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The multi-criteria assessment of ecosystem services at a landscape level to support decision-making in regional and landscape planning

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Die multikriterielle Erfassung von Ökosystemdienstleistungen auf Landschaftsebene zur Unterstützung der Entscheidungsfindung in der Regional- und Landschaftsplanung

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Die Übereinstimmung dieses Exemplars mit dem Original der Dissertation zum Thema:

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wird hiermit bestätigt.

Statement of the PhD Candidate

I hereby confirm that this copy is identical with the original dissertation titled:

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Abbreviations

CLC	Corine Land Cover
DPSIR	Driving forces, Pressures, States, Impacts and Responses
EMLC	EuroMap Land Cover
EP	Ecosystem potential
ES	Ecosystem services
GIS	Geographical Information Systems
GISCAME	Geographical Information System - Cellular Automaton - Multi-criteria Evaluation
LULC	Land use/land cover
LULCC	Land use/ land cover change
LMC	Land management change
MCA	Multi-criteria assessment
IWAS	International Water Research Alliance Saxony
IWRM	Integrated Water Resources Management
MCDM	Multi-Criteria Decision-Making
ÖSDL	Ökosystemdienstleistungen
SächsLPlG	Sächsisches Landesplanungsgesetz (State planning law for Saxony)
REGKLAM	Regionales Klimaanpassungsprogramm für die Modellregion Dresden (Regional Climate Change Adaptation Program Dresden Region)
RZAWZ	Root Zone Available Water Capacity

Summary

The continuously growing pressure on natural resources has led to a widespread acknowledgement of the services nature provides for humans (MA 2005). The broad agreement that ecosystems should be managed sustainably was followed by political initiatives to safeguard biodiversity and ecosystems (e.g. at EU level the Convention on Biological Diversity, 2012) and divers attempts to develop suitable planning instruments for decision support. Yet, the appropriate representation of the benefits of sustainable land use in decision-making (tools) is still a challenge (Robinson et al. 2012). Ecosystem services (ES) are defined as the benefits humans derive from ecosystems (MA 2005). The ES concept has attracted much attention as the basis for natural resources management because of its interdisciplinary character bridging evaluation approaches of natural and socio-economic sciences (Müller and Burkhard 2007). The assessment of ES at a landscape level may play an important role as a starting point for an integrated land use planning.

In the present doctoral thesis entitled “The multi-criteria assessment of ES at a landscape level to support decision-making in regional and landscape planning”, four main research objectives have been addressed:

(i) Development of a transferable methodical approach to assess and evaluate the impact of land use/ land cover change (LULCC) on ES.

(ii) Identification of alternative land use options to better support planning of sustainable land use including synergies and trade-off analyses.

(iii) Identification of alternative land use options in the context of water resources management using a spatially explicit assessment approach.

(iv) Evaluation of the potential of the ES concept for planning with stakeholder participation.

The doctoral thesis resulted from work carried out within the joint research projects REGKLAM, Regional Climate Change Adaptation Program Dresden Region, and IWAS Água DF, International Water Research Alliance Saxony with project region in Brazil. Both project regions were used as case study areas to test the application of the developed ES assessment approach.

The ES concept built the methodological framework for the assessment as it offers a universal approach to evaluate the impact of LULCC on human well-being. Since standardized methodical approaches for ES assessment at the landscape level are lacking, a particular requirement was to conceive a method that is easily transferable to other case study areas. Further the method should enable the use of existing and easily available environmental data, and it should be transparent for stakeholders and decision makers.

This thesis is being conceived as cumulative dissertation consisting of four peer-reviewed articles in international journals.

Chapter 1 “Introduction” provides an overview of the motivation and background of the thesis. **Chapter 2 “Methods”** gives information on the methodical development steps (mainly based on Koschke et al. 2012) and the tools used within the two case studies. The case study areas are also described here. **Chapter 3 “Results”** presents results of the assessments of the impacts of simulated LULCC in the case study areas referring to the publications Koschke et al. (2012, 2013, 2014a). In addition, outcomes of the analysis of stakeholder processes in ES studies (Koschke et al. 2014b) are illustrated. **Chapter 4 "Discussion"** is dedicated to reflect the transferability and applicability of the assessment approach. Further, a comprehensive evaluation of the findings is given including a critical analysis of the methodical approach and existing methodical challenges, the model uncertainty and the applicability of the ES concept in participatory planning. **Chapter 5 "Conclusions"** provides a conclusion on findings, existing challenges with respect to landscape level ES assessment and involvement of stakeholders in participatory (decision-) processes. An outlook where further application- and development needs are identified is integrated in the conclusions.

A key output of the thesis is a routine for the (spatially explicit) assessment of ES that has been implemented in the spatial decision support platform GISCAME as the basic procedure for LULCC impact assessment for currently three land use data sets. It allows the comparison of the impact of LULCC (and land management change, LMC) on multiple ES on a qualitative, relative, ordinal scale. It is the precondition for extended assessments taking into account LULC configuration and composition using landscape metrics (cf. Frank et al. 2012, 2013, 2014a).

In **Koschke et al. (2012)** the indicator based assessment framework was developed. Applying the CORINE Land Cover (CLC) data I could demonstrate the utility of the approach – implemented in GISCAME – to test alternative LULC scenarios and compare the performance of ES. Assessment results were checked for plausibility. Consequently, questions about the uncertainty of assessment results and the suitability of the CLC data set for regional planning issues appeared.

In the second application case (**Koschke et al. 2013**), EuroMap Land Cover (EMLC) data have been used, making necessary to expand the assessment procedure according to a divers set of soil management and crop rotation options. I could demonstrate that a land use data set with a higher spatial and thematic resolution allows for the consideration of management options in the agriculture sector. Dealing with local stakeholders and land managers, this can be considered as a major advantage in comparison to rough spatial data sets. This is because management options are more important drivers of ES provision at local to landscape level than LULCC which seldom occurs in significant amounts in Germany and moreover cannot be influenced by single decision makers mostly. Results of an uncertainty analysis showed great uncertainty inherent in the static, indicator based assessment approach. Assessment results can vary significantly upon the change of single indicator values.

The third case study (**Koschke et al. 2014a**) focused on the question how threatened water resources in the Pipiripau river basin in central Brazil can be protected from further depletion and how the provision of hydrological ES can be enhanced through LULCC in the course of integrated water resources management (IWRM). Using further environmental parameters, a spatially explicit assessment method was introduced for this case study for the hydrological ES water purification, sediment retention, water retention, and the provision of food and fodder.

Using the developed assessment approach, priority areas for LULCC can be more efficiently identified and arguments for safeguarding areas with high importance for regulating services more convincingly formulated. Findings suggest that less intensively managed LULC classes result in synergies among regulatory ES and ecological integrity. In contrast, provisioning services tend to decrease with increasing surface area share of, e.g. less intensively managed arable land, grassland and forest.

The fourth publication (**Koschke et al. 2014b)** dealt with the application of the ES concept in practice, i.e. in ecosystem management and spatial planning contexts that include stakeholders. Challenges and potential drawbacks of applying the ES concept in participatory processes were identified and evaluated and potential facilitations of stakeholder processes suggested. In order to ensure a positive impact of ES, it is recommended - based on the findings - to adapt the communication with stakeholders with respect to the addressed problem, decision-making level and involved stakeholder group(s).

Overall, the results show that the presented rapid ES assessment and mapping approach can have an added value in the course of discussing (and visualizing) the impact of LULCC alternatives at a landscape level. By integrating fragmented and divers data sources, the approach has potential to add relevant information to planning and decision-making processes, e.g. on synergies and conflicts between ES and priorities of differing stakeholders. Similar mapping approaches can be also used for ES assessments at larger (regional, national, global) scales. However, concerns relate to the variability of utilized indicator values, possible double counting, accuracy of employed land use data sets, and a currently lacking implementation of the ES concept in participatory planning processes. Uncertainty of the results should always be addressed and properly communicated.

Zusammenfassung

Der stetig wachsende Druck auf die natürlichen Ressourcen hat zu einer breiten Anerkennung der Leistungen von Ökosystemen für den Menschen geführt (MA 2005). Der breiten Zustimmung, dass Ökosysteme nachhaltig genutzt werden sollten, folgten politische Initiativen zur Sicherung von Biodiversität und Ökosystemen (z.B. auf Ebene der EU die Biodiversitäts-Konvention, 2012) und Versuchen geeignete Planungsinstrumente zur Entscheidungsunterstützung zu entwickeln. Die angemessene Berücksichtigung der Vorteile einer nachhaltigen Landnutzung in Entscheidungsfindungsprozessen und den sie unterstützenden Werkzeugen ist jedoch nach wie vor eine Herausforderung (Robinson et al. 2012). Ökosystemdienstleistungen (ÖSDL) werden definiert als der Nutzen den Menschen durch Ökosysteme (MA 2005) haben. Das ÖSDL Konzept hat viel Aufmerksamkeit als Grundlage für die Bewirtschaftung der natürlichen Ressourcen erfahren. Dies beruht vor allem auf dem interdisziplinären Charakter des Konzeptes, der es ermöglicht Bewertungsansätze der Umwelt- und sozioökonomischen Wissenschaften zu vereinen (Müller und Burkhard, 2007). Die Erfassung von ÖSDL auf einer Landschaftsebene kann eine wichtiger Ausgangspunkt für eine integrierte Landnutzungsplanung sein.

In der vorliegenden Doktorarbeit mit dem Titel “Die multi-kriterielle Erfassung von Ökosystemdienstleistungen auf Landschaftsebene zur Unterstützung von Regional- und Landschaftsplanung“ wurden vier Forschungsziele verfolgt:

(i) Die Entwicklung eines übertragbaren methodischen Ansatzes um den Einfluss von Landnutzungs- und Landbedeckungsänderungen auf ÖSDL zu erfassen und zu bewerten.
(ii) Die Identifizierung von alternativen Landnutzungsoptionen zur besseren Unterstützung nachhaltiger Landnutzungsplanung unter Berücksichtigung von Synergien und Zielkonflikten.
(iii) Die Identifizierung von alternativen Landnutzungsoptionen im Kontext eines integrierten Wasserressourcenmanagements unter Verwendung eines erweiterten, räumlich expliziten Bewertungsansatzes.
(iv) Die Bewertung des Potentials des ÖSDL-Konzeptes zur Planungsunterstützung in Prozessen mit Stakeholderbeteiligung.

Die Doktorarbeit ist das Ergebnis der Arbeit in den Forschungsprojekten REGKLAM (Regionales Klimaanpassungsprogramm für die Modelregion Dresden) und IWAS Água DF (Internationale WasserforschungsAllianz Sachsen) mit Projektgebiet in Brasilien. In beiden Projektgebieten wurden Fallstudien durchgeführt um den entwickelten Bewertungsansatz zu testen.

Das ÖSDL Konzept war der methodologische Rahmen für die Erfassung, da es einen universalen Ansatz darstellt den Einfluss von Landnutzungs- und Landbedeckungsänderungen auf das menschliche Wohlbefinden zu bewerten. Da standardisierte methodische Herangehensweisen für die Erfassung von ÖSDL auf Landschaftsebene fehlen, wurde besonderes Augenmerk darauf gelegt, eine Methode zu entwickeln, die leicht auf unterschiedliche Untersuchungsgebiete übertragbar ist. Weiterhin sollte die Methode die Verwendung von schon vorhandenen, leicht zugänglichen Umweltdaten ermöglichen und transparent für beteiligte Akteure und Entscheidungsträger sein.

Die vorliegende Doktorarbeit wurde in kumulativer Form angefertigt und basiert auf vier Publikationen in ausgewiesenen internationalen Journalen mit Gutachtersystem.

Kapitel 1 "Introduction" beinhaltet eine Übersicht über die Motivation und den Hintergrund der Arbeit. **Kapitel 2 „Methods"** enthält Ausführungen über die methodischen Entwicklungsschritte (hauptsächlich basierend auf Koschke et al. 2012) und die Werkzeuge die im Rahmen der zwei Fallstudien verwendet wurden. Auch die zwei Fallstudiengebiete sind hier beschrieben. In **Kapitel 3 „Results"** werden Ergebnisse des „Impact Assessments" der simulierten Landnutzungs- und Landbedeckungsänderungen in den Fallstudiengebieten präsentiert die sich auf Koschke et al. (2012, 2013, 2014a) beziehen. Darüber hinaus werden Ergebnisse der Analyse von Stakeholderprozessen in ÖSDL Studien illustriert (Koschke et al. 2014b). **Kapitel 4 „Discussion"** widmet sich der Frage der Übertragbarkeit und Anwendbarkeit des Bewertungsansatzes. Außerdem enthält es eine umfassende Bewertung der Ergebnisse, eine kritische Analyse des methodischen Ansatzes und der bestehenden methodischen Herausforderungen, der Modellunsicherheit und der Anwendbarkeit des ÖSDL Konzeptes in der partizipativen Planung. In **Kapitel 5 „Conclusions"** werden die Ergebnisse zusammengefasst, bestehende Herausforderungen in Bezug auf die Erfassung von ÖSDL auf Landschaftsebene und die Einbeziehung von Stakeholdern in partizipativen Entscheidungsprozessen thematisiert. Ein Ausblick auf weiteren Anwendungs- und Weiterentwicklungsbedarf rundet das Kapitel ab.

Ein wichtiges Ergebnis der Arbeit ist eine Routine zur (räumlich expliziten) Erfassung und Bewertung von ÖSDL die in das räumliche Entscheidungsunterstützungssystem GISCAME implementiert wurde. Die Routine dient hier der Folgenabschätzung von simulierten Landnutzungs- und Landbedeckungsänderungen für gegenwärtig drei Landnutzungsdatensätze. Die Bewertungsroutine erlaubt einen Vergleich der Auswirkungen von Landnutzungs- und Landbedeckungsänderungen (und Änderungen der Bewirtschaftung) auf mehrere ÖSDL auf einer qualitativen, relativen, ordinalen Skala. Die Methodik ist die Voraussetzung für erweiterte Bewertungsansätze die auch die Anordnung und Zusammensetzung von Landnutzungsklassen mittels Landschaftsstrukturmaßen berücksichtigen (vgl. Frank et al. 2012, 2013, 2014a).

In **Koschke et al. (2012)** wurde der Indikator basierte Bewertungsansatz entwickelt. Unter Verwendung des CORINE Land Cover (CLC) Datensatzes konnte ich die Brauchbarkeit des in GISCAME integrierten Ansatzes demonstrieren, um Auswirkungen von alternativen Landnutzungs-/ Landbedeckungsszenarien auf ÖSDL abzuschätzen. Die Ergebnisse wurden auf Plausibilität geprüft, woraufhin sich Fragen zur Unsicherheit und der Eignung des CLC Datensatzes für regionalplanerische Themen ergaben.

Im zweiten Anwendungsfall (**Koschke et al. 2013**) wurde der EuroMap Land Cover (EMLC) Datensatz verwendet. Dadurch wurde es nötig die Methodik insofern zu erweitern, dass unterschiedliche Bodenbearbeitungsverfahren und Fruchtfolgeoptionen in der Landwirtschaft berücksichtigt werden konnten. Ich konnte zeigen, dass ein Landnutzungsdatensatz mit einer hohen räumlichen und thematischen Auflösung die Einbeziehung von Managementoptionen ermöglicht. In Bezug auf lokale Stakeholder und Landbewirtschafter kann dies als maßgeblicher Vorteil im Vergleich zu gröberen Datensätzen angesehen werden. Auf der lokalen bis zur Landschaftsebene sind Bewirtschaftungsoptionen bedeutsamer für die Bereitstellung von ÖSDL als Änderungen der Landnutzung bzw. Landbedeckung. Diese finden in Deutschland nur selten in größerem Umfang statt und können kaum von einzelnen Entscheidern beeinflusst werden. Die Ergebnisse der Unsicherheitsanalyse zeigten auch die große Unsicherheit die mit dem statischen, Indikator basierten

Ansatz verbunden ist. Demzufolge können die Ergebnisse in Abhängigkeit unterschiedlicher, einzelner Indikatorwerte stark voneinander abweichen.

Im Fokus der dritten Fallstudie (**Koschke et al. 2014a**) stand die Frage, wie bedrohte Wasserressourcen im Eizugsgebiet des Pipiripau in Zentralbrasilien vor weiterer Degradierung geschützt werden können und wie die Bereitstellung von hydrologischen ÖSDL durch Landnutzungs-/ Landbedeckungsänderungen im Rahmen eines integrierten Wasserressourcenmanagement (IWRM) gesteigert werden kann. Unter Verwendung verschiedener Umweltparameter wurde eine räumlich explizite Methode eingeführt um Bereitstellung von Nahrungsmitteln und Futter und die hydrologischen ÖSDL Wasserreinigung, Sedimentrückhalt und Wasserrückhalt zu erfassen.

Mit dem vorgestellten Ansatz zur Erfassung von ÖSDL können Vorranggebiete für Landnutzungs-/ Landbedeckungswandel besser identifiziert werden. Weiterhin können Argumente für den Schutz von besonders schützenswerten Gebieten hoher Leistungsfähigkeit in Bezug auf regulierende ÖSDL überzeugender formuliert werden. Die Ergebnisse deuten darauf hin, dass weniger intensiv bewirtschaftete Landnutzungen-/ Landbedeckungen zu Synergien unter regulierenden ÖSDL und ökologischer Integrität führen. Demgegenüber tendieren bereitstellende ÖSDL mit zunehmendem Flächenanteil von z.B. weniger intensiv bewirtschafteten Agrarland, Grasland und Wald in geringerem Umfang erzeugt zu werden.

Die vierte Publikation (**Koschke et al. 2014b**) befasst sich mit der Verwendung des ÖSDL Konzeptes in der Praxis, das heißt im Kontext der Bewirtschaftung von Ökosystemen und in der räumlichen Planung mit Stakeholderbeteiligung. Herausforderungen und potentielle Nachteile die aus der Anwendung von ÖSDL in partizipativen Prozessen resultieren können wurden identifiziert und bewertet. Mögliche Vereinfachungen von Stakeholderprozessen wurden vorgeschlagen. Um einen positiven Einfluss sicherzustellen, wird auf Grundlage der Ergebnisse empfohlen, die Kommunikation zur Komplexität des ÖSDL Konzeptes mit den beteiligten Akteuren in Bezug auf die konkrete Fragestellung, die Entscheidungsebene und die involvierten Stakeholdergruppen anzupassen.

Insgesamt zeigen die Ergebnisse, dass der vorgestellte Ansatz zur schnellen Erfassung und Kartierung von ÖSDL einen Mehrwert im Rahmen der Diskussion (und Visualisierung) der Auswirkungen von Landnutzungs- und Landbedeckungsänderungen auf Landschaftsebene haben kann. Durch die Integration von unterschiedlichen und fragmentierten Datenquellen hat der Ansatz das Potential relevante Informationen in Planungs- und Entscheidungsfindungsprozesse einzubringen. Beispielsweise in Bezug auf Synergien und Konflikte zwischen ÖSDL und Prioritäten von beteiligten Akteuren. Ähnliche Ansätze zur Kartierung von ÖSDL können auch für die Erfassung von ÖSDL auf größeren Skalenebenen (regional, national, global) genutzt werden. Bedenken bestehen im Hinblick auf die Variabilität der verwendeten Indikatorwerte, dem möglichen Problem der doppelten Bewertung, der Genauigkeit der benutzten Landnutzungsdaten und der gegenwärtig fehlenden Implementierung des ÖSDL Konzeptes in partizipativen Planungsprozessen. Die Unsicherheit der Ergebnisse sollte stets thematisiert und angemessen kommuniziert werden.

1. Introduction

1.1 Motivation

The pressure on natural resources still increases in many areas of the world mainly as a consequence of climate change and population growth (MA 2005). The continued depletion of natural resources led to an increased recognition of the value of ES and their contribution to human well-being. ES are considered the benefits humans derive from ecosystems. They are the ultimate purpose of natural resources management (MA 2005; de Groot et al. 2010). New policy approaches are in development to better govern ES and the assessment and mapping of ES are therefore the basis for a sustainable land use and sustained provision of ES.

The main work for this thesis was carried out within the joint research projects REGKLAM (www.regklam.de) and IWAS Água DF (http://www.ufz.de/index.php?de=18253). The integrated and sustainable management of land use was a central topic in both projects. In the REGKLAM model region of Dresden, the mitigation of and adaptation to climate change related impacts by LULCC/LMC was put into focus within the work package „Integrated Land Use Assessment“. The goal of the research carried out in the Distrito Federal do Brasil (the Federal District) was the protection of water supply through IWRM in the working group „Land Consumption and Land Use”. Both projects were supported by the Federal Ministry of Education and Research (BMBF, FKZ 01LR0802B and 02WM1166/02WM1070).

In both projects, the ES concept was used as a framework to assess the impact of LULCC in the context of the respective project goals. Subsequent to an increased acceptance and implementation of the ES concept in policy making (Maes et al. 2012), the operationalization of the concept for decision-making practice has been identified as a major challenge (van der Meulen et al. 2012). Lacking standardized assessment approaches, a missing commonly accepted definition of ES, difficulties of using various, not harmonized data sources and problems related to the integration of stakeholders have been identified as main obstacles to successfully integrate ES for example into regional and landscape planning processes (Albert et al. 2014; de Groot et al. 2010; Menzel and Teng 2010). The presented thesis investigates key aspects of the mentioned challenges.

1.2 Background and context of the thesis

1.2.1 Assessing ES at meso-scale or landscape level

For a sustainable use of land and its resources, an integrated land use planning is one of the key requirements. The ES concept has become widely recognized and accepted in recent years as a tool that supports integrated decision-making in natural resource management, land use policy design, biodiversity conservation and land use planning (e.g. Grêt-Regamey et al. 2008).

The cascade model of Haines-Young and Potschin (2010a) illustrates that biophysical structures and processes are the basis for ecosystem functions, ES and finally the benefits or values humans derive from ecosystems (see Figure 1). Figure 1 shows further how the DPSIR (Driving forces, Pressures, States, Impacts and Responses) indicator framework (see Borja et al. 2006; Burkhard and Müller 2008b) can be linked to the cascade and how decision-making and planning processes come into play in an adaptive management cycle.

For decisions related to the allocation of land uses, the spatial distribution of ES needs to be known. Assessing and mapping ES is therefore a crucial factor for enhancing the recognition and implementation of ES into decision-making (Daily and Matson 2008; Burkhard et al. 2012a; Brouwer et al. 2013). The assessment, monitoring and mapping of ES often results in maps that visualize patterns of ES provision and ES demand. Methodological approaches differ widely as a function of e.g. study goals, data availability, spatial scale and scope (e.g. Kienast et al. 2009; Brenner et al. 2010; Haines-Young et al. 2006; Willemen et al. 2008). Also, the complexity of methods ranges from rapid, simplified assessment methods (Burkhard et al. 2009; Kienast et al. 2009; Willemen et al. 2008) to sophisticated, complex (process) models (e.g. Smith et al. 2002; Naidoo and Ricketts 2006; Troy and Wilson,2006). Consequently, outputs of ES assessments and their values are given in varying units ranging from qualitative dimensionless scales (e.g. 0 to 5; Burkhard et al. 2009), to biophysical units (e.g. t C ha^{-1} a^{-1}; Nelson et al. 2009) and monetary values (e.g. € ha^{-1} a-^{1}, € t^{-1} a^{-1}; Costanza et al., 1997). Simplified approaches use land cover or ecosystem data as proxy to directly estimate provision of ES by means of general assumptions or single indicators. Simplified models have been broadly applied in recent years at local to global scales (e.g. Naidoo and Ricketts 2006; Burkhard et al. 2009; Helfenstein and Kienast 2014; Kandziora et al. 2013b; Kienast et al. 2009; Willemen et al. 2008).

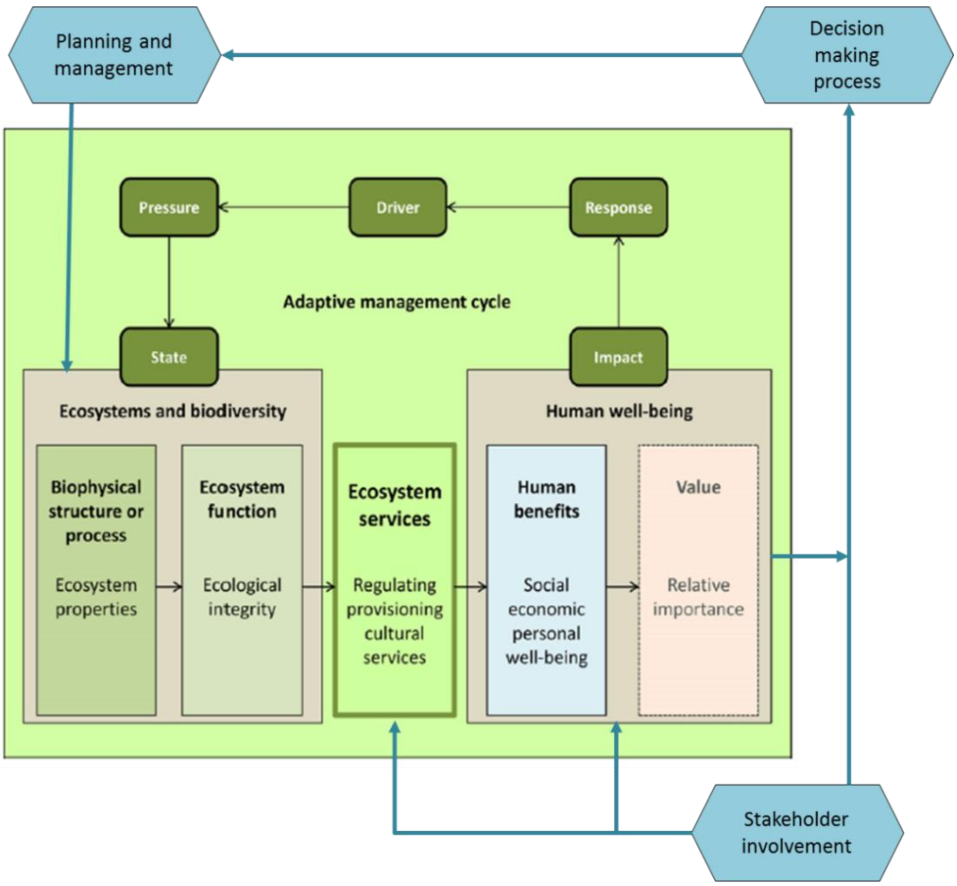


Figure 1 Link of the ‘ecosystem services cascade’ with the adaptive DPSIR indicator framework and their interaction with decision-making processes and the adaptive management cycle (cited from De Groot (2006) and Kandziora et al. (2013a) who modified after Haines-Young and Potschin (2010a,b), De Groot et al. (2010) and Müller and Burkhard (2010)).

A single ecosystem function might support various ES (Granek et al. 2010) leading to problems such as double counting and selection of indicators, which is a major issue in ES assessments. This relates to issues connected to the spatial scale for instance: how does the spatial scale and the resolution of land use data sets and land use classifications impact indicated supply of ES. Further, the temporal reference is crucial: how do ES (indicators) change over time and can the variability be captured with existing indicators and monitoring systems? Indicator selection is challenging, as they should be: a) applicable in different contexts and landscapes and for different LULC classes, b) specific and sensitive enough to reflect actual impacts on ES through management and/or LULCC, c) sensitive for temporal dynamics, d) transparent, e) supportive for decision-making, and f) easily measurable or otherwise available (compiled after e.g. Helfenstein and Kienast 2014; Wiggering and Müller 2004).

The Millennium Ecosystem Assessment (MA 2005) classifies ES into supporting, provisioning, regulation, and cultural services. Subsequently, *ecological integrity* (Müller 2005; Burkhard and Müller 2008a; Kandziora et al. 2013a) emerged as a term used instead of supporting services. It is used to bundle ecosystem functions which result from ecosystem properties, i.e. the biophysical structures and processes. Thus, ecological integrity is a necessary prior condition to provide provisioning, regulating and cultural services (Figure 1). In this thesis I used ecological integrity accordingly.

In the frame of this thesis, *the potential supply* of several ES was assessed. Thereby I mean in line with Burkhard et al. (2012b, 2014) the hypothetical, regional, maximum supply of selected ES (in contrast to the actual flow). It can be further distinguished into the potential of a LULC class and the ecosystem potential if site specific conditions such as soil quality parameters, slope etc. are included (cf. Koschke et al. 2014a). The latter refers to the site specific suitability or capacity of an ecosystem to provide a specific ES (see Bastian et al. 2012).

1.2.2 ES in the context of regional planning and the participation of stakeholders

Land use and management planning at the landscape level can balance the needs of stakeholders between different spatial scales and the amount of ES produced. Since landscape level decision-making operates at the interface between different disciplines (sectors, actors, stakeholder groups), integrated spatial planning acts as instrument for consensus finding. In Germany, regional planning corresponds to the landscape scale planning level and accounts for the need for integration of environmental and socio-economic concepts. Targets of state development plans (Landesentwicklungsplan) are translated into regional development plans (Regionalplan) by regional planning authorities at an intermediate planning level. Using the guideline decisions of the state development plan as a basis, regional planners are responsible for the provision of information on how and where development should (not) take place. The developed plans have a steering function and provide frame conditions and data for more specific development planning of municipalities in a top down manner.

For instance, in Saxony landscape planning is integrated in regional planning (cf. SächsLPlG). Thus the interdisciplinary and comprehensive character would make regional planning a promising recipient for ES-based planning approaches. Integrated planning and management requires the participation of stakeholders, i.e. people that affect or are affected by the planning. In the context of this thesis, *stakeholders* are considered to be not only residents and land mangers (e.g. foresters, farmers) but also decision-makers who impact development at the landscape scale including regional planners. As ES puts into focus the needs of humans and the benefits they obtain from the natural capital, participation is an integral part of ES research (Müller et al. 2011). This highlights the role and the necessity for participation in planning processes as well as in ES assessments.

The implementation of the ES concept into planning practice was supposed to be supportive in terms of finding consensus and integrated solutions (e.g. Brauman et al. 2014). However, actual implementation remains restricted (Plieninger et al. 2010; Primmer and Furman 2012; Albert et al. 2014). Convincing examples for its successful application in practical planning contexts are rare, especially at a landscape scale which has been recognized as most important for sustainable development (Kates and Parris 2003; Wiek et al. 2006; Selman 2012). Better linking science and practice will be necessary to improve the application of ES in planning and management (Albert et al. 2014).

1.3 Research objectives and scope

The general objective of the conducted research activities was to provide regional (and landscape) planners with a methodical approach for impact assessments at spatial scales ranging from around 1:10,000 to 1:100,000, i.e. from sectoral (management) to landscape and regional planning. Further, the consideration of ES in land management and in regional and participatory planning should be increased by providing a suitable set of methods and data. An integrated approach was to be adopted focusing on the land use sectors agriculture and forestry with the ultimate purpose to develop strategies to mitigate and adapt to environmental risks (e.g. soil erosion, floods, water shortages) triggered by climate change (REGKLAM project) and adverse LULCC (IWAS project).

Further, this thesis is a contribution to the set-up of the spatial decision support system GISCAME which has been developed for landscape level assessments in various research projects (e.g. Fürst et al. 2010). GISCAME aims at supporting decision-making of stakeholders such as regional planners and decision-makers in the land use sector by assessing impacts of LULC patterns and land management strategies on ES.

Prior to the application of GISCAME, an assessment approach had to be developed that is suitable to be implemented in the system. The approach had to be conceived in a way that makes it usable for different data sources and transferable to different case study areas. The project areas of REGKLAM and IWAS Água DF were used as case study areas to apply the assessment approach with GISCAME.

The main objectives and associated research questions of this thesis were:

(i) To develop a transferable methodical approach to assess and evaluate the impact of LULCC on ES.

- Are available LULC and indicator data an appropriate basis for a rapid, comparative assessment of ES at a landscape level?
- How can the applicability and transferability of such an assessment approach be evaluated?

(ii) To identify alternative land use options to better support planning of sustainable land use including synergies and trade-off analyses.

- Which role plays uncertainty of results and error propagation?

(iii) To identify alternative land use options in the context of IWRM.

- Does the inclusion of spatially explicit environmental parameters (e.g. slope, soil) significantly enhance the basic, spatially inexplicit assessment of ES?

(iv) To evaluate the potential of the ES concept in participatory processes to support land use planning and land management.

- How can the impact of the ES concept on stakeholder processes be evaluated?
- Is the ES concept a suitable framework for regional planning?

1.4 List of original articles and structure of the thesis

This thesis consists of the following four peer-reviewed articles which can be found in the Appendix:

Koschke, L., Fürst, C., Frank, S., Makeschin, F. 2012. A multi-criteria approach for an integrated land-cover-based assessment of ecosystem services provision to support landscape planning. Ecological Indicators. 21, 54-66. doi.org/10.1016/j.ecolind.2011.12.010.

Koschke, L., Fürst, C., Lorenz, M., Witt, A., Frank, S., Makeschin, F. 2013. The integration of crop rotation and tillage practices in the assessment of ecosystem services provision at the regional scale. Ecological Indicators. 32, 157-171. dx.doi.org/10.1016/j.ecolind.2013.03.008.

Koschke, L., Lorz, C., Fürst, C., Lehmann, T., Makeschin, F. 2014. Assessing hydrological and provisioning ecosystem services in a case study in Western Central Brazil. Ecological Processes 3: 2. doi:10.1186/2192-1709-3-2.

Koschke, L., Van der Meulen, S., Frank, S., Schneidergruber, A., Kruse, M., Fürst, C., Neubert, E., Ohnesorge, B., Schröder, C., Müller, F., Bastian, O. 2014. Do you have 5 Minutes to spare? The challenges of stakeholder processes in ecosystem services studies. Landscape Online. 37, 1-25. http://dx.doi.org/10.3097/LO.201437.

The articles can be arranged around the four basic topics most relevant for this PhD study (Figure 2). Koschke et al. (2012) provides above all information on the methodical basis and stakeholder participation. Different methods for weighting ES are examined and it also contains the first application example in the REGKLAM area using CLC data. Koschke et al. (2013) deals with crop rotation classes and how they can be integrated into the assessment approach using the EMLC data set which provides a better thematic and spatial resolution than CLC. Here, also an uncertainty analysis of assessment results is provided. A smaller study area within the REGKLAM area is used as demonstration example. The land cover based assessment approach was extended by a spatially explicit component using further environmental data in Koschke et al. (2014a) for hydrological ES in Central Western Brazil. Finally, Koschke et al. (2014b) examined the challenges of applying the ES concept in stakeholder participation processes based on an online questionnaire and a literature review.

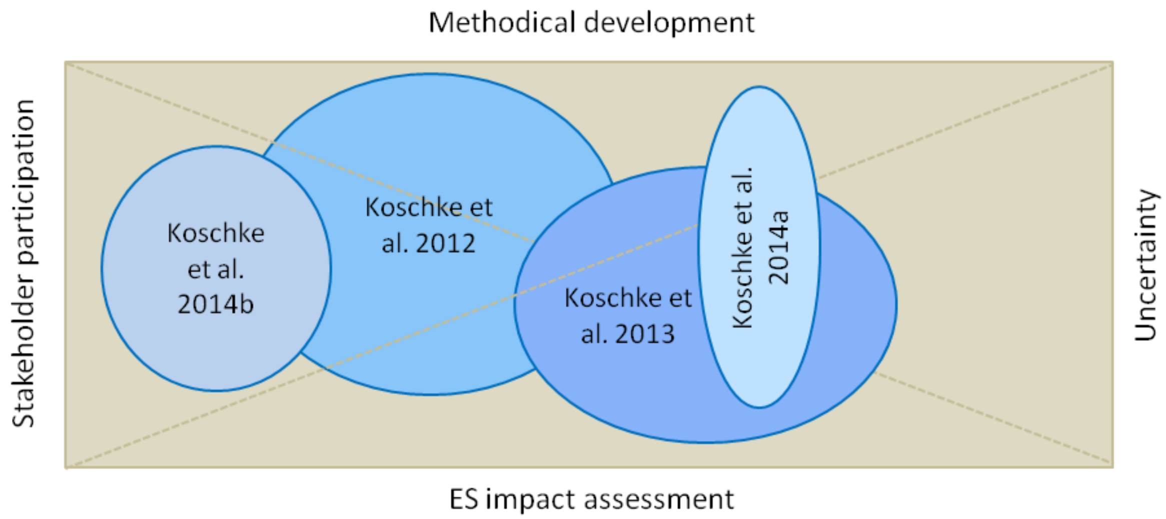


Figure 2 Overview of the publications and to which degree they address the four main topics of the presented PhD study.

2. Methods

2.1 Technological and Scientific Platform – GISCAME application

The technological and scientific platform GISCAME (formerly called "Pimp Your Landscape") was developed in the past years at the Chair of Soil Science and Soil Protection at the Institute of Soil Science and Site Ecology of the TU Dresden and at the Center for Development Research (ZEF) of the University of Bonn. GISCAME aims at supporting land use and landscape planning and management. GISCAME is a raster based 2-D cellular automaton platform which allows testing LULCC alternatives and the impact assessment of these on land use planning targets, which can be expressed as ES (Fürst et al. 2010; Fürst et al. 2012; Koschke et al. 2012; Lorz et al. 2012a). The system is characterized by three main components: it offers functionalities that support spatial analyses similar to those known from common Geographical Information Systems (GIS), it has elements of a cellular automaton (CA), and it uses a qualitative multi-criteria evaluation (ME) for the assessment (Figure 3).

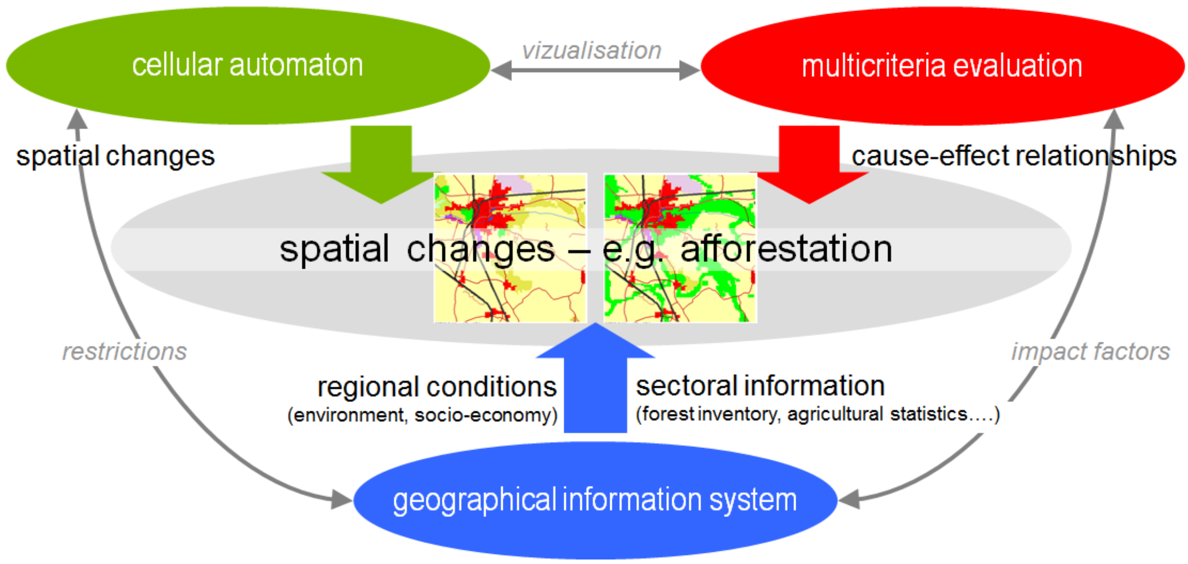


Figure 3 Main components of GISCAME (Fürst et al. 2013)

In GISCAME each cell carries as the main attribute the LULC class taken from the LULC map. The resolution of these maps is case study dependent. Environmental attributes such as slope, soil, distance to a river, climate data etc. can be added as supplementary attribute layers (Fürst et al. 2010). The core of GISCAME is to enable the user to change directly the LULC of single cells or patches of cells and to derive immediate feedback of the impact on ES. GICAME was used to test different LULCC and LMC alternatives, henceforth also referred to as scenarios, to identify more sustainable land use options. Within the time frame this thesis was carried out, the assessment results of simulated LULCC scenarios could be visualized to the user as star diagram, point tables or as ES distribution maps.

2.2 Multi-criteria assessment (MCA) approach

Developing an integrated assessment approach

The LULC based ES assessment approach was developed in Koschke et al. (2012) (see chapter 3.1 of the thesis). Given the several, partly competing interests, multiple criteria involved, and needing to take complex frame conditions and quantitative as well as qualitative information on indicators into account, the assessment of ES for land use planning and management face classical multi-criteria decision-making (MCDM) problems (e.g. Mendoza and Martins 2006; Helming 2009; Kangas et al. 2001). The developed compositional MCA approach which was applied for the basic assessment is depicted in Figure 4.

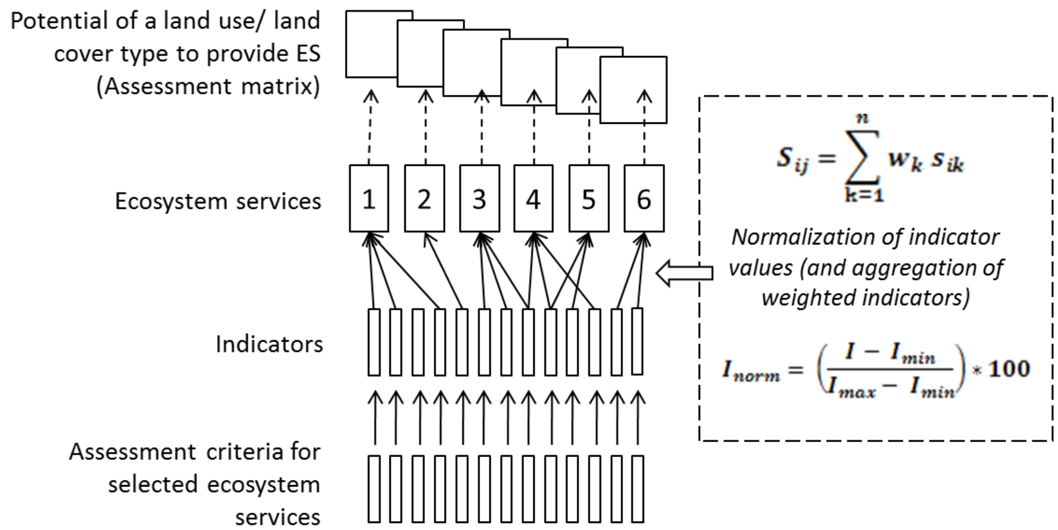


Figure 4 Flowchart of the MCA procedure introduced in Koschke et al. (2012) (figure adapted after Bastian and Schreiber 1999).

The basic assessment starts with defining regionally relevant ES together with stakeholders prior to a weighting and aggregation of criteria to ES. These criteria are assessed through indicators. Because of lacking formalized criteria and indicator sets, relevant criteria had to be identified and an indicator framework had to be developed according to available data and with respect to the chosen ES. The basic assessment approach focuses on the main information layer of GISCAME which is the LULC map. The LULC classes are used as proxies to estimate the provision of ES.

A benefit transfer approach (Plummer et al. 2009; Troy and Wilson 2006), i.e. the mapping of values to land use classes, was applied making necessary the collection of indicator values found in preferably regional databases or otherwise suitable lookup tables or expert estimations (e.g. for cultural services). Within the GISCAME working group, we decided to generate output in the form of a qualitative, relative value point scale in order to be able to compare the performance of different ES based on regional thresholds and to enable trade-off analyses. With thresholds I mean maximum values for ES provision per LULC class that can be found in the respective study region. Following a normalization of initial indicator values and an aggregation of weighted indicators, to each of the LULC classes a relative, qualitative value ranging from 0-100 points is assigned. A value of 100 would mean the maximum regional potential delivery of the ES whereas a value of 0 indicates lacking or no relevant potential supply of an ES (Fürst et al. 2010; Koschke et al. 2012). Subsequent to the transfer of the assessment matrix' values into GISCAME, the software calculates the area weighted mean according to the share of all LULC classes that can be found in the studied area.

The basic assessment (benefit transfer) approach was applied in Koschke et al. (2012; 2013). Since also the spatial pattern, i.e. the configuration and composition of LULC classes impacts the provision of some ES at the landscape level (Syrbe and Walz 2012), an additional assessment step focusing on the landscape composition was developed and implemented into GISCAME in the frame of another doctoral thesis (Frank et al. 2014b).

Using a refined land use data set

The CLC data set was used to assess ES in the whole REGKLAM region (Koschke et al. 2012). The quality of the given land use, ecosystem diversity, habitat properties and forest and agricultural management conditions were not explicitly referred to. To account for the need to include land management information such as tree species composition and tillage practices, and to test and use data with a different spatial and thematic resolution, the more detailed EMLC data set was developed within the REGKLAM project. The supplemented EMLC data set was utilized to discuss (sector specific) land use/management options and for scenario development in a smaller case study area within the REGKLAM region in Koschke et al. (2013) (chapter 3.2). The data set was derived from remote sensing data for the general land use classification of the case study area. Planning information from forestry (forest development types based on forest site mapping) and agriculture (soil map) developed in Witt et al. (2013) and Lorenz et al. (2013) respectively were used to reclassify forest and agricultural land use and land management classes.

Implementing a spatially explicit assessment

In order to include site specific conditions, I used GIS based analyses to identify areas with differing ecosystem potential within Koschke et al. (2014a) (chapter 3.3.) (Figure 5). Prior to the production of maps showing high, medium and low ecosystem potential, the conceptualization of links between ecosystem properties, processes and ES was a major methodical step. For this, I developed and applied rule-sets how to process environmental data (e.g. soil, topography). The ecosystem potential maps are qualitatively linked with the LULC specific ES potential and yields the hypothetical maximum provision of ES (see Burkhard et al. 2012b, 2014; Bastian et al. 2012).

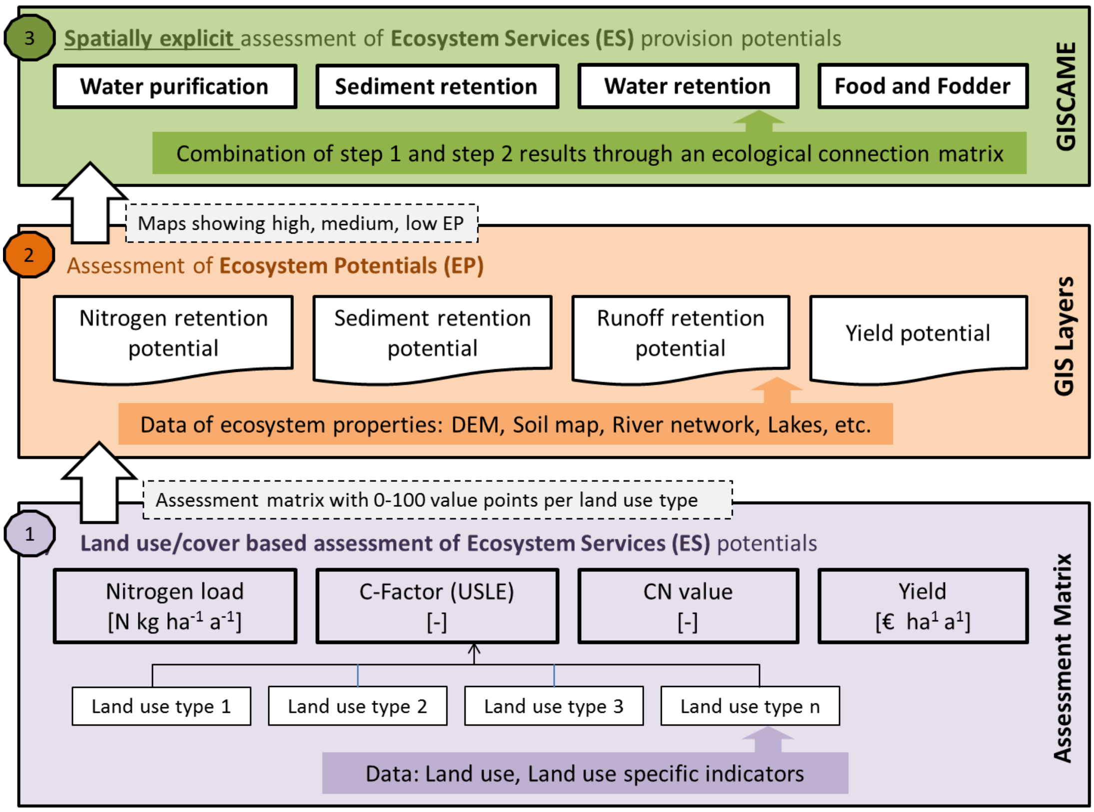


Figure 5 General workflow of the spatially explicit assessment with the ES assessed in Koschke et al. (2013). Trough combination of ecosystem potentials (EP) with LULC based assessment matrix in GISCAME, ecosystem services (ES) can be assessed in a spatially explicit manner.

In Koschke et al. (2014a), besides slope, distance to water bodies and the existence of riparian buffer strips, the root zone available water capacity (RZAWZ) was taken as an indicator to estimate the nitrogen retention potential (Figure 5, step 2). Table 1 shows exemplarily, how classification of RZAWC values was conducted according to regional minima and maxima.

Table 1 Overview of soil types of the Pipiripau river basin, RZAWC values and thresholds used for the classification of the nitrogen retention potential in the right column.

Soil Type	RZAWC total [mm H2O]*	Nitrogen retention potential [class, mm H2O]
Cambissolo (CXd)	62.6	
Solos Hidromórficos (Hi)	110.5	Low
Neossolo Quartz. (RQd)	136.7	<142 mm
Solos Hidromórficos (Hi)	137.0	
Latossolo V.-Amarelo (LVAd)	144.0	
Cambissolo (CXd)	146.0	
Nitossolo (NVe)	152.7	
Espodosolo (HpD)	163.2	Intermediate
Plintossolo (FX)	165.3	142-244 mm
Latossolo V.-Amarelo (LVAd)	176.8	
Cambissolo (CXd)	197.5	
LatossoloVermelho (LVd)	203.7	
Cambissolo (CXd)	362.2	
LatossoloVermelho (LVd)	389.0	High
Latossolo V.-Amarelo (LVAd)	418.5	>244 mm
LatossoloVermelho (LVd)	440.0	

*Sum of RZAWCHorizon 1 + RZAWCHorizon 2 + ... + RZAWCHorizon n. Valus were taken from Strauch M. (personal comm.)

Further, Table 2 illustrates an example how the different parameters of the ecosystem potential have been processed to classify the case study area into areas with high, intermediate and low nitrogen retention potential and yield potential. The outcome of the assessment is again translated into final values ranging between 0 and 100 value points.

Table 2 Classification of environmental parameters to conduct site specific classification of (a) the nitrogen retention potential and (b) the yield potential.

	High (1)	Intermediate (2)	Low (3)
(a)	Nitrogen retention potential		
RZAWC total [mm H2O]	>244	142-244	<142
Slope [Degree]	0.00 - 4.26	4.27 - 12.99	13.00 - 60.43
Riparian buffer strips*	Cerrado (tree Savanna), Mata (natural forest), Afforestation	Degraded Cerrado, pasture and meadows, and Campo (grass savanna)	Arable land, Irrigated land, Bare soil, Build up areas
Distance to surface waters [m]	>800	200-800	<200
(b)	Yield Potential		
RZAWC total [mm H2O]	>244	142-244	<142
Saturated hydraulic conductivity [mm h-1]**	>42	15-42	<15
Soil depth [mm]	>1500	500-1000	<500
C_{org} topsoil [%]	>2.8	1-2.8	<1
Slope [%]	<8	8-16	>16

*Considers current land use within a distance of 200 m from surface waters ** Mean saturated hydrological conductivity

2.3 Case study areas

2.3.1 The REGKLAM model region in Saxony

In the context of the case study REGKLAM in Saxony, Germany (Figure 6), the multi-criteria assessment approach was developed and applied in order to support regional planning in developing land use strategies for a better adaptation to climate change related threats (soil erosion, drought) which integrates targets and data of agriculture and forestry (Fürst et al. 2011). The study region has a total area of 4778 km^2. The lower mountain range in the south is dominated by forests and grassland/pastures. The loess belt and the Lower-Lusatian heathland in the north-western and northern part are characterized by fertile loess and sandy soils leading to widespread intensive agriculture (Hanspach and Porada, 2008; Mannsfeld and Syrbe 2008). The impact of alternative LULC options such as afforestation, change of land use from agriculture to grassland, forest conversion, and crop rotation change were simulated and assessed.

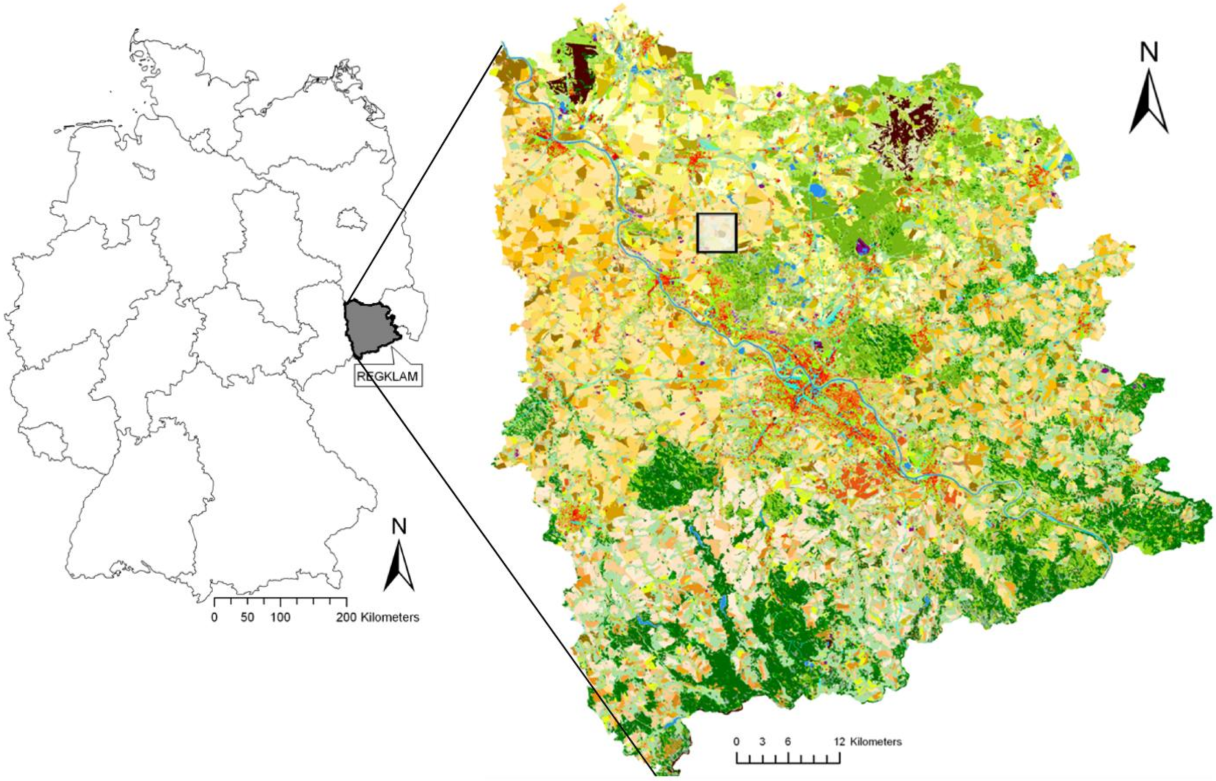


Figure 6 Location of the REGKLAM case study area in Saxony, Germany (left). In Koschke et al. (2012) the whole REGKLAM area (right) was investigated using CLC data, while in Koschke et al. (2013) only a smaller case study area (right, black square) was analyzed using EMLC data.

2.3.2 The Pipiripau river basin in Central Brazil

The second case study was conducted in the frame of the IWAS-ÁGUA DF project in the Pipiripau river basin which is situated in the north-eastern Distrito Federal (DF) in Brazil (Figure 7). The Pipiripau River basin is situated within the Brazilian Central Plateau and characterized by a semi-humid tropical climate. The river basin covers an area of about 215 km² where the predominant land uses are arable land (47% share of the surface area) and Brachiaria pasture (23%) and smaller areas of irrigated horticulture. Leftovers of natural gallery forests (Mata) and natural Savanna vegetation (Cerrado, Campo) can be found mainly along water courses (Strauch et al. 2013). Due to urban sprawl and expanding intensive agriculture, natural vegetation areas have been reduced during the last 50 years from nearly 100% to 20% in the DF. This led to degradation of water resources including reduced (raw) water quality and water quantity due to silting of reservoirs (Lorz et al. 2012b). IWAS aimed at mitigating the pressure on water resources by means of an integrated water resources management (IWRM). The Pipiripau river basin was a focus area to study changes in terms of soil erosion and nutrient runoff following land use/management changes.

In the Pipiripau case study, an individual land use map provided by project partners was applied.

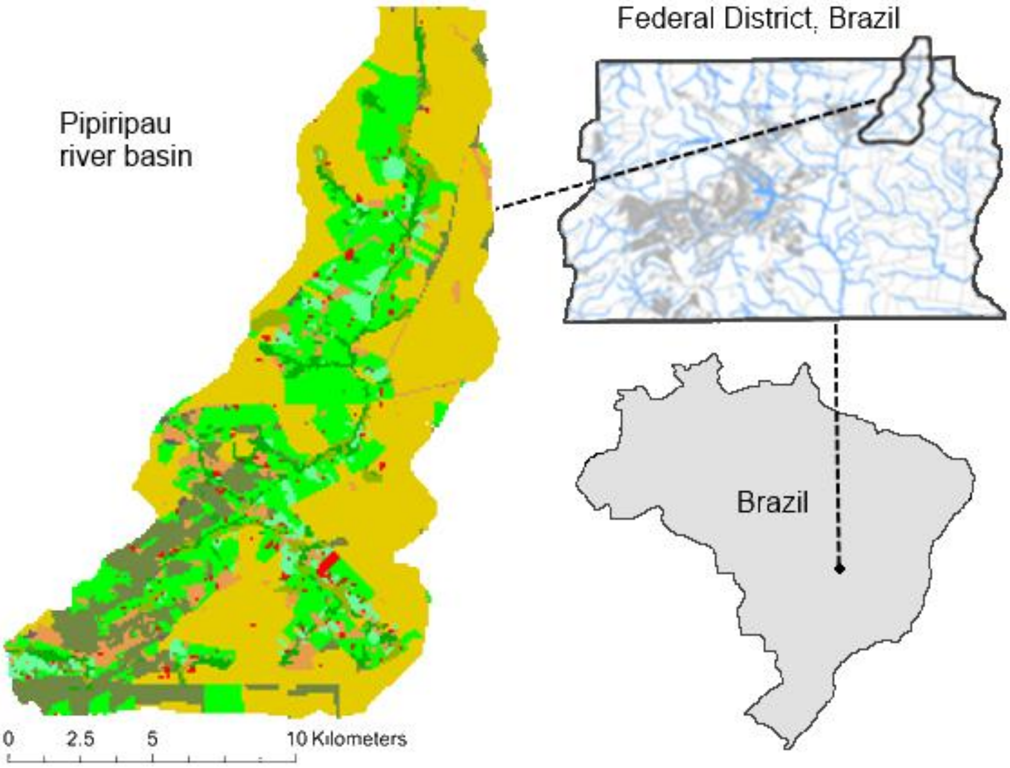


Figure 7 The Pipiripau river basin in the northeastern part of the Federal District in Central Brazil was analyzed in Koschke et al. (2014a).

2.4 Assessment and evaluation of applying the ES concept in stakeholder processes – a survey and literature analysis

During meetings and workshops with stakeholders involved in the REGKLAM project, I observed several issues related to the application of the ES concept in stakeholder processes. For instance the identification, definition and weighting of regionally important ES have been subject of discussions (see Koschke et al. 2012). In order to gain more insights in terms of the general applicability of the ES concept in stakeholder processes and as a basis for decision-making in land use planning and management, an online survey addressing ES researchers was performed. To discuss findings in comparison with information provided in publications, a literature analysis was conducted. Findings are presented in Koschke et al. (2014b) (chapter 3.4).

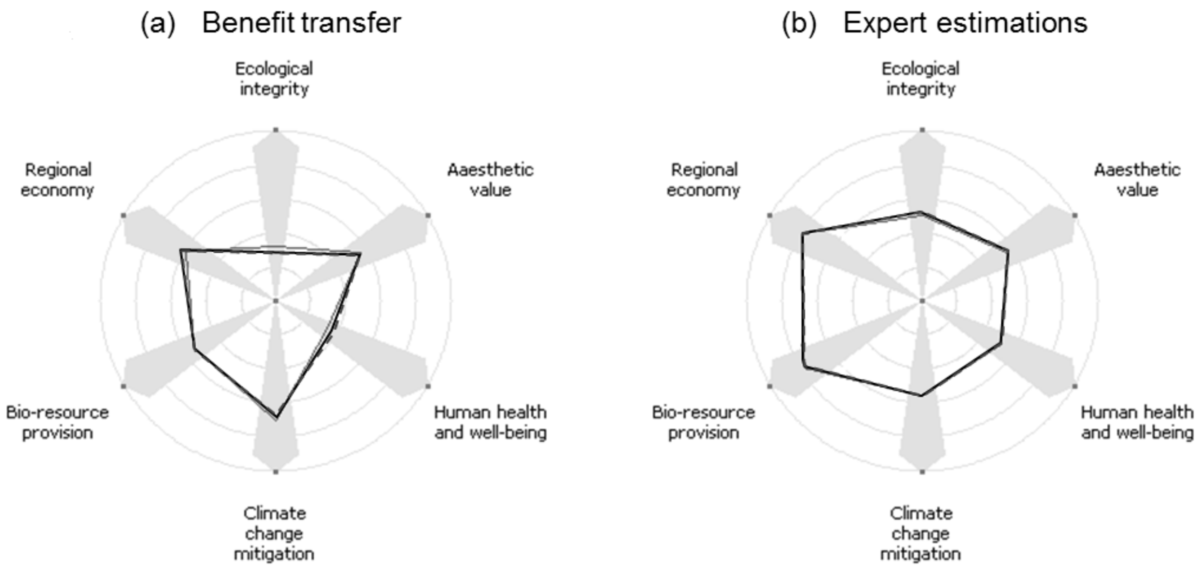
3. Results

The articles can be found in their published form in the Appendix (1-4). A summary of the contribution of each article to the main research objectives is provided in the following paragraphs.

3.1 The result of developing an assessment approach

Koschke, L., Fürst, C., Frank, S., Makeschin, F. 2012. A multi-criteria approach for an integrated land-cover-based assessment of ecosystem services provision to support landscape planning. Ecological Indicators. 21, 54-66. doi.org/10.1016/j.ecolind.2011.12.010.

In this article a generic methodical approach to assess LULCC impacts on ES was developed. I introduced an approach to use CLC data for a comparative landscape level assessment of selected ES. It was demonstrated how different information sources and quantitative and qualitative indicator values and expert knowledge can be integrated. I found that existing knowledge on functional relations between land use and ES provision is limited for some ES (cf. Kienast et al. 2009) making a consistent assessment and comparison difficult. Comparing results of the benefit transfer and the expert estimations, I assessed ES in the whole REGKLAM area using the CLC data set (Figure 8).



Ecological integrity	Aesthetic value	Human health and well-being	Climate change mitigation	Bioresource provision	Regional Economy		Ecological integrity	Aesthetic value	Human health and well-being	Climate change mitigation	Bioresource provision	Regional Economy
28	48	30	67	56	63	AHP-weights	46	48	47	53	81	79
26	48	31	63	56	65	Likert-weights	47	48	47	54	81	80
26	48	32	62	56	66	Balanced weights	47	48	47	53	81	81

Figure 8 Assessment results of the potential of the REGKLAM region to provide ES groups based on (a) benefit transfer and (b) expert estimations. Radar charts display results for six ecosystem services groups. Lines indicate applied weighting method (grey=AHP, black=Likert scale, dashe line=balanced weights). Standardized mean values are displayed in the table below, again referring to the individual weighting method (taken from Koschke et al. 2012).

Using the resulting values, maps of ES distribution (Figure 9) can be produced easily either with a common GIS or with GISCAME. Figures 8 and 9 show the partly big differences of the benefit transfer compared to the expert based assessment results. In the course of this study, I could identify strengths and weaknesses of the assessment approach and possible chances and drawbacks related to identifying land use alternatives for supporting regional planning processes with GISCAME.

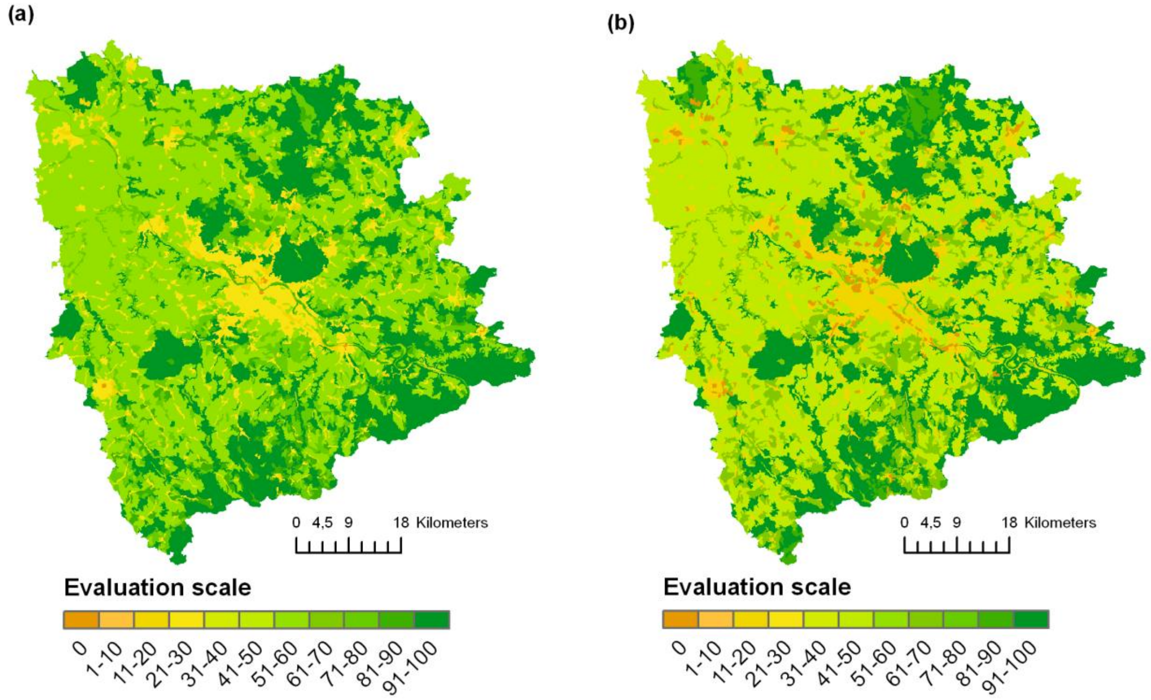


Figure 9 Mapping of the climate change mitigation potential in the REGKLAM region as a result of aggregation of equally weighted ES local climate regulation, global climate regulation, water balance regulation, and soil erosion protection for (a) benefit transfer data and (b) the expert based assessment (Koschke et al. 2012)

3.2 Application of the assessment approach in the REGKLAM case study area

Koschke, L., Fürst, C., Lorenz, M., Witt, A., Frank, S., Makeschin, F. 2013. The integration of crop rotation and tillage practices in the assessment of ecosystem services provision at the regional scale. Ecological Indicators. 32, 157-17. dx.doi.org/10.1016/j.ecolind.2013.03.008.

In this case study, the basic assessment approach was adapted to the EMLC data set which enabled to investigate not only LULCC but also LMC scenarios. Given the detailed EMLC data set, statistical data on regional agricultural land management practices could be included and some differences compared to the application of the CLC data set could be identified. Assessment of provisioning and regulating services and ecological integrity showed that improved management measures such as conservation tillage and crop rotation change in agriculture can enhance the provision of regulating services and ecological integrity at the landscape scale. Iterative combinations of LULCC (e.g. afforestation, greening of discharge paths) and LMC (tillage, crop rotation, tree species composition) scenarios are therefore most suitable to explore in a cross-sectoral way, how regulating services can be increased with acceptable trade-off in terms of regulating services (see for example Figure 10).

Special focus was put on an uncertainty analysis of the assessment results. For this, I varied indicator values (e.g. for yield in t ha^{-1} a^{-1}) in 1000 iterations randomly within ±30% around the initial value. Depending on the individual ES and tested scenarios, resulting possible scenario values ranged for instance between +13% and -6% of the mean value with respect to soil erosion protection and between +53% and -27% for flood regulation (Figure 11). In these cases, standard deviation of value points ranged from 0.4 to 5.8 points and 7.7 to 9.5 points respectively across the tested scenarios. While low standard deviation of final value points and stable ranking of scenarios in terms of soil erosion protection indicate relatively robust results for this ES, results for flood regulation show larger value ranges. Also the ranking was much less stable. Only in 18.1% of iterations the scenario ranking of the initial assessment could be reproduced.

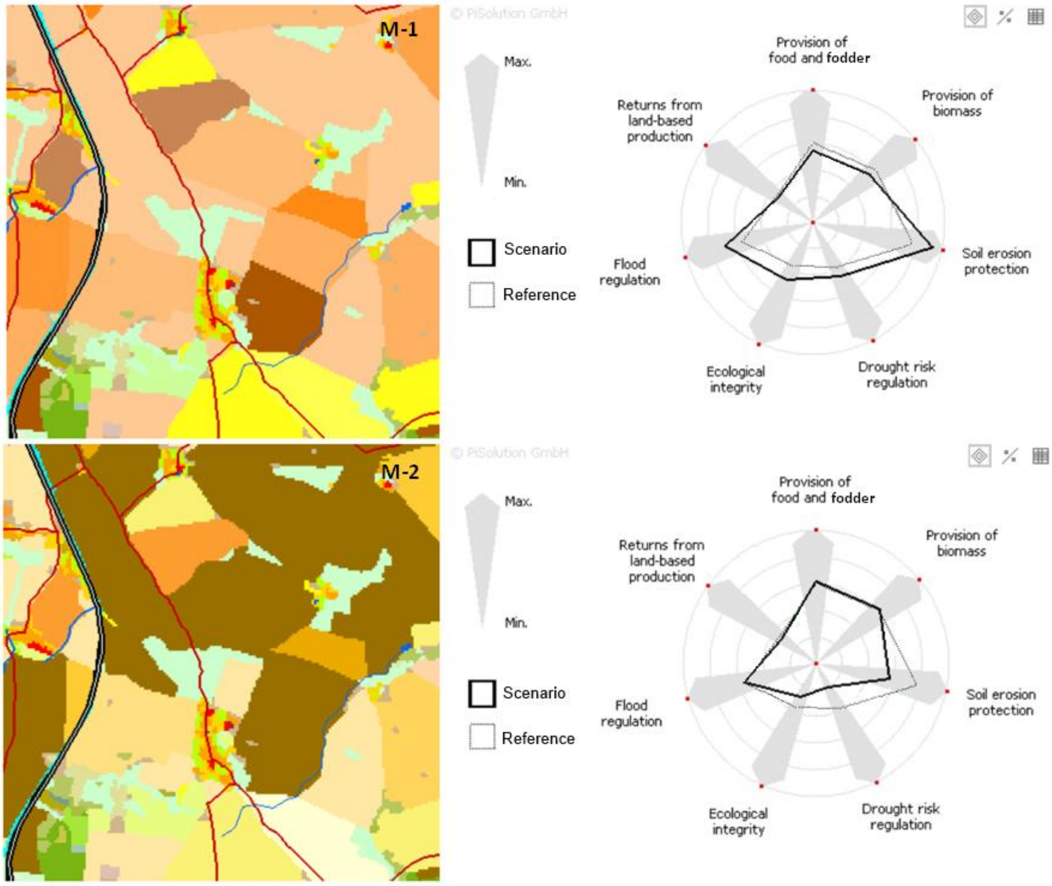


Figure 10 Land use/ land management patterns and assessment results for exemplary scenarios M-1, change of conventional tillage practice ploughing of present crop rotations into conservation tillage; M-2, silage corn on 40% of cultivated area (left). Black lines in the spider chart indicate scenario results in comparison to dotted lines which represent the initial pattern/reference (right). (Screenshot taken from GISCAME)

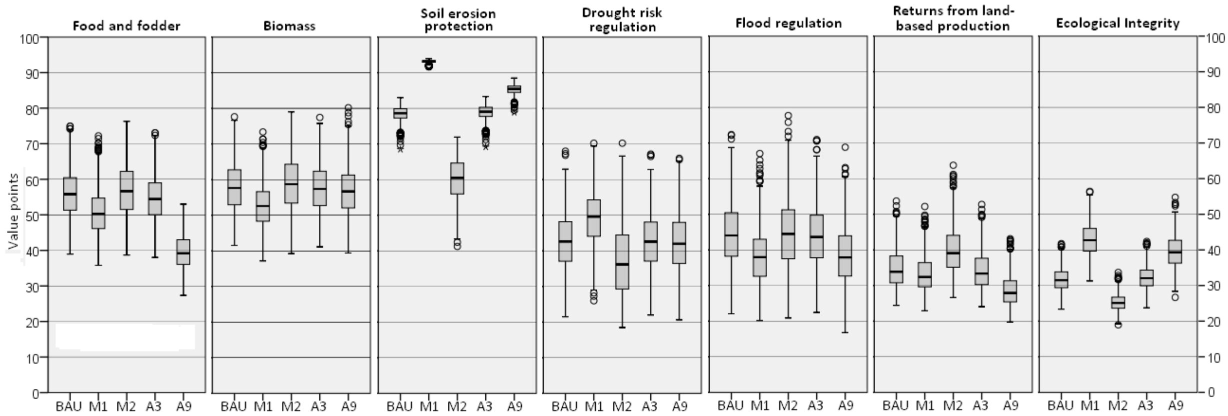


Figure 11 Boxplots of normalized landscape level values of tested scenarios resulting from uncertainty analysis. A general error of indicator values of 30% was assumed. Maximum and minimum values (whiskers), upper and lower quartiles (box), median (horizontal bar) and outliers (circles) are shown.

3.3 Testing the spatially explicit assessment in the Pipiripau case study in Brazil

Koschke, L., Lorz, C., Fürst, C., Lehmann, T., Makeschin, F. 2014. Assessing hydrological and provisioning ecosystem services in a case study in Western Central Brazil. Ecological Processes, *3*:2. *doi:10.1186/2192-1709-3-2.*

In this paper, assumptions to link ecosystem processes to ES provision have been developed for selected hydrological and provisioning ES. The combination of the LULC class specific potential to deliver ES with the site specific or ecosystem potential (Figure 5) led to a spatially explicit assessment of ES. Here, I investigated whether the qualitative evaluation of environmental attributes such as soil and topography parameters could help decision makers optimize land allocation based on ES provision. The refinement of the assessment approach indeed led to a more meaningful LULCC scenario development than based on a LULC map alone. I could show that a further land consumption at the expense of natural savanna vegetation (Cerrado) would lead to further significant potential depletion of soil and water resources in the Pipiripau river basin in the Federal District (Figure 12). Further, priority areas for establishing land use types which might efficiently provide demanded ES could be identified.

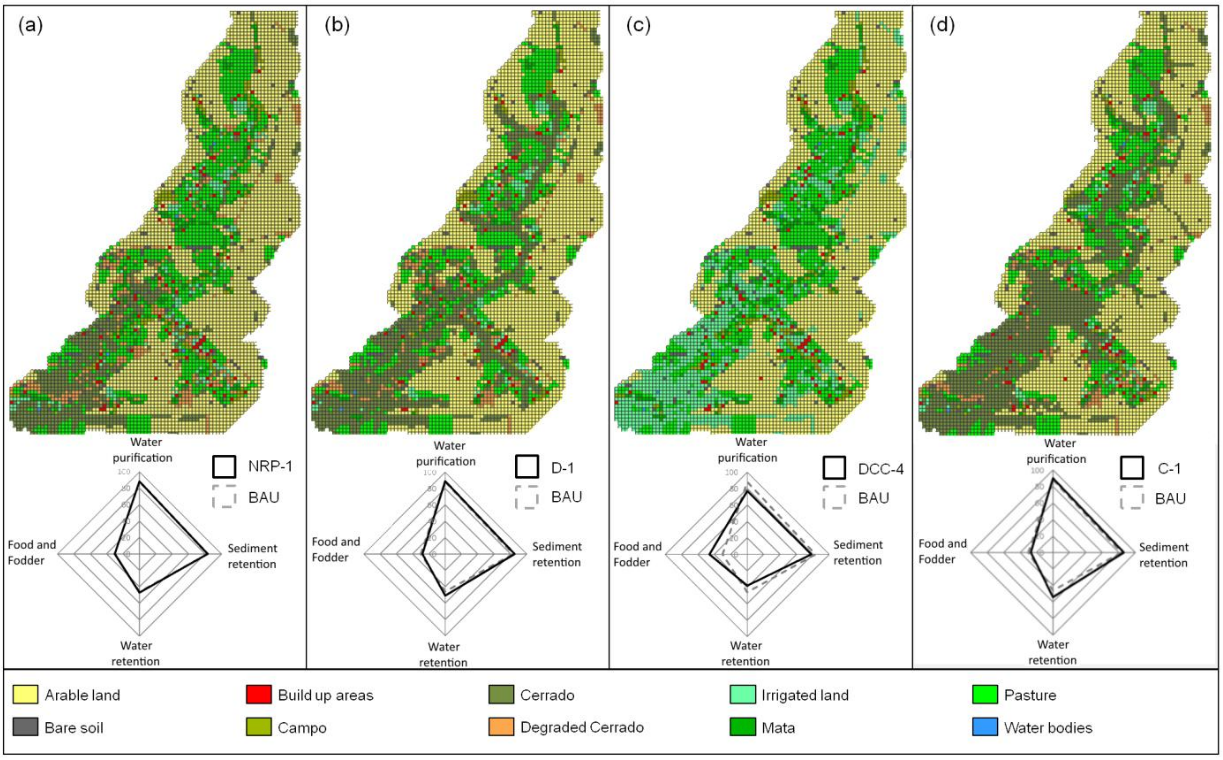


Figure 12 Land use patterns and assessment results for selected LULCC scenarios (Koschke et al. 2014a). Resulting spider charts display scenario results (black line) and results of the initial land use pattern (BAU, dotted line). The different colors in the maps represent the individual land use classes (see legend below). (a) NRP-1, change of areas with low nitrogen retention potential toward Cerrado; (b) D-1, change of areas close to surface waters (irrespective of their current land use) toward Cerrado; (c) DCC-4, change of degraded Cerrado and Cerrado to arable land (general, no-till) toward irrigated land; (d) C-1, change of areas with low potential for water purification, water retention, sediment retention, and production potential.

Within the REGKLAM and IWAS case studies, it could be shown that LULCC that is linked to an intensification of land use - according to indicator data (and expert estimations) - leads to an increased delivery of provisioning services (e.g. food, fodder, biomass) which is often accompanied by decreasing regulating services (e.g. soil erosion regulation, water purification).

3.4 Stakeholder participation

Koschke, L., Van der Meulen, S., Frank, S., Schneidergruber, A., Kruse, M., Fürst, C., Neubert, E., Ohnesorge, B., Schröder, C., Müller, F., Bastian, O. 2014. Do you have 5 Minutes to spare? The challenges of stakeholder processes in ecosystem services studies. Landscape Online. http://dx.doi.org/10.3097/LO.201437.

Outcomes of an online survey and a literature analysis were used to assess how other scientists evaluate the potential of the ES concept in participatory processes related to land use and land management decisions. I found that major issues that should be accounted for in terms of using ES in participatory processes are the complexity, terminology and classification of ES. The impact of ES on stakeholder processes was mostly positive. Yet, depending on the purpose of the individual study and the spatial or institutional level of analysis, the study design, e.g. the communication strategy warrants special attention and should be adapted to the involved stakeholder group(s). Moreover, scale and decision-making level seem to play an important role for the success of applying ES in land use planning and management, i.e. to realize potential benefits of using ES. Whether the concept is a suitable framework to support decision-making in regional planning or other spatial planning contexts appears to depend among others on the actual context, the decision-making level and involved stakeholder groups.

4. Discussion

4.1 Assessment basics: A critical reflection of the transferability and applicability of the assessment approach

In Koschke et al. (2012), the applied land cover data set of CLC provided a very general and therefore more easily transferable approach to assess ES. No additional attributes have been integrated in this first assessment attempt. In Koschke et al. (2013) and in Koschke et al. (2014a) two differing approaches as to the question how more (detailed) environmental planning information can be integrated have been used. In Koschke et al. (2013), detailed information on site conditions (e.g. soil conditions) and regional preferences for crops (e.g. as a consequence of climatic differences) have been integrated in the EMLC data set through the distinction of 85 land use/ land management classes. In contrast, in Koschke et al. (2014a), a LULC data set that contained only 11 LULC classes was utilized, but site conditions have been taken into account more explicitly by means of an additional assessment step. Although the data sets used within the different case studies differed considerably in terms of spatio-temporal resolution and information content, application of the assessment approach could be easily conducted.

Because of the homogenous classification of LULC classes and broad availability, the CLC based assessment allows a comparable analysis of different regions and should be favored for assessments targeting regional to global scale levels. The development of very specific land use data sets such as the EMLC data set is very data intensive and laborious (Lorenz et al. 2012). Although, such information can be very meaningful also at a local level, high initial development effort and lacking possibility to compare results with other regions might restrict broad application of such approaches. A promising concept might be to use readily available data sets and individually evaluated environmental input data such as demonstrated in Koschke et al. (2014a) to assess LULCC in a comparative manner. Thus, regional differences in terms of landscape characteristics and environmental frame conditions could be taken into account while ensuring comparability.

The assessment approach is applicable within the GISCAME platform because it is compatible with the given technological infrastructure and allows fast computation of results of LULCC simulations. Despite high potential errors, for assessing and mapping ES, simple proxy methods such as the presented approach are quite popular and most commonly used at larger scales (Egoh et al. 2012; Larondelle and Haase 2012; Pelzer et al. 2012). Using aggregated values for larger regions, the developed approach has advantages in terms of applicability at the expense of accuracy of results leading to a comparably good input/output ratio (Figure 13). In comparison to other, more complex assessment approaches (e.g. Tallis et al. 2013), the presented method has a relatively low data demand and low demands for model parametrization. It is more easily comprehensible which makes it usable in stakeholder processes. The now existing functionality of GISCAME to produce maps of ES distribution (ES mapping) should be used more intensively in addition to the common radar charts to visualize ES patterns.

There are several issues that should be taken into consideration before the application. Linking ES directly to LULC classes is often difficult due to an inherent fuzziness in the description and definition of LULC classes. Further, the linking and aggregating of values tends to be too simplistic to reflect complex ecosystem processes. The change of ES production from local to landscape scale needs to be extrapolated properly as some ES might otherwise not be adequately assessed or even not recognized which would lead to false recommendations and decision-making (Kienast et al. 2009;

Herrmann et al. 2011). An increased spatial and thematic resolution such as applied in Koschke et al. (2013) allows for a refined, more accurate assessment and mapping of ES, more plausible scenario simulations and better information exchange with stakeholders.

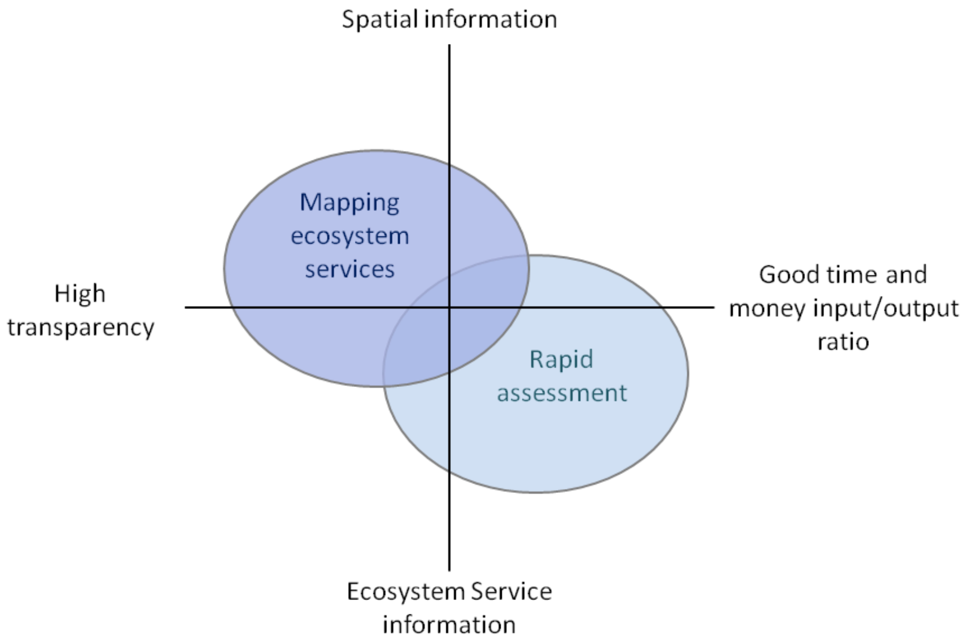


Figure 13 Contrasting approaches in ES assessments (Helfenstein and Kienast 2014). In contrast to (more elaborate) mapping approaches (e.g. with process models), rapid assessment approaches appear to have a good input/output ratio at the expense of spatial information and transparency.

In some cases, selected ES and applied indicators do not precisely match the LULC classes due to the availability of data preferably for arable land, forests, pasture/grassland and the lacking data for less well studied land uses. Lacking applicability of indicators for instance for urban areas were hindrances for an integrated assessment (Koschke et al. 2012). Selection of appropriate indicator (sets) for ES assessment is challenging and an adaptation of the assessment steps is necessary to varying degrees when applied to other case study areas. Given that respective (indicator) data are readily available, the basic assessment can be easily conducted and handled flexibly. Collecting data usually is very time consuming since intensive search in manifold, fragmented data bases is mostly necessary. Further, the available data have to be cross-checked for validity and reliability before use. Conversion of indicators units is often required in order to establish a comparable quantitative or qualitative unit prior to normalization of indicator values. Often a mismatch between available information provided in look-up tables and statistics and the assessment unit (e.g. ha-1 a-1 vs. planning /municipality area) were hindrances for a consistent assessment (see Koschke et al. 2012). Due to the qualitative character of the approach, data gaps can be pragmatically bridged by expert knowledge which can be easily integrated in the analytical framework and processing structure (Koschke et al. 2012; Werneck Lima et al. forthc.).

Although various lists with potential indicators are available (MA 2005; Kandziora et al. 2013a) only a few indicators seem to be commonly applied. Beyond provision (and regulating) services, for which suitable indicators are quite obvious and data often available, applied indicators for cultural and regulating services show a big diversity (Egoh et al. 2012). Common definitions of rule sets for up-scaling of information from local scales to landscape scales could not only help to minimize the problem of indicator selection and comparison between assessment results, but also improve applicability and reduce “unnecessary duplication of effort in the conceptualization and application of ecosystem services” (Burkhard et al. 2012b: 3).

Together with other ES-based rapid assessment approaches (e.g. Burkhard et al. 2009, 2014; Willemen et al. 2008) the presented method could be applied for monitoring biodiversity and ES in EU member states according to Action 5 of the EU Biodiversity Strategy to 2020 (EC 2011). It allows to providing an overview on ES potentials and possible positive and negative impacts of LULCC on human well-being. However, the ability of these simplified models to assess the links between land use change and management alternatives and the provision of ES is limited (Granek et al. 2010). In order to prevent wrong conclusions from up-scaling issues, site specific heterogeneity should be included as well as the quantification of the links between functions and services.

Provision ES (food, fodder etc.) for instance are largely provided at local scale, while cultural or regulating services commonly refer to broader scales (Herrmann et al. 2011). Accordingly, at local scales, stakeholders put more weight on provisioning services while they favor regulating ES such as water purification at higher levels (Hein et al. 2006). Therefore, future tasks should also involve the investigation of how the dependence of ES delivery from scale level impacts decision-making.

Besides issues related to spatial resolution of input data, relevant ES might not be detected or overestimated due to certain temporal aspects. Besides management schemes which can vary on a yearly basis, in the case of the Pipiripau case study, seasonal changes of climatic conditions, precipitation and water flow appear to be important environmental parameters influencing the site specific potential to provide ES. The presented assessment approach implemented in GISCAME currently uses pseudo time steps. This means that the transition time between simulated LULCC and their effects on ES provision is not further specified. Thus, it was assumed that provision, e.g. of food, would remain constant within the individual pseudo time steps. Thus, if resources (e.g. time, money, work force, data) and knowledge are available, process models should be preferred because of their overall better accuracy and ability to refer to temporal and spatial differences in ES provision and their increased credibility (e.g. Smith et al. 2002; Naidoo and Ricketts 2006; Troy and Wilson 2006).

The raster cell perspective and the focus on land use neglect the influence of the spatial composition and configuration of landscapes and its elements. In several cases it could be confirmed that the LSM based assessment is useful and necessary as some impacts of LULCC scenarios can only be detected taken landscape structure into account (Frank et al. 2014b). Landscape structural aspects impact to a minor degree, e.g. provisioning services as these are produced on local scale. Yet, they have a fundamental impact on cultural and regulating services such as aesthetics and soil erosion regulation, local climate regulation, and pollination which operate at larger (regional) scales and cannot be properly assessed with land use/cover data (Frank et al. 2012; Lautenbach et al. 2011, Herrmann et al. 2011). This highlights the need to apply indicators reflecting important structural and functional features of landscapes instead of relying only on functional indicators (Schneiders et al. 2011). The impacts related to land use patterns have been disregarded within this thesis as they have been the subject of another thesis carried out within the frame of the GISCAME development (see Frank et al. 2012, 2013, 2014a).

I found that it was difficult to provide planners with information that would have sensibly increased their information basis. Also, some of their prevailing planning topics (such as wind energy planning) could not be addressed with the given - basic - assessment approach. Summing up, the assessment approach is quite easily transferable to other case study areas and widely applicable. Its practical use and added value for decision-making in landscape or regional planning however remains uncertain.

4.2 MCA approach - uncertainty and error propagation

MCA approaches will necessarily be based on a compromise between feasibility and integration of different indicators and goals (Bockstaller et al. 2008). Ecosystem functioning and ecosystem processes are inherently complex and sensitive to a number of scale dependent impacts and the effects of LULCC are often non-linear and ambiguous (Konarska et al. 2002; Lautenbach et al. 2011). The assessment approach is hence subjected to two major sources of uncertainty related to the impact of (i) input data such as land use maps, environmental data, indicators and their links to ES, and (ii) the MCA approach and its aggregation procedure.

(i) Eigenbrod et al. (2010) distinguish three major types of generalization errors in benefit transfer methods, the uniformity error, the sampling error, and the regionalization error. The presented approach is especially subjected to these errors (for further discussion see Eigenbrod et al. 2010; Koschke et al. 2012). An analysis of differences resulting from the applied LULC maps could provide further insight into effects of data input. In further research, emphasis should be put on the validation of results with measured data or data from process modeling. Major challenges remain in the assessment of ES dynamics. To increase reliability, standard rules need to be developed for assessing and quantifying ES based on individual land use data sets. A comparison of results enabling for an analysis of scale effects and uncertainties might encourage acceptance of stakeholders (Kandziora et al. 2013b; Kroll et al. 2012; Plummer et al. 2009). Although, land use dynamics cannot be accounted for in sufficient detail by given land use data sets, alternatives for landscape level assessments are not available (Kienast et al. 2009).

The way selected ES are defined and mapped will add uncertainty especially when different study outcomes are to be compared. The choice and assigning of indicators to ES is still challenging and often subjective. One ecosystem function can sustain several ES as much as several functions may support single ES (Willemen et al. 2008; Granek et al. 2010). Similarly, one indicator can be used for different ES and different indicators can describe the same or several ES.

(ii) The structure of assessment approach, i.e. using one or few indicators per ES makes the assessment sensitive to changing indicator values for instance as a consequence of sampling or regionalization errors. Further, the normalization approach is sensitive to minimum and maximum indicator values that are used to describe the regionally observed or assumed range of values and also the weights assigned to criteria will likely undergo changes over time or when derived from other stakeholders.

Uncertainty originating from (i) input data and incomplete knowledge on ecosystem processes propagates in the course of the assessment (cf. Hou et al. 2013). In addition (ii) methodical variations can impact ranking and subsequent prioritization of LULCC and LMC scenarios. In Koschke et al. (2013) I could show that varying indicator values and the normalization procedure were responsible for up to 51% deviation of ES values from average assessment results. Thus, only these two sources of error can impact significantly assessment outcomes and lead to contrasting conclusions about trade-offs and synergies between ES. Additionally, also choice and weighting of ES by stakeholders will alter assessment results. Consequently, the recommendation of strategies to adapt current land use and land management might be biased. Together, these errors results in a cumulative model uncertainty and its quantification remains difficult if not impossible.

Since individual decisions on the use and interpretation of data sources significantly impact assessment results, a careful documentation of methodical steps and applied data will help to improve transparency on how results have been produced. Extended uncertainty analyses will allow considering the white noise in the simulation outcomes which will then lead to facilitate communication with stakeholders and increase credibility and acceptance of results.

4.3 Applicability of the ES concept in the planning context and conceptual issues

After a phase with a focus on conceptual aspects (e.g. Boyd and Banzhaf 2007; Haines-Young and Potschin 2010a), scientific discussion on ES is now increasingly shifting towards the applicability of the ES concept in planning practice (Burkhard et al. 2013; Hauck et al. 2013a, b; Albert and von Haaren 2012a, b).

As ES only recently found their way into public discussions, it is widely assumed that it is necessary to provide regional planners with information and tools for impact assessment that enhance (interdisciplinary) communication, information transfer and involvement and cooperation of regional stakeholders. In general, the holistic and integrative character of ES reflects regional planning approaches. The operationalization of ES for integrated land use planning involves the use of context specific information that is relevant for planners and consistent with their objectives (Koschke et al. 2012). Von Haaren and Albert (2011) pointed out that methods used in environmental planning for assessment and evaluation agree with methods applied in ES research. Yet, convincing examples for the application of ES in practice are largely missing so far. The ES concept appears to be not compatible for planning which addressed Cook and Spray (2012) as the "implementation gap". The implementation of ES in planning is limited through for instance lacking formal institutional assignments and regulatory frame conditions to use ES (Albert et al. 2014) and information on ES supply that do not match planners information needs. Conceptual issues such as difficulties to consistently define and classify ES are likely to represent an additional burden for stakeholders which was also a finding of Menzel and Teng (2009) and Grêt-Regamey et al. (2012). As different ES classifications exist, the use of terms in scientific literature is quite divers and dynamic. The continuous development of the ES concept is reflected also in the use of terms and ES categories within the individual articles of this thesis.

As to the implementation of an integrated approach, the term ecosystem provoked conceptual difficulties through the need to define (eco-)systems to which ES refer and as to the question, whether urban areas, settlements and infrastructure elements (streets, railways) should be incorporated into the assessment or not. Simply ignoring these land uses or disqualifying them as service providing units appeared not to be constructive since for instance settlements do increase human well-being (Schetke et al. 2008). Another issue is the lacking and varying accessibility of data (and indicators) for planners to assess ES at a landscape level. Integration of ES in regional planning suffers also from lacking standardized methods for assessment, interpretation and (dis)aggregation of existing data, and differing concepts of what is being assessed (e.g. landscape potentials, threats, risks) (see also Herrmann et al. 2011). Finally, almost all ES are indeed already considered "at least to some extent" in regional or landscape plans (Albert et al. 2014: 1305). Therefore, applicability and added-value of landscape level ES assessment approaches for decision-making in regional or landscape planning appears to be limited.

5. Conclusion

The integrated assessment of a range of ES in decision-making in regional and landscape planning processes is necessary to sustainably use natural resources, to identify possible trade-offs regarding the provision of ES and to balance the needs of different stakeholder groups. An increasing availability of environmental data at the different planning levels is accompanied by difficulties to make use of the wealth of data in a consistent manner. Within this thesis I present an approach which allows the assessment of multiple ES to support land use planning at the landscape level.

Referring to **research objective (i),** the *developed assessment approach for ES at a landscape level* provides a simplified and rapid method to evaluate the impact of land use and land management options on ES in order to support and adjust recommendations of regional planners and land managers. The method is widely applicable and easily adaptable (transferable) for different case study areas. Therefore the thesis provides a contribution to the development of the GISCAME platform and assessment framework.

The work carried out to develop the assessment approach revealed the challenges connected to the selection of suitable and widely applicable indicators (cf. Koschke et al. 2012). In a few cases data availability allows measurement of indicators directly linked to ES, while in the majority of cases proxy indicators need to be applied. In order to increase the consistency of the approach the number of addressed land use classes might be reduced to land uses where suitable indicators and meaningful indicator values are available (see for instance the problem of comparing the soil erosion protection potential between different agricultural land uses and sealed surfaces such as buildings).

The presented approach can support the analysis of the current state and also trends of ES related to given land use/land cover/land management classes and changes of land use patterns. Thus, it allows the *identification and evaluation of alternative land use options* addressed in **research objective (ii) and (iii)**.

The presented assessment approach, which in many cases might not reflect sufficiently the complex character and interaction of landscape processes, might cause misleading or even wrong conclusions. Hence, results of trade-off analyses and recommendations on land use options based on LULC as a proxy for assessment should be evaluated with care (cf. Haines-Young et al. 2012; Kandziora et al. 2013b). If feasible, the assessment of ES should not only be based on LULC information. The parameterization of land use and environmental attributes within the spatially explicit assessment and a better resolution of land use data can enhance plausibility and relevancy of results. Yet, uncertainty and potential errors will remain significant for most ES and must always be assessed and communicated appropriately to involved stakeholders and decision makers. Extended standardized modeling approaches such as attempted within the InVEST framework (Nelson et al. 2009) might be suitable to improve comparability of assessment results and to harmonize assessment approaches.

Given the increased information needs of land users and land managers at local level, the assessment approach should not be used at these management levels. It appears to be best applied at a regional or landscape level to discuss general trends and consequences of LULCC in a wider context.

However, provided information appear to not sufficiently match the information needs of regional planners and other stakeholders.

As to **research objective (iv)**, my findings support the view that the *applicability of the concept of ES in planning contexts* can vary considerably and that the operationalization of ES is currently limited (Koschke et al., 2014). Besides challenges to accurately quantify ES, there are several conceptual issues, such as the consistent definition and classification of ES, which hamper the practical application of ES and which might negatively influence the success of participatory planning. The potential added value for decision-making of planners and land managers to use ES needs to be further investigated. Currently, ES appear to be an overarching scientific paradigm to frame assessments rather than a blueprint for management planning.

The presented assessment approach has to be further applied in planning processes in order to collect more feedback from stakeholders, such as regional planners and land managers. The experiences gained in these processes would help to refine the methodical approach regarding for instance the selection of appropriate indicators and the adaptation to existing planning procedures and evaluation concepts. The integration of actual ES flows and demands (see Burkhard et al., 2012b, 2014) in addition to ES provision potentials would be a promising improvement. This would be challenging as currently available data might hamper the estimations of meaningful ES flows and demands at a landscape level. However, altogether this would help to elaborate a more practice-oriented ES classification system and to make the application of ES more attractive for planners.

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