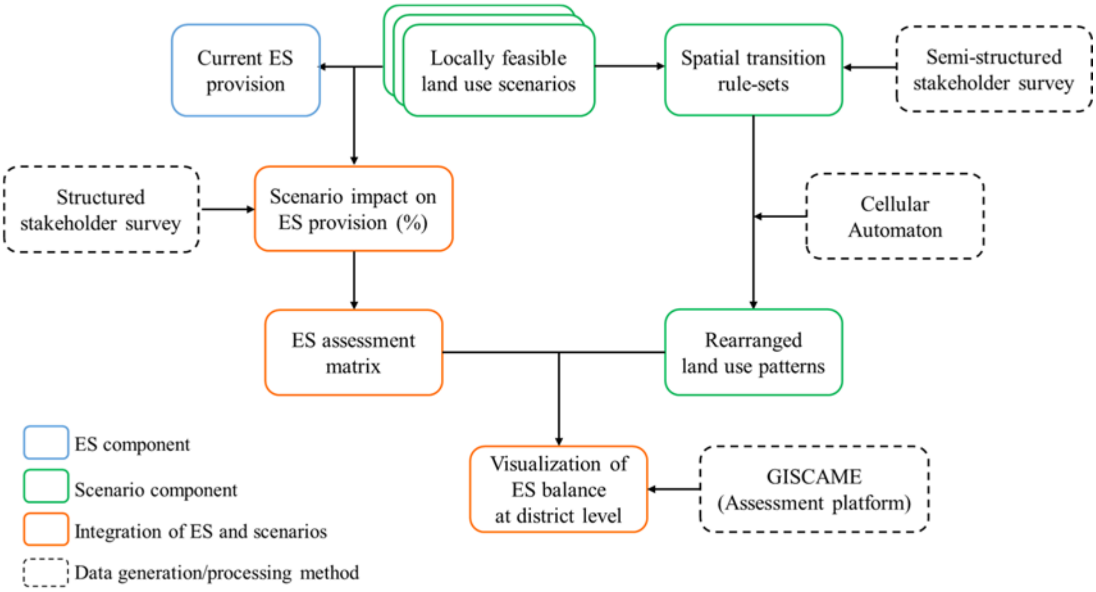

Figure 3. Integrative assessment process of ecosystem services and land use scenarios.

The stakeholders were asked for each land use scenario if they expect any change in ES provision (increase/decrease/constant) in order to identify trade-offs and synergies of ES provision of the potential land use (Table S4 in Supplementary). The level of change was specifically asked as percentage change in relation to current ES provision, e.g., 20% potential increase in food provision by agroforestry. All ES values were standardized in a range from 0 (the minimum potential to provide ES) to 100 (the maximum potential to provide ES), that expressed the extent of ES contribution by the specific land use type with a comparable scale [70,71]. The standardized values were used for an assessment matrix that displays the relationship between land use types and their capacity to supply the ES. In order to simulate and assess potential impacts of the developed scenarios, a web-based modeling platform called GISCAME that consists of a cellular automaton (CA) and GIS modules was used. The CA module allows for the implementation of scenarios by reflecting locally specific characteristics. The CA is a spatially discrete dynamic gridded system where the development of an individual cell at the time t + 1 depends primarily on the cell states in a given neighborhood at the time t [72]. The CA module in GISCAME updates land use types of all cells in a map synchronously based on a rule-set for transition, thereby formulating new land use patterns according to future scenarios [73]. The rule-set was determined based on information from the stakeholders regarding transition probabilities of land use types, the neighborhood of land use types (proximity effects), and environmental attributes [74]. For instance, the stakeholders were asked regarding the likelihood (%) of land use change from maize monocropping to maize intercropping with legumes, by different conditions of neighboring land use types and environmental attributes (e.g., soil type and slope). The land use patterns that were generated by the CA were combined with the ES assessment matrix, which allows the evaluation of impacts of the simulated land use patterns on the provision of ES at district level [70,73]. The assessed results were displayed in a spider chart and an ES balance table that were derived as the mean values for the ES supplied by each land use cell of rearranged land use patterns.

3. Results

3.1. Locally Feasible Land Use Scenarios

In total, fifteen land use scenarios were identified together with the stakeholders as feasible options, which were categorized as crop intercropping, afforestation/agroforestry, and soil conservation (Table 3). Scenarios were expressed on the basis of the currently existing land use types (e.g., from cereal monocropping to cereal-dominant intercropping), since the stakeholders perceived a complete change of land use types as unlikely (e.g., from cereal monocropping to maize monocropping). "Being dominant" implied that a land use type occupies over 50% of the investigation cell unit (25 × 25 m^2). This detail ensured higher applicability and facilitated a better perception of future consequences for the stakeholders. The developed scenarios were implemented with transition conditions (transition probabilities, neighboring land use types, soil types, and slope) that were determined by the perspectives of the stakeholders (Table S5 in Supplementary). Taking "a cereal-dominant intercropping scenario" as an example, the stakeholders regarded a conversion from cereal monocropping to cereal-dominant intercropping with a probability of 90% or higher. A specific condition of the conversion was provided for cereals or legumes as neighboring land use types, due to the fact that farmers tend to be more likely to conduct intercropping when the respective crop is already cultivated near the field, with sandy loamy/sandy soil as soil types, and there is a moderate or higher risk of surface runoff (10 t ha^{-1} yr^{-1} based on [49]).

Table 3. Locally feasible land use scenarios and their descriptions.

Land Use Scenario			Description
Crop intercropping	1	Cereal-dominant intercropping	Conversion of cereal monocropping into cereal-dominant intercropping with legumes
	2	Maize-dominant intercropping	Conversion of maize monocropping into maize-dominant intercropping with legumes
	3	Legume-dominant intercropping	Conversion of legume monocropping into legume-dominant intercropping with cereals and maize
Afforestation and agroforestry	4	Grassland afforestation	Conversion of grassland into afforested land
	5	Mixed vegetation afforestation	Conversion of mixed vegetation into afforested land
	6	Cereal intercropping with mango (fruit tree)	Conversion of cereal monocropping into cereal-dominant intercropping with mango
	7	Maize intercropping with mango (fruit tree)	Conversion of maize monocropping into maize-dominant intercropping with mango
	8	Legume intercropping with mango (fruit tree)	Conversion of legume monocropping into legume-dominant intercropping with mango
	9	Cereal intercropping with leucaena (fodder tree)	Conversion of cereal monocropping into cereal-dominant intercropping with leucaena
	10	Maize intercropping with leucaena (fodder tree)	Conversion of maize monocropping into maize-dominant intercropping with leucaena
	11	Legume intercropping with leucaena (fodder tree)	Conversion of legume monocropping into legume-dominant intercropping with leucaena
Soil conservation	12	Stone or soil bunds on cereals	Establishment of bunds on cereal monocropping fields
	13	Stone or soil bunds on maize	Establishment of bunds on maize monocropping fields
	14	Windbreak on cereals	Establishment of windbreak though planting trees on cereal monocropping fields
	15	Windbreak on maize	Establishment of windbreak though planting trees on maize monocropping fields

3.2. Capacity of Land Use Types to Provide Ecosystem Services

The ES capacity of current and future land use types that were influenced by different scenarios (Table S6 in Supplementary) are presented in Tables 4 and 5. In Bolgatanga, future land use types related to crop intercropping showed higher potential to provide food than other land use types (Table 4). Particularly, legume-dominant intercropping showed the highest value for food provision. The afforestation of grassland was identified to have the highest capacity to provide fodder. The afforestation of mixed vegetation was most effective for the provision of energy and construction materials. Future land use types associated with legumes scored relatively higher for the ES provision of marketable products than other land use types. Erosion control as ES was effectively provided by afforestation and legume-related agroforestry. All future land use types indicated lower values in water provision, compared to other ES that presented at least a slight increase or consistency to current land use types.

Table 4. Assessment matrix for Bolgatanga to display the relationship between current and future land use types and their potential to provide the selected ecosystem services within a scale from 0 (no provision, in white) to 100 (highest level of provision, in dark blue).

	Land Use Type	Food	Fodder	Energy	Construction Materials	Marketable Products	Water	Erosion Control
Current	Cereal-monocropping	58	7	29	4	30	97	60
	Maize-monocropping	52	12	7	4	43	98	62
	Legume-monocropping	60	4	3	4	65	97	95
	Rice-monocropping	44	1	3	0	70	83	88
	Grassland	1	100	32	37	11	95	98
	Mixed vegetation	19	47	63	63	12	98	100
	Tree/Forest	28	7	57	31	54	97	100
	Bare/Artificial surfaces	0	0	0	0	0	100	0
	Water body	0	0	0	0	0	100	100
Future	Cereal-dominant intercropping	96	12	34	4	46	30	90
	Maize-dominant intercropping	89	19	8	4	71	31	86
	Legume-dominant intercropping	100	6	4	4	100	28	97
	Grassland afforestation	2	100	53	60	18	20	99
	Mixed vegetation afforestation	27	49	100	100	17	31	100
	Cereal intercropping with mango	51	7	32	4	36	0	77
	Maize intercropping with mango	46	11	8	4	52	1	78
	Legume intercropping with mango	86	5	4	4	95	6	97
	Cereal intercropping with leucaena	71	11	39	4	38	8	83
	Maize intercropping with leucaena	64	19	10	4	55	9	84
	Legume intercropping with leucaena	70	7	4	4	85	20	98
	Soil or stone bunds on cereals	94	11	42	4	52	20	87
	Soil or stone bunds on maize	85	18	11	4	75	7	87
	Windbreak on cereals	89	11	43	4	44	32	84
	Windbreak on maize	80	18	11	4	63	33	85

With respect to Bongo (Table 5), future land use types associated with cereals had higher potential to provide food than other types. Cereal-dominant intercropping was especially identified to be most effective for food provision. Similar to Bolgatanga, the afforestation of grassland scored highest in fodder provision. The afforestation of mixed vegetation was identified to have the highest potential in the provision of energy and construction materials. Legume-related future land use types showed high potential in the provision of marketable products, and legume-dominant intercropping was most effective to supply the ES among the future land use types. For Bongo, erosion control as ES presented the similar provisioning patterns as for Bolgatanga, which was highly provided by afforestation and legume-related future land use types. In contrast to water provision in Bolgatanga, cereal-dominant intercropping and maize-dominant intercropping showed the possibility to improve water provision.

Table 5. Assessment matrix for Bongo to display the relationship between current and future land use types and their potential to provide the selected ecosystem services within a scale from 0 (no provision, in white) to 100 (highest level of provision, in dark blue).

	Land Use Type	Food	Fodder	Energy	Construction Materials	Marketable Products	Water	Erosion Control
Current	Cereal-monocropping	63	6	28	6	42	88	71
	Maize-monocropping	56	11	6	6	60	89	63
	Legume-monocropping	53	16	0	5	71	88	96
	Rice-monocropping	51	15	0	0	69	92	92
	Grassland	11	97	11	65	20	89	99
	Mixed vegetation	21	53	68	68	20	94	100
	Tree/Forest	33	13	62	24	60	94	100
	Bare/Artificial surfaces	0	0	0	0	0	89	0
	Water body	0	0	0	0	0	100	100
Future	Cereal-dominant intercropping	100	9	32	6	65	94	85
	Maize-dominant intercropping	90	15	6	6	92	100	78
	Legume-dominant intercropping	75	19	0	5	100	14	97
	Grassland afforestation	15	100	17	99	30	0	100
	Mixed vegetation afforestation	29	70	100	100	27	15	100
	Cereal intercropping with mango	79	7	32	7	61	0	79
	Maize intercropping with mango	70	13	7	7	86	0	73
	Legume intercropping with mango	76	20	0	6	94	30	97
	Cereal intercropping with leucaena	75	10	37	7	52	19	83
	Maize intercropping with leucaena	67	16	8	7	73	20	78
	Legume intercropping with leucaena	69	25	0	6	90	3	97
	Soil or stone bunds on cereals	99	10	38	8	63	28	91
	Soil or stone bunds on maize	88	16	8	8	89	28	88
	Windbreak on cereals	88	9	39	9	55	28	84
	Windbreak on maize	78	15	9	9	78	28	80

3.3. Impact of Land Use and Land Management Scenarios to Provide Ecosystem Services at District Level

The application of the assessment matrices (Tables 4 and 5) with the rule-sets for transition probabilities in GISCAME resulted in changes of land use patterns (examples in Figures 4b and 5b), and, consequently, changes of ES provision at district level (examples in Figures 4c and 5c). The GISCAME output of ES provision for all fifteen land use scenarios in Bolgatanga are shown in Table 6. All alternatives to current land use led to a positive effect on food provision, except the scenarios associated with cereal/maize intercropping with mango (Scenarios 6 and 7). Cereal-dominant intercropping (Scenario 1) and soil or stone bunds on cereals (Scenario 12) were most effective to supply food among the scenarios. None of the scenarios, on the other hand, influenced the status of fodder provision. Scenarios related to afforestation (Scenarios 4 and 5) were identified to be more effective to provide biomass for energy provision than other scenarios. However, the cereal-related scenarios (Scenarios 1, 6, 9, 12, and 14) also presented the possibility of improving energy provision. Only the scenarios related to afforestation (Scenarios 4 and 5) marked an increase in the provision of construction materials. Afforestation of mixed vegetation had more potential to provide construction materials than grassland afforestation. Regarding the provision of marketable products and erosion control, the majority of the scenarios were assumed to enhance the supply of these ES. On the contrary, all scenarios of future land use showed a negative effect on water provision for human direct use.

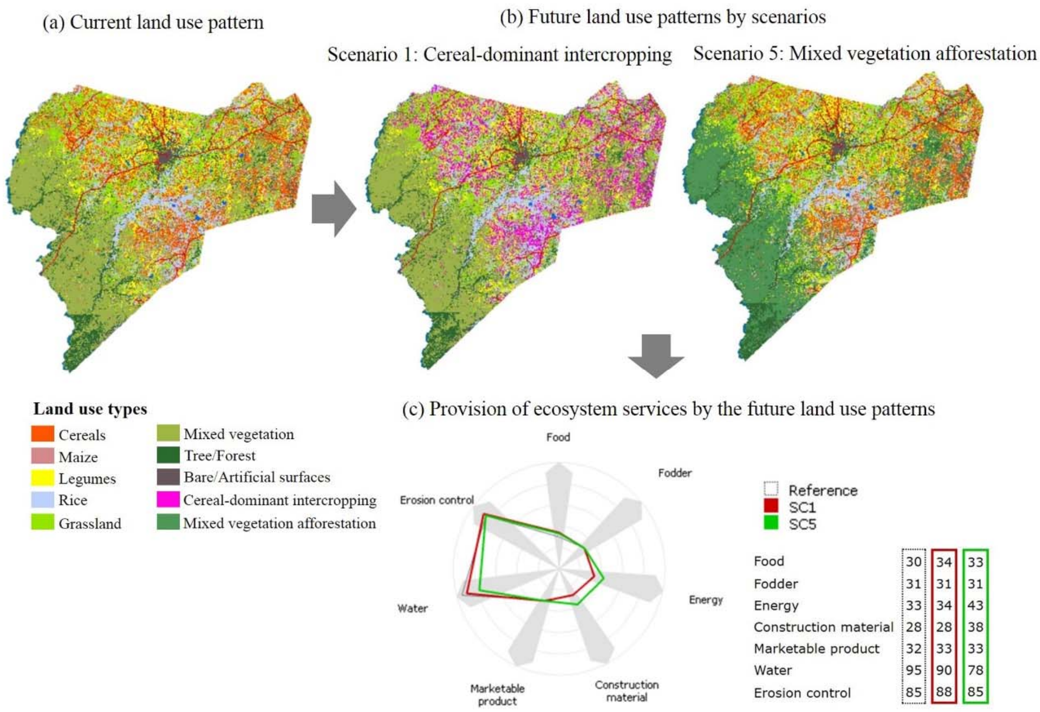

Figure 4. Future land use patterns of selected scenarios and spider charts for the ecosystem services balance supplied by the model output for Bolgatanga. As an example, influences of cereal-dominant intercropping (SC 1) and mixed vegetation afforestation (SC 5) on the current land use pattern were generated by cellular automaton (**b**). In the spider chart (**c**), changes in the provision of ecosystem services compared to the current provision of ecosystem services as reference are displayed for SC1 and SC5. The values of ecosystem services of the two scenarios corresponding to the spider chart are presented in the table.

The GISCAME output of ES provision for all fifteen land use scenarios in Bongo are shown in Table 7. Cereal-dominant intercropping (Scenario 1) and soil or stone bunds on cereals (Scenario 12) were most effective to supply food. Contrary to the effect of scenarios on fodder provision in Bolgatanga, all future land use types reflected an increase in fodder provision. Scenarios related to the conversion of cereals (Scenarios 1, 6, 9, 12, and 14) and afforestation (Scenarios 4 and 5) had the potential to enhance energy provision. Scenarios of afforestation (Scenarios 4 and 5) were observed to improve the provision of construction materials. However, the afforestation of grassland was more effective than the afforestation of mixed vegetation in contrast to Bolgatanga. All scenarios improved the provision of marketable products, except the mixed vegetation afforestation scenario (scenario 5). All scenarios except cereal-dominant intercropping and maize-dominant intercropping (Scenarios 1 and 2) led to a decrease in water provision. The most negative effect on water provision was caused by grassland afforestation (Scenario 4). Scenarios associated with cereals (Scenarios 1, 6, 9, 12, and 14) were identified to be effective to positively influence erosion control. The establishment of soil or stone bunds on cereal fields was especially shown as the best scenario for erosion control.

Table 6. The fifteen land use scenarios and their potential changes in ecosystem services provision for Bolgatanga. The increase from the current status is expressed by green color, whereas the decrease is indicated by red color. White means no change in the provision of ecosystem services compared to current land use.

	Land Use Scenario	Food	Fodder	Energy	Construction Materials	Marketable Products	Water	Erosion Control
	Current Status	**30**	**31**	**33**	**28**	**32**	**95**	**85**
1	Cereal-dominant intercropping	35	31	34	28	34	87	89
2	Maize-dominant intercropping	32	31	33	28	33	93	86
3	Legume-dominant intercropping	34	31	33	28	36	88	86
4	Grassland afforestation	31	31	36	30	33	85	85
5	Mixed vegetation afforestation	33	31	44	37	34	76	85
6	Cereal intercropping with mango	30	31	34	28	33	83	88
7	Maize intercropping with mango	30	31	33	28	32	92	86
8	Legume intercropping with mango	33	31	33	28	35	86	86
9	Cereal intercropping with leucaena	32	31	35	28	33	84	88
10	Maize intercropping with leucaena	31	31	33	28	32	92	86
11	Legume intercropping with leucaena	31	31	33	28	34	88	86
12	Soil or stone bunds on cereals	35	31	35	28	35	85	89
13	Soil or stone bunds on maize	32	31	33	28	33	92	86
14	Windbreak on cereals	34	31	35	28	34	87	88
15	Windbreak on maize	31	31	33	28	33	93	86

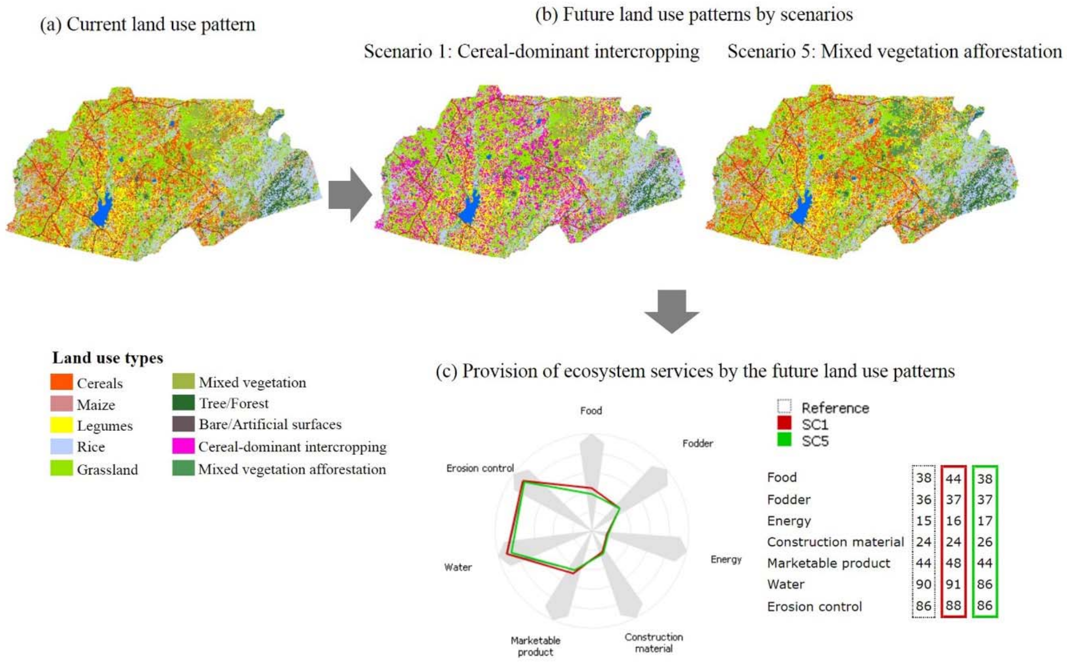

Figure 5. Future land use patterns of selected land use scenarios and spider charts for the values of ecosystem services supplied by the model output for Bongo. The example shows the impacts of cereal-dominant intercropping (SC 1) and mixed vegetation afforestation (SC 5) on the current land use patterns (**b**), and resulting changes in ecosystem services provision (**c**).

Table 7. The fifteen land use scenarios and their potential changes in ecosystem services provision for Bongo. The increase from the initial (current) status is expressed by green color, while the decrease is displayed by red color. White means no change in the provision of ecosystem services compared to current land use.

	Land Use Scenario	Food	Fodder	Energy	Construction Materials	Marketable Products	Water	Erosion Control
	Initial Status	**38**	**36**	**15**	**24**	**44**	**90**	**86**
1	Cereal-dominant intercropping	44	37	16	24	48	91	88
2	Maize-dominant intercropping	39	36	15	24	46	90	87
3	Legume-dominant intercropping	40	37	15	24	48	80	86
4	Grassland afforestation	39	37	16	33	46	67	86
5	Mixed vegetation afforestation	38	37	17	26	44	86	86
6	Cereal intercropping with mango	40	36	16	24	47	75	87
7	Maize intercropping with mango	38	36	15	24	45	86	86
8	Legume intercropping with mango	40	37	15	24	47	82	86
9	Cereal intercropping with leucaena	40	37	16	24	46	78	88
10	Maize intercropping with leucaena	38	36	15	24	45	87	87
11	Legume intercropping with leucaena	40	37	15	24	46	79	86
12	Soil or stone bunds on cereals	44	37	17	25	47	80	89
13	Soil or stone bunds on maize	39	36	15	24	45	87	87
14	Windbreak on cereals	42	37	17	25	46	79	88
15	Windbreak on maize	39	36	15	24	45	87	87

4. Discussion

4.1. Local Perception on the Land Use and Land Management Scenarios

The consideration of context- and site-specific knowledge from a particular group based on their actual experiences and observations can provide a differentiated view compared to conventional approaches in natural sciences [75]. The integration of local knowledge in scenario development and land use assessments that was presented in this study is a new attempt in the West African context. Prior impact assessments of future scenarios were rather scientist-oriented (e.g., [76–80]). Ideally, most relevant stakeholders in the investigated area should be identified, their roles to contribute to the assessment need to be clarified, and they should be involved from the early stage of the process in a participatory assessment [12]. Even though the number of the stakeholders who participated in this study seems small (26 in total), they represent interests of farmers as well as local government, since they serve as a bridge between the two actors. They also showed a strong relationship with other actors in the agricultural sector as a cooperator and an advisor, thereby influencing agricultural land use activities at district level. The stakeholders were involved from the beginning of the ES assessment by identifying locally relevant ES and developing future land use scenarios.

The results of this study help to understand how the stakeholders perceive potential impacts of future options, i.e., why a certain practice is expected to be more effective or not to improve the current status of ES in this region. In accordance with the capacity of ES provision by land use types (Tables 4 and 5), local perception focused more on positive aspects of intercropping between staple crops in terms of diversity of land use products, efficiency of land use, and stability of root systems as proven in existing studies (e.g., [81,82]). There could also be negative aspects related to interference in crop growth, due to the competition between component crops for nutrients, moisture, and sunlight in intercropping (e.g., [83,84]), which might not have been considered by the stakeholders. Impacts of incorporating mango trees into cereals/maize were observed as being different between the districts. The stakeholders in Bolgatanga perceived the presence of mango trees as hindrance to the growth of cereals/maize due to shade and nutrient competition, thereby reducing food provision. The stakeholders in Bongo, on the other hand, valued mango trees as a source of food for household, which led to an increase in food provision by the mango agroforestry scenario. This fact reflects the importance in considering regional differences. Intercropping with leucaena was perceived to bring potentially positive synergies between multiple ES by using the decomposed leaves for improving soil fertility, and consequently, to enhance land productivity in both districts. The formation of bunds or windbreaks as scenarios, which are specifically aimed to prevent erosion, did not enhance erosion control significantly, compared to other scenarios. Considering that the erosion problem is mainly caused by the poor vegetative or degraded land cover in this area [85], the stakeholders regarded the expansion of cover crops and scenarios with vegetation on bare soil as effective measures against erosion control.

There is a noticeable trend in local perception regarding the impact of the land use alternatives on water provision, which showed a decrease in most of the scenarios. As water provision in this study indicated the potential amount of surface water flowing to water bodies, which is utilized for direct human use, the level of water requirement by land use types was considered as a critical factor to determine water availability for household consumption. Most of the intercropping scenarios were understood to increase water demand of land surface because of the diverse water requirements by different plant species. The expansion of tree cover by afforestation and agroforestry was considered to increase water stress on agricultural area due to the expected high water demand of trees. Furthermore, the formation of bunds was regarded to enhance water absorption efficiency of the crops, which reduced surface water availability for human use. These scenarios, thus, were identified to negatively influence water provision for households. A number of previous studies are in line with this local perception: the total water consumption by intercropping was higher than by monocropping [86,87], and densely vegetated cover consumed more water than agricultural areas, which resulted in a loss of stream flow [88–90].

4.2. District Capacity of Ecosystem Services Provision Characterized by Land Use Scenarios

Previously, Leh et al. (2013) [26] presented how to map the variation of regulating services depending on the spatial changes of existing land use types in West Africa. Our study goes beyond the mapping of ES by identifying the practicability and likelihood of land use scenarios. We presented how land use scenarios can influence spatial distribution of current land use patterns with introducing new land use types, and how those altered land use patterns can generate different provisioning and regulating services relevant to the region. First, a change in distribution of the land use types, besides local perception, accounts for similarity and dissimilarity of the capacity to provide ES between the two districts (Tables 6 and 7). Cereals were most largely cultivated among staple crops in both districts (Table 1). Consequently, the changes in cereals were expected to generate a great effect on provisioning ES, as seen in higher levels of improved food provision by cereal-related scenarios (Scenarios 1, 6, 9, 12, and 14) than by other crop scenarios. Maize-related scenarios (Scenarios 2, 7, 10, 13, and 15), on the contrary, produced relatively marginal effects on overall ES provision, due to the fact that the share of maize is low in both districts. Grassland and mixed vegetation was the main land use type among the afforestation scenarios, but its share differed between the districts and caused a discrepancy in the provision of construction material. The area of mixed vegetation is twice as large as grassland in Bolgatanga, whereas Bongo has more grassland than mixed vegetation. It explains different impacts of the afforestation scenarios due to distributional effects of grassland and mixed vegetation, although local perception regarding the impacts of the scenarios on the provision of construction materials is similar between these two districts. In this study, land use changes were determined by the surrounding environment, i.e., there were impacted plots and non-impacted plots within a same land use type, depending on their location. These results emphasize that regional planning should consider the influence of spatial configuration of land use types in a region.

One of the crucial roles of scenarios in environmental assessment is to link science with land use policy by illuminating consequences of land use changes, and thereby suggest future land use strategies [17]. The spatially explicit visualization of future effects is especially helpful to communicate between different actors, and to convince them of the necessity for appropriate land use planning and management [91]. The stakeholders can easily understand the impacts on ES provision, such as trade-offs and synergies, that could be generated by a specific future choice, as shown in this study (Figures 4 and 5). The stakeholders were able to identify the best land use scenarios that would be most suitable for the region with regard to increasing the provision of multiple ES or minimizing trade-offs based on the results. In Bolgatanga, for instance, the scenarios of cereal-dominant intercropping, cereal intercropping with leucaena, stone or soil bunds on cereals, and windbreak on cereals, can be considered as the best scenarios for synergies between the most diverse ES. These scenarios increased the provision of food, energy, and marketable products, and erosion control compared to current land use. As best scenarios that can reduce trade-offs between ES, maize-dominant intercropping and windbreak on maize can be suggested, which had the lowest impact on water provision. In terms of best scenarios that deliver synergies between multiple ES in Bongo, cereal-dominant intercropping, soil, or stone bunds on cereals, and windbreak on cereals can be considered, which displayed an increase in six different ES. With respect to the best scenarios related to the lowest trade-off effect between ES, cereal-dominant intercropping and maize-dominant intercropping can be regarded as most suitable, because they did not negatively influence any ES. The stakeholders can also set priorities to address different land use concerns, and seek for management and planning options to improve the condition. For instance, the formation of bunds on cereals can be suggested for Bolgatanga if the stakeholders focus on improved food provision and marketable products. When the stakeholders in Bongo prefer an increase in overall ES provision in future, cereal-dominant intercropping can be recommended as the most effective option to enhance the provision of food, marketable products, and water.

4.3. Limitations of a Stakeholder-Based Modeling Approach

Although this stakeholder-based approach allows the identification of relationships between the provision of locally important ES and future land use alternatives, limitations exist related to intangible ES. Regarding atmospheric regulation as ES, for instance, it was difficult for the stakeholders to appreciate dissimilarities among the impacts of different land use types and scenarios on the ES. Therefore, atmospheric regulation was not included in this study, regardless of its significance in the African context (e.g., [14,26,92]). Local stakeholders prefer future land use options as modifications based on ongoing farm practices, which is, as a strategy to avoid failure that could be potentially caused by a totally new technique or measure [93]. New farming methods that are proven to enhance ES provision, but that are not familiar to local stakeholders, accordingly, are likely to be disregarded in stakeholder-based scenario development [94]. There are also limitations in using such a scenario modeling approach. Firstly, complex dynamics of interaction between land use decisions and ES were inevitably simplified in the process of quantification of local knowledge, due to the scarcity of field data and the lack of modeling capacity to deal with all feedback loops. In addition, unlike the immediate response in the modeling platform, a time lag to observe ecological and socio-economic consequences of land use decisions in reality needs to be considered [95].

Some of the limitations need to be resolved and improved as a further step. Impacts on intangible but important ES can be incorporated by finding an equivalent and understandable local definition or a benefit transfer method. The modeled results of ES trade-offs and synergies become more transferrable to policies when they can be quantified in monetary terms or percentages [96,97]. Further than focusing on the angle of local stakeholders, the reflection of perceptions by scientists or experts and the integration of field experiments could broaden the context and could improve the assessment of ES provision of different land use types and land use scenarios.

5. Conclusions

This study presented an assessment of potential impacts of land use scenarios on the provision of ES using local knowledge in northern Ghana. The involvement of stakeholders allowed for the identification of locally feasible land use options which are expected to mitigate climate change impacts on agriculture. The role of stakeholders was also important in ES assessment in terms of understanding the perspectives of an ES beneficiary on the capacity of land use system as an ES supplier. The integration of local knowledge, and the ES concept in a modeling process facilitated the spatially explicit simulation of local perceptions on the influence of different land use decisions related to ES provision. Identified trade-offs or synergies between locally important ES as potential scenario impacts can contribute to the suggestion of future land use strategies. Challenges in a stakeholder-oriented approach are related to ES where links between provision potential and land use types are difficult to be identified by stakeholders. In addition, simplification in a modeling approach is unavoidable, due to the lack of data and the insufficient capacity of the platform to address all interactions between humans and ecosystems. However, this context-based approach helps to give an insight into how to design viable land use alternatives and strategies to improve the current ES status in a local context.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-445X/7/2/59/s1, Table S1: Template of the stakeholder survey to select ecosystem services based on the importance related to agricultural land use, Table S2: Template of the stakeholder survey to identify the perceptibility of the differences on the provision of ecosystem services between land use types, Table S3: Template of the stakeholder survey for data generation, Table S4: Part of a stakeholder survey template for the identification of scenario impacts, Table S5: Application conditions of land use scenarios, Table S6: Impact of land use scenarios on the ecosystem services provision based on a stakeholder survey. Each percentage implies the extent of potential increase or decrease from the supply capacity of the current land use types when a scenario is applied.

Author Contributions: H.K. conceived and designed the study. H.K. also collected data through fieldwork and stakeholder surveys, and analyzed the data. H.K. and J.K. conducted a literature review and wrote the paper. C.F. developed a modeling platform for analysis and reviewed the paper.

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Article

Integrating Ecosystem Services into Land-Use Modeling to Assess the Effects of Future Land-Use Strategies in Northern Ghana

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Abstract: In West Africa, where the majority of the population relies on natural resources and rain-fed agriculture, regionally adapted agricultural land-use planning is increasingly important to cope with growing demand for land-use products and intensifying climate variability. As an approach to identify effective future land-use strategies, this study applied spatially explicit modeling that addresses the spatial connectivity between the provision of ecosystem services and agricultural land-use systems. Considering that the status of ecosystem services varies with the perception of stakeholders, local knowledge, and characteristics of a case study area, two adjoining districts in northern Ghana were integrated into an assessment process of land-use strategies. Based on agricultural land-management options that were identified together with the local stakeholders, 75 future land-use strategies as combinations of multiple agricultural practices were elaborated. Potential impacts of the developed land-use strategies on ecosystem services and land-use patterns were assessed in a modeling platform that combines Geographic Information System (GIS) and Cellular Automaton (CA) modules. Modeled results were used to identify best land-use strategies that could deliver multiple ecosystem services most effectively. Then, local perception was applied to determine the feasibility of the best land-use strategies in practice. The results presented the different extent of trade-offs and synergies between ecosystem services delivered by future land-use strategies and their different feasibility depending on the district. Apart from the fact that findings were context-specific and scale-dependent, this study revealed that the integration of different local characteristics and local perceptions to spatially explicit ecosystem service assessment is beneficial for determining locally tailored recommendations for future agricultural land-use planning.

Keywords: land-use planning; scenario; agriculture; spatially explicit simulation; modeling; stakeholder; participatory assessment

1. Introduction

The status of ecosystem services (ES) is characterized by consequences of anthropogenic environmental changes and their influence on human well-being and benefits [1–3]. ES assessments, thus, have been considered useful to support land-use and management planning [4]. The potential impacts of land-use decisions on the flow of ES and trade-offs and synergies between different ES help to identify future alternatives for the effective and efficient provision of ES [5–7]. Especially, spatially explicit ES assessments can facilitate the integration of ES in land-use planning by providing information about potential ES mismatches, hotspots, and optimized allocation of land for specific uses [1,4,8,9]. There has been various research that incorporated such ES approaches into land-use planning globally.

Taking case studies of Europe, Asia, and America as an example, the impact of past and current land-use and land-cover changes on the provision of specific ES (e.g., fresh water provision and air quality) was analyzed in order to give an insight into relevant land-use schemes and policies [10,11]. Different future pathways according to social-ecological drivers and their potential implications to the ES status were explored and discussed based on the experts and stakeholders' opinions [12,13]. In addition, changes in multiple ES provision depending on the future land-use and landscape patterns were quantified for identifying optimal future options considering ES trade-offs [14–16]. However, there is still a lack of attempt to apply ES assessments for adapted land-use planning in West Africa, where people are heavily dependent on land-use activities and resultant products and benefits [17,18].

In West Africa, more than 60% of the population is engaged in agriculture and approximately 70% of the land is used for cultivation, which is mainly for rain-fed agriculture [19–21]. High reliance on climate-sensitive farming makes the agricultural systems vulnerable to climate variability and causes high uncertainties about the sustainable supply of food and raw materials [22,23]. In addition, the rapid population growth increases pressures on land-use systems and food security levels [24]. There is an urgent need to reduce risks and to cope with the increasing demand in land use through regionally adapted land-use strategies [25]. However, as one of the poorest regions in the world, its insufficient economic and institutional capacity makes it difficult to properly respond to such situations [19]. The integration of the ES concept in designing agricultural land-use strategies has the potential to support future land-use planning as presented above, but there should be an understanding why such approaches are still not well applied in the West African context. Consequently, there is the need to improve the applicability of the ES concept for land-use planning in West Africa. Firstly, it is necessary to understand how people in the region obtain agricultural land-use-related ES and how they exploit them. In West Africa, land-use products from one type of land are commonly used for various purposes, such as forest for providing food, fodder, construction materials, and fuel [26,27]. Agroforestry as a combination of crops and tree plantations also provides multiple ES such as food, fiber, timber for fuel wood and construction, micro-climate regulation, soil erosion control, pest control, pollination, and carbon sequestration [28,29]. Thus, the multifunctionality of a land-use system needs to be emphasized in ES assessment and future agricultural land-use planning, which provides various benefits to fulfil different economic, social, and ecological requirements by a society [30]. Secondly, the heterogeneous demands on multifunctional land-use systems can be well reflected from perspectives of stakeholders. The consumption patterns of agricultural land-use products of one local community might differ from another community outside the area, and regionally specific distribution of ES influences preferred land-use strategies among stakeholders in the region [31]. Therefore, the participation of stakeholders who own local knowledge regarding agricultural land use in their particular environment is essential for designing future land-use strategies [32,33]. Stakeholders can engage in screening adoptable land-use alternatives by expressing their preferences and perspectives [34,35]. This offers an opportunity to stakeholders as ES beneficiaries to take part in decision-making processes that influence their future lives, and furthermore, their participation can raise the public acceptance of decisions [36,37]. However, participatory approaches might be limited to interpreting the narratives of stakeholders regarding a complex land-use context or uncertain future outcomes [38,39]. Accordingly, assessments that include stakeholder feedback process can be time-demanding and restricted [35,40]. Here, a simulation model can be appropriate to be used for integrating a participatory approach and ES assessments for agricultural land-use planning, which presents potential effects of future land-use decisions through mapping and visualization [41,42]. Visualized simulation results can especially facilitate communication with stakeholders in evaluating process and deriving recommendations [43]. As a simulation approach, spatially explicit modeling in particular is suitable for addressing the spatially variable nature of ES provision linked to the effects of land-use patterns [8,44]. However, existing studies in West Africa are missing either the participatory component or spatially explicit relationships between land use and multiple ES provision. For example, Kleemann et al. [23] used a non-spatially explicit participatory modeling approach for northern Ghana, but they considered only one ES (food provision) due to increasing complexity in using a bundle of ES. Leh et al. [17] conducted a spatially explicit assessment for the effects of land-use changes on multiple ES provision, but the assessment process was only based on the perspective of scientists rather than actual local perception on ES. Ahmed et al. [45] and Salack et al. [46] identified the interlinkage between land-use systems and climate changes and their impact on food provision, but their results were also not backed-up by local representatives or experts.

In order to investigate the applicability of ES concept for future land-use planning in West Africa, this study suggests a spatially explicit ES modeling approach in combination with stakeholder participation in the agricultural context of Ghana, West Africa. Two districts in northern Ghana were taken as case studies where perspectives of local stakeholders were reflected in an overall assessment process. This included the development of agricultural land-use strategies, simulation conditions of developed land-use strategies, and feedback on the simulated results. Especially, the feedback from the stakeholders on the simulated results was considered as an essential step to present the interaction between local knowledge and land-use modeling. This study is based on the results of previous studies [27,47], which assessed the impacts of various land-use scenarios on the provision of multiple ES in Northern Ghana. They covered the identification of a locally legitimate stakeholder group at district level, the selection of locally relevant ES and indicators, and the development of applicable agricultural land-use scenarios that were applied as management options for elaborating future strategies in this study. Using the previously obtained results and data and newly generated data regarding future land-use strategies and feedback from stakeholders, this study focused on addressing the following research questions:

- How can local perspectives be reflected in identifying the most feasible land-use strategies?
- What kind of synergies and trade-offs appear between ES depending on land-use strategies?
- How do local perspectives and characteristics influence the results on district level?

In addition, methodological and conceptual questions will be discussed:

- What are the advantages and challenges of the applied stakeholder-based ES modeling approach?
- How the application of the ES concept in land-use planning in the West African context can be improved?

Firstly, future land-use strategies were elaborated based on management options for agricultural land, which were expressed in a spatially explicit way. Impacts of the developed land-use strategies on current land-use patterns and ES provision were then assessed in a modeling platform, which combines Geographic Information System (GIS) and Cellular Automaton (CA) modules. According to the simulated results, best land-use strategies were determined that could provide multiple ES most effectively. The feasibility of the best land-use strategies in practice was identified in order to suggest recommendations for future agricultural land-use planning. In the discussion, the strength and weakness of the applied stakeholder-based ES modeling approach and the future directions of using the ES concept for land-use planning in West Africa were discussed.

2. Material and Methods

2.1. Case Study Area

The study area is located in northern Ghana and includes Bolgatanga Municipal district (hereafter, Bolgatanga) and Bongo district (Figure 1). Bolgatanga covers a total area of 729km^2 and, Bongo has a total area of 460km^2 [48]. The districts have two seasons—a dry season from October to the beginning of April and a rainy season spanning from April/May to September/beginning of October—with the average annual rainfall ranging between 645mm and 1250mm [49]. Erratic climatic patterns regarding the time of onset, span, and the quantity of rainfall make it difficult to ensure sufficient amounts of water for the various uses. The majority of soil in this area is coarse textured and low in accumulation of organic matter, which is prone to surface runoff by intensified rainfall exceeding the soil infiltration capacity [50]. Despite of unfavorable conditions for climate-sensitive cultivation, this area still heavily relies on rain-fed small-scale agriculture as do many other West African regions. Approximately 60% of households in Bolgatanga and 96% of households in Bongo are engaged in agriculture, and more than 70% of the land in both districts is used for cultivation [48]. These adjoining districts have similar environmental and land-use conditions. However, each district has an individual political and administrative system due to a decentralization program of Ghana [51]. The decision-making process especially related to agricultural land use is based on agricultural extension services of each district [27]. The land-use pattern of the study area consists of nine land-use types, according to the classification by Forkuor [52].

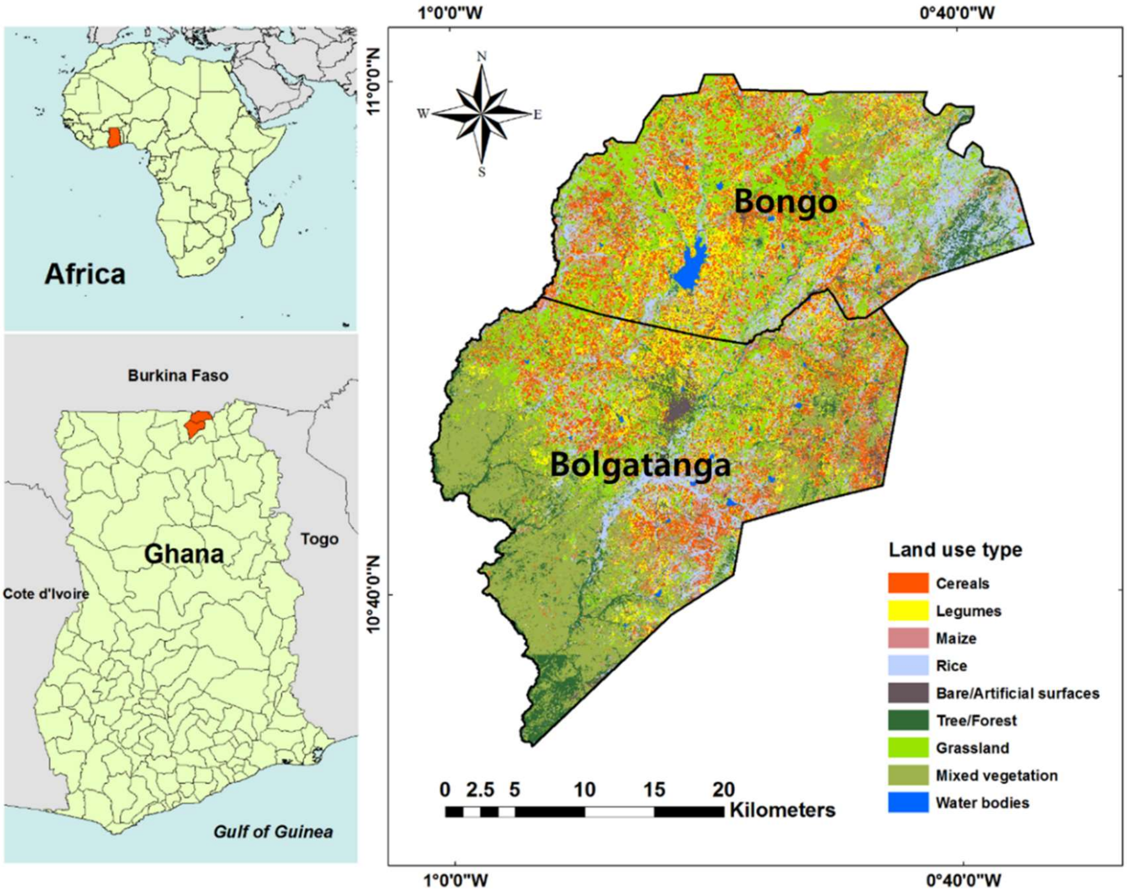


Figure 1. Location and land-use patterns of the study area in northern Ghana. The land-use classification is based on RapidEye images of 2013 with resolution of 25 × 25 m^2. (Forkuor [52]). The description and the areal percentage of each land-use type are presented in Table S1 in the Supplementary Materials.

2.2. Database and Selection Processes

This study was based on previous studies in northern Ghana where data have been gathered by Koo et al. [27,47] and integrated in the modeling approach. Here, a short overview of used data and selection processes is provided.

Selection of stakeholders and participatory approach: The stakeholders were selected considering their interest and influence in decision-making on agricultural land use at the district level [27]. Based on interviews with various actors in the agricultural sectors such as farmers, NGOs, and officers of governmental bodies (the Water Resources Commission, the Forestry Commission, the Ministry of Food and Agriculture) and literature [20,53,54], agricultural extension agents (hereafter, extension officers) of the Ministry of Food and Agriculture of Ghana (MOFA) were chosen as stakeholders for this study. Although farmers as direct land users have high interest in farming conditions, their decisions primarily influence land-use activities at farm level and often indirectly affect agricultural decision-making and policies at district level. On the other hand, extension officers are in charge of several communities with the main duty to give advice in farming, introduce new techniques and policies to farmers, and regularly monitor and report cultivation conditions to the district office of MOFA [55,56]. Since they perform as mediators between farmers and district policy makers, their knowledge and expertise considerably influence land-use practices of farmers and the implementation of agricultural policies and strategies of MOFA [27]. They also highly influence agricultural programs launched by NGOs and governmental authorities as field experts. Extension officers, accordingly, play a decisive role in actual farming decisions and implementation of agricultural policies at district level [47]. All extension officers who are in charge of Bolgatanga (15 officers) and Bongo (11 officers) participated as stakeholders, and their knowledge and opinions were collected through stakeholder surveys. Questionnaires and interviews are common practice in collecting information about the ES perception and valuation [57,58]. Semi-quantitative approaches with questionnaires allow a better comparability of responses than from qualitative approaches using only open questions. In this study, semi-structured and structured surveys with the stakeholders were conducted to generate pertinent information and input for land-use simulation.

Selection of ecosystem services (ES): In this study, ES are defined as human benefits obtained from agricultural land-use activities. Regarding locally relevant ES in the agricultural context, firstly, a preliminary set of ES was identified based on existing ES studies [17,59–66]. The specific ES were then determined from the preliminary list through a semi-structured stakeholder survey [27]. The criteria of the selection were: (1) ES that are perceived to be important for agricultural land use, and (2) ES that can be recognized by their different provisioning levels based on the land-use types (Table 1, [27]). The selected ES were the provision of food, fodder, energy, construction material, marketable product, water, and erosion control. ES values of current land-use types were calculated using the indicators in Table 1. Indicators for the provision of food, fodder, energy, construction materials, and marketable products that are perceived as direct benefits from agricultural land-use activities were developed to reflect local consumptive patterns of varied land-use products (e.g., grains, stalks, branches, and leaves). They were identified through a stakeholder survey [27]. For example, a proportion to be consumed as animal feed out of the entire cereal products inclusive of grains, stalks, and leaves (assumption: 100% of use) was calculated as fodder provision of cereals. With respect to water provision and erosion control as a concomitant and indirect benefits of agricultural activities, proxy indicators from existing studies were used [17,67,68].

Table 1. Locally relevant agriculture related ecosystem services and indicators to assess the ecosystem services as identified in Koo et al. [27,47].

Ecosystem Service	Definition	Indicator
Food	Benefit of agricultural land-use activities linked with food	Proportion of land-use products consumed as food for households (%)
Fodder	Benefit of agricultural land-use activities linked with fodder	Proportion of land-use products consumed as animal feed (%)
Energy	Benefit of agricultural land-use activities linked with fuel for household	Proportion of land-use products used for fuel (cooking and heating) (%)
Construction material	Benefit of agricultural land-use activities linked with construction materials	Proportion of land-use products used for construction purposes (roofs, pillars) (%)
Marketable product	Benefit of agricultural land-use activities linked with economic value	Proportion of land-use products used for selling in the market (%)
Water	Surface water yield to flow to water bodies for human direct use	Potential water yields determined through a gap between precipitation and evapotranspiration (mm $cell^{-1} yr^{-1}$)
Erosion control	Potential to prevent surface run-off	Potential soil erosion level calculated by the RUSLE model (t $ha^{-1} yr^{-1}$)

Selection of land-management options: Future land-use strategies need to be developed considering ES protection, improvement, or trade-off between different ES [69]. Designing land-use strategies based on potential scenarios is useful in terms of the uncertain future development and the investigation of viable actions to implement [70]. In this study, land-use strategies indicate combinations of different agricultural management practices. We assumed that the application of multiple management options as strategies is more effective to enhance various ES than a single management option, since the cumulative positive impact of the management options of each strategy can be expected. The management options used for developing land-use strategies were identified in the previous study [27], and they were associated with crop-intercropping, agroforestry, afforestation, and soil conservation (Table S2 in the Supplementary Materials). In total, 15 agricultural land-management options were selected according to the following criteria: (1) the possibility to mitigate climate change impacts on agricultural areas such as a decrease in land productivity and loss of soil, and (2) the applicability in the local context based on perspectives of stakeholders [27].

Selection of a modeling approach: Since experiments on landscape scale on land-use changes are time-consuming and costly, the simulation of impacts of land-use changes has been widely used [71,72]. The selection of the appropriate land-use model is dependent on characteristics such as non-spatial versus spatial, dynamic versus static, descriptive versus prescriptive, and deductive versus inductive [73,74]. In order to address spatially variable characteristics of ES depending on the modifications of land-use patterns, this study adopted the spatially explicit simulation modeling platform GISCAME that consists of GIS modules and a CA module. This modeling approach allowed us to simulate spatially explicit changes in land-use patterns according to variable scenarios and to visualize their impacts on the ES provision [75].

2.3. Development of Future Land-Use Strategies

As explained above, a future land-use strategy is elaborated as a combination of 15 different land-management options [27]. Target land-use types were cereals, maize, legumes, grassland, and mixed vegetation, which have a high likelihood of conversion in the local context. Rice has a low probability of conversion due to its restricted farming conditions and high value in the local market and, therefore, was excluded [76]. In addition, forest cover was excluded because it is mostly influenced by statutory land-use planning of the Town and Country Planning Department and the Forest Commission [77]. All possible combinations of the 15 land-management options were applied to the 5 target land-use types (75 land-use strategies, Figure 2). For instance, future land-use strategy 6 indicates a combination of cereals with crop intercropping (CI), maize with mango agroforestry (MM), legumes with leucaena agroforestry (LL), grassland with afforestation (GA), and mixed vegetation with afforestation (MxA).

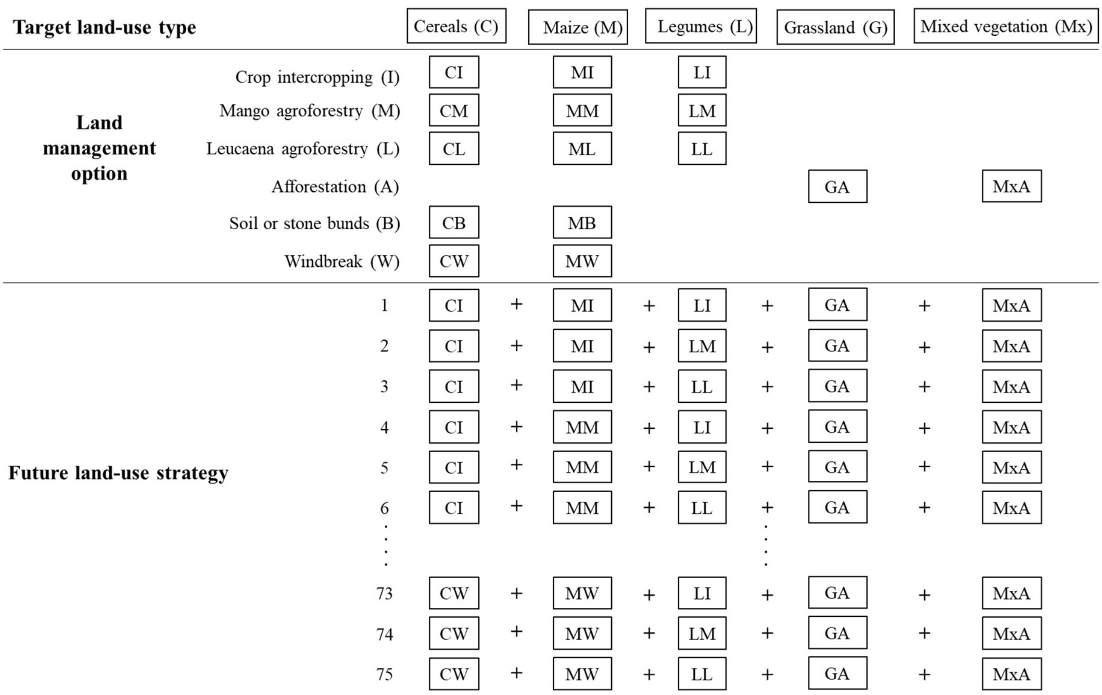


Figure 2. Development of future land-use strategies. Land-use strategies are considered as combinations of land-management options applied to target land-use types. Each box indicates which land-use management option applies to which land-use type. For instance, "CI" means a crop intercropping management applied to cereals. The meanings of abbreviated land-use management options are as below: CI: Cereal-dominant intercropping; MI: Maize-dominant intercropping; LI: Legume-dominant intercropping; GA: Grassland afforestation; MxA: Mixed vegetation afforestation; CM: Cereal intercropping with mango; MM: Maize intercropping with mango; LM: Legume intercropping with mango; CL: Cereal intercropping with leucaena; ML: Maize intercropping with leucaena; LL: Legume intercropping with leucaena; CB: Soil or stone bunds on cereals; MB: Soil or stone bunds on maize; CW: Windbreak on cereals; MW: Windbreak on maize.

2.4. Assessment Process for Potential Impacts of Land-Use Strategies on Ecosystem Services

The developed future land-use strategies were assessed by the process presented in Figure 3. The impact of a land-use strategy was determined by the combined effect of agricultural land-management options that compose the strategy. At first, the capacity of land-management options for ES provision was identified based on a stakeholder survey (blue boxes in Figure 3, and Section 2.4.1). The ES capacities were expressed in a range from 0 to 100 through standardization. Future land-use patterns influenced by land-use strategies were generated as the next step, in consideration of spatial transition conditions of land-management options in the local context (red boxes in Figure 3, and Section 2.4.2). These two parts were coupled in a modeling platform GISCAME in order to assess ES values at the district level. The best land-use strategies that can potentially provide the highest level of multiple ES (more than three different ES) at the district level were selected based on the simulated results (yellow boxes in Figure 3, and Section 2.4.3). Finally, the feasibility of these best land-use strategies in practice was identified by the local stakeholders in order to derive recommendations for future land-use planning (green boxes in Figure 3, and Section 2.4.3).

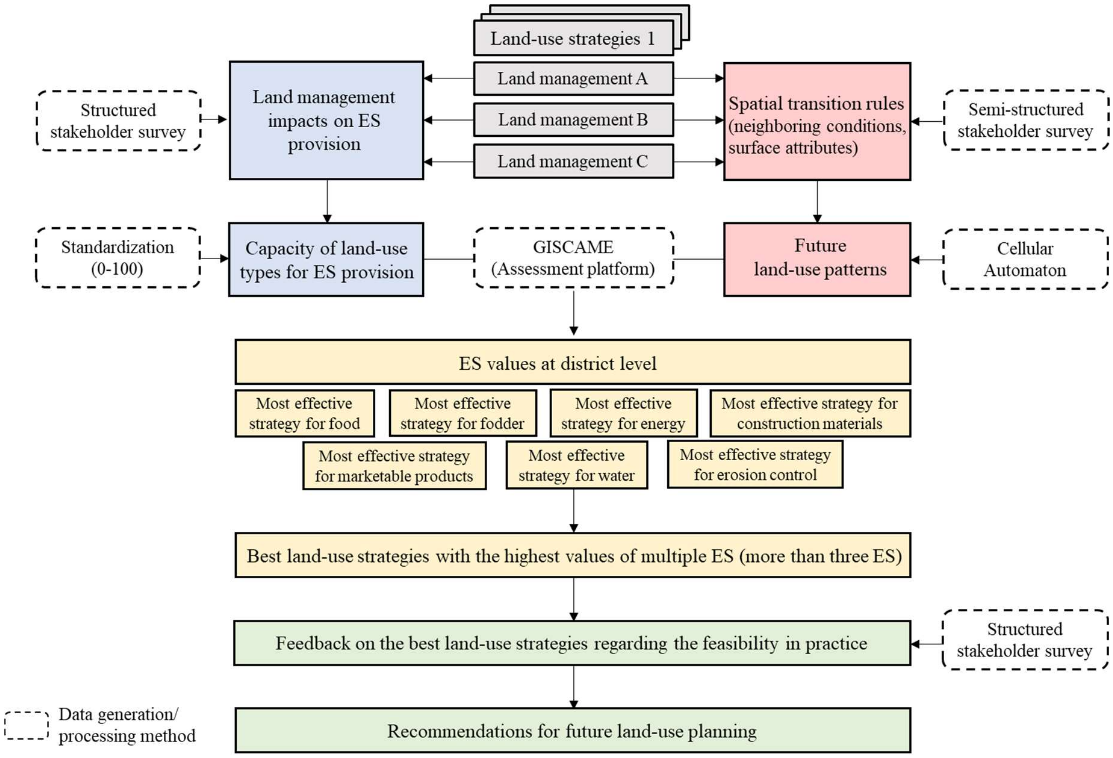


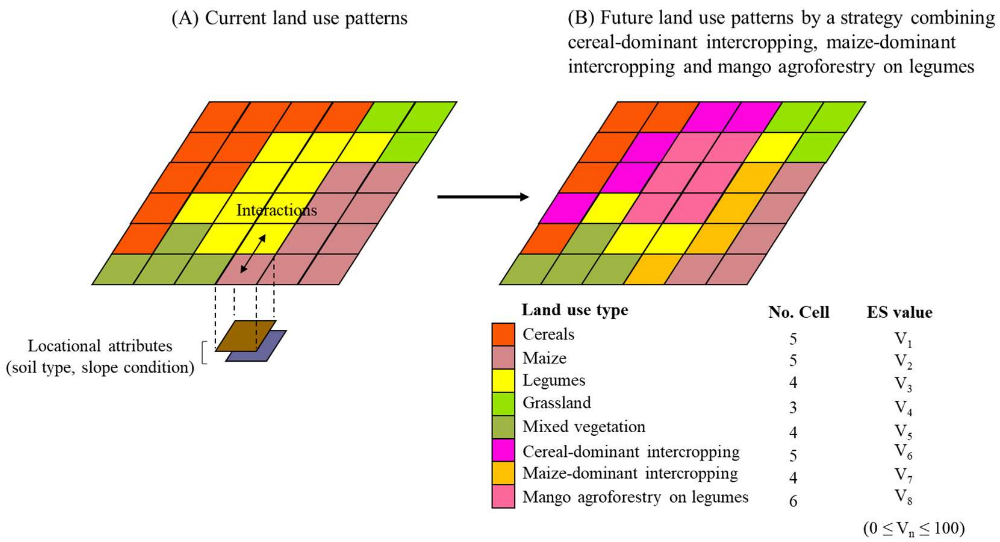
Figure 3. Assessment framework of impact of future land-use strategies on the provision of ecosystem services (ES) at district level.

2.4.1. Capacity of Land-Use Types to Provide Ecosystem Services

In order to assess the capacity of land-use strategies to supply ES at district level, it is necessary to first identify ES values of land-use types influenced by agricultural land-management options, which comprise the strategies. Here, the ES values of land-use types that were assessed in the previous study [47] were applied, and they were analyzed considering potential trade-offs and synergies between different ES as land-management impacts. For example, mango intercropping with maize as an agroforestry management option can lead to synergies between multiple ES through supplying fruits, firewood, and fence materials, while preventing surface run-off by the root system of mango trees [78,79]. On the other hand, benefits associated with the yield of maize can be reduced because the intercropping practice could have a negative impact on maize growth due to the competition for space, soil nutrients, and water with the mango trees, as a trade-off [80,81]. Such potential impacts were identified based on the experience of the stakeholders. The expected changes were expressed as percentages of increase or decrease compared to the current status of each ES (e.g., 30% potential increase in construction material provision by agroforestry). The final ES values were standardized to a relative scale between 0 (lowest ES provision) and 100 (highest ES provision) in order to compare ES values assigned to land-use types with the same unit [64]. In this assessment, we weighted all selected ES equally. The standardized values were composed of an assessment matrix that presents the relationships between all land-use types in future land-use patterns and their capacity for ES provision (Table S3 in the Supplementary Materials, [47]).

2.4.2. Future Land-Use Patterns by Land-Use Strategies

Land-use strategies were spatially implemented as an aggregation of rearranged land-use patterns by agricultural land-management options. The CA module in GISCAME was used to simulate future land-use patterns according to spatially explicit rule-sets that govern how and where to apply future options [75]. The CA, which is a spatially discrete dynamic gridded model, updates states of cells, i.e., land-use types, in a defined area called the neighborhood based on locational conditions of the cells [7,82]. The rule-sets were elaborated based on consulted information with the stakeholders regarding transition probabilities, neighboring land-use types, and environmental conditions. For instance, the consulted information included the probability (%) of land-use change from cereal (current state) to cereal intercropping (future state), neighboring land-use types (proximity effects), and environmental attributes (e.g., soil and slop conditions) as conversion conditions (Table S4 in the Supplementary Materials, [47]). When a land-use strategy is composed of cereal-dominant intercropping, maize-dominant intercropping, and mango agroforestry on legumes management options, a new land-use pattern can be generated by the simultaneous application of rule-sets of those management options through the CA (Figure 4).



$$\text{District ES value} = \frac{(5 \times V_1) + (5 \times V_2) + (4 \times V_3) + (3 \times V_4) + (5 \times V_5) + (5 \times V_6) + (3 \times V_7) + (6 \times V_8)}{36}$$

Figure 4. Generation of future land-use patterns by a land-use strategy and resultant ecosystem service values at district level. According to transition rule-sets for land-use management options (interactions with neighboring cells and locational attributes), land-use patterns are changed from A to B. An ecosystem service value at district level is calculated as a mean value for the ecosystem service supplied by each cell of changed land-use patterns.

2.4.3. Identification of Ecosystem Services Values and Feasible Land-Use Strategies at District Level

The ES values of the whole district area were calculated as mean values for the ES provided by each land-use cell of rearranged land-use patterns according to future land-use strategies (Figure 4). In other words, the final assessment score indicated the mean capacity of the all land-use types in the district map to supply ES. The capacity of a district to provide ES according to the land-use strategies was expressed in a spider chart and an ES balance table. This representation of results allowed a visual comparison of the expected impact of land-use strategies, which were interpreted as trade-offs and synergies between ES. According to the ES values at district level, the most effective land-use strategies to provide each ES were determined. The best land-use strategies were identified that can supply more than three different ES with the highest ES potential.

The reflection of local perspectives is essential to identify feasible future strategies of a specific context [83]. Although a certain land-use strategy is assumed to be effective to enhance various ES based on the simulated results, the strategy might be unrealistic without the consent of stakeholders. In this sense, a structured stakeholder survey was conducted to investigate the feasibility of the best land-use strategies using a Likert-scale (from 0 = unrealistic to 5 = very likely) with the visualized simulation results. The mean and coefficient of variation of the feasibility level were used to identify the land-use strategies with the highest feasibility to be adopted in the districts and the highest capacity to provide multiple ES.

3. Results

3.1. Ecosystem Services Values of Future Land-Use Strategies at District Level

As potential land-use alternatives, 75 future land-use strategies that consist of different management options (acronym) were evaluated (Table S5 in the Supplementary Materials). The application of the land-use strategies led to rearranged land-use patterns (examples in Figure 5a and Figure S1a in the Supplementary Materials), changes in spatial distribution of ES provision (examples in Figure 5b and Figure S1b in the Supplementary Materials), and altered ES provision at district level (examples in Figure 5c and Figure S1c in the Supplementary Materials). For example in Figure 5b, the amount of green areas (high capacity to provide food) in the map of strategy 13 was higher than in strategy 20. The spider chart and ES balance table (Figure 5c) also showed that the positive impact of strategy 16 on multiple ES was higher than strategy 20. Regarding the ES values in Bolgatanga as output of GISCAME for all 75 land-use strategies (Table S6 in the Supplementary Materials), most land-use strategies showed either no change or a positive impact on the provision of all ES, except for water provision. Specifically, land-use strategies that included cereal-dominant intercropping and legume-dominant intercropping (e.g., land-use strategies 1, 10, and 13) showed higher food provisioning levels than other strategies. On the contrary, land-use strategies that included mango agroforestry on cereals (e.g., land-use strategies 17, 19, 20, 23, 27, and 30) were considered less effective for providing food. The provision of fodder and construction materials was similarly increased by overall land-use strategies. Energy provision was higher in land-use strategies that included the windbreak as management option on cereals (e.g., land-use strategies 61–75). The provision of marketable products increased in land-use strategies that incorporated the combination of legume-dominant intercropping and soil or stone bunds on cereals (e.g., land-use strategies 46, 55, and 58), whereas the effect through land-use strategies that included agroforestry as management option (e.g., land-use strategies 20, 23, 30, 36, and 39) was lower than the effect by other strategies. Water provision was drastically decreased by all land-use strategies, especially land-use strategies that included mango agroforestry on cereals. According to the simulated results, strategy 13 (CI + MW + LI + GA + MxA) is one of the most effective strategies for increasing multiple ES, whereas strategy 20 (CM + MM+ LM + GA + MxA) is less effective than others.

With respect to ES values in Bongo (Table S7 in the Supplementary Materials), land-use strategies with cereal-dominant intercropping (e.g., land-use strategies 1, 2, and 11) were shown as more effective for food provision than others, while land-use strategies that included agroforestry on crops (e.g., land-use strategies 21–24, 33–39, and 45) proved to be less effective for increasing food provision. Unlike Bolgatanga, land-use strategies with leucaena (fodder tree) agroforestry on legumes (e.g., land-use strategies 33, 39, 42, 45, 48, 54, 57, and 60) proved to be effective for the increase in fodder provision. Energy provision was increased more through land-use strategies with a windbreak on cereals as a management option (e.g., land-use strategies 64–75) than through other strategies. The provision of construction materials was increased equally by most land-use strategies. Regarding the improved provision of marketable products, land-use strategies that included legume-dominant intercropping (e.g., land-use strategies 1, 4, and 46) presented to be more effective than others. Water provision was notably reduced by all land-use strategies dissimilar to other ES, and the negative effect was especially greater through land-use strategies with mango agroforestry on cereals (e.g., land-use strategies 19, 21, 24, 27, and 30). The enhancement of erosion control was more effective in land-use strategies with soil or stone bunds on cereals (e.g., land-use strategies 46–60). Simulated results showed that strategy 1 is one of the most effective strategies to enhance various ES, while strategy 36 is less effective than other strategies.

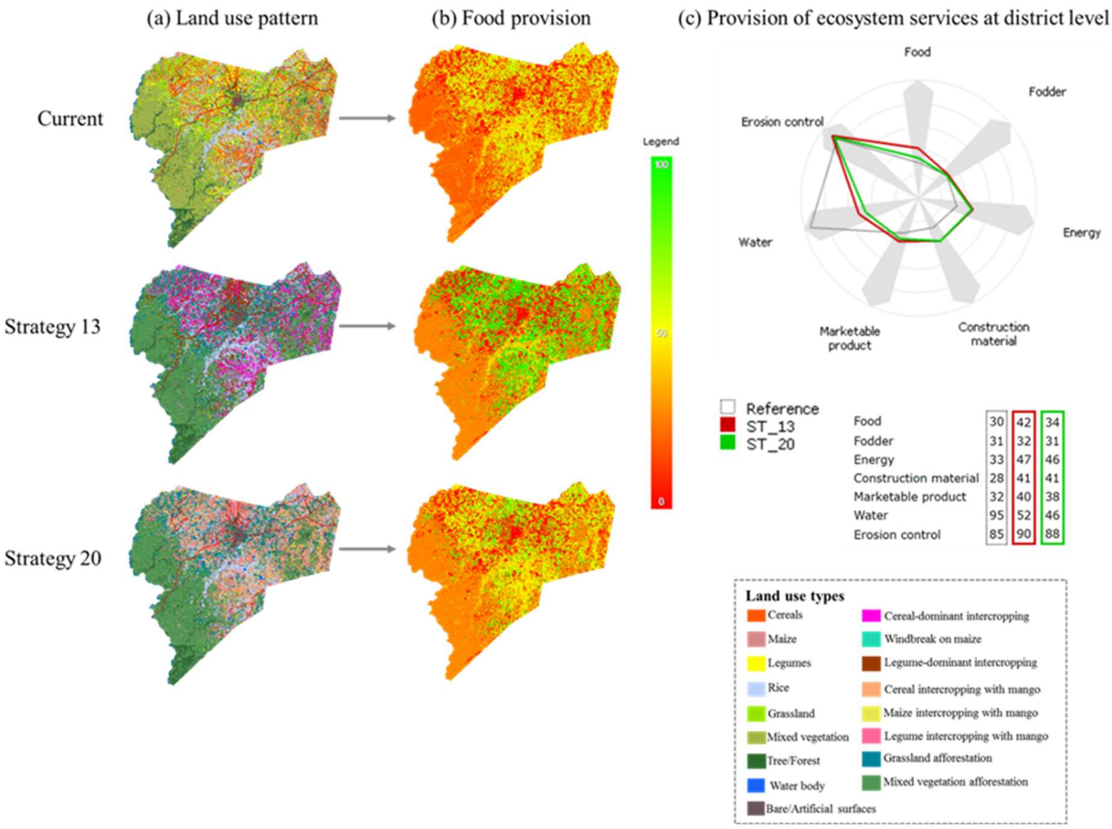


Figure 5. Potential impacts of land-use strategies on the land-use patterns and the provision of ecosystem services in Bolgatanga. The application of strategy 13 (ST_13) and strategy 20 (ST_20) results in rearranged land-use patterns (**a**). Provisioning maps for ecosystem services (e.g., food provision) show the impacts of the rearranged land-use patterns on the spatial distribution of ecosystem services (**b**). The spider chart and the ecosystem services balance table show changes in the provision of ecosystem services compared to the current provision of ecosystem services as reference (**c**). When these two strategies are compared, strategy 13 is more effective to enhance ecosystem services. The images were captured from GISCAME.

As the best land-use strategies that provide more than three different ES with the highest values (green color in Tables S6 and S7 in the Supplementary Materials), 14 land-use strategies in Bolgatanga and eight land-use strategies in Bongo were identified (yellow color in Tables S6 and S7 in the Supplementary Materials). The best land-use strategies in Bolgatanga were based on legume-dominant intercropping (LI) and soil conservation applied in cereals (CB, CW) as agricultural land-management options. Those strategies especially enhanced food provision more effectively than other ES. In Bongo, land-use strategies that contained soil or stone bunds on cereals (CB) and agroforestry in legumes (LM, LL) tended to be the best land-use strategies. They increased particularly the provision of food and marketable products. All the best strategies in Bolgatanga and Bongo led to a decrease in water provision as trade-off.

3.2. Locally Recommendable Land-Use Strategies

Among the best land-use strategies (14 strategies in Bolgatanga and eight strategies in Bongo), recommendable land-use strategies were determined in consideration of their feasibility in practice. The feasibility based on a stakeholder survey is presented in Table 2. In terms of Bolgatanga, most of the best land-use strategies were above the moderate level of feasibility (mean value ≥ 3). In particular, (I) a combination of crop intercropping on cereals, maize, and legumes, and afforestation on grassland and mixed (land-use strategy 1) and (II) a combination of windbreak on cereals, crop intercropping on maize and legumes, and afforestation on grassland and mixed vegetation (land-use strategy

61, visualized impact on ES provision and land-use patterns in Figure 6) presented slightly higher mean values and lower variation. Therefore, these two land-use strategies can be considered as locally recommendable land-use strategies that have the potential to enhance multiple ES with high feasibility to be implemented in the local context. On the other hand, land-use strategy 64, which consisted of windbreak on cereals, maize intercropping with mango, legume-dominant intercropping, and afforestation on grassland and mixed vegetation, was perceived as being less feasible to be adopted.

Table 2. The feasibility of best land-use strategies in Bolgatanga and Bongo. Mean values and the coefficient of variation (CV) of a Likert-scale survey result (from 0 = unrealistic to 5 = very likely) are used for the identification of most feasible land-use strategies.

Bolgatanga			
		Feasibility	
N°	**Land-use strategy**	**Mean**	**CV**
1	CI + MI + LI + GA + MxA	3.78	0.12
10	CI + MB + LI + GA + MxA	4	0.25
13	CI + MW + LI + GA + MxA	3.78	0.26
46	CB + MI + LI + GA + MxA	3.56	0.25
55	CB + MB + LI + GA + MxA	3.67	0.14
57	CB + MB + LL + GA +MxA	3.78	0.22
58	CB + MW + LI + GA + MxA	3.22	0.21
61	CW + MI + LI + GA + MxA	4.22	0.16
63	CW + MI + LL + GA + MxA	3.56	0.25
64	CW + MM + LI + GA +MxA	2.56	0.21
67	CW + ML +LI +GA + MxA	3.44	0.29
70	CW + MB + LI + GA + MxA	3.67	0.19
73	CW + MW + LI + GA + MxA	3.22	0.37
75	CW + MW + LL + GA +MxA	3.11	0.30
Bongo			
		Feasibility	
N°	**Land-use strategy**	**Mean**	**CV**
1	CI + MI + LI + GA + MxA	3.78	0.18
2	CI + MI + LM + GA + MxA	4.10	0.18
46	CB + MI + LI + GA + MxA	4.11	0.15
47	CB + MI + LM + GA + MxA	3.78	0.18
48	CB + MI + LL + GA + MxA	3.56	0.20
54	CB + ML + LL + GA + MxA	3.78	0.26
57	CB + MB + LL + GA +MxA	3.89	0.15
60	CB + MW + LL + GA +MxA	3.44	0.29

All best land-use strategies in Bongo that provide the highest ES potential for multiple ES showed also higher feasibility than the moderate level (mean value ≥ 3). Especially, (I) a combination of soil or stone bunds on cereals, crop intercropping on maize and legumes, and afforestation on grassland and mixed vegetation (land-use strategy 46, visualized impact on ES provision and land-use patterns in Figure 6) and (II) a combination of crop intercropping on cereals and maize, legume intercropping with mango, and afforestation on grassland and mixed vegetation (land-use strategy 2) presented slightly higher feasibility than other land-use strategies considering their mean values and coefficient of variation. Thus, they can be regarded as locally recommendable land-use strategies in Bongo. A combination of soil or stone bunds on cereals, windbreak on maize, legume intercropping with leucaena, and afforestation on grassland and mixed vegetation (land-use strategy 60), on the contrary, was regarded as a less feasible strategy.

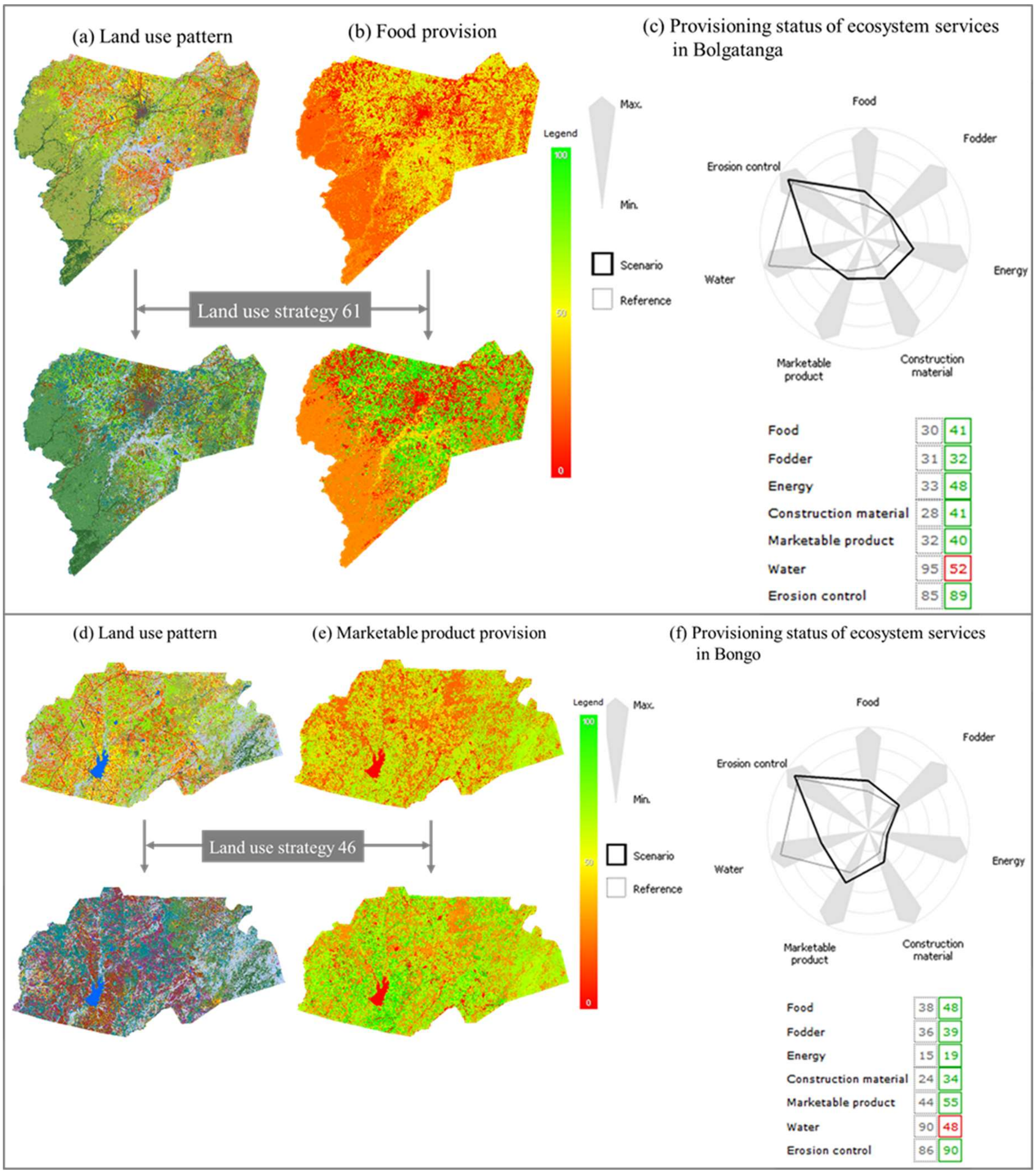


Figure 6. Future land-use pattern and changes in the provision of ecosystem services according to locally recommendable land-use strategies in Bolgatanga (top) and Bongo (bottom). The application of land-use strategies generates future land-use pattern (**a**,**d**). The spatial distribution of ecosystem services (e.g., food and marketable products provision) is influenced by the newly generated land-use pattern (**b**,**e**). The spider chart and the table present the changes in the provision of overall ecosystem services at district level compared to the current status as reference values (**c**,**f**). Green numbers indicate an increase in the provision of ecosystem services, and a red number signifies a decrease in the provision of ecosystem services. The images were captured from GISCAME.

4. Discussion and Outlook

4.1. Discussion of the Findings

The quantified ES values enabled an understanding of the potential impacts of land-use strategies associated with district characteristics and local perception. For instance, since cereals were the main staple crops in both districts (Table S1 in the Supplementary Materials), food provision was mainly influenced by the management option applied for cereal fields. Different perceptions existed on the capacity of the cereal-related management options to provide food (Table S3 in the Supplementary Materials). For example, land-use strategies with agroforestry on cereals were considered to provide less food than land-use strategies including cereal-dominant intercropping. In terms of the provision of marketable products, legume-dominant intercropping showed the highest capacity to provide the ES (Table S3 in the Supplementary Materials) and substantially contributed to the effectiveness of land-use strategies in both districts. Different perceptions explain dissimilarities between the two districts regarding the ES provision of land-use strategies. For example, management options with leucaena agroforestry for fodder provision and soil or stone bunds for erosion control were considered to be more effective according to the opinion of the stakeholders in Bongo. The stakeholders in Bolgatanga perceived cereal-dominant intercropping management options as more effective for providing those ES. This can be explained by the different experiences of stakeholders in the fields and by more economic oriented preferences for land-use practices. Bolgatanga as regional capital hosts the main markets and has a higher purchasing power than Bongo. Therefore, "bestsellers" such as cereals have been chosen to ensure the economic income of farmers. In addition, the decentralized program in Ghana that enabled individual decision-making system for each district [53] also influences such differences between the districts. Malinga et al. [84] and Mensah et al. [85] also found out with case studies in South Africa that ES provided by a certain landscape and land-use system, and their usage in practice can be differently perceived depending on the socio-economic status (age, gender, income, etc.), knowledge, and experiences of the stakeholder group.

All land-use strategies presented a remarkable decrease in water provision as a trade-off to the increase in other ES (Tables S6 and S7 in the Supplementary Materials). Since water provision here is defined as the amount of surface water directly used by people, land-use types with a high-water demand lead to a negative impact on the ES [47]. For instance, intercropping and agroforestry practices were considered to highly increase surface water demand due to the varied water requirements of different intercropped species in both districts (Table S3 in the Supplementary Materials). Thus, land-use strategies as combinations of various management options that have a higher water demand could potentially amplify such a negative impact on the provision of water at district level. Previous studies also showed that combined management options (e.g., intercropping) led to an increase in the total surface water demand and water stress, thereby reducing water yield [86,87]. However, there has been a debate about the effect of land-use practices on water yield, and this is closely related to spatial scales. Specifically, in Africa, the role of trees and forests is often focused as water consumers and competitors for other water uses at local level, while they provide water to the atmosphere and contribute to precipitation development at regional and global level [88,89]. This interaction between land-use types and the provisioning level of atmospheric moisture should be especially considered in semi-arid West Africa. In this assessment, all selected ES were equally weighted as done in other existing ES studies [90–92]. The application of different weight values to ES, which allows us to reflect preferred or prioritized ES from the stakeholder perspective could present more realistic results regarding trade-offs and synergies between ES. When different importance of ES is considered, specific land-use strategies can be recommended. For instance, if the stakeholders regard that food provision is most crucial in this area, strategy 1 can be more recommendable than strategy 61 in Bolgatanga, and strategy 2 can be chosen as a recommendable strategy rather than strategy 46 in Bongo due to their more effective capacity to provide food. In this light, future land-use strategies for supporting the efficient use of limited agricultural land focusing on the provision of more important ES in the local context could be also identified.

4.2. Methodological Discussion

This study integrated a participatory method and spatially explicit simulation modeling as a transdisciplinary approach to apply the ES concept for assessing future land-use strategies. Table 3 presents advantages and challenges of the applied methods. A participatory method through stakeholder surveys allowed us to reflect local preferences and characteristics in assessing the potential impacts on multiple ES provision. Land-use strategies based on local perspectives allowed the development of more acceptable and feasible future land-use alternatives. However, stakeholder perspective-based data might cause a reliability issue and the ignorance of important environmental aspects. In addition, the involvement of only a certain group in the assessment process has a limitation to address conflicting objectives.

Regarding spatially explicit simulation modeling, GISCAME as an assessment platform runs with simplified data reflecting locally relevant details, thereby easily testing various future alternatives. The visualization of ES provision according to the simulated results can improve the understanding of potential impacts of future decisions (trade-offs and synergies between ES). Quantified and visualized results allowed a better feedback from stakeholders. Furthermore, such simulation approaches can also improve the communication between different land-use actors, which helps to establish shared understandings and visions on future actions. On the other hand, modeling always deals with an abstract of the complex environment. Various direct and indirect factors influence agricultural systems, but the applied modeling approach simplified the environmental factors that influence land-use decisions of the stakeholders. Another challenge of this local ES assessment is related to the transferability to other regions or different spatial scales. The findings are based on the context-specific as well as scale-dependent empirical data, which were generated by the stakeholder involvement. However, the applied assessment framework, which presented the stepwise process of collecting ES and land-use-related local knowledge and integrating the local knowledge into land-use modeling, can be used in other contexts and regions. GISCAME, which was used for spatially explicit simulation in this framework has been already applied in Germany, Chile, Ecuador, and Brazil [64,75,93]. Future research in the context of this study can be directed towards scalar interactions of land-use systems, i.e., land-use decisions at district level influence the land-use conditions at farm level and land-management policies at regional level. Depending on the spatial scales, the stakeholder group should be adapted, since other stakeholders might be more relevant on the regional and national level.

Table 3. Advantages and challenges of applied participatory and simulation modeling approaches.

	Advantage	**Challenge**
Participatory method	• Local preferences and characteristics were reflected in identifying the relationships between future land-use strategies and ES provision. • ES and indicators were identified relevant to actual land-use activities in the local context: the multifunctionality of land-use systems can be considered [94,95]. • Acceptable and feasible land-use strategies were generated based on agricultural land-management options from a local perspective: this can complement existing statistical and biophysical data-based scenario assessments in West Africa (e.g., [22,45,46,96]).	• Reliability of results can be criticized due to the subjective data based on the perspectives of the stakeholders. • Important environmental aspects may not have been considered by the stakeholders (e.g., impact of land-use systems on climate regulation service). • Only a specific stakeholder group was involved: potential conflicts and trade-offs between the interests of different actors were not considered [97,98].
Spatially explicit simulation modeling	• It can incorporate stakeholders' perspectives vis-à-vis the spatial peculiarity of ES provision, whose distribution and values are dependent on land-use patterns [8,99,100]. • It has potential to be used as a transdisciplinary planning approach that integrates a participatory method and ES mapping, especially in the West African context, where locally adapted methodological frameworks are still limited [18]. • GISCAME runs with simplified data reflecting locally relevant details rather than requiring extensive and big-data, which allows easier integration with various types of local data and transformation of the modeled results into decision-making relevant information • The visualization of ES provision can improve the understanding of potential impacts of future decisions and can support land-use decision-making and planning as an ex-ante assessment of future land-use alternatives [101,102]. • Quantified and visualized results allow stakeholders to compare different alternatives and to be actively involved in a decision process. • The approach can be used as feedback mechanism and also as a communication tool between different stakeholder groups [103].	• A simplification of the complex environment was needed for modelling [104,105]: dynamics of interactions between future land-use decisions and ES provision were limited. • Agricultural conditions are greatly influenced by various direct and indirect factors such as the use of fertilizers labor availability, subsidy programs, and market situation [106,107], which were not included due to the increasing complexity and the lack of adequate data. • The transferability of results to other regions or different spatial scales is limited because the applied data contains stakeholder-specific knowledge [108,109]. • The analysis was conducted at district level, which is nested between the field and national level [110]. However, the scalar interactions were not considered due to the modeling complexity and the lack of regional data for multi-scale assessments.

4.3. Future Directions of Using the Ecosystem Service Concept for Land-Use Planning in West Africa

The integration of the social and the ecological systems is essential for land-use decision making [3,32,101,111,112] and the involvement of stakeholders improves the understanding of such linkages [109]. The transdisciplinary concept of ES could serve as a bridge between the social and ecological system and different actors. Therefore, the ES concept has the potential to contribute to participatory land-use planning [35,113]. However, the implementation of the ES concept in actual planning and decision making is still in the initial stage and existing approaches to make use of ES values need to be further tested in practice [114], especially in West Africa. Previous studies addressed the challenges to apply the ES concept in spatial planning in West Africa, which are related to the lack of awareness and common understanding of the ES concept, low public participation, and the lack of tools and approaches to support practical implementation of land-use strategies [18,26]. Since local people in West Africa are still unacquainted with the ES concept and related scientific terms, we used "benefit of agricultural land-use activities" instead of "ES" during discussion and surveys with the local stakeholders. ES indicators were also determined to reflect their consumptive patterns of the benefits, which the multifunctionality of agricultural land was considered from the local perspective.

We adopted an assessment framework that used qualitative and semi-quantitative data as simulation input and evaluation of ordinal scale for identifying locally recommendable strategies. This approach is useful in applying the ES concept in the West African context, since it can serve as a preliminary basis for decision-making through presenting changes in ES provision depending on probable future decisions of the local stakeholders. Such consideration of local perspectives allows the better public understanding of the ES concept [35,113] and increases the acceptance of the ES assessment results. The involvement of various agricultural related actors (e.g., farmers, NGOs, agribusinesses, other governmental bodies, and experts) in the feedback process can increase the validity of the findings and further support consensus building thereby encouraging collective actions [113].

In order to make better use of ES assessment for land-use planning in West Africa, it should be investigated how ES information can be operationalized in a specific policy context [115]. Regarding land-use planning, the spatial distribution and peculiarity of ES in a certain area is a key information since stakeholders and decision-makers are more interested to know where to implement planning as a spatial solution [113]. Such information can be more applicable with practical knowledge respecting how and when the information and tested approaches can actually support planning practice [114]. In Ghana, land-use planning has been criticized for focusing mostly on managing physical growth and developing urban areas, despite the fact that the majority of the land still needs to be used for food and natural resources. Besides, the ES concept has been so far rarely emphasized in any Ghanaian spatial development schemes [18]. Thus, there should be further research concerning which ES-relevant information is required by planners and decision-makers and how to establish a new standard or criteria of ES plans coordinated with existing decision-making structures [114].

5. Conclusions

This study suggested an assessment framework to support future land-use planning for agricultural land through integration of local knowledge into spatially explicit ES simulation modeling. Considering that existing studies for assessing the impact of land-use systems in West Africa, which did not consider either local perspectives or the spatial peculiarity of ES, the applied approach in this study can be a novel attempt to connect narratives of stakeholders and explicit approaches. Especially, the development of land-use strategies based on stakeholder perspectives allowed identification of more accountable alternatives for effective ES-based adaptation in the local context. Converted local knowledge and perception to model input for spatially explicit simulation allowed to understand the interrelationships between future land-use decisions by stakeholders, changes in land-use patterns, and their consequent impact on ES provision. The results reflecting different local perceptions on the land-use systems presented that different land-use strategies were regarded as effective and feasible in the two adjacent districts despite their similar land use and environmental conditions. This implies that local knowledge and characteristics such as the multifunctionality of land-use systems and locally preferred land-use activities, which could be influenced by socio-economic factors and decision-making process of districts are important in identifying effective future strategies for improving locally relevant ES. The quantified and visualized impacts of land-use strategies facilitated the communication with the local stakeholders for obtaining their feedback. This shows the potential of a modeling approach to contribute to elaborating locally tailored land-use schemes as a transdisciplinary way. As a stakeholder-based simulation modeling, there are some weaknesses to contemplate regarding the simplification of complex human-nature systems, transferability of results to other regions or spatial scales and limitations in considering various socio-economic aspects due to the lack of data. In addition, the involvement of various actors in assessment and feedback processes should be also considered. However, the suggested modeling approach gives an insight into how to design decision-supporting frameworks for future land-use planning from the transdisciplinary perspective, which reflects the interaction between land-use stakeholders and their surroundings through an integration of different methods.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-445X/9/10/379/s1, Figure S1: Potential impacts of land-use strategies on the land-use patterns and the provision of ecosystem services in Bongo. Strategy 1 (ST_1) and strategy 36 (ST_36) lead to rearranged land-use patterns (a). The spatial distribution of ecosystem services (e.g., food provision) is changed according to the strategies (b). Impacts on the provision of ecosystem services at district level compared to the current status as reference are expressed in the spider chart and the ecosystem services balance table (c). When these two strategies are compared, strategy 1 is more effective to enhance ecosystem services. The images were captured from GISCAME. Table S1: The percentage of the area occupied by each land-use type and their descriptions [27]. Table S2. Agricultural land-management options and their description [47]. Table S3. Ecosystem services assessment matrix to display the capacity of current land-use types and agricultural land-management options to provide ecosystem services in Bolgatanga and Bongo [47]. The values are presented within a scale from 0 (lowest level of provision) to 100 (highest level of provision). Table S4. Transition probability-based application conditions for land-management options [47]. Table S5. Applied future land-use strategy. Table S6. Ecosystem service values provided by land-use strategies in Bolgatanga. Ecosystem service values based on the current land-use pattern are used as reference values (R), in blue color. The highest value of each ecosystem service is expressed as green color (the provision of construction materials is excluded as it is equally increased by all land-use strategies). The best land-use strategies that have the potential to provide more than three different ES with the highest values are expressed as yellow color. Table S7. Ecosystem service values provided by land-use strategies in Bongo. Ecosystem service values based on the current land-use pattern are used as reference values (R), in blue color. The highest value of each ecosystem service is expressed as green color (the provision of construction materials is excluded as it is equally increased by all land-use strategies). The best land-use strategies that have the potential to provide more than three different ES with the highest values are expressed as yellow color.

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Eidesstattliche Erklärung / *Declaration under Oath*

Ich erkläre an Eides statt, dass ich die Arbeit selbstständig und ohne fremde Hilfe verfasst, keine anderen als die von mir angegebenen Quellen und Hilfsmittel benutzt und die den benutzten Werken wörtlich oder inhaltlich entnommenen Stellen als solche kenntlich gemacht habe.

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