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The Impact of Socio-Economic Land Use Decisions on the Provision of Ecosystem Services

Dissertation

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Summary

The concept of ecosystem services (ESS) is aimed at a paradigm shift in ecosystem management by expanding the traditional view of the relationship between human well-being and ecosystems. Thus, it is based on the idea that ecosystems should be appreciated for the entirety of beneficial processes and functions that contribute to human well-being. These services can be provided in both tangible as well as intangible form, while their contribution to well-being might accrue from monetary and non-monetary benefits alike. The concept has received growing academic attention, and is regarded as a powerful policy instrument to meet the ongoing deterioration of Earth's ecosystems. Yet, the idea creates considerable challenges in terms of practical implementation in ecosystem management. In this context, the key research gap is a lack of appropriate mechanisms to measure the multiscale benefits of ESS and relate them to their role in environmental decision-making. Furthermore, the holistic nature of the concept requires multidisciplinary contributions about complex human-environment interactions, which results in high levels of uncertainty that hamper deterministic modelling of how management decisions influence ESS provision.

In the course of 3 papers, the presented thesis addresses these gaps by analyzing how benefits from ESS influence farmers' decision-making about crop choice, and modelling how these land use decisions determine the provision of ESS from their agricultural plots. The study is implemented in Haean watershed, South Korea, where agricultural production causes severe water pollution due to high soil particle and nutrient exports. In the first paper, decisions to plant rice, annual crops, or perennial crops, as well as to implement organic or conventional farming are analyzed based on socio-psychological interviews examining several behavioural and structural features. Following the theory of planned behaviour, these features include farmers' expected benefits from the ESS marketable biomass production, soil erosion reduction, water quality improvement, and plant and animal conservation. In the second paper, a Bayesian network is used to model farmers' decision-making as a function of their expected benefits from ESS. Finally, in paper 3, the Bayesian network is expanded with biophysical data in order to model the influence of farmers' management decisions on the provision of ESS.

The results from paper 1 showed that farmers' decisions to plant perennial crops were underpinned by higher benefit expectations from the ESS biomass production, soil erosion reduction, and water quality improvement. At the same time, perennial crop farming was perceived as more restricted by required skills and knowledge, as well as by necessary

financial means. Organic farming on the other hand, was not influenced by higher benefit expectations from ESS, but was perceived as more restricted by money availability. This information was used to model land use decisions as a function of expected benefits from ESS in paper 2. The Bayesian network yielded accurate results for predicting the choice of perennial crops, but less good classifications for rice and annual crops. This was remediated by adding slope steepness values to model land use decisions in paper 3, which resulted in good classification results for all crop types. Furthermore, modelling the provision of ESS showed that perennial crops are likely to increase water quality and reduce soil erosion, while organic farming increased water quality but also came along with reduced biomass production.

In conclusion, the results of this study show that the influential factors for farmers' decision-making in Haean catchment mostly evolve around financial motives. Therefore, policy programs trying to influence their decision-making should preferably aim at creating monetary incentives. Furthermore, the introduction of perennial crops and organic farming seems capable of mitigating the water-related issues. The latter, however, is attended by trade-offs in form of reduced biomass production. The presented approach shows that socio-psychological measurements can be used to identify the role of multiscale benefits from ESS in agricultural management decisions, which can yield crucial information for incorporating the ESS concept into effective policy programs. Bayesian networks, on the other hand, are capable of coupling decision-making modelling based on socio-psychological data with ESS provision modelling based on biophysical data. Such a property represents an indispensable prerequisite if the concept of ESS is to be operationalised in a practical manner that stays true to the concept's holistic nature.

Zusammenfassung

Das Konzept der Ökosystemdienstleistungen (ÖSL) zielt auf einen Paradigmenwechsel im Agrarökosystemmanagement ab, der die Sicht auf die Beziehung zwischen menschlichem Wohlergehen und Ökosystemen erweitern soll. Das Konzept basiert auf der Idee, Ökosysteme für alle nutzenstiftenden Prozesse und Funktionen wertzuschätzen, die zur Steigerung des menschlichen Wohlergehens beitragen. Diese Dienstleistungen können materieller wie immaterieller Natur sein, während ihr Beitrag zum Wohlergehen aus monetärem wie nicht-monetärem Nutzen erwachsen kann. Während das Konzept als geeignetes Politikinstrument angesehen wird, der anhaltenden Zerstörung von Ökosystemen zu begegnen, stellt die Idee in der Praxis eine große Herausforderung dar. Der zentrale Forschungsbedarf in diesem Zusammenhang besteht aus einem Mangel an Mechanismen, den multiskalierten Nutzen von ÖSL zu messen und seiner Bedeutung in Entscheidungsprozessen zuzuordnen. Des Weiteren erfordert der ganzheitliche Ansatz multidisziplinäre Untersuchungen komplexer Mensch-Umwelt Interaktionen. Dies verursacht ein hohes Maß an Unsicherheit, was eine deterministische Modellierung der Auswirkungen von Managemententscheidungen auf ÖSL erschwert.

Im Laufe dreier Artikel zielt die hier vorgelegte Arbeit darauf ab, den Einfluss des Nutzens von ÖSL auf die Entscheidungen von Bauern bei der Feldfruchtauswahl zu analysieren und die Auswirkung dieser auf die Erbringung von ÖSL zu modellieren. Die Arbeit bezieht sich auf das Wassereinzugsgebiet Haean, Süd-Korea, wo die Landwirtschaft starke Wasserverunreinigungen verursacht. Im ersten Artikel wird die Entscheidung zwischen dem Anbau von Reis, einjährigen Pflanzen und mehrjährigen Pflanzen, sowie zwischen organischem und konventionellem Anbau anhand sozio-psychologischer Fragebögen analysiert, welche mehrere verhaltens- und strukturbedingte Eigenschaften abfragen. Dem "theory of planned behaviour" Ansatz folgend beziehen sich diese Eigenschaften unter anderem auf den erwarteten Nutzen aus den ÖSL Produktion marktfähiger Biomasse, Bodenerosionsverringerung, Wasserqualitätsverbesserung und Erhalt der Pflanzen- und Tierwelt. Im zweiten Artikel wird ein Bayes'sches Netz benutzt, um Entscheidungen als Funktion des erwarteten Nutzens aus ÖSL zu modellieren. Abschließend wird in Artikel 3 das Bayes'sche Netz mit biophysikalischen Daten erweitert, so dass es eine Modellierung des Einflusses der Managemententscheidungen auf ÖSL erlaubt.

Die Ergebnisse aus Artikel 1 zeigten, dass die Entscheidung für ganzjährige Pflanzen durch höhere Nutzenerwartungen an die ÖSL Biomasseproduktion,

Bodenerosionsverringerung und Wasserqualitätsverbesserung untermauert war. Gleichzeitig wurde ihr Anbau als stärker durch benötigte Fertigkeiten und finanzielle Mittel eingeschränkt empfunden. Organischer Anbau wurde nicht durch erwarteten Nutzen von ÖSL beeinflusst, wurde jedoch als finanziell einschränkender empfunden. Mit Hilfe dieser Informationen konnte das Bayes'sche Netz in Artikel 2 die Entscheidung für mehrjährige Pflanzen präzise voraussagen. Weniger genau waren die Voraussagen für Reis und einjährige Pflanzen. Dies konnte durch die zusätzliche Berücksichtigung von Hangneigungsinformation in Artikel 3 behoben werden, was eine gute Klassifizierung aller Feldfrüchte zur Folge hatte. Darüber hinaus zeigte die Modellierung der Auswirkung von Landnutzungsentscheidungen, dass mehrjährige Pflanzen die Wasserqualität verbessern und Bodenerosion verringern, während organischer Landbau die Wasserqualität verbessert, aber auch mit einer geringeren Biomasseproduktion verbunden ist.

Zusammenfassend lässt sich sagen, dass die Ergebnisse auf eine zentrale Rolle finanzieller Motive bei landwirtschaftlichen Entscheidungen in Haean hinweisen. Aus diesem Grund sollten Politikprogramme vornehmlich auf die Schaffung monetärer Anreize abzielen. Des Weiteren scheint die Einführung mehrjähriger Pflanzen und organischen Landbaus ein geeignetes Mittel, um die wasserbezogenen Probleme abzumildern, auch wenn letztere Maßnahme mit einer Verringerung der Biomasseproduktion einhergeht. Die angewandten Methoden zeigen, dass sozio-psychologische Messungen die Bedeutung des multiskalierten Nutzens von ÖSL in landwirtschaftlichen Entscheidungen identifizieren können. Dies liefert entscheidende Informationen, um das Konzept der ÖSL erfolgreich in Politikmaßnahmen einzubauen. Bayes'sche Netze haben sich als angemessen erwiesen, die Modellierung sozio-psychologisch untersuchter Landnutzungen mit der Modellierung biophysikalisch erbrachter ÖSL zu vereinen. Diese Eigenschaft stellt eine unabdingbare Voraussetzung dar, um das Konzept der ÖSL auf eine praktische Art und Weise zu operationalisieren, welche dem ganzheitlichen Ansatz des Konzeptes gerecht wird.

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Table of contents

Abbreviations and *Symbols*

A	Parent node
AHP	Analytical Hierarchy Process
a.s.l.	Above sea level
AttB	Attitudes toward the behaviour
AUC	Area under the receiver operating characteristics curve
B	Child node
b	Specific state of node B
BN	Bayesian network
CPT	Conditional probability table
e	Evidence
ESS	Ecosystem services
ha	Hectare
kg	Kilograms
km^2	Square kilometres
m	Metres
MA	Millennium Ecosystem Assessment
P	Probability
RUSLE	Revised Universal Soil Loss Equation
SN	Social norms
t	Tonnes
TPB	Theory of planned behaviour
PBC	Perceived behavioural control
yr	Year

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List of individual contributions

The work presented in this thesis refers to the following three papers. Paper 1 is published in *Land Use Policy* (Chapter 2). Paper 2 is accepted for revision at *Environmental Modelling & Software* (Chapter 3). Paper 3 is *in preparation* (Chapter 4).

<u>Paper 1</u>

Title:	Do attitudes toward ecosystem services determine agricultural land use practices? An analysis of farmers' decision-making in a South Korean watershed
Author(s):	Patrick Poppenborg, Thomas Koellner
Journal:	*Land Use Policy*
Status:	published

Individual contributions:

Patrick Poppenborg	Study design, methods, data collection, data analysis, discussion, manuscript writing and editing (corresponding and first author)
Thomas Koellner	Study design, methods, discussion, manuscript editing

<u>Paper 2</u>

Title:	A Bayesian network approach to model farmers' crop choice using socio-psychological measurements of expected benefits from ecosystem services
Author(s):	Patrick Poppenborg, Thomas Koellner
Journal:	*Environmental Modelling & Software*
Status:	accepted for resubmission after revision

Individual contributions:

Patrick Poppenborg	Study design, methods, data collection, data analysis and modelling, discussion, manuscript writing and editing (corresponding and first author)
Thomas Koellner	Study design, methods, discussion, manuscript editing

<u>Paper 3:</u>

Title:	Linking benefits from ecosystem services to ecosystem functions and service provision: An integrated Bayesian network modelling approach
Author(s):	Patrick Poppenborg, Sebastian Arnhold, Bumsuk Seo, Thomas Koellner
Status:	in preparation

Individual contributions:

Patrick Poppenborg	Study design, methods, data collection, data analysis and modelling, discussion, manuscript writing and editing (corresponding and first author)
Sebastian Arnhold	Data collection and modelling, manuscript editing
Bumsuk Seo	Data collection and modelling, manuscript editing
Thomas Koellner	Study design, methods, discussion, manuscript editing

1. Synopsis

1.1. Background

1.1.1. The concept of ecosystem services and its role in agricultural management decisions

From the production of goods like timber or food, to the maintenance of processes and functions like generation of oxygen or landscape amenity - Earth's ecosystems build the foundation for sustaining and fulfilling human life (Daily, 1997). Driven by increasing demands of a steadily growing world population however, human use of ecosystems as a resource base has led to substantial changes of their structure and functioning. Climate-relevant biogeochemical cycles are being altered and losses of biodiversity occur at rates unprecedented in human history (Secretariat of the Convention on Biological Diversity, 2010; Vitousek et al., 1997), which is to name but a few of the most notable consequences.

The gravity of these changes has brought about initiatives to reconsider the dominant ways of ecosystem management. In a large-scale attempt to gather scientific knowledge for improving the conservation and sustainable use of ecosystems, a team of more than 2,000 authors and reviewers compiled the Millennium Ecosystem Assessment (MA) report in 2005 (MA, 2005). The central issue of the MA evolved around the linkages between ecosystems and human well-being, with a particular focus on the concept of ecosystem services (ESS). Thus, ecosystem services are the benefits people obtain from ecosystems, and can be grouped into provisioning services (e.g. food, water, timber), regulating services (e.g. regulation of climate or water quality), cultural services (e.g. recreation or landscape aesthetics), and supporting services (e.g. soil formation or photosynthesis) (MA, 2005).

The novelty of the ESS concept lies within its holistic, multiscale approach. Holistic because it aims at appreciating ecosystems for all their benefits - including those that come in non-material, intangible form like landscape amenity. Multiscale because the appreciation of these benefits can be expressed on several scales using more than one measurement unit. Thus, while traditional ecosystem management schemes typically focus on increasing economic returns from marketed services (Daly, 2005), the ESS approach also takes into account costs and benefits associated with the non-marketed services affected by a management decision. The valuation methods of these costs and benefits can take various forms. Standard economic approaches usually try to derive monetary values by means of investigating peoples' 'stated preferences' or 'revealed preferences' for non-marketed ESS (Whitehead et al., 2008). Non-monetary methods on the other hand rely on what is often referred to as socio-cultural values, which typically assess and compare preferences toward different scenarios based on importance scores derived from stakeholder evaluations (Daily et al., 2000; de Groot et al., 2002).

Each of these methods comes with its particular advantages and disadvantages (Bateman et al., 2011; Farber et al., 2002; Howarth and Farber, 2002; Limburg et al., 2002; Wilson and Howarth, 2002), which will be dealt with in more detail later on. What all valuation approaches have in common however, is their aim to aggregate human preferences with respect to the choices and trade-offs involved in decision-making processes (Daily et al., 2000). Thus, in case of competing ecosystem management options, a decision-maker will weigh the benefits against the costs of every alternative and choose the most highly valued option according to his preferences (Costanza, 2000). This makes the valuation of ecosystem services an essential step for integrating the ESS concept into ecosystem management decisions (Daily and Matson, 2008).

A prime example for the importance of holistic valuation approaches are agricultural ecosystems, which cover an area of about 25% of Earth's land surface (MA, 2005). Among the major types of ecosystems, agricultural ones are being managed with the strongest focus on satisfying human needs. Thus, their cultivation has been primarily geared toward food, fibre and fuel provision in human history (Swinton et al., 2007), which results in trade-offs with the provision of other ecosystem services. With the growing recognition of the ESS concept however, this focus is starting to shift as agricultural ecosystems are increasingly being appreciated for a wider range of provided services. For instance, they are highly valuable in providing the habitats allowing for natural pollination and pest control to occur (Costamagna and Landis, 2006; Tscharntke et al., 2005), by regulating soil loss and water quality (Whitmire and Hamilton, 2005), or by creating opportunities for tourism and recreation (Knoche and Lupi, 2007).

This appreciation has also found its way into agricultural policy initiatives, which are progressively moving away from traditional subsidy and trade policies. Instead, they put more emphasis on programs that create incentives for farmers to increase the supply of a variety of ecosystems services (Antle and Valdivia, 2006; Kinzig et al., 2011). In order for these programs to be successful, it is mandatory to understand the drivers of farmers' land use decision-making, as it defines how much and what kinds of ESS are being provided by agricultural ecosystems.

1.1.2. State of the art and research gaps

Valuation of ecosystem services in decision-making

The concept of ecosystem services has received considerable academic attention (Seppelt et al., 2011), and its basic idea has been widely accepted as a foundation for gearing ecosystem management toward a more sustainable use of ecosystem resources. However, albeit acclaimed theoretically, the concept is still far away from being incorporated routinely into practical decision-making. According to Daily et al. (2009), a framework of how to integrate ESS into decision-making would need to incorporate factors as those displayed in figure 1.1.

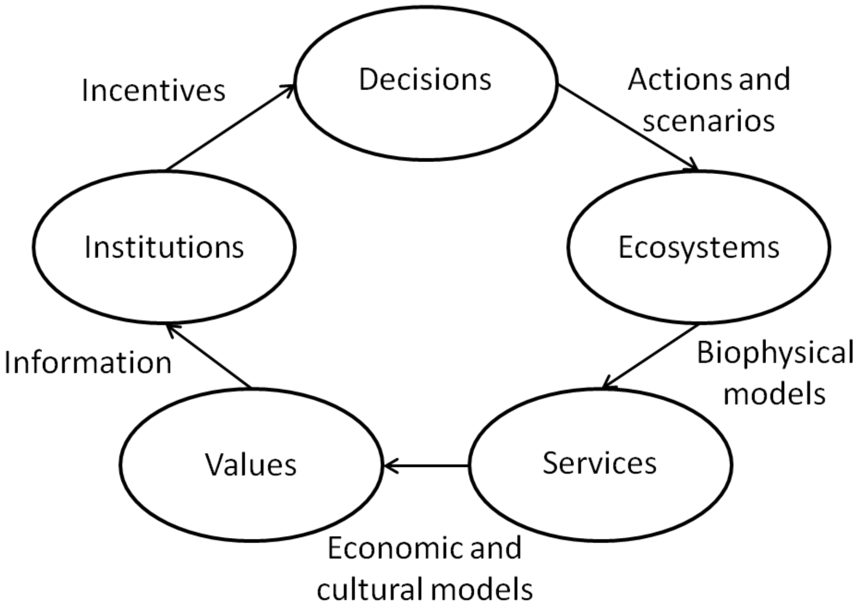

Figure 1.1: Graphical framework of how to integrate ecosystem services into decision-making (adapted from Daily et al., 2009).

Thus, management decisions influence ecosystem processes and functions, which in turn determine the level of service provision. Based on the evaluation of how much these services contribute to human well-being, institutions then try to create incentives for those decisions that lead to the provision of the most preferable services. One of the major obstacles in this framework, however, is the lack of mechanisms to turn the valuation of ESS into effective policy and finance programs. Daily et al. (2009) attribute this to our poor understanding of ecosystem management decisions and a shortage of integrated research in institutional design and policy implementation. In this context, they emphasise the importance of an improved understanding of stakeholders' motives and the evolvement of social norms in the context of ecosystem management decisions. Thus, changes in decisions and behaviour can be brought about by a number of different motivations – from monetary rewards, over legal sanctions, to feelings of guilt or approval by social peers (Tversky and Kahnemann, 1981). Clearly, such motives necessitate the development of both monetary and non-monetary evaluation methods, which need to be implemented in approaches that move away from stakeholder confrontation to participation (Daily et al., 2009).

As touched upon earlier, one way for valuating ESS are financial approaches. They evolve from traditional economic theory, which implies the assumption that decisions are based on an individual's striving for the highest possible utility as proposed in welfare economics (Just et al., 2004). Utility, however, is highly subjective and does not allow for scaling results between different individuals. Economists usually work around this shortcoming by approximating utility via profit, which is being measured in terms of monetary units that allow for inter-individual comparisons. With respect to agriculture, using profit maximisation as the underlying rationale for predicting farmers' decision-making can yield useful results, especially on large spatial scales where land use is defined by the overarching ecological and socio-economic properties of a given ecoregion (e.g. agriculture versus livestock breeding) (Antle and Valdivia, 2006; Edwards-Jones, 2007; Wossink and Swinton, 2007). On smaller scales however, purely economic based approaches can be much less informative, as local land use preferences are increasingly determined by the non-financial motives, values and attitudes of a decision-maker (e.g. cultivation of green pepper versus red pepper) (Morris and Potter, 1995; Rogers, 2003; Willock et al., 1999) (figure 1.2).

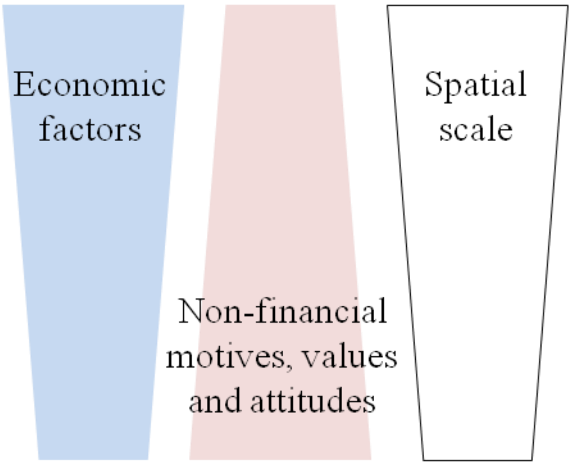

Figure 1.2: Importance of economic versus non-financial factors in land use decision-making on different spatial scales.

In such situations, the effectiveness of policy programs is mostly influenced by farmer and household characteristics, farm structure, and social milieu (Edwards-Jones, 2007). Burton (2004) refers to such joint considerations of motivational and structural/economic factors as ‘behavioural approaches’. These have been applied successfully in numerous studies about the influence of agricultural policies on farmers’ decision-making (e.g. Beedell and Rehman, 2000; Fielding et al., 2005; Morris and Potter, 1995; Sutherland, 2011). However, despite their well-proven applicability for investigating decision-making in a way that could meet the challenges identified by Daily et al. (2009), very few studies following a behavioural approach have been applied in the field of ecosystem service research (Vignola, 2010, Koellner et al. 2010).

Modelling of ecosystem management decisions in the context of ecosystem services

Besides appropriate methods for evaluating benefits from ecosystem services, incorporating the concept into decision-making also heavily relies on the use of statistical models (cf. figure 1.1). Primarily, these are being used to foresee the changes in ecosystem service provision resulting from different management decisions. Thus, biophysical models elucidate the link from actions to ecosystem functions, while socio-economic models translate functions into services (Daily, 2009). The holistic, multiscale nature of the ESS concept, however, brings about several challenges. From the notion of valuating specific services differently evolves the idea of relative importance, which requires multivariate statistics capable of incorporating choices between competing options. The usage of different scales for measuring the values which are not commensurable on a monetary scale also involves multidisciplinary input from different scientific fields. Therefore, the model needs to be able to incorporate both quantitative as well as qualitative data (Smith et al., 2011). Furthermore, seeing ecosystems as closely coupled socio-economic systems implies complex interactions between humans and nature, most of which are poorly understood (Daily et al., 2000). This results in high levels of uncertainty, while at the same time it necessitates the availability of very detailed data (Antle and Valdivia, 2006). Finally, the prospect of a less confrontational conservation approach demands models that are flexible and comprehensible enough to allow for close stakeholder participation.

A common modelling approach in this context is the use of agent-based models, which represent interactions between autonomous entities (e.g. humans, animals, water bodies) in a common environment using a rule-based approach (Kelly et al., 2013). They are particularly well-suited for applications aiming at close cooperation with stakeholder groups, where they can contribute significantly to a common understanding of socio-ecological systems (e.g. Murray-Rust et al., 2011). Among their main disadvantages, however, is a high demand for detailed data about agent interactions, and a lack of appropriate mechanisms to address uncertainty in model outputs (Kelly et al., 2013). This limits their applicability in cases where data is missing or processes are poorly understood. Another statistically strong approach to tackle the specific ESS challenges is the use of Bayesian network (BN) models, which are a form of graphical model based on probabilistic logic to analyze the complexity and uncertainty involved in causal or correlative relations between variables. Bayesian networks are increasingly popular in ESS related research as they can handle uncertainty in an explicit way; incorporate data from various sources; deal with missing data and be easily updated in case new data becomes available; and display data dependencies in an intuitively understandable way (Aguilera et al., 2011; Chan et al., 2012; Smith et al., 2011; Uusitalo, 2007).

These qualities have led to manifold applications of BNs in ecosystem services studies, where the majority focuses on investigating a single, typically well-documented service like food provision, genetic resources or water regulation (Landuyt et al., 2013). By focussing on one service, however, they forego the consideration of potential trade-offs with other services. Additionally, most of the studies apply BNs solely from a natural science perspective and neglect a direct consideration of decision-making factors. Thus, they look at the influence of various management scenarios on a number of predictor variables, which in turn are used as determinants of biophysical or ecological response variables that affect the level of ESS provision (McCann et al., 2006). Only some studies take a more participatory approach and include the perspectives of actors that hold stakes in the context of the modelled management decision. This stakeholder participation usually comes in the form of consultation workshops, where relevant variables are selected and related based upon the viewpoints of all participants (e.g. Barton et al., 2008; Bromley et al., 2005; Celio et al., 2012; Varis and Lahtela, 2002; Zorrilla et al., 2010).

An even smaller number of studies use BNs in a multidisciplinary approach and include behavioural factors for investigating stakeholders' decision-making in the context of ESS. For instance, Casteletti and Soncini-Sessa (2007) used direct interviews to model farmers' choices under different psychological conditions and linked them to a hydrological model. Haines-Young (2011) identified stakeholders' social valuation of landscape as a cultural entity and joined them with spatial models about vegetational carbon storage. The use of BN models in these studies turned out as a powerful method for combining the analytical rigor of quantitative natural science data with the interpretive complexity of qualitative social science data.

Yet the existing studies share quite a limited perception of how ecosystem management decisions and benefits from ecosystem service provision are linked. Thus, they model the impact of different management scenarios on ecosystem functions, which are subsequently translated into services by modelling their contribution to well-being in terms of benefit output. While such an approach basically follows the framework proposed in figure 1.1, Daily et al. (2009) themselves state that this framework represents only the simplest understanding of the role of ecosystem services in decision-making. Thus, any two of the nodes could be linked, in any direction (Daily et al., 2009). This limited view of humans as providers of impacts, and ecosystems as providers of services in return, neglects how benefits from ESS influence land use decision-making in the first place (Fish, 2011). Thus, the focus on benefits as an output of service provision carries the inherent danger of obfuscating how such a variegated term as well-being maps back onto service provision, or, as put by Fish (2011), "A focus on the 'services provided' is rather like starting a business without conducting the proper market research".

Research gaps

- Although the concept of ecosystem services is widely regarded as an appropriate approach for gearing ecosystem management toward more sustainable resource use, its practical implementation suffers from a poor understanding of its role in environmental decision-making.

- Attempts to elucidate the role of ESS in decision-making mostly assume that people act based on economic rationale, which implies that the benefits from ecosystem services are measurable on and appropriately reflected by monetary scales. While true for some services, this assumption does not allow for addressing the multiscale nature of the ESS concept, which includes non-monetary benefits as well.
- Behavioural approaches for analyzing farmers' multiscale motives in decision-making as a response to agricultural policy programs have been applied successfully numerous times, yet they have hardly been used to analyze farmers' decision-making in relation to ecosystem services.
- Modelling approaches of decision-making in the context of ESS successfully apply Bayesian networks, yet they usually depict benefits as an emergent property of service provision without taking into account the relation between benefits and ecosystem management decision-making.
- Bayesian network studies typically consider only one ecosystem service, which they depict from a natural science perspective, thereby foregoing to address trade-offs as well as the holistic, multidisciplinary approach of the concept.

1.2. Research goal and methodological approach

1.2.1. Research goal

The main goals of this thesis are a) to contribute to a better understanding of farmers' decision-making in the context of ecosystem services as a political framework for improving ecosystem management; and b) to operationalise this knowledge by means of a Bayesian network approach that takes into account the holistic and multiscale properties of the ecosystem service concept. The guiding questions in reaching these aims were:

1) What role do socio-economic benefits from ecosystem services play in farmers' decision-making about crop choice and cultivation method?

2) Can environmental decision-making be modelled as a function of socio-economic benefits from ecosystem services by means of a Bayesian network?

3) How can a Bayesian network be expanded in a multidisciplinary manner such that it includes biophysical data to model the impact of socio-economic land use decisions on the provision of several ecosystem services?

While these questions made up the overall framework for the presented thesis, the specific methods for reaching the intended goals were chosen in accordance with the South Korean case study region that was used for data collection. Thus, a short introduction to agricultural policy in South Korea as well as to the case study region Haean catchment will be given in the next section. It is followed by an explanation of the methodological approach taken for decision-making analysis and Bayesian network modelling. Afterwards, answers to the above stated questions are presented in form of summaries of the results from three papers, which were written as part of this cumulative thesis.

1.2.2. Research area

Agricultural policy in South Korea

Agricultural policy programs in South Korea aim at promoting environmentally friendly farming by means of certification schemes, promotion acts, as well as direct payment schemes. Most of the programs' budget is spent on behalf of paddy rice production (Im and Lee, 2007), which illustrates its great importance in the agricultural sector. Thus, paddy rice production has contributed to the economic, social as well as cultural life for hundreds of years, with benefits that go beyond what can be measured on monetary scales (Groenfeldt, 2006). This points to how closely agricultural productive functions in South Korea are intertwined with socio-cultural functions.

Today's agricultural practices in South Korea often result in heavy environmental degradation, mostly in form of water-related issues. Hence, soil erosion, water quality and water supply are among the most urgent problems addressed by the Korean Ministry of Environment. A major program of theirs is the Four Major Rivers Project, which supports initiatives to ensure sufficient water supply, reduce floods, and improve water quality (Moon, 2004). One of these four major rivers is the Han River, which transports fresh water to South Korea's capital Seoul. Accordingly, watersheds contributing to the pollution of the Han River are a prime target for Korean water improvement initiatives.

Case study area Haean catchment

One of the pollution hot spots designated by the Korean government is Haean catchment, as it feeds one of the two main tributaries of the Han River. Haean catchment is 64 km² in size and located in Yanggu County, Gangwon Province, South Korea (longitude 128°5'-128°11' East and latitude 38°13'-38°20' North). The catchment covers a range of 500 m to 1,100 m a.s.l. in altitude and features a kettle-like topography that has given it its local name 'Punch Bowl'. Land use in Haean is mostly made up of agricultural production areas which account for approximately 40% of the land area (Korean Ministry of Environment, personal communication). Agricultural crop distribution in Haean roughly follows the terrain's gradient - from paddy rice in the flat core areas, to annual dryland crops (mainly radish, cabbage and potato fields) and perennial crops (mainly ginseng, fruit tree varieties and bonnet bellflower) on the outskirts of the catchment.

Especially during heavy rain events in monsoon season, soil loss from agricultural fields can be very high and streams get heavily loaded with eroded sediment. To compensate for the soil loss farmers often renew the lost top soil layers with the sediments that accumulated along the rivers. This added soil, however, is prone to abrasion, and thus the cycle of soil loss and renewal starts over again. Although farmers are aware of the water pollution associated with their routines, past attempts to influence their land use behaviour or mitigate the consequences by the Korean government showed little success (Environment, Culture and Tourism Bureau of Gangwon, personal communication). Most recent governmental endeavours aim at fostering organic farming and introducing perennial crops in Haean. Thus, the permanent rooting of perennial crops is supposed to stabilise the soil throughout the year, thereby reducing erosion. The restricted use of chemical fertiliser and pesticides in organic farming, on the other hand, is presumed to improve water quality. In order to promote these options, however, it is of outmost importance to understand the land use decision-making of farmers who decide whether to implement them or not.

1.2.3. Decision-making analysis

Methods for analyzing famers' decision-making were chosen against the background of the open research question stated earlier, as well as in accordance with the circumstances of Haean catchment. Thus, given the small size of the catchment and the deep cultural roots of agriculture in South Korea, decision-making analysis was based on a behavioural approach in the sense of Burton (2004). He defines studies following this approach as those that a) seek to understand behaviour of individual farmers responsible for land management; b) focus on psychological constructs such as attitudes, values and goals, but also gather data on farm structure and economic situation; and (c) employ quantitative methodologies, in particular psychometric scales such as Likert-type scales for investigating psychological constructs.

Accordingly, a questionnaire was constructed that comprised both general as well as behavioural questions. The general questions addressed farmers' place of residence, years of farming experience, age, gender, highest scholar education, and approximate yearly household income. The behavioural questions were formulated according to a well-established socio-psychological decision making analysis tool - the theory of planned behaviour (TPB) (Ajzen, 1991). The TPB measures intentions to engage in a behaviour based on the components attitudes toward the behaviour (AttB), perceived behavioural control (PBC), and subjective norms (SN). Thus, strong behavioural intentions depend on a positive cost-benefit expectancy of performing the behaviour (AttB), the appreciation of important peers who determine social norms associated with the behaviour (SN), and control over performing the behaviour (PBC). Given the Korean government's current attempts to gear agricultural practices in Haean toward a more sustainable land use, the behaviours under consideration were farmers' choice between planting rice, annual crops, or perennial crops as well as their choice between implementing organic or conventional farming.

Following recommendations by Ajzen (2006) salient beliefs associated with the behaviours under consideration were elicited during a pre-survey field trip. As a result, the four most important attitudes were farmers' cost-benefit expectations from the ecosystem services marketable biomass production, soil erosion reduction, water quality improvement, and plant and animal conservation. The most important control factors were money availability, skills and knowledge, physical plot characteristics (soil quality, water availability, temperature, slope), and given legislation. Most important peers turned out to be household members, fellow farmers, people living downriver outside Haean, and environmental protection agencies. All TPB questions were measured on fully anchored 5-point unipolar Likert-type scales ranging from 1 (very low) to 5 (very high). Finally, priorities among the investigated TPB items were measured by means of the Analytical Hierarchy Process (AHP), which analyzes how much more one item dominates another with respect to a given attribute using pairwise comparisons for each combination of items (Saaty, 2008).

Given the environmental problems associated with agricultural production in Haean as well as the failure of the current agricultural policy programs to mitigate these problems, the analysis of the behavioural questions was geared toward testing the following hypotheses.

Hypotheses:

Farmers with a more positive attitude toward the ecosystem services production of marketable biomass, reduction of soil erosion, improvement of water quality, and conservation of plants and animals are more likely to:

1) plant perennial crops, instead of rice or annual crops;

2) implement organic farming instead of conventional farming.

Hypothesis testing was done using logistic regression analysis, whereas potential patterns among the observed behavioural data were investigated by means of latent class analysis. Data from the AHP analysis was used to calculate priority scores for each TPB item by normalizing a pairwise comparison matrix containing the preference values of each item.

1.2.4. Modelling of decision-making and ecosystem service provision

The decision-making analysis identified the extent to which farmers' land use decisions are influenced by socio-economic factors including cost-benefit expectations from ecosystem services. In the following step, this knowledge ought to be used to model farmers' crop choice and cultivation method as well as the resulting impact of these decisions on the provision of ecosystem services. Therefore, Bayesian networks were being created, which are directed acyclic graphs that use nodes to represent discrete random variables. In a Bayesian network, each variable is parameterized by a finite set of mutually exclusive states. Causal or correlative relations between variables are indicated by a directed link from one node (*A*) to another node (*B*). The strength of this relation is quantified by a conditional probability table (CPT), which indicates the probability (*P*) of a state of child node (*B*) given the state of its parent node (*A*) according to $P(B|A)$. Unconditioned parent nodes, on the other hand, are characterized by their marginal probability $P(A)$. In case of new evidence on the states of a conditioned node, probability distributions are updated based on Bayes' rule $P(b|e)=P(b,e)/P(e)$, with b as a representation of a specific state of node B, and e as a representation of evidence on a parent of B (Pearl, 2009; Kjaerulff and Madsen, 2008).

The performance of the Bayesian networks in terms of predicting farmers' land use decisions was evaluated with the help of confusion matrices, which contrasted known observations with highest-probability predictions by the model. This was done for the 'full model' containing all interview observations, as well as for subsets of the observations in a five-fold cross validation procedure. The number of false predictions was characterized as percentage error rates and area under the receiver operating characteristic curve (AUC). The networks were further evaluated by several analyses evolving around the measurement of entropy, which expresses a variable's randomness by measuring the degree of uncertainty in its probability distribution. Thus, evidence sensitivity analysis was performed to show how the probability distribution of farmers' land use decisions changed as a result of variations in the probability distributions of the remaining variables in the network. Also, value of information analysis was used to identify those variables that contribute most to reducing the entropy in the probability distribution of farmers' land use decisions. To allow for predicting the impacts of the modelled decisions on ecosystem service provision, data from natural science projects that worked in the same case study area were being used, above all those of Arnhold et al. (2013).

1.3. Main results

1.3.1. Paper 1: Do attitudes toward ecosystem services determine agricultural land use practices? An analysis of farmers' decision-making in a South Korean watershed

Analysis of farmers' attitudes toward ecosystem services showed that they had the lowest cost-benefit expectations from plant and animal conservation. In terms of behavioural constraints, all farmers felt most restricted by money availability and plot characteristics, while household members and fellow farmers were the most influential social peers. Of lowest influence were people living downriver and environmental protection agencies.

Using multinomial logistic regression analysis resulted in a final model with biomass production, erosion reduction, water quality improvement, skills and knowledge, and money availability as significant regression factors for crop choice ($Chi^2=211.35$, $p<0.001$). All of these were positively correlated with farmers' decisions to plant perennial crops. In other words, decisions to plant perennial crops were underpinned by more positive attitudes toward ecosystem services, while at the same time they were perceived as more demanding in terms of money and skills. The only significant difference with respect to organic versus conventional farming in binomial regression was found with respect to restrictions by money availability ($Chi^2=6.24$, $p<0.05$), which were significantly higher for organic farmers.

Furthermore, latent class analysis showed that farmers could be categorized into two groups: those with negative and those with positive attitudes toward the ecosystem services soil erosion reduction, water quality improvement, and conservation of plants and animals. Using income level as explaining factor for membership to these groups showed that with increasing income the probability of belonging to the class with negative attitude decreased, while it increased for the class with positive attitudes.

1.3.2. Paper 2: A Bayesian network approach to model farmers' crop choice using socio-psychological measurements of expected benefits from ecosystem services

As the work in paper 2 is a consequential advancement of the results from paper 1, only the ecosystem services that had turned out to be significant in terms of farmers' crop choice were used for modelling. Furthermore, results from latent class regression analysis were also included. Thus, land use decisions were modelled as a function of farmers' attitudes toward the ecosystem services biomass production, soil erosion reduction, and water quality improvement, as well as their perceived restrictions by money availability and skills and knowledge. The attitudes toward soil erosion reduction and water quality improvement, in turn, were modelled in dependence on income. The results from AHP analysis were used to introduce nodes that capture farmers' priorities among the considered attitudes and restrictions, respectively.

Predicted land use decisions for Haean amounted to a probability distribution of 36% rice, 41% annual crops, and 24% perennial crops. The confusion matrix for the five-fold cross validation procedure revealed error rates between 28% and 40%, and AUC values between 0.76 and 0.79. The error rate of the full model amounted to 37% with an AUC value of 0.78. The model performed best at predicting the choice of perennial crops, but less good for distinguishing between rice and annual crops. Furthermore, new evidence was entered into the network to examine an 'average attitude' scenario, for which the most probable state of each of the attitudinal nodes was instantiated. This scenario changed the probability distribution of farmers' crop choice to 37% rice, 51% annual crops, and 12% perennial crops.

Evidence sensitivity analysis revealed that the nodes obtained via AHP analysis had the greatest influence on crop choice. They were followed by the nodes describing farmers' perceived restrictions by money availability, their attitudes toward producing biomass, and their perceived limitations by skills and knowledge. According to the results from value of information analysis, the AHP nodes also turned out to have the greatest potential for reducing the entropy associated with the probability of farmers' crop choice.

1.3.3. Paper 3: Linking benefits from ecosystems services to ecosystem functions and service provision: An integrated Bayesian network modelling approach

The work in paper 2 had been concentrated on modelling land use decisions based on socio-psychological measurements of benefits from ecosystem services. Paper 3 went one step further and added the biophysical impact of these land use decisions on the provision of ecosystem services. As the performance of the model in paper 2 had suffered from not being able to distinguish rice and annual crops accurately, slope steepness was included as additional variable to explain crop choice. This was supposed to improve performance especially for predicting rice as a crop choice, since its cultivation requires a level surface. Furthermore, probabilities for choosing organic or conventional farming were modelled as a function of farmers' restrictions by money availability according to the results from paper 1.

Provision of the ecosystem service soil erosion reduction was modelled based on elements from the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997). For water quality improvement modelling, soil loss rates were related to particulate Phosphorus and Nitrogen losses according to enrichment ratios based on formulae by Sharpley (1985) and Auerswald (1989). Biomass production was modelled using average crop yield data from the Korean Statistical Information Service (www.kosis.kr). The effects of different land use distributions on ecosystem service provision were modelled in absolute terms as well as in percentage changes relative to a baseline, which corresponded to the BN's average output of the respective services.

Including slope steepness to model crop choice resulted in a land use probability distribution of 22% rice, 65% annual crops, and 13% perennial crops. The corresponding error rate was 26% with an AUC value of 0.85. The share of organic versus conventional farming was 26% to 74%, respectively. Mean soil erosion amounted to 27 $t*ha^{-1}*yr^{-1}$. Mean nutrient losses equalled 15 $kg*ha^{-1}*yr^{-1}$ for particulate Phosphorus and 29 $kg*ha^{-1}*yr^{-1}$ for total Nitrogen.

As in paper 2, the network was used to run several scenarios by entering new evidence. The four considered scenarios were an 'Annual crops' and a 'Perennial crops' scenario, as well as an 'Organic' and a 'Conventional' farming scenario. For the first two scenarios land use was assumed to have a 100% probability for the respective crop choice, while mean slope steepness was assumed to be 7°, slope length 30 metres, and rainfall erosivity factor 6500 $MJ*mm*ha^{-1}*h^{-1}*yr^{-1}$. For the latter two scenarios farmers' cultivation method was assumed to be either 100% organic or conventional. The 'Annual crops' scenario allowed for comparing the BN results with those of Arnhold et al. (2013), who modelled soil erosion of annual crops in Haean catchment under the above stated biophysical circumstances. The residual scenarios were chosen to reflect changes in ecosystem service provision, if the Korean agricultural policy programs of fostering perennial crops and organic farming were successfully implemented.

Under the 'Annual crops' scenario mean soil erosion amounted to 37 $t*ha^{-1}*yr^{-1}$, while particulate Phosphorus and total Nitrogen losses equalled 17 and 33 $kg*ha^{-1}*yr^{-1}$, respectively. As a result, water quality deteriorated by -110% on average. Biomass production amounted to a mean increase of 5%. On the other hand, the 'Perennial crops' scenario resulted in an average soil erosion of 31 $t*ha^{-1}*yr^{-1}$. Phosphorus and Nitrogen losses amounted to 17 and 33 $kg*ha^{-1}*yr^{-1}$, respectively. Mean biomass production was predicted to increase by 8%.

Modelling the 'Organic' scenario resulted in 27 $t*ha^{-1}*yr^{-1}$ soil erosion and nutrient losses of 17 and 33 $kg*ha^{-1}*yr^{-1}$ for particulate Phosphorus and total Nitrogen, respectively. Water quality improved by 29%, while biomass production decreased by an average of -10%. The 'Conventional' scenario yielded a mean erosion amount of 27 $t*ha^{-1}*yr^{-1}$. Particulate Phosphorus losses averaged 16 $kg*ha^{-1}*yr^{-1}$, losses of total Nitrogen amounted to 29 $kg*ha^{-1}*yr^{-1}$. The water quality index showed an increase slightly above average with 11%, while biomass production increased by 10%.

1.4. Discussion

The results from paper 1 confirmed the first hypothesis: decisions to plant perennial crops in Haean are significantly influenced by more positive attitudes toward ecosystem services in comparison to decisions about planting rice or annual crops. Similar results were obtained by Zubair and Garforth (2006), who found that beliefs about farm level tree planting in Pakistan were accompanied by positive attitudes such as economic benefits and environmental friendliness. However, perennial crops were also perceived as most demanding in terms of required financial means, which might be due to the lack of financial returns in the initial years of implementation. Furthermore, they were seen as significantly more challenging with respect to the skills and knowledge required for their cultivation. A possible reason could be farmers' inexperience with perennial crops, as they are not traditionally grown in the research area.

The second hypothesis of paper 1 had to be rejected. Decisions to implement either organic or conventional farming were not influenced by farmers' attitudes toward ecosystem services. Thus, the choice of cultivation method did not seem to be a matter of environmental concerns. More influential for environmental attitudes was farmers' income, as was shown in latent class regression modelling. The higher farmers' income, the more likely they held positive attitudes toward ecosystem services. Interestingly, best model fit was found when excluding the service of biomass production, which is the only one of the examined ESS that is monetarily traded on markets. This gives rise to the idea that only wealthier farmers can afford the consideration of environmental issues. However, this idea contradicts observations by Battershill and Gilg (1997), who found that personal attitudes about environmentally friendly farming mostly dominated pure profit maximization endeavours, even for farmers under financial constraints.

In summary of the decision-making analysis in paper 1, it seems as if mainly financial factors would determine farmers' attitudes toward ecosystem services as well as their choice of cultivation method. Having a sufficient monetary foundation seems to give farmers the liberty to consider environmental effects associated with their agricultural production, instead of having to concentrate on generating monetary returns as paramount objective. This might also explain the low importance of plant and animal conservation in comparison to the other ecosystem services. While biomass is evaluated monetarily via market prices, reduced soil loss and improved water quality are both likely to have indirect effects on agricultural production costs. Plant and animal conservation however, is difficult to evaluate monetarily and might thus be of lowest importance to profit-oriented farmers.

Using the expected benefits from ecosystem services to model farmers' decisions in paper 2 returned a land use probability distribution that almost equals the observations obtained from the questionnaire in paper 1 (35% rice, 40% annual crops, and 25% perennial crops). While prediction performance for perennial crops was very accurate, misclassifications between rice and annual crops contributed most to the error rates of 28% to 40%. These results confirm the model's general ability to predict crop choice of perennial crops based on socio-psychological measurements of expected benefits from ESS. An improved distinction between rice and annual crops however, would presumably require including additional information such as slope values, as a level surface is a crucial prerequisite for cultivating rice.

The results of evidence sensitivity and value of information analysis in paper 2 indicate a great influence of the information from the Analytical Hierarchy Process. Thus, the nodes containing the priority values from AHP analysis are the most valuable variables to observe in future samplings as they contribute most to entropy reduction, while also being the variables with the highest impact on the posterior probability distribution of farmers' crop choice. According to the calculated priority values biomass production was the most important criterion among the investigated benefits, while money availability had the highest importance among the perceived behavioural control factors. Both results are in line with the trends observed in the logistic regression analysis in paper 1.

As indicated by these results, socio-psychological measurements of expected benefits from ESS can be used to effectively model ecosystem management decisions in a Bayesian network. One of the approach's distinctive advantages is that it is not restricted to the use of monetary scales for evaluating ESS benefits at the decision-making level, which offers the kind of flexibility that is necessary for meeting the multidisciplinary aspects of the ecosystem service concept (Daily et al., 2009). Thus, it can incorporate benefits derived from services both tangible as well as intangible in the same modelling environment, which allows for addressing the holistic idea behind the ESS concept.

Furthermore, the relative importance between different ecosystem services was handled effectively by using elements from the Analytical Hierarchy Process. The added value to using only the theory of planned behaviour is that the AHP elements allow for mitigating the social desirability bias often occurring in questionnaires (Handfield et al., 2002). Thus, farmers might state that they give high priorities to socially desirable ecosystem services, although they actually do not care about them personally. Using pairwise comparisons like in the AHP motivates interviewees to reflect critically on their opinions, thereby helping to reduce uncertainty in the elicitation process (Kuhnert et al., 2010).

Since the ecosystem services covered in paper 2 were selected according to their importance for the decision-makers involved, the presented approach ensures a high level of stakeholder involvement as called for by Daily et al. (2009). Furthermore, using benefits from ecosystem services as a driver for ecosystem management has shown how links between well-being and decisions influencing service provision can be operationalised by means of a Bayesian network.

However, while the Bayesian network in paper 2 reasonably represents the interview data from paper 1, it does not depict the actual land use distribution in Haean watershed (23% rice, 65% annual crops, and 12% perennial crops). This discrepancy is due to the lack of geo-spatial reference for the modelled decisions, as only socio-psychological factors were considered. Thus, the model is capable of predicting crop choice as a function of expected benefits from ecosystems services, yet it cannot account for the locations and number of plots these decisions may be made for. Some of the uncertainty associated with this lack of spatial reference is remediated by the ‘average attitude’ scenario, as it disregards the more unlikely attitudes and models crop choice of one hypothetical farmer who represents the most likely observations. The probability of this average farmer choosing perennial crops equals the exact percentage of perennial crops in Haean, which underlines the model’s good performance with respect to this crop category. The less accurate results for rice and annual crops, on the other hand, point toward the limitations of the approach. Using only socio-psychological information to classify actual land use distributions does not predict all crop categories sufficiently.

Therefore, the model from paper 2 was developed further in paper 3, where slope steepness values were used to improve predictions of the actual land use distribution, while additional biophysical data were used to model the impacts of land use decisions on the provision of ecosystem services. The addition of slope steepness to the expected benefits from ESS for predicting crop choice yielded a land use probability distribution that is almost identical to the actual land use distribution in Haean catchment (23% rice, 65% annual crops, and 12% perennial crops). Furthermore, overall model performance with respect to the decision-making modelling part improved considerably, as was shown by a reduced error rate and an increased AUC value in comparison to the results from paper 2. Furthermore, using slope steepness offers a potential interface to geographic information systems, which would allow for displaying the results in a spatially explicit manner (Celio et al., 2013; Grêt-Regamey et al., 2008; Stassopoulou et al., 1998).

Reliable performance in terms of soil erosion modelling was indicated by the ‘Annual crops’ scenario, which predicts erosion amounts that are well within the range of values reported by Arnhold et al. (2013). A comparison with the ‘Perennial crops’ scenario indicates that annual crops produce higher soil losses and as a consequence higher Phosphorus and Nitrogen losses as well. Comparing organic with conventional cultivation on the other hand, reveals that organic production comes along with a decrease in biomass production, while it increases water quality due to lower Phosphorus and Nitrogen losses. The interpretation of these outputs however, has to be made with the model’s limitations in mind. Thus, the water quality and biomass modelling parts in particular are simplified representations of more specialized disciplinary models (e.g. Neitsch et al., 2005). Furthermore, predictions of the BN cannot be as precise as results obtained from deterministic models due to the information loss associated with discretizing continuous variables (Aguilera et al., 2011; Jensen and Nielsen, 2007).

Seeing the simplifications and information loss often involved in Bayesian network applications from a single scientific discipline’s point of view make BNs seem unfavourable for investigating ESS (Landuyt et al., 2013). In a multidisciplinary context, however, these limitations can be outweighed by the BN’s capability of providing an integrated framework that allows for assessing several ecosystem services, which can greatly support decision-making about multilayered ecosystem management options. Furthermore, simplifying model elements can foster social learning in participatory modelling processes, as it helps participants to comprehend the interrelations and uncertainties involved in the given system (Zorrilla et al., 2010).

These qualities recommend the presented BN as a powerful tool for political decision makers in Haean. It provides an integrated framework not only for identifying the most influential factors on farmers' land use decision-making, but also for modelling how these decisions affect the provision of ecosystem services. Thus, endeavours to foster perennial crops in the research area seem beneficial in terms of reducing erosion and improving water quality. On the other hand, organic farming improves water quality, but also comes along with a trade-off in biomass production.

1.5. Concluding remarks

Conclusion

The applied theory of planned behaviour successfully identified the factors relevant for farmers' decision-making in Haean watershed. However, although the chosen approach is capable of measuring benefits beyond monetary scales, the results indicate that farmers' rationale in choosing their crops is dominated by economic incentives. Thus, factors either directly (biomass production, money availability) or indirectly (water quality improvement, soil erosion reduction) related to monetary issues played the most influential role in farmers' decision-making.

These results give limited support to the claim of a stronger focus on social norms in the context of environmental decision-making; at least for the decisions and factors considered in the context of Haean watershed. Instead, they give support to initiatives trying to create economic incentives to influence farmers' decisions. Thus, schemes like payments for ecosystem services seem more promising. For such a scheme potential demanders of the ecosystems services from Haean could be found further downstream, where several drinking water and hydropower companies could profit from an improved water quality. Instead of spending money on clearing the reservoirs of their dams, they could create payment schemes that give financial rewards to farmers who reduce the sediment and chemical loads from their agricultural plots.

Nevertheless, in the overall context of the ecosystem services concept, a behavioural approach has its distinctive advantages. Given the wide spectrum of potential benefits from ecosystem services, it can be argued that an approach capable of reflecting benefits on multiple scales is more appropriate. The presented way of using the theory of planned behaviour offered this kind of flexibility. As a standardized and repeatable methodology, it furthermore allows for comparisons between actors on different temporal and spatial scales. These features make the presented approach a viable option for meeting the challenges identified by Daily (2009), as it improves the understanding of stakeholders' motives in the context of ecosystem management decisions and allows for non-monetary evaluation methods for ESS, which helps to develop a broader vision of environmental conservation.

Furthermore, the usage of the theory of planned behaviour for measuring benefits from ESS also creates the kind of interface that allows for combining 'values' from social science methods with 'facts' from natural science methods in a multidisciplinary modelling environment. As shown in this thesis, an appropriate platform for dealing with this kind of constellation is a Bayesian network modelling approach. Thus, the presented BN was capable of successfully modelling ecosystem management decisions as a function of both socio-psychological and biophysical variables. This was done in a way that not only allowed for identifying how benefits from ESS map back onto farmers' decisions, but also for assessing how management decisions impact the provision of ESS. Although afflicted with information loss in comparison to more specialized disciplinary models, the modelled provisions of ecosystem services lay within realistic ranges.

This might not recommend BNs as an alternative for deterministic models about a single ESS, but it does emphasise their usefulness for addressing the ecosystem services concept holistically. Thus, the ability to model the immediate influence of benefits from ecosystem services on ecosystem management decisions gives direct insight into the links between well-being and ESS, thereby helping to create more effective policy programs. Without this understanding, the postulated role of ESS in constituting benefits to humans runs the risk of becoming a black box, where the how and why ESS matter in decision-making are being obfuscated. Additionally, being able to model the interrelations between value-based management decisions and their factual impacts on ecosystem service provision represents an indispensable prerequisite for operationalising the ecosystem services concept in practical ecosystem decision-making.

Summary

In summary, the presented thesis contributes following new insights to the field of ecosystem services and decision-making:

- The influence of socio-economic benefits from ecosystem services on decision-making can be identified by means of a behavioural approach using the theory of planned behaviour, which recommends this approach as a multiscale evaluation method for systematically integrating the ESS concept into ecosystem management decisions
- Socio-economic benefits from ecosystem services play an immediate role in shaping ecosystem management decisions. Thus, they should not only be considered as an emergent property of service provision, but also as an input to those decisions that directly influence ecosystem processes and functions
- The links between socio-economic benefits from ecosystem services and environmental decision-making can be operationalised explicitly by means of Bayesian network models, which makes them a powerful support tool for turning ecosystem service valuation into effective environmental policy programs
- Bayesian networks can be used to effectively incorporate multidisciplinary information from different data sources, which facilitates the realisation of the holistic and multiscale approach of the ecosystem services concept. Thus, they provide an integrated modelling environment for predicting ecosystem management decisions as a function of socio-economic benefits from ecosystem services, and for predicting how these management decisions impact biophysical ecosystem processes and functions

Research outlook

The information value of the results from this thesis could be increased further by more research about decision-making in the context of ecosystem services, as well as Bayesian network modelling. Thus, testing the applied method for decision-making analysis in additional case study areas would allow for a better assessment of the approach's validity and transferability. While the results of this thesis point towards an economic rationale of farmers, results may differ significantly in other regions where farming might be less business oriented.

Results of the Bayesian network approach would benefit from a more sophisticated modelling of the biophysical impacts of management decisions on ecosystem processes and ecosystem service provision. Recent advancements indicate that Bayesian networks offer appropriate means for realising this goal, as inference algorithms capable of dealing with continuous data have been developed and tested successfully (Aguilera, 2010; Shenoy and West, 2011). However, such an endeavour would require joint research efforts of several scientific disciplines with dedication to a multidisciplinary modelling project.

Finally, an important step to consider in future research would be to extend the presented Bayesian network modelling in a spatially-explicit manner. While attempts to couple BNs with geographical information systems have already been implemented successfully (e.g. Haines Young, 2011; Smith et al., 2007), explicit consideration of spatial dependencies and interactions in ecosystem service provision is still largely lacking (Giretti et al., 2012; Landuyt et al., 2013). Such considerations, however, would be particularly helpful for addressing spatial heterogeneity of those variables that determine ESS provision, but are largely uninfluenceable by management decisions (e.g. climate).

1.6. Literature

Aguilera, P.A., Fernández, A., Fernández, R., Rumí, R., Salmerón, A., 2011. Bayesian networks in environmental modelling. Environmental Modelling & Software 26(12) 1376-1388.

Ajzen, I., 1991. The theory of planned behavior. Organizational behavior and human decision processes 50(2) 179-211.

Ajzen, I., 2006. Constructing a Theory of Planned Behavior Questionnaire. Icek Ajzen (accessed 06/24/2011 at http://www.people.umass.edu/aizen/pdf/tpb.measurement.pdf).

Antle, J.M., Valdivia, R.O., 2006. Modelling the supply of ecosystem services from agriculture: a minimum-data approach. Australian Journal of Agricultural and Resource Economics 50(1) 1-15.

Arnhold, S., Ruidisch, M., Bartsch, S., Shope, C., Huwe, B., 2013. Simulation of runoff patterns and soil erosion on mountainous farmland with and without plastic-covered ridge-furrow cultivation in South Korea. Transactions of the ASABE 56(2) 667-679.

Auerswald, K., 1989. Predicting nutrient enrichment from long-term average soil loss. Soil Technology 2(3) 271-277.

Barton, D.N., Saloranta, T., Moe, S.J., Eggestad, H.O., Kuikka, S., 2008. Bayesian belief networks as a meta-modelling tool in integrated river basin management - Pros and cons in evaluating nutrient abatement decisions under uncertainty in a Norwegian river basin. Ecological Economics 66(1) 91-104.

Bateman, I., Mace, G., Fezzi, C., Atkinson, G., Turner, K., 2011. Economic Analysis for Ecosystem Service Assessments. Environmental and Resource Economics 48(2) 177-218.

Battershill, M.R.J., Gilg, A.W., 1997. Socio-economic constraints and environmentally friendly farming in the Southwest of England. Journal of Rural Studies 13(2) 213-228.

Beedell, J., Rehman, T., 2000. Using social-psychology models to understand farmers' conservation behaviour. Journal of Rural Studies 16(1) 117-127.

Bromley, J., Jackson, N.A., Clymer, O.J., Giacomello, A.M., Jensen, F.V., 2005. The use of Hugin® to develop Bayesian networks as an aid to integrated water resource planning. Environmental Modelling & Software 20(2) 231-242.

Burton, R.J.F., 2004. Reconceptualising the `behavioural approach' in agricultural studies: a socio-psychological perspective. Journal of Rural Studies 20(3) 359-371.

Castelletti, A., Soncini-Sessa, R., 2007. Bayesian Networks and participatory modelling in water resource management. Environmental Modelling & Software 22(8) 1075-1088.

Celio, E., Brunner, S.H., Grêt-Regamey, A., 2012. Participatory Land Use Modeling with Bayesian Networks: a Focus on Subjective Validation, In: Seppelt, R., Voinov, A.A., Lange, S., Bankamp, D. (Eds.), International Environmental Modelling & Software Society (iEMSs). 2012 International Congress on Environmental Modelling & Software. Managing Resources of a Limited Planet, Sixth Biennial Meeting: Leipzig, Germany.

Celio, E., Koellner, T., Grêt-Regamey, A., 2013. Modeling land use decisions with Bayesian networks: Spatially explicit analysis of driving forces. Environmental Modelling & Software (in press).

Chan, T.U., Hart, B.T., Kennard, M.J., Pusey, B.J., Shenton, W., Douglas, M.M., Valentine, E., Patel, S., 2012. Bayesian network models for environmental flow decision making in the Daly River, Northern Territory, Australia. River Research and Applications 28(3) 283-301.

Costamagna, A.C., Landis, D.A., 2006. Predators exert top-down control of soybean aphid across a gradient of agricultural management systems. Ecological Applications 16(4) 1619-1628.

Costanza, R., 2000. Social Goals and the Valuation of Ecosystem Services. Ecosystems 3(1) 4-10.

Daily, G., Söderqvist, T., Aniyar, S., Arrow, K., Dasgupta, P., Ehrlich, P., Folke, C., Jansson, A., Jansson, B., Kautsky, N., 2000. The value of nature and the nature of value.

Daily, G.C., 1997. Nature's services: societal dependence on natural ecosystems. Island Press, Washington.

Daily, G.C., Matson, P.A., 2008. Ecosystem services: From theory to implementation. Proceedings of the National Academy of Sciences 105(28) 9455-9456.

Daily, G.C., Polasky, S., Goldstein, J., Kareiva, P.M., Mooney, H.A., Pejchar, L., Ricketts, T.H., Salzman, J., Shallenberger, R., 2009. Ecosystem services in decision making: time to deliver. Frontiers in Ecology and the Environment 7(1) 21-28.

Daly, H.E., 2005. Economics in a full world. Scientific American 293(3) 100-107.

de Groot, R.S., Wilson, M.A., Boumans, R.M.J., 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecological Economics 41(3) 393-408.

Edwards-Jones, G., 2007. Modelling farmer decision-making: concepts, progress and challenges. Animal Science 82(06) 783-790.

Farber, S.C., Costanza, R., Wilson, M.A., 2002. Economic and ecological concepts for valuing ecosystem services. Ecological Economics 41(3) 375-392.

Fielding, K.S., Terry, D.J., Masser, B.M., Bordia, P., Hogg, M.A., 2005. Explaining landholders' decisions about riparian zone management: The role of behavioural, normative, and control beliefs. Journal of Environmental Management 77(1) 12-21.

Fish, R.D., 2011. Environmental decision making and an ecosystems approach: Some challenges from the perspective of social science. Progress in Physical Geography 35(5) 671-680.

Giretti, A., Carbonari, A., Naticchia, B., 2012. A spatio-temporal Bayesian network for adaptive risk management in territorial emergency response operations. In: Premchaiswadi, W. (Ed.), Bayesian Networks. InTech, Rijeka, Croatia, 49-70.

Grêt-Regamey, A., Bebi, P., Bishop, I.D., Schmid, W.A., 2008. Linking GIS-based models to value ecosystem services in an Alpine region. Journal of Environmental Management 89(3) 197-208.

Groenfeldt, D., 2006. Multifunctionality of agricultural water: looking beyond food production and ecosystem services. Irrigation and Drainage 55(1) 73-83.

Haines-Young, R., 2011. Exploring ecosystem service issues across diverse knowledge domains using Bayesian belief networks. Progress in Physical Geography 35(5) 681-699.

Handfield, R., Walton, S.V., Sroufe, R., Melnyk, S.A., 2002. Applying environmental criteria to supplier assessment: A study in the application of the Analytical Hierarchy Process. European Journal of Operational Research 141(1) 70-87.

Howarth, R.B., Farber, S., 2002. Accounting for the value of ecosystem services. Ecological Economics 41(3) 421-429.

Im, J., Lee, Y., 2007. Progress and Challenges of Direct Payment Programs in Korea Agricultural Sector. Korean Journal of Agricultural Management and Policy 34(1) 169-195.

Jensen, F.V., Nielsen, T.D., 2007. Bayesian networks and decision graphs. Springer, New York.

Just, R.E., Hueth, D.L., Schmitz, A., 2004. The welfare economics of public policy. Edward Elgar, Cheltenham, UK.

Kelly, R.A., Jakeman, A.J., Barreteau, O., Borsuk, M.E., ElSawah, S., Hamilton, S.H., Henriksen, H.J., Kuikka, S., Maier, H.R., Rizzoli, A.E., van Delden, H., Voinov, A.A., 2013. Selecting among five common modelling approaches for integrated environmental assessment and management. Environmental Modelling & Software 47(0) 159-181.

Kinzig, A.P., Perrings, C., Chapin, F.S., Polasky, S., Smith, V.K., Tilman, D., Turner, B.L., 2011. Paying for ecosystem services – Promise and peril. Science 334(6056) 603-604.

Kjaerulff, U.B., Madsen, A.L., 2008. Bayesian networks and influence diagrams: a guide to construction and analysis. Springer, New York, USA.

Knoche, S., Lupi, F., 2007. Valuing deer hunting ecosystem services from farm landscapes. Ecological Economics 64(2) 313-320.

Koellner, T., Sell, J., Navarro, G., 2010. Why and how much are firms willing to invest in ecosystem services from tropical forests? A comparison of international and Costa Rican firms. Ecological Economics 69(11) 2127-2139.

Kuhnert, P.M., Martin, T.G., Griffiths, S.P., 2010. A guide to eliciting and using expert knowledge in Bayesian ecological models. Ecology Letters 13(7) 900-914.

Landuyt, D., Broekx, S., D'Hondt, R., Engelen, G., Aertsens, J., Goethals, P.L.M., 2013. A review of Bayesian belief networks in ecosystem service modelling. Environmental Modelling & Software 46(0) 1-11.

Limburg, K.E., O'Neill, R.V., Costanza, R., Farber, S., 2002. Complex systems and valuation. Ecological Economics 41(3) 409-420.

MA, 2005. Millennium Ecosystem Assessment. Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC.

McCann, R.K., Marcot, B.G., Ellis, R., 2006. Bayesian belief networks: applications in ecology and natural resource management. Canadian Journal of Forest Research 36(12) 3053-3062.

Moon, T.H., 2004. Environmental Policy and Green Government in Korea. ekoreajournal (accessed 06/24/2011 at http://www.ekoreajournal.net/upload/html/HTML44039.html).

Morris, C., Potter, C., 1995. Recruiting the new conservationists: Farmers' adoption of agri-environmental schemes in the U.K. Journal of Rural Studies 11(1) 51-63.

Murray-Rust, D., Dendoncker, N., Dawson, T.P., Acosta-Michlik, L., Karali, E., Guillem, E., Rounsevell, M., 2011. Conceptualising the analysis of socio-ecological systems through ecosystem services and agent-based modelling. Journal of Land Use Science 6(2-3) 83-99.

Neitsch, S., Arnold, J., Kiniry, J., Williams, J., King, K., 2005. Soil and water assessment tool: theoretical documentation, version 2005. Texas, USA.

Pearl, J., 2009. Causality: Models, Reasoning and Inference, 2nd ed. Cambridge University Press, Cambridge.

R Development Core Team, 2011. R: A language and environment for statistical computing. R Foundation for Statistical Computing: Vienna, Austria.

Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D., Yoder, D., 1997. Predicting soil erosion by water: a guide to conservation planning with the revised universal soil loss equation (RUSLE). Agriculture Handbook No. 703, USDA, Washington, D.C.

Rogers, E.M., 2003. Diffusion of innovations. Free Press, New York.

Saaty, T., 2008. Decision making with the analytic hierarchy process. International Journal of Services Sciences 1(1) 83-98.

Secretariat of the Convention on Biological Diversity, 2010. Global Biodiversity Outlook 3. Montréal, Canada.

Seppelt, R., Dormann, C.F., Eppink, F.V., Lautenbach, S., Schmidt, S., 2011. A quantitative review of ecosystem service studies: approaches, shortcomings and the road ahead. Journal of Applied Ecology 48(3) 630-636.

Sharpley, A.N., Smith, S.J., Berg, W.A., Williams, J.R., 1985. Nutrient Runoff Losses as Predicted by Annual and Monthly Soil Sampling. Journal of Environmental Quality 14(3) 354-360.

Shenoy, P.P., West, J.C., 2011. Inference in hybrid Bayesian networks using mixtures of polynomials. International Journal of Approximate Reasoning 52(5) 641-657.

Smith, R.I., Dick, J.M., Scott, E.M., 2011. The role of statistics in the analysis of ecosystem services. Environmetrics 22(5) 608-617.

Stassopoulou, A., Petrou, M., Kittler, J., 1998. Application of a Bayesian network in a GIS based decision making system. International Journal of Geographical Information Science 12(1) 23-46.

Sutherland, L.-A., 2011. Effectively organic: Environmental gains on conventional farms through the market? Land Use Policy 28(4) 815-824.

Swinton, S.M., Lupi, F., Robertson, G.P., Hamilton, S.K., 2007. Ecosystem services and agriculture: Cultivating agricultural ecosystems for diverse benefits. Ecological Economics 64(2) 245-252.

Tscharntke, T., Klein, A.M., Kruess, A., Steffan-Dewenter, I., Thies, C., 2005. Landscape perspectives on agricultural intensification and biodiversity – ecosystem service management. Ecology Letters 8(8) 857-874.

Tversky, A., Kahneman, D., 1985. The framing of decisions and the psychology of choice, In: Behavioral decision making. Springer, New York, pp. 25-41.

Uusitalo, L., 2007. Advantages and challenges of Bayesian networks in environmental modelling. Ecological Modelling 203(3-4) 312-318.

Varis, O., Lahtela, V., 2002. Integrated water resources management along the Senegal River: introducing an analytical framework. International Journal of Water Resources Development 18(4) 501-521.

Vignola, R., 2010. Decision making concerning the management of ecosystem goods and services. Dissertation at the Swiss Federal Institute of Technology Zurich.

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

Whitehead, J.C., Pattanayak, S.K., Van Houtven, G.L., Gelso, B.R., 2008. Combining revealed and stated preference data to estimate the nonmarket value of ecological services: An assessment of the state of the science. Journal of Economic Surveys 22(5) 872-908.

Whitmire, S.L., Hamilton, S.K., 2005. Rapid Removal of Nitrate and Sulfate in Freshwater Wetland Sediments. J. Environ. Qual. 34(6) 2062-2071.

Willock, J., Deary, I.J., Edwards-Jones, G., Gibson, G.J., McGregor, M.J., Sutherland, A., Dent, J.B., Morgan, O., Grieve, R., 1999. The Role of Attitudes and Objectives in Farmer Decision Making: Business and Environmentally-Oriented Behaviour in Scotland. Journal of Agricultural Economics 50(2) 286-303.

Wilson, M.A., Howarth, R.B., 2002. Discourse-based valuation of ecosystem services: establishing fair outcomes through group deliberation. Ecological Economics 41(3) 431-443.

Wossink, A., Swinton, S.M., 2007. Jointness in production and farmers' willingness to supply non-marketed ecosystem services. Ecological Economics 64(2) 297-304.

Zorrilla, P., Carmona Garcia, G., De la Hera, A., Varela Ortega, C., Martinez Santos, P., Bromley, J., Henriksen, H.J., 2010. Evaluation of Bayesian networks in participatory water resources management, Upper Guadiana Basin, Spain. Ecology and Society 15(3) 12.

Zubair, M., Garforth, C., 2006. Farm Level Tree Planting in Pakistan: The Role of Farmers’ Perceptions and Attitudes. Agroforestry Systems 66(3) 217-229.

2. Paper 1: Do attitudes toward ecosystem services determine agricultural land use practices? An analysis of farmers' decision-making in a South Korean watershed

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2.1. Abstract

Land use practices directly influence the provision of ecosystem services from agrarian landscapes, and are thus key factors for the development of environmental policy programs. This study analyzes farmers' decision-making processes with respect to land use in a South Korean watershed, based on the Theory of Planned Behaviour. Decisions between cultivation of rice, annual or perennial crops, and between organic and conventional farming were compared among farmers as a function of their attitudes towards the following ecosystem services: biomass production, prevention of soil erosion, improvement of water quality, and conservation of plants and animals. Results show that decisions to plant perennial crops are most often accompanied by positive attitudes towards ecosystem services, whereas no differences were found between organic and conventional farming. In addition, latent class analysis reveals that positive attitudes towards ecosystem services are most likely held by farmers with high income, showing that financial means are key determinants of farmers' environmental attitudes.

Keywords: ecosystems services; organic farming; theory of planned behaviour; land use decision-making; latent class analysis

2.2. Introduction

Understanding and modelling farmer decision-making is of key importance to environmental policy makers as it lays the foundation for design and implementation of successful programs. Accordingly, analysis of decision-making receives considerable academic attention and is addressed by various scientific disciplines. One main approach evolving from traditional economic theory is based on the assumption that farmers' decisions are driven by their desire to achieve the greatest possible utility as defined in welfare economics. Although theoretically appropriate, several shortcomings arise when this idea is to be implemented in real life situations. Since utility is highly subjective and lacks consistent scalability, it does not lend itself for inter-individual comparisons. The usual economists' workaround is to approximate it by measuring profit via monetary returns, which offers the possibility of scaling and relating results from different actors.

As pointed out by Edwards-Jones (2007) decision analyses solely based on the assumption of rational profit-maximizing behaviour yield useful results on large spatial scales where economic factors define the overall agricultural land use as a function of the given ecoregion (e.g. livestock farming vs. crop farming). However, solely economic descriptors can lose most of their predictive power when it comes to analyzing decisions on small scales, since more and more non-financial factors start taking effect on land use preferences. Studies with input from sociology and psychology indicate that these preferences are influenced by a variety of motives, attitudes and values intrinsic to every individual decision-maker (Morris and Potter, 1995; Rogers, 2003; Willock et al., 1999). Variables that are most influential can be summarized under (a) farmer characteristics, (b) household characteristics, (c) farm structure, (d) social milieu, and (e) the characteristics of the policy under consideration (Edwards-Jones, 2007).

This joint consideration of motivational and structural/economic features has been termed 'behavioural approach' by Burton (2004) who argues that this approach is especially well suited for investigating farmers' responses to policy initiatives. Its distinctive advantages are the consideration of factors that reflect more than monetary motives and the use of standardized and repeatable methodologies which allow for comparisons between actors on different temporal and spatial scales (Beedell and Rehman, 2000). These qualities have led to an increasing implementation of behavioural studies for analyzing farmers' reactions to agricultural policies of the European Union.

Since the late 1980s policy makers have been increasingly interested in diversifying rural land use and focus has shifted away from intensive commodity production towards a multifunctional design, which also takes into account the cultural and environmental heritage of agrarian landscapes. Corresponding studies are numerous and cover a wide range of topics such as general analyses dealing with farmers' conservation behaviour (Beedell and Rehman, 1999; Beedell and Rehman, 2000; Carr and Tait, 1991; Lynne et al., 1995; Sutherland, 2010) or with environmentally-friendly farming (Battershill and Gilg, 1997; Willock et al., 1999), but also more specific works about for instance organic farming (Beharrell and Crockett, 1992; Fairweather, 1999; Locke, 2006; Midmore et al., 2001; Sutherland, 2011), management of field boundary vegetation (Morris et al., 2002), and riparian zone management (Fielding et al., 2005).

The idea of multifunctionality is closely associated with that of ecosystem services (ES), which was substantially conceptualized by the Millennium Ecosystem Assessment (MA) in 2005. Aiming at a paradigm shift in the appreciation of agricultural as well as of natural landscapes in general, the MA expanded the traditional view of the relationship between human well-being and ecosystems. In addition to the benefit of producing tangible goods, they placed emphasis on those merits of nature that bring about intangible services sustaining human life (MA, 2005). Although the vision of the MA to foster nature conservation by recognizing its full value holds more and more sway in the minds of individual and institutional decision makers, appropriate policy mechanisms for its successful incorporation into everyday decision-making are widely lacking. Daily et al. (2009) summarize three main areas that would aid this process: (a) understanding and discussion of peoples' motives and the evolvement of social norms in the context of natural ecosystems (Ehrlich and Kennedy, 2005; Pergams and Zaradic, 2008) , (b) incorporation of traditional knowledge and practices into modern conservation approaches (Berkes and Folke, 2000), and (c) development of a broader vision for conservation and approaches that move from confrontation to participatory efforts seeking a wide range of benefits (Goldman et al., 2007; Manning et al., 2006; Pejchar et al., 2007; Theobald et al., 2005).

Following this vein, this study aims to investigate the motives and social norms involved in farmers' land use decision-making, with particular focus on the importance of ecosystem services in shaping these decisions. While market-based approaches for managing ES are relatively common (e.g. Ananda and Herath, 2003; Kant and Lee, 2004), actor-oriented analyses are far more scarce (Koellner et al., 2008; Sell et al., 2006; Sell et al., 2007). Dealing specifically with ES supply from agricultural landscapes, Antle and Valdivia (2006) addressed the topic from a financial perspective and created a production model based on the spatial distribution of opportunity costs for providing ES. Likewise following economic rationale Wossink and Swinton (2007) examined farmers' willingness to supply non-marketed ES in dependence on their jointness in production with other agricultural commodities. Vignola et al. (2010), in contrast, included more than monetary motives and modelled decisions about soil conservation measures based on farmers' beliefs and knowledge, risk perceptions, values, and a set of socioeconomic characteristics. There are further studies that deal with topics along these lines, such as farmers' management of riparian zones and field boundary vegetation, even though the findings of these studies are not related to ecosystem services as a concept (Fielding et al., 2005; Morris et al., 2002).

Despite the well-proven applicability of behavioural studies for analyzing policy programs and the steadily growing recognition of ecosystem services as a powerful program for the future, these two approaches have hardly been combined. Existing literature that uses behavioural approaches rarely addresses ES as a driver for agricultural land use decision-making. The ones that do either follow different methodologies, seldom consider more than one service simultaneously, or deal with the topic on a conceptual basis. This study strives to fill this gap by putting several ecosystem services into the focus of a behavioural analysis about farmers' decision-making. It examines the role of four services, namely primary production, flood regulation, water purification and biodiversity with respect to their influence on farmers' decisions to plant rice, annual dryland crops, or perennial crops, respectively. The approach is implemented in a watershed dominated by agricultural land use in South Korea, where most policy measures to mitigate environmental degradation show little success. In this context, the attempt to elucidate determinants of farmers' decision-making is based on the following hypotheses: farmers with more positive attitudes[1] towards the aforementioned ecosystem services are more likely to decide (1) to plant perennial crops instead of rice or annual crops, and (2) to implement organic farming instead of conventional farming. Although studies from the same field of investigation underline the importance of these variables (see Fielding et al., 2005; Schwenk and Möser, 2009), these hypotheses were above all

[1] The term attitudes refers to one component of the Theory of Planned Behavior (Ajzen, 1991), which constitutes the theoretical framework for this study. A detailed description is given in the methodology chapter.

chosen in accordance with the characteristics of the study area, as will be described in detail hereafter.

2.3. Study area and background

2.3.1. Environmental policy in South-Korea

Similar to the trends in the European Union, South Korea started attempts to gear its agricultural production towards multifunctionality as of the mid-1990s. Policy reforms were introduced that aimed at promoting environmentally friendly farming by means of certification schemes, promotion acts as well as various kinds of direct payment schemes. The largest part of the latter's total budget was spent on behalf of paddy rice production, which accounted for as much as 97% in 2005 (Im and Lee, 2007). This underlines the tremendous role that paddy rice cultivation has played in South Korea's agricultural production ever since. For hundreds of years it has been forming the backbone of economic, social and cultural life, with benefits going beyond what monetary scales alone can reflect (Groenfeldt, 2006). It therefore serves as good example why productive functions of agriculture in South Korea cannot be seen separate from various environmental and sociocultural functions.

Modern-day mainstream agricultural practices, however, pursue economic returns as paramount objective, while most other functions are neglected. As a result, farming often comes along with severe environmental degradation. Most prominent damages in this context are water related, hence soil erosion, water quality and water supply are issues topping the list of budget allocations by the Korean Ministry of Environment. One approach to improve water management is the Four Major Rivers Project, which supports measures to ensure ample water supply, prevent floods, improve water quality and restore ecosystems (Moon, 2004). Among these four rivers is the Han River, which carries freshwater to Korea's capital Seoul and is the fourth longest of the country. In order to restore its water quality level, watersheds contributing most to the pollution of the Han River and its tributaries are a main target of water improvement initiatives.

2.3.2. Study area Haean watershed

The present study was conducted in Haean, a 64 km² basin designated as pollution hot spot by the Korean government (longitude 128° 5' to 128° 11' East and latitude 38° 13' to 38° 20' North). This catchment in Yanggu County, Gangwon Province, contributes to the Soyang River, which feeds one of the two main tributaries of the Han River. The kettle-like topography of Haean Basin has a range in altitude from 500 to 1,100 m a.s.l. and the area's appearance can best be described by its local name 'Punch Bowl'. Land use is dominated by agricultural production, which accounts for approximately 40% of the area. Another 55% are forests while the rest is mainly residential area (Korean Ministry of Environment, personal communication). Crop distribution roughly follows the terrain's gradient: from rice paddies in the flat core areas to dryland crops and some sites of perennial crops in the steeper outskirts, until finally land cover changes to forest on the rims of the catchment where steepness precludes agricultural activities. Besides rice the main dryland crops are radish, cabbage and potato, whereas perennial crops are mostly Ginseng, various fruit tree varieties and Bonnet Bellflowers (*Codonopsis* spec.).

With Haean's lower boundary of upland forest being continuously pushed uphill to make room for agricultural land uses, former forest soils on the slopes are rendered vulnerable to erosion processes. Especially during heavy rain events in monsoon season, soil loss can be tremendous and streams get heavily loaded with eroded sediment. To compensate the loss from their fields farmers often add sandy soil as new top layer, since it is especially well suited for growing root crops. At the same time, however, it is very prone to abrasion, hence the cycle of soil loss and renewal starts over again. Although farmers are aware of their large contribution to water pollution and the associated consequences, initiatives by the Korean government to change their behaviour or mitigate the consequences show little success. Policy programs are often considered useless, legal prohibition of soil addition is widely disregarded, and officially endorsed soil loss prevention facilities seldom built (Environment, Culture and Tourism Bureau of Gangwon, personal communication).

Most recent governmental endeavours aim at fostering organic farming and introducing perennial crops, which are deemed less environmental harmful both in general as well as with respect to water related issues, which is of particular importance for Haean watershed. The permanent rooting of perennial crops is supposed to stabilize the soil the whole year round, hence reducing erosion. The restricted use of chemical fertilizer and pesticides in organic farming, on the other hand, is presumed to decrease water pollution. What makes these endeavours very promising is their potential to generate mutual benefits; not only do they seem capable of mitigating environmental problems, but they can also present viable land use options for farmers. In order to promote these options, however, it is of great importance to understand the rationale of farmers who decide whether to implement them or not. Therefore, emphasis was put on the relation between ecosystem services and farmers' decision-making with respect to perennial crops and organic farming in the hypotheses of this study.

2.4. Methodology

The term behavioural in this study is used in the sense of Burton (2004), who defines studies following this approach as those that (a) seek to understand the behaviour of individual farmers directly responsible for land management, (b) focus on psychological constructs such as attitudes, values and goals, but also commonly gather additional relevant data on farm structure, economic situation, etc., and (c) employ largely quantitative methodologies, in particular psychometric scales such as Likert-type scaling procedures for investigating psychological constructs. Thus, a team of five Korean assistants worked in two groups which either visited randomly selected homes of Haean farmers, or interviewed randomly addressed farmers on the streets and around agricultural plots, respectively. Following this procedure it was possible to collect a total of 220 interviews after six days of sampling.

The questionnaire consisted of 33 questions divided into two parts; one comprising 9 general and the other up to 24 behavioural questions. General questions asked about place of residence, years of farming experience, age, gender, and highest scholar education. Approximate yearly household income was asked on a 6-point ordinal scale ranging from less than 10M Korean Won to more than 50M Korean Won per year (approximately 8,600 and 43,200 USD, respectively). Another set of questions addressed the specific types of cultivated crops, which served as basis for dividing respondents into rice, annual and perennial crop farmers for testing hypothesis 1. Furthermore, farmers were asked whether they grow their crops organically or conventionally to build the respective groups for testing hypothesis 2.

Depending on which crop type(s) farmers actually cultivated, they were asked the respective behavioural questions in the second part of the questionnaire. The questions' structure was adapted from the Theory of Planned Behaviour (TPB) (Ajzen, 1991), which measures intentions to engage in a behaviour based on three components: attitudes towards the behaviour (*A*), perceived behavioural control (*PBC*), and subjective norms (*SN*). Computation of the magnitude of these components follows an expectancy-value calculus, which multiplies one belief based measure with one personal evaluation measure. Thus, attitudes are determined by the product of the outcome belief strength (*ob*) about the subjective probability that a given behaviour (*i*) will produce a certain outcome, and the outcome evaluation (*oe*) which reflects the personal utility derived from the occurrence of that outcome ($A=ob_i*oe_i$). In a similar fashion perceived behavioural control consists of control belief strength (*cb*) multiplied with perceived power of control (*pc*) ($PBC=cb_i*pc_i$), and finally subjective norms are obtained from the product of normative belief strength (*nb*) and motivation to comply (*mc*) ($SN=nb_i*mc_i$) (figure 2.1). In other words, strong intentions to engage in a behaviour depend on a positive outcome evaluation of performing the behaviour, the appreciation of important reference persons who determine social norms associated with the behaviour, and volitional control over the behaviour's performance.

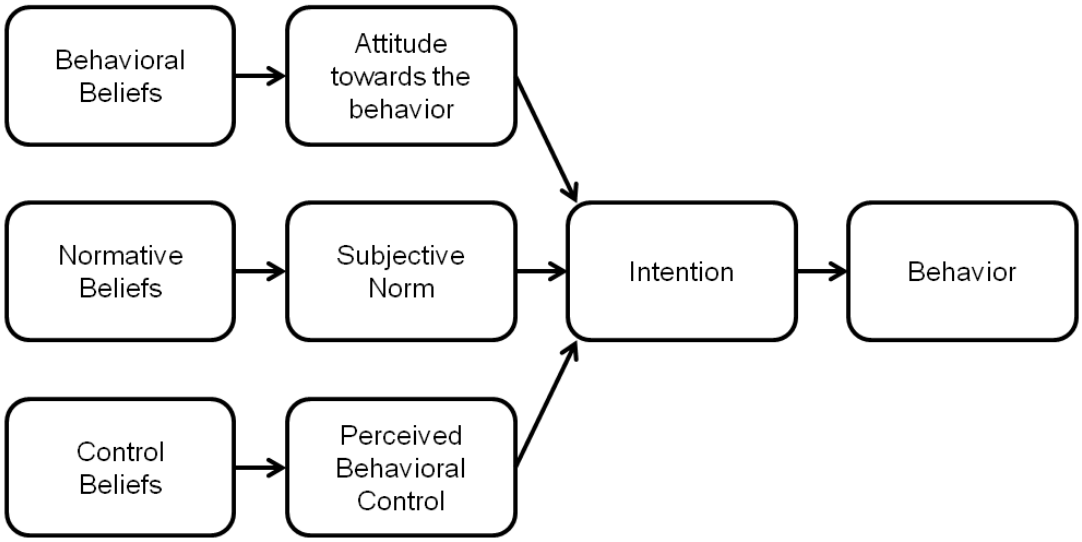

Figure 2.1: Components of the Theory of Planned Behaviour (adapted from Ajzen, 2006).

Following recommendations by Ajzen (2006) salient beliefs associated with the behaviours under consideration were elicited during a pre-survey field trip. Interviews with five government officials and twelve farmers were used to identify the four most important attitudes, control factors, and reference groups in terms of cultivating rice, annual and perennial crops, respectively. The most frequently named attitudes associated with farmers' crop choice were towards the ecosystem services (A1) biomass production, (A2) prevention of soil erosion, (A3) improvement of water quality, and (A4) plant and animal conservation. The most influential control factors were (PBC1) availability of money, (PBC2) skills and knowledge, (PBC3) physical plot characteristics (soil quality, water availability, temperature, and slope), and (PBC4) given legislation. Finally, social reference groups identified as having stakes in crop choice turned out to be (SN1) household members, (SN2) fellow farmers, (SN3) people living further down the river outside Haean, and (SN4) environmental protection agencies.

All questions following the TPB were measured on fully anchored 5-point unipolar Likert-type scales with a range from 1 to 5. Scale anchors gave a verbal description of the possible response options. The question for measuring outcome belief strength about the effects of planting one of the crop types on each of the ecosystem services was 'Does planting [rice; annual crops; perennial crops] in Haean lead to [(A1) high biomass production; (A2) a prevention of soil erosion; (A3) improvement of water quality; (A4) conservation of plants and animals]?'. The corresponding response options were described as: (1) very unlikely, (2) rather unlikely, (3) not sure, (4) rather likely, and (5) very likely. The corresponding outcome evaluation was formulated as 'How important is the effect of planting [rice, annual crops, perennial crops] in Haean on [A1-A4] for you personally?'. Wording for the scale anchors were: (1) very unimportant, (2) unimportant, (3) irrelevant, (4) rather important, and (5) very important. Questions about perceived behavioural control measured control belief strength by asking 'How much is planting [rice, annual crops, perennial crops] in Haean restricted by [PBC1-PBC4]?'; and 'How much do you personally feel prevented from planting [rice, annual crops, perennial crops] by [PBC1-PBC4]?' for perceived power of control. Social norms were elicited with the questions 'How much is planting [rice, annual crops, perennial crops] in Haean appreciated by [SN1-SN4]?' for normative belief strength; and 'How much do you personally care about the appreciation of [SN1-SN4] to plant [rice, annual crops, perennial crops]?' for motivation to comply. Wording for the response options to all latter questions was: (1) very little, (2) rather little, (3) moderately, (4) rather much, and (5) very much.

All statistical computations were done using R version 2.14.1 (R Development Core Team, 2011). Logistic regression analysis was applied for hypothesis testing, as it allows predicting the discrete outcomes of both dichotomous or polytomous dependent variables from a set of categorical or continuous independent variables. In logistic regression models the log odds (or logits) of outcomes of the dependent variable are modelled as a linear combination of the independent predictor variables. The corresponding model equation can be written as $logit(p)=log(p/1-p)=\beta_0+\beta_i X_i$, where p is the probability of one particular outcome of the dependent variable, β_0 the model's constant or intercept, β_i the parameter estimate for the ith independent predictor variable, and X_i the vector of independent variables. In order to obtain predicted probabilities of the dependent variables the model equation can be rearranged into $p=exp(\beta_0+\beta_i X_i)/1+exp(\beta_0+\beta_i X_i)$.

The multinomial form of logistic regression analysis was used for testing the significance of differences in behavioural scores between farmers' decisions to plant rice, annual and/or perennial crops (hypothesis 1). Since analysis focuses on differences between decisions rather than individuals, answers of farmers belong to different groups when they cultivate more than one crop type. Binomial logistic regression analysis was used for testing differences between organic and conventional farmers (hypothesis 2). These groups were built irrespective of which crop type a farmer chose to grow. Thus, the group of organic farmers contains data of those who decided to grow all their rice, annual and/or perennial crops organically. Again, answers of farmers who decided to grow one of their crop types organically and the other conventionally belong to different groups. Answers of farmers who apply both cultivation methods for the same crop type were excluded.

Since final behavioural scores are the result of multiplying two 5-point scales, their maximum value is 25. In order to ease graphical interpretation of the results these final scores were re-projected onto a 5-point scale by dividing them by 5. In case of the binomial regression (hypothesis 2) only two categories are compared. Thus, regression coefficients describe the change in log odds of implementing conventional farming versus implementing organic farming. In the multinomial regression (hypothesis 1), however, there are three categories to be compared, which is why the category of perennial crop farmers was chosen as a baseline. Accordingly, regression results refer to the change in log odds of choosing perennial crops versus choosing rice, and of choosing perennial crops versus choosing annual crops. Wald statistics were used to test the significance of each independent variable, while odd ratios ($exp(\beta_i)$) were compiled to illustrate how the relative ratio of odds changes with the independent variable in question. For testing whether the final regression models perform significantly better than just a null model with intercept only, likelihood ratio tests were applied.

Furthermore, latent class regression modelling was used to reveal underlying, unobserved latent variables that explain patterns among observed manifest data. Latent class models probabilistically group observations into latent classes, in order to subsequently calculate expectations about the response of that observation on each manifest variable. That way, observations with similar sets of responses are clustered within the same latent class. In the basic form of these models, the same probability of belonging to each latent class prior to observing the responses is attributed for every observation. As soon as covariates are included for latent class regression modelling, however, prior probabilities change by individual as a function of the set of concomitant variables (Linzer and Lewis, 2011). Latent class analysis is similar to cluster analysis in that it can be used to find basic groups within a set of cases sampled on several variables. Its advantage over cluster analysis, however, is its high suitability for analyzing ordinal scale data such as that derived from Likert-scales. In this study, the R package 'poLCA' was used to run the latent class analysis for polytomous variables. The estimation algorithms of poLCA were run several times for every model to avoid local maxima solutions.

2.5. Results

A total of 220 respondents gave complete answers to the behavioural questions about at least one of the investigated crop types. They had a mean age of 56 years and an average of 30 years experience in farming. The vast majority was male (97%) and had their place of residence in Haean (98%). 37% of respondents belonged to income class 1 (less than 10M Won), followed by class 2 (10M to 20M Won) with 20% and class 3 (20M to 30M Won) with 14%. The rest was distributed over classes 4 to 6 with 7%, 10% and 12%, respectively. 37% of farmers finished primary school, 20% secondary school, 14% high school and 8% graduated from a university. The residual 22% indicated to have no or other forms of scholar education. The 220 interviews contained 125 answers for rice growing, 143 for dryland crops and 87 for perennial crops. About 67% apply conventional cultivation methods for rice and annual crops, and 23% for perennial crops.

A strikingly high number of 56% of perennial crop farmers, however, did not answer the question about cultivation method (table 2.1).

Table 2.1: Total number of datasets for each crop type and percentage share of answers about cultivation method.

	Rice (n=125)	**Annuals (n=143)**	**Perennials (n=87)**	**All crops (n=355)**
Cultivation method [%]				
Conventional	65	70	23	56
Organic	16	21	21	19
Both	5	3	0	3
No answer	14	6	56	22

Mean scores of attitudes towards ecosystem services show that plant and animal conservation ranks lowest for all farmers. Money availability and plot characteristics are among the most important behavioural control factors, while household members and fellow farmers are the most influential social reference groups. Downstream people and environmental protection agencies, in contrast, are of lowest importance to all farmers. Interestingly, mean scores of perennial crop farmers are the highest for all attitudes towards ecosystem services and perceived behavioural control factors (table 2.2).

Table 2.2: Means and standard deviations of behavioural scores separated by cultivated crop type and cultivation method.

	Rice	Annual crops	Perennial crops	Organic farming	Conventional farming
Attitudes towards behaviour					
Biomass production	2.5 (1.04)	2.79 (1.11)	3.63 (1.11)	2.69 (1.11)	2.86 (1.12)
Soil loss reduction	2.81 (1.3)	1.9 (1.17)	3.32 (1.38)	2.41 (1.47)	2.42 (1.36)
Water quality improvement	2.71 (1.14)	1.87 (1.03)	3.01 (1.31)	2.46 (1.32)	2.35 (1.19)
Plant and animal conservation	1.74 (1.14)	1.62 (1.05)	2.06 (1.43)	1.82 (1.3)	1.68 (1.09)
Perceived behavioural control					
Money availability	3.26 (1.57)	3.87 (1.34)	4.09 (1.16)	4.04 (1.29)	3.54 (1.5)
Skills and knowledge	1.5 (1.02)	1.78 (1.2)	3.24 (1.45)	1.88 (1.33)	1.82 (1.28)
Plot characteristics	2.34 (1.37)	2.45 (1.47)	2.9 (1.44)	2.35 (1.5)	2.41 (1.38)
Given legislation	2.06 (1.52)	1.98 (1.48)	2.14 (1.46)	2.07 (1.44)	2.02 (1.52)
Social norms					
Household members	3.04 (1.48)	2.87 (1.45)	3.01 (1.48)	2.99 (1.54)	3.02 (1.42)
Fellow farmers	2.22 (1.18)	2.24 (1.31)	2.1 (1.15)	2.18 (1.3)	2.27 (1.23)
Downstream people	1.3 (0.61)	1.21 (0.49)	1.51 (0.99)	1.31 (0.63)	1.31 (0.64)
Environmental protection agencies	1.28 (0.66)	1.26 (0.61)	1.59 (1.01)	1.35 (0.82)	1.31 (0.67)

Backward stepwise elimination of insignificant factors in the multinomial regression analysis resulted in a final model including biomass production, soil loss reduction, water quality improvement, skills and knowledge, and money availability as significant regression factors for crop choice ($Chi^2=211.35$, $p<0.001$) (table 2.3).

Table 2.3: Multinomial regression results of the final model for farmers' crop choice. Presented are significant results with the group of perennial crop farmers as baseline category (Chi²=211.35, p<0.001).

	Rice				Annual crops			
	β (*std. err.*)	Wald's Chi² (*df*=1)	*p*	e^{β}	β (*std. err.*)	Wald's Chi² (*df*=1)	*p*	e^{β}
Intercept	6.742 (0.998)	6.759	.000	---	7.091 (0.996)	7.121	.000	---
Attitudes towards behaviour								
Biomass production	-0.915 (0.165)	-5.533	.000	0.4	-0.555 (0.158)	-3.509	.000	0.574
Soil loss reduction	-0.274 (0.145)	-1.891	.058	0.759	-0.682 (0.145)	-4.706	.000	0.505
Water quality improvement	0.117 (0.156)	0.752	.451	1.125	-0.476 (0.161)	-2.961	.003	0.620
Perceived behavioural control								
Money availability	-0.269 (0.132)	-2.027	.042	0.763	-0.099 (0.135)	-0.733	.463	0.905
Skills and knowledge	-0.963 (0.144)	-6.689	.000	0.381	-0.657 (0.125)	-5.235	.000	0.518

All of the regression factors are positively correlated with farmers' decisions to plant perennial crops, i.e. an increase in the predictor variable is always associated with a significant decrease in the log odds of planting rice and/or annual crops versus planting perennial crops. This relation applies to both rice and annuals in terms of attitudes towards biomass production, and the perceived behavioural control factor skills and knowledge. Yet it only holds with respect to annuals when looking at the ecosystem services soil loss protection and water quality improvement. An increase in the perceived behavioural control factor money availability, on the other hand, is only associated with a significant decrease of the log odds for rice cultivation.

An illustration of the predicted probabilities for crop choice in dependence on farmers' attitudes towards ecosystem services is given in figure 2.2, which allows a more intuitive way of interpreting the regression results with respect to hypothesis 1. It displays how predicted probabilities change over the full attitudinal scale towards one ecosystem service, while attitudes towards the respective other services are being held constant at a value of 3. Thus, farmers with high attitudes towards biomass production are more likely to plant perennial crops instead of rice or annual crops, while farmers with high attitudes towards soil loss reduction and water quality improvement are more likely to plant perennial crops than annual crops.

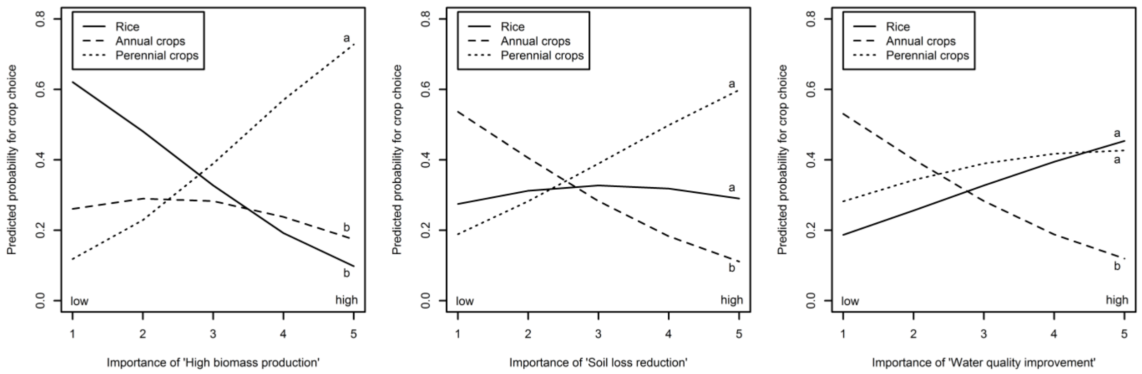

Figure 2.2: Predicted probabilities of choosing rice, annual crops or perennial crops in dependence on attitudes towards the ecosystem services biomass production, soil loss reduction, and water quality improvement. Letters indicate statistically significant differences (p<0.05).

Separating answers by cultivation method (organic vs. conventional) resulted in 68 datasets for organic and 200 for conventional farming. The only significant difference after stepwise elimination in binomial regression is found with respect to restrictions by money availability ($Chi^2=6.24$, $p<0.05$), where an increase of the latter's behavioural score leads to a decrease in the log odds of farmers being conventional versus organic by -0.255 (table 2.4).

Table 2.4: Binomial regression results of the final model for farmers' choice of cultivation method. Presented are significant results for conventional versus organic farming ($Chi^2=6.24$, $p<0.05$).

	β (*std. err.*)	Wald's Chi^2 (*df*=1)	*p*	e^{β}
Intercept	2.049 (0.441)	4.641	.000	---
Perceived behavioural control				
Money availability	-0.255 (0.106)	-2.403	.016	0.775

As the focus of this paper lies on decision-making with respect to ecosystem services, latent class modelling was applied to the four ES summarized under attitudes towards the behaviour. Best goodness of fit according to Akaike information criterion was found when running the model with 2 latent classes and including soil erosion, water quality, and plant and animal conservation. Class 1 summarizes observations with a high probability of loading low on the behavioural scores, thus indicating a negative attitude towards the considered ecosystem services. Class 2 groups together those likely to hold a positive attitude. Probabilities of respective class membership are 0.67 for class 1 and 0.33 for the second class (figure 2.3).

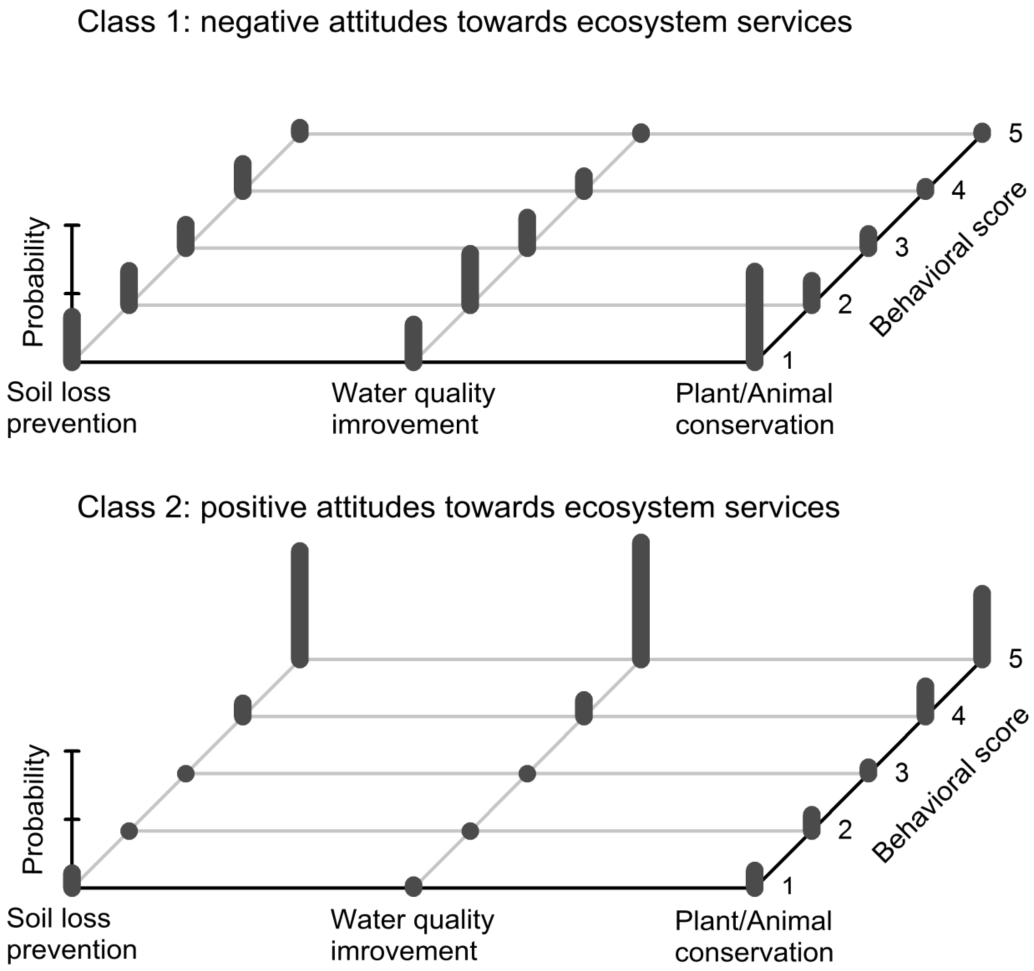

Figure 2.3: Probability distributions of behavioural score values for the latent classes of 1) negative, and 2) positive attitudes towards the ecosystem services soil loss reduction, improvement of water quality, and conservation of plants and animals.

In addition to merely differentiating groups, latent class regression modeling reveals factors that can predict class membership. None of the gathered additional data (place of residence, years of farming experience, age, gender, scholar education) changed much of the observed probability distributions for class membership when used as regression factors. However, using income level yielded a possible explanation for the differences between farmers with negative and those with positive attitudes towards the ecosystem services displayed in figure 2.3. Plotting the probabilities of class memberships over the investigated income levels shows that with increasing income the probability of belonging to class 1 (negative attitude) decreases, while it increases for class 2 (positive attitude) (figure 2.4). Starting at the lowest income level with probabilities of approximately 0.8/0.2 for holding negative over positive attitudes, the income effect changes this relation at a point after income level 5 where probabilities equal about 0.5.

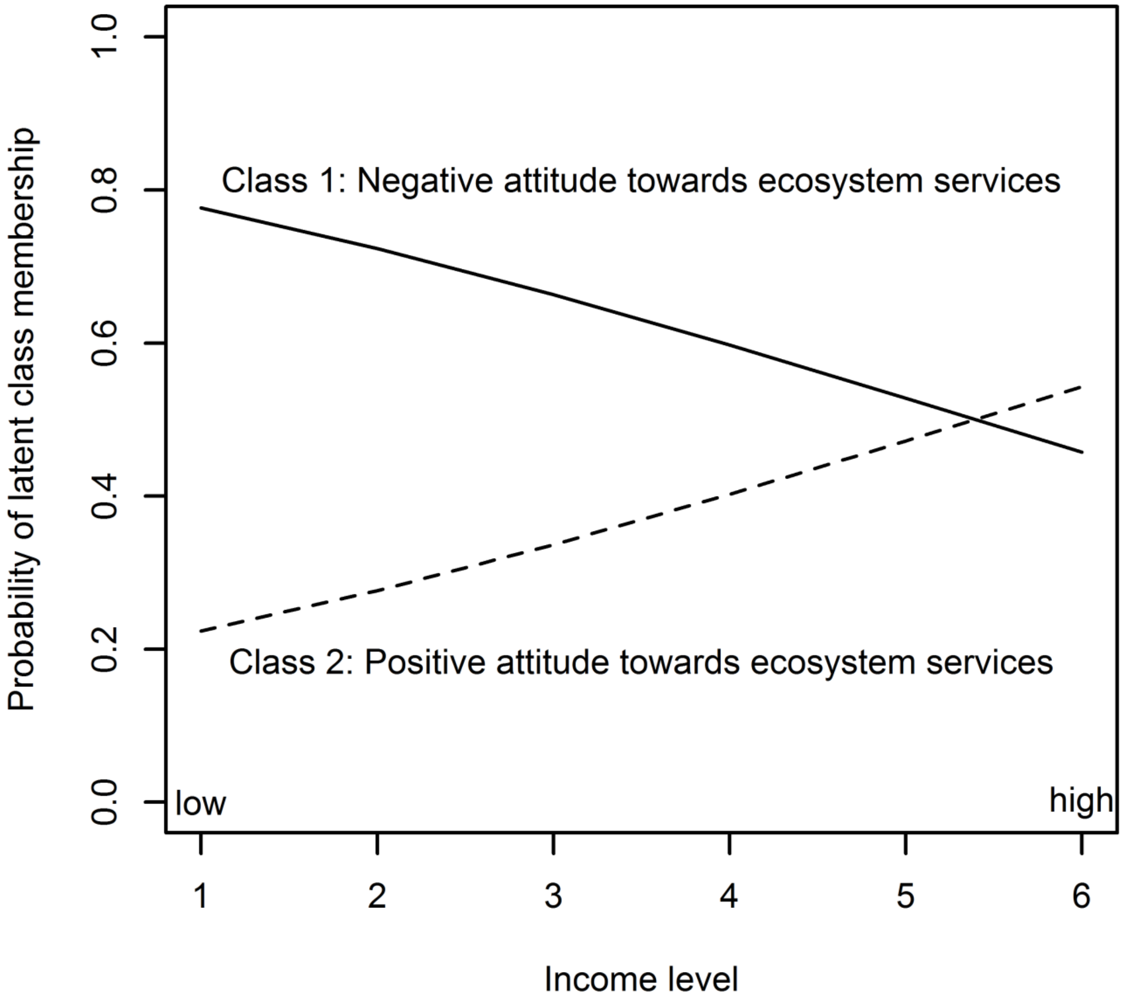

Figure 2.4: Latent class regression model with income level as predictor of membership to classes 1) negative attitude, and 2) positive attitude towards the ecosystem services soil loss reduction, improvement of water quality, and conservation of plants and animals.

2.6. Discussion

The significant differences between farmers of the three different crop types confirm our first hypothesis. Decisions to plant perennial crops are significantly influenced by high attitudes towards ecosystem services. This is especially striking in comparison to the behavioural scores for annual crops, which except for plant and animal conservation rank lower on all other services. Results pointing into a similar direction were obtained by Zubair and Garforth (2006), who found that beliefs about farm level tree planting in Pakistan were underpinned by positive attitudes such as economic benefits and environmental friendliness. Indication why perennial crops are not yet cultivated more extensively in Haean watershed comes from the results for farmers' perceived behavioural control. Perennials score significantly higher with respect to restrictions by money availability, which might be due to the lack of monetary returns in the initial years of implementation. They are also perceived as being most demanding in terms of required skills and knowledge, probably because they are no traditional crop of the research area and farmers are largely inexperienced with their cultivation. Growing perennial crops thus seems to be encouraged by a positive attitude towards ecosystem services, but it has to come along with required financial and technical capacities.

No significant differences turned out between attitudes towards organic and conventional farming, which disproves our second hypothesis. Organic farming does not seem to be chosen out of an environmental concern. What rather seems to influence farmers' environmental attitude is their income level, as shown in the latent class regression analysis. Best model fit was found when biomass production is omitted, which is the only one of the considered ES that is directly compensated monetarily on markets. Thus, it seems that only the wealthiest farmers can afford to consider environmental issues. This idea is further supported by the higher financial restrictions that were indicated for organic farming. This outcome contradicts observations in the study of Battershill and Gilg (1997) where personal attitudes about environmentally friendly farming mostly dominated pure profit maximization endeavours, even for farmers under financial constraints. However, the given study's datasets for organic versus conventional farming largely lack answers by perennial farmers (see table 2.1). Since they hold the highest attitudes towards ecosystem services their responses supposedly would have had great influence on the results.

In the end, it seems to be mainly finances that decide about farmers' attitudes towards ecosystem services and their choice of crop type and cultivation method. As soon as there is a sufficient monetary foundation, farmers can start considering environmental effects of their agricultural production, rather than first and foremost caring about their monetary returns. This might also explain the higher importance of the ecosystem services biomass production, soil loss reduction and water quality improvement in comparison to plant and animal conservation. Produced biomass is evaluated monetarily via market prices, thus changes in production are directly reflected by farmers' income. Although there is no market available for soil loss and water quality, they nevertheless have income effects which can be seen rather immediately by farmers as both are likely to change agricultural production costs. Translating the conservation of plants and animals into monetary returns, however, is more difficult and might therefore be of lower importance for farmers who seek economic profit above all.

According to the results of this study, policy makers interested in changing agricultural practices in Haean should primarily focus on programs that deliver economic incentives. Both cultivation of perennial crops as well as organic farming are significantly impeded by monetary restrictions, thus financial support seems most promising if these practices are to be fostered. One approach could be the establishment of payments for ecosystem services, which are most attractive in areas where ES providers are low-income landholders (Engel et al., 2008). Potential demanders especially for the water related services of reduced soil loss and improved water quality could be found in areas further downstream outside Haean, where several hydropower and drinking water companies are situated. Instead of spending money for clearing the reservoirs of their dams or sanitizing polluted water, they could pay farmers for reducing the sediment and chemical loads from their fields.

2.7. Conclusion

By using a behavioural instead of a purely economic approach the aim was to reveal determinants of land use decisions that reflect more than monetary incentives. While the method itself worked well, the results still point towards economic rationales in the end. Apart from factors either directly (e.g. biomass production, money availability) or indirectly (e.g. soil loss, water quality) linked to monetary issues, only plot characteristics and household members had a noteworthy influence on farmers. However, these influences held for all considered groups and did not allow for differentiating between farmers' crop choice. These findings give limited support to studies calling for an increased consideration of social norms in the context of incorporating ecosystem services into environmental decision-making; at least for the decision factors and the given context of this study where environmental behaviour was above all influenced by farmers' income. They rather emphasise the importance of economic incentives as provided by schemes like payments for ecosystem services.

2.8. Acknowledgments

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2.9. Literature

Ajzen, I., 1991. The theory of planned behavior. Organizational behavior and human decision processes 50, 179-211.

Ajzen, I., 2006. Constructing a Theory of Planned Behavior Questionnaire. Icek Ajzen (accessed 06/24/2011 at http://www.people.umass.edu/aizen/pdf/tpb.measurement.pdf).

Ananda, J., Herath, G., 2003. Incorporating stakeholder values into regional forest planning: a value function approach. Ecological Economics 45, 75-90.

Antle, J.M., Valdivia, R.O., 2006. Modelling the supply of ecosystem services from agriculture: a minimum-data approach. Australian Journal of Agricultural and Resource Economics 50, 1-15.

Battershill, M.R.J., Gilg, A.W., 1997. Socio-economic constraints and environmentally friendly farming in the Southwest of England. Journal of Rural Studies 13, 213-228.

Beedell, J., Rehman, T., 1999. Explaining farmers' conservation behaviour: Why do farmers behave the way they do? Journal of Environmental Management 57, 165-176.

Beedell, J., Rehman, T., 2000. Using social-psychology models to understand farmers' conservation behaviour. Journal of Rural Studies 16, 117-127.

Beharrell, B., Crockett, A., 1992. New Age food! New Age consumers! British Food Journal 94, 5-13.

Berkes, F., Folke, C., 2000. Linking social and ecological systems: management practices and social mechanisms for building resilience. Cambridge University Press, 476 pp.

Burton, R.J.F., 2004. Reconceptualising the 'behavioural approach' in agricultural studies: a socio-psychological perspective. Journal of Rural Studies 20, 359-371.

Carr, S., Tait, J., 1991. Differences in the attitudes of farmers and conservationists and their implications. Journal of Environmental Management 32, 281-294.

Daily, G.C., Polasky, S., Goldstein, J., Kareiva, P.M., Mooney, H.A., Pejchar, L., Ricketts, T.H., Salzman, J., Shallenberger, R., 2009. Ecosystem services in decision making: time to deliver. Frontiers in Ecology and the Environment 7, 21-28.

Edwards-Jones, G., 2007. Modelling farmer decision-making: concepts, progress and challenges. Animal Science 82, 783-790.

Ehrlich, P.R., Kennedy, D., 2005. Millennium Assessment of Human Behavior. Science 309, 562-563.

Engel, S., Pagiola, S., Wunder, S., 2008. Designing payments for environmental services in theory and practice: An overview of the issues. Ecological Economics 65, 663-674.

Fairweather, J.R., 1999. Understanding how farmers choose between organic and conventional production: Results from New Zealand and policy implications. Agriculture and Human Values 16, 51-63.

Fielding, K.S., Terry, D.J., Masser, B.M., Bordia, P., Hogg, M.A., 2005. Explaining landholders' decisions about riparian zone management: The role of behavioural, normative, and control beliefs. Journal of Environmental Management 77, 12-21.

Goldman, R.L., Thompson, B.H., Daily, G.C., 2007. Institutional incentives for managing the landscape: Inducing cooperation for the production of ecosystem services. Ecological Economics 64, 333-343.

Groenfeldt, D., 2006. Multifunctionality of agricultural water: looking beyond food production and ecosystem services. Irrigation and Drainage 55, 73-83.

Im, J., Lee, Y., 2007. Progress and Challenges of Direct Payment Programs in Korea Agricultural Sector. Korean Journal of Agricultural Management and Policy 34, 169-195.

Kant, S., Lee, S., 2004. A social choice approach to sustainable forest management: an analysis of multiple forest values in Northwestern Ontario. Forest Policy and Economics 6, 215-227.

Koellner, T., Sell, J., Gähwiler, M., Scholz, R.W., 2008. Assessment of the management of organizations supplying ecosystem services from tropical forests. Global Environmental Change 18, 746-757.

Linzer, D.A., Lewis, J.B., 2011. poLCA: An R Package for Polytomous variable latent class analysis. Journal of Statistical Software 42.

Locke, R., 2006. Decision modeling: Why farmers do or do not convert to organic farming. ISP Collection 325.

Lynne, G.D., Franklin Casey, C., Hodges, A., Rahmani, M., 1995. Conservation technology adoption decisions and the theory of planned behavior. Journal of Economic Psychology 16, 581-598.

MA, 2005. Ecosystems and human well-being: synthesis. Island Press.

Manning, A.D., Fischer, J., Lindenmayer, D.B., 2006. Scattered trees are keystone structures - Implications for conservation. Biological Conservation 132, 311-321.

Midmore, P., Padel, S., McCalman, H., Isherwood, J., Fowler, S., Lamkpin, N., 2001. Attitudes Towards Conversion To Organic Production Systems: A Study Of Farmers In England, Institute of Rural Studies. University of Wales, Aberystwyth, Wales, UK.

Moon, T.H., 2004. Environmental Policy and Green Government in Korea. ekoreajournal (accessed 06/24/2011 at http://www.ekoreajournal.net/upload/html/HTML44039.html).

Morris, C., Potter, C., 1995. Recruiting the new conservationists: Farmers' adoption of agri-environmental schemes in the U.K. Journal of Rural Studies 11, 51-63.

Morris, R., Oreszczyn, S., Stoate, C., Lane, A., 2002. Farmers' attitudes, perceptions and the management of field boundary vegetation on farmland, in: Frame, J. (Ed.), Conservation pays? Reconciling environmental benefits with profitable grassland systems. Proceedings of the joint British Grassland Society/British Ecological Society Conference, University of Lancaster, pp. 105-108

Pejchar, L., Morgan, P.M., Caldwell, M.R., Palmer, C., Daily, G.C., 2007. Evaluating the Potential for Conservation Development: Biophysical, Economic, and Institutional Perspectives. Conservation Biology 21, 69-78.

Pergams, O.R.W., Zaradic, P.A., 2008. Evidence for a fundamental and pervasive shift away from nature-based recreation. Proceedings of the National Academy of Sciences 105, 2295-2300.

R Development Core Team, 2011. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Rogers, E.M., 2003. Diffusion of innovations. Free Press, New York.

Schwenk, G., Möser, G., 2009. Intention and behavior: a Bayesian meta-analysis with focus on the Ajzen–Fishbein Model in the field of environmental behavior. Quality and Quantity 43, 743-755.

Sell, J., Koellner, T., Weber, O., Pedroni, L., Scholz, R.W., 2006. Decision criteria of European and Latin American market actors for tropical forestry projects providing environmental services. Ecological Economics 58, 17-36.

Sell, J., Koellner, T., Weber, O., Proctor, W., Pedroni, L., Scholz, R.W., 2007. Ecosystem services from tropical forestry projects - The choice of international market actors. Forest Policy and Economics 9, 496-515.

Sutherland, L.A., 2010. Environmental grants and regulations in strategic farm business decision-making: A case study of attitudinal behaviour in Scotland. Land Use Policy 27, 415-423.

Sutherland, L.A., 2011. Effectively organic: Environmental gains on conventional farms through the market? Land Use Policy 28, 815-824.

Theobald, D.M., Spies, T., Kline, J., Maxwell, B., Hobbs, N.T., Dale, V.H., 2005. Ecological Support for Rural Land-Use Planning. Ecological Applications 15, 1906-1914.

Vignola, R., Koellner, T., Scholz, R.W., McDaniels, T.L., 2010. Decision-making by farmers regarding ecosystem services: Factors affecting soil conservation efforts in Costa Rica. Land Use Policy 27, 1132-1142.

Willock, J., Deary, I.J., Edwards-Jones, G., Gibson, G.J., McGregor, M.J., Sutherland, A., Dent, J.B., Morgan, O., Grieve, R., 1999. The Role of Attitudes and Objectives in Farmer Decision Making: Business and Environmentally-Oriented Behaviour in Scotland. Journal of Agricultural Economics 50, 286-303.

Wossink, A., Swinton, S.M., 2007. Jointness in production and farmers' willingness to supply non-marketed ecosystem services. Ecological Economics 64, 297-304.

Zubair, M., Garforth, C., 2006. Farm Level Tree Planting in Pakistan: The Role of Farmers' Perceptions and Attitudes. Agroforestry Systems 66, 217-229.

3. Paper 2: A Bayesian network approach to model farmers' crop choice using socio-psychological measurements of expected benefits from ecosystem services

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3.1. Abstract

Models about ecosystem management typically consider benefits from ecosystem services as an output of ecological or biophysical response variables, whose level is defined as a function of different management decisions. This study uses farmers' expected benefits from ecosystem services as input variables in order to model their decision between planting rice, annual crops or perennial crops. Based on the theory of planned behaviour, a Bayesian network is constructed to model crop choice depending on attitudes toward the ecosystem services biomass production, reduction of soil erosion, and water quality improvement. Trade-offs between these decision-making criteria are quantified with elements of the Analytical Hierarchy Process. Results indicate the Bayesian network's capability of using socio-psychological measurements to model decision-making. Especially as an extension to biophysical or economic models, it can serve as powerful tool for grasping the more abstract socio-psychological dimensions of benefits from ecosystem services, and how they translate into the decisions of ecosystem managers.

Keywords: Bayesian network; theory of planned behaviour; ecosystem services; decision-making modelling; Analytical Hierarchy Process

3.2. Introduction

Under the growing recognition of the concept of ecosystem services (ES) (MA, 2005), ecosystem management is becoming an increasingly multilayered task that has to account for the interests of numerous stakeholders. With benefits being derived from both tangible as well as intangible services, management options need to incorporate biophysical, economic and socio-political demands alike. While praised for this multidisciplinary approach on a conceptual level, the idea of ES poses substantial difficulties when it comes to practical application in decision-making. Daily et al. (2009) attribute these difficulties to our poor understanding of the decision-making processes of individual stakeholders, and the lack of integrated research in institutional design and policy implementation. Their suggestions for possible solutions include (i) stakeholder collaboration in order to define which services are important to them; (ii) development of monetary and non-monetary evaluation methods for ES at the decision-making level; and (iii) using flexible, transparent models that can deal with measures of both the biophysical as well as the social values of ES. Technically, modelling such multidisciplinary decision-making problems requires tools that can handle input from various data sources in a comprehensive and efficient manner.

One approach that has drawn considerable attention is the use of Bayesian network (BN) models, which are graphical decision support tools representing causal and correlative relationships between variables based on their conditional probability distributions (Cain, 2001). BN models are used to support ecosystem management decisions in a great number of environmental studies (see Aguilera et al., 2011), where their increasing popularity is mainly due to their (i) explicit way of handling uncertainty and complexity; (ii) ability to incorporate both quantitative and qualitative data; (iii) capability of being easily updated, extended or modified in case new knowledge becomes available; and (iv) their intuitive understandability that facilitates stakeholder communication and engagement (Chan et al., 2012; Smith et al., 2011). However, despite the ample indications that BNs are capable of dealing with challenges such as those put forward by Daily et al. (2009), rather few are actually being geared to the ES concept in particular (Landuyt et al., 2013).

Most of the existing BN models in ES research address one single, typically well-documented, service like genetic resources, recreation, water regulation or food supply

(Landuyt et al., 2013). In doing so, the majority of these models is limited to a natural science perspective and depicts the effects of management decisions for various predictor variables, which in turn influence ecological or biophysical response variables that determine the level of service provision (McCann et al., 2006). Fewer models take a more integrative approach and include factors identified as relevant for decision-making by the involved stakeholders themselves. Typically, this stakeholder information is elicited in consultation workshops where the BN is constructed based upon the viewpoints of every stakeholder group, while conditional probabilities are derived from either raw data, other process-based models or expert opinion (e.g. Barton et al., 2008; Bromley et al., 2005; Cain, 2001; Celio et al., 2012; Chan et al., 2010; Varis and Lahtela, 2002; Zorrilla et al., 2010).

In more multidisciplinary approaches, Ticehurst et al. (2011) added socio-psychological factors and combined social survey results with data describing other factors relevant for farmers' decisions about the fencing of bushland. The BN merging these data sets was constructed with the help of conventional, i.e. non-Bayesian, statistics for the 'other factors' as well as expert opinion in case of the social survey results. Castelletti and Soncini-Sessa (2007) investigated the decision-making process of involved stakeholders by linking hydrological models with a BN representing farmers' choices in terms of cultivated crop type and irrigation technique. Lacking, as they put it, a 'physical law' to determine behaviour, they modelled farmers' choices based on direct interviews that address their reactions to two given actions under different levels of psychological condition. Haines-Young (2011) took another approach and used several case studies for developing two BNs: one mapping the standing crop of vegetational carbon based on land-cover stocks, the other identifying stakeholders' social valuation of different landscape scenarios as a cultural entity.

In conclusion, BNs turned out to be capable of handling the multidisciplinary aspects of the ES approaches in these studies. Moreover, they provided the kind of analytical-deliberative tools that Fish (2011) considered necessary for dealing with the socio-scientific challenges he identified as being inherent to the field of environmental decision-making and ES. Thus, the BN approach is suited for (i) combining analytical rigor with interpretive complexity, (ii) investigating and representing links across knowledge domains in an exploratory manner, and (iii) providing means of communication for generating new ideas and perspectives among new communities of interest (Haines-Young, 2011).

Another challenge put forward by Fish (2011) that has not yet been addressed in a BN approach originates from our limited perception of the relationship between ecosystem services and human well-being. In its current form, the concept of ES considers ecosystems as providers of different services that endow people with benefits contributing to their well-being. In return, human activities induce a cascade of impacts that change the level of service provision (Haines-Young and Potschin, 2010). Human well-being is finally determined in terms of costs and benefits, which are derived as a function of these changes in service provision (Landuyt et al., 2013). This focus on 'services provided', however, omits operational links characterizing how well-being and service provision might be related in the first place (Fish, 2011). Thus, the benefits that ecosystem managers derive from specific ecosystem services are a driving force that is often neglected in analyses about their decision-making.

The study at hand elaborates on this train of thought and models management decisions as a function of expected benefits from ecosystem services by means of a BN approach. Data for populating the model is derived from interviews based on the theory of planned behaviour (TPB) (Ajzen, 1991), a well-established socio-psychological method for decision-making analysis. It was used by Poppenborg and Koellner (2013) to study farmers' decisions in a South-Korean watershed, where the choice between planting rice, annual crops or perennial crops was analyzed as a function of farmers' attitudes toward biomass production, erosion protection and water quality improvement. Furthermore, elements from the Analytical Hierarchy Process (AHP) are used to account for trade-offs between the covered ecosystem services.

The approach presented here aims to show how the relationship between benefits from ES and agricultural decision-making can be operationalised in a BN modelling framework based on socio-psychological data. Drawing upon elements from AHP, it furthermore addresses farmers' priorities among ES benefits, which makes it capable of dealing with ecosystem service bundles. The result can be particularly useful for policy-makers interested in fostering specific services, as it shows the importance of ES for the decisions of those who directly influence service provision. Moreover, the use of a standardized socio-psychological method such as TPB in combination with flexible models such as BNs, allows for repeating and adapting the presented methodology to various decisions and ecosystem services. Thus it can be used as a versatile tool that is adjustable to the respective contexts of different research questions.

3.3. Methodology

3.3.1. Decision-making analysis

Data about farmer decision-making originated from a study in Haean watershed (Poppenborg and Koellner, 2013), South Korea, where agricultural production is associated with severe environmental degradation. Interspersed with plots of perennial crops, the research area's kettle-like topography is dominated by rice paddies in the flat core terrain, while predominantly annual crops are grown on steeper slopes toward the rims of the catchment. Approximate share in the total number or agricultural plots of these land use categories amounted to 23% for rice, 65% for annual crops, and 12% for perennial crops in 2009 (Korean Ministry of Environment, personal communication). The given agricultural land use practices resulted in heavy soil erosion and water pollution, as sediment was washed away during the monsoon season and accumulated in rivers within and outside of the Haean catchment. Political mitigation efforts aim to combat these issues by promoting the cultivation of more perennial crops, which should stabilize soils throughout the year.

In this context, interviews to examine farmers' land use decisions with respect to their choice between cultivating rice, annual crops or perennial crops were conducted in Poppenborg & Koellner (2013). Questions were based on the theory of planned behaviour (Ajzen, 1991), which measures behavioural intentions based on three components: a decision-maker's (i) attitudes toward the behaviour (AttB), which investigate the outcome evaluation of performing the behaviour; (ii) perceived behavioural control (PBC), which addresses the volitional control over performing the behaviour; and (iii) subjective norms (SN), which measure the appreciation of important reference persons associated with the behaviour. Farmers' attitudes, control factors and norms were sampled during a pre-survey field trip, and the four most frequently mentioned items per component were chosen for further investigation. Thus, most frequently mentioned were biomass production, soil loss reduction, water quality improvement, and conservation of plants and animals in terms of attitudes; money availability, skills and knowledge, plot characteristics, and given legislation in terms of control factors; and household members, fellow farmers, people living down the stream outside Haean, and environmental protection agencies in terms of social reference groups. Each of these twelve items was investigated for every crop category a farmer actually cultivated, i.e. up to three times per farmer in case they had rice, annual and perennial crops in their portfolio. This procedure resulted in 220 interviews with 125 data sets for rice farming, 143 for annual and 87 for perennial crops. Answers to the behavioural questions were quantified on fully anchored 5-point unipolar scales ranging from 1 (low) to 5 (high). In addition to the behavioural part, general questions were asked to gather data on the level of education, economic situation, etc.

Multinomial regression analysis in Poppenborg & Koellner (2013) showed that a total of five items had a significant influence on crop choice (n=355, Chi^2=211.35, $p<0.001$). Thus, choosing perennial crops over either rice and/or annual crops was positively correlated with farmers' attitudes toward the ES biomass production, soil loss reduction, and water quality improvement; as well as with their perceived behavioural control over money availability, and required skills and knowledge. In other words, farmers chose perennial crops due to their high potential of producing marketable biomass, as well as their ability to reduce erosion and water pollution. At the same time however, they were seen as the most demanding crops in terms of investment costs and required farming skills. Using information from the general questions as regression factors for farmers' attitudes toward ES, the only observed influence was related to income, which was measured on a 6-point ordinal scale ranging from 1 (less than 10M Korean Won per year) to 6 (more than 50M Korean Won per year). Thus, latent class analysis revealed that higher income levels increased the probability of farmers holding positive attitudes toward soil loss reduction and water quality improvement. A more detailed description of the study can be found in Poppenborg & Koellner (2013).

3.3.2. Bayesian network modelling

Bayesian network construction

Bayesian network construction was done with Hugin® Expert A/S software version 7.3 (www.hugin.com). By definition, BNs are directed acyclic graphs with nodes as representations of discrete random variables, which are characterized by a finite set of mutually-exclusive states. Probabilistic dependencies between variables are indicated via edges, such that every link from one node (A) to another node (B) requires the quantification of a conditional probability table (CPT). While a CPT indicates the probability (P) of a state of 'child' node (B) given the state of its 'parent' node (A) according to *P(B|A)*, nodes without parents are quantified with tables of unconditional (marginal) probability distributions *P(A)*. Probability distributions can be updated in case new information becomes available according to Bayes’ rule $P(b|e)=P(b,e)/P(e)$, where *b* represents a specific state of node B and *e* represents evidence on a parent of B. A detailed description of the mathematical properties of Bayesian networks can be found in Pearl (2009) or Kjaerulff and Madsen (2008).

The structure of a BN can be derived from domain knowledge or data, preferably supported by existing theories or hypotheses (Chen and Pollino, 2012). For the study at hand, only items with significant influence on crop choice according to the theory of planned behaviour analysis in Poppenborg & Koellner (2013) were used as background information. In order to facilitate verbal description of the graphical structure, nodes were stratified horizontally into 5 levels (figure 3.1). Reflecting the result from latent class analysis on level 1, income (‘Income’) is parent node to attitudes toward soil erosion reduction (‘AttB_SE’) and water quality improvement (‘AttB_WQ’). Both of the latter can be found on level 2, together with attitudes toward biomass production (‘AttB_Bio’) as well as perceived behavioural control over money availability (‘PBC_MA’) and skills and knowledge (‘PBC_SaK’). All of them constitute the parents to nodes describing farmers’ crop choice. The creation of these dependencies reflects the significant results from multinomial regression analysis, where crop choice was modelled as a function of all variables on level 2. However, instead of having only one common child node for crop choice, each of these variables is connected to their own node for crop choice on level 3 (‘Crop_Bio’, ‘Crop_SE’, ‘Crop_WQ’, ‘Crop_MA’, ‘Crop_SaK’).

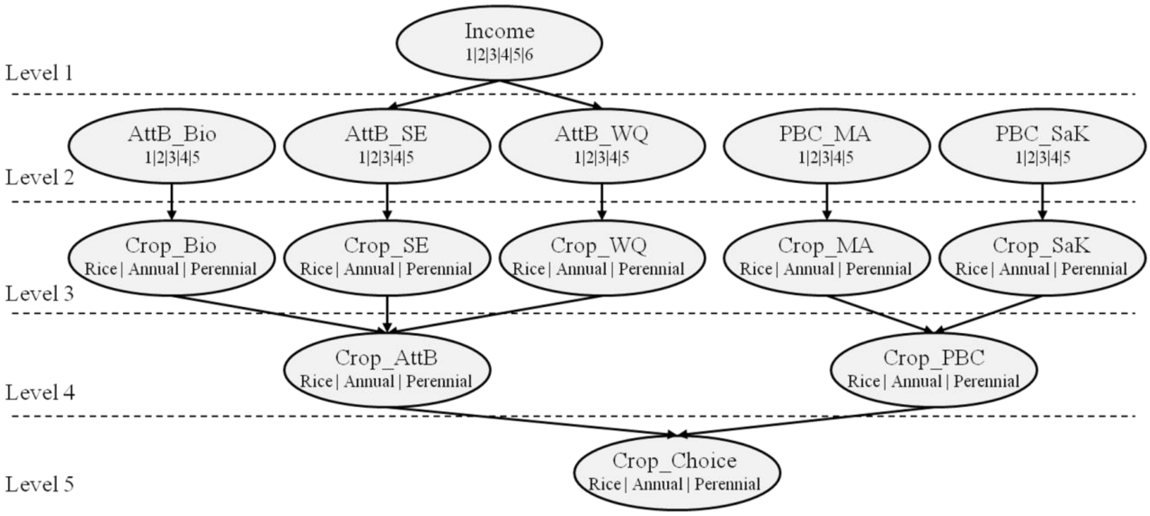

Figure 3.1: Graphical structure of the Bayesian network showing probabilistic dependencies between variables. Nodes contain the name of the variable they represent, as well as all states the represented variable can take on. Abbreviations stand for farmers' attitudes toward the behaviour (AttB) with respect to the ecosystem services biomass production (Bio), soil erosion reduction (SE), and water quality (WQ), as well as farmers' perceived behavioural control (PBC) over money availability (MA), and skills and knowledge (SaK).

This partitioning step allowed for the introduction of nodes that reflect trade-offs between farmers' preferences on level 4. Although not presented in Poppenborg & Koellner (2013), questions about priorities among the decision items were asked as part of the original interviews. They were structured according to the Analytical Hierarchy Process, which is a multiple criteria decision-making analysis method that relies on pairwise comparisons to measure how much more one item dominates another with respect to a given attribute (Saaty, 2008). Initially, AHP requires a pairwise comparison for each combination of items. Thus, farmers were asked to rate the item pairs within each component of the theory of planned behaviour for relative importance on a scale from 1 (much more important) to 5 (much less important). This information was then used to populate a pairwise comparison matrix containing the preference values for each item. After normalization of this matrix, the normalized score of each item was averaged in order to calculate the final priority vector. Based on this process, nodes reflecting the relative importance of each item belonging to attitudes toward the behaviour ('Crop_AttB') and perceived behavioural control ('Crop_PBC') are used on level 4. These nodes allowed for the consideration of farmers' priorities in situations with conflicting preferences. For instance, farmers might most often choose rice due to its small contribution to soil erosion, while annual crops are highly favoured for their high biomass production. Level 4 nodes weight these preferences with the help of priority values from AHP and indicate crop choice based on which item is more important.

Finally, both 'Crop_AttB' and 'Crop_PBC' are parents to node 'Crop_Choice', which represents the probability of farmers' crop choice on level 5.

Bayesian network population

Although it is possible to specify required probability distributions manually, they can also be learnt from data sets with the help of an Estimation-Maximization (EM) algorithm built into Hugin®. The EM algorithm can furthermore be used to estimate distributions for data sets with incomplete or missing observations. The EM learning procedure aims at finding the network with the highest likelihood based on given data by running a sequence of stepwise iterations. First, it uses Bayesian inference to calculate the log-likelihood of an existing network, followed by the maximization of this quantity based on both given and estimated data. This process is repeated until the tolerance threshold of minimum relative improvement between log-likelihoods of two successive iterations is exceeded.

The CPTs of all nodes on levels 1, 2 and 3 were populated using the EM algorithm, which was set to converge at a tolerance threshold of 10^{-4}. The probability tables of nodes on the first two levels were populated by given data, as all marginal and conditional distributions were provided by information from the interviews. However, probability tables on level 3 required information about crop choice depending on each TPB item individually, as opposed to depending on all items together, as provided by the interview data. Therefore, their distributions were estimated by the algorithm. CPTs for nodes on level 4 were populated manually with the results from AHP analysis, which provided priority values of 0.44, 0.29 and 0.27 for biomass production, soil erosion reduction and water quality improvement, and 0.63 and 0.37 for money availability and skills and knowledge, respectively (table 3.1).

Table 3.1: Conditional probability table of node 'Crop_PBC' as an example of how priority values from the Analytical Hierarchy Process were used to weight the importance of different decision items. The percentage probabilities of farmers' crop choice depending on all perceived behavioral control items ('Crop_PBC') are shown, reflecting the importance of restrictions by money availability ('Crop_MA') relative to those by skills and knowledge ('Crop_SaK').

Conditional probabilities of 'Crop_PBC' [%]

'Crop_MA'	Rice			Annuals			Perennials		
'Crop_SaK'	Rice	Ann.	Per.	Rice	Ann.	Per.	Rice	Ann.	Per.
Rice	100	63	63	37	0	0	37	0	0
Annuals	0	37	0	63	100	63	0	37	0
Perennials	0	0	37	0	0	37	63	63	100

The final node 'Crop_Choice' mediates the probability distributions from level 4 similarly to the AHP nodes, but with equally weighted probabilities of 0.5 and 0.5. Based on the hitherto described dependencies and prior probability distributions, the network was compiled and posterior probability distributions for all nodes were computed by propagating the given information.

Bayesian network analysis and validation

Model prediction performance was evaluated by means of confusion matrices contrasting known observations with highest-probability predictions. They were used to display the results of a five-fold cross validation, which characterized performance in terms of classifying land use decisions. Thus, the original data were randomly split into five groups. While four of these groups, i.e. 80% of the data, were used for model population, the fifth was taken as a test group. Information from the test group was then entered into the compiled network as evidence. For this, observed states of all variables on level 2 were instantiated, i.e. they were assigned a 100% probability. This newly entered evidence was subsequently propagated in the network, such that all probability distributions were updated. Entering observations from one farmer at a time, the observed crop category was then compared to the predicted crop category with the highest probability in 'Crop_Choice'. This process was repeated with each of the five groups as test group. Error rates were given in terms of percentage of false predictions and area under the receiver operating characteristic curve (AUC). Another confusion matrix as well as both error rate and AUC were also given for the full model, i.e. the network populated with all interview observations. Furthermore, posterior probabilities for crop choice of the full model were compared to the percentage share of observations per crop type from the interview data, and to the actual numbers of land use distribution in Haean.

Several other analyses were run for further characterization of the network, most of which are related to the measurement of entropy. Entropy describes a variable's randomness by measuring the degree of uncertainty in its probability distribution according to $H(X)=-\sum_X P(X)*logP(X)\geq 0$, where $H(X)$ represents the entropy of a discrete random variable X with n states x_1, …, x_n and probability distribution $P(X)$. Thus, minimum entropy (0) is achieved with all probability mass located on a single state, and maximum entropy (log(n)) with a uniform distribution over all states of the variable. Based on this concept it is possible to derive conditional entropy values, which measure the uncertainty of a hypothesis variable given the observations on another variable. The conditional entropy of X given an observation on a random variable Y is computed according to $H(X|Y)=-\sum_Y P(Y)*\sum_X P(X|Y)*logP(X|Y)$. Finally, mutual information values (also called cross entropy) measure how much information a hypothesis variable shares with another variable. Assuming that X is the random variable of interest, the mutual information I with another random variable Y is computed according to $I(X,Y)=\sum_Y P(Y)*\sum_X P(X|Y)*log(P(X,Y)/P(X)P(Y))$ (Kjaerulff and Madsen, 2008).

Conditional entropy measurements were used to perform evidence sensitivity analysis. The results help find the variables with the highest impact on the hypothesis variable ('Crop_Choice') by showing how much its posterior probability distribution changes due to variations in the probability distributions of other nodes in the network. Mutual information, on the other hand, was used for value of information analysis. It helps identify the variables that contribute most to reducing the entropy of a hypothesis variable, hence being the most valuable to observe in case additional samplings are to be performed.

Furthermore, the BN was used to evaluate a user-specified scenario, which modeled crop choice as a function of evidence about farmers' attitudes toward ecosystem services. Therefore, the most probable state of all nodes describing farmers' attitudes on level 2 was instantiated. This 'average attitude' scenario could, for instance, be of interest to a user interested in modeling crop choice for a land use plot whose owner is unknown. Instead of modeling crop choice given the uncertainties associated with the attitudes toward ES of all farmers, the 'average attitude' scenario models crop choice of a single farmer who represents the most likely attitudes to be observed in the watershed.

3.4. Results

Populating the above described network with the EM algorithm and compiling it in Hugin® resulted in a posterior probability distribution of 36% for rice, 41% for annual crops, and 24% for perennial crops for the final node 'Crop_Choice' (figure 3.2). Using the compiled network to run the 'average attitude' scenario resulted in a probability distribution of 37% rice, 51% annual crops, and 12% perennial crops when 'AttB_Bio', 'AttB_SE' and 'AttB_WQ' were instantiated on states '2', '1', and '2', respectively.

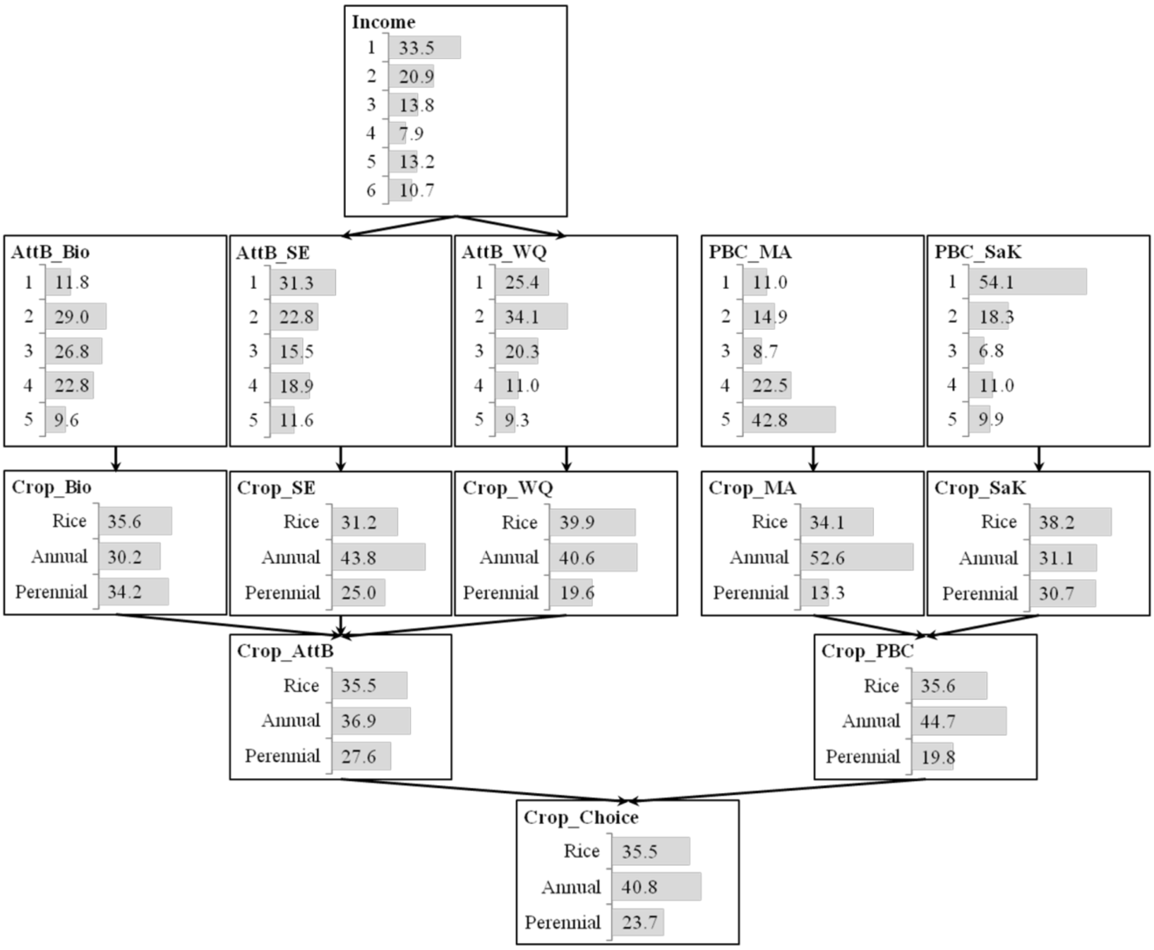

Figure 3.2: Posterior probability distributions [%] of all nodes after network population with the EM algorithm. Abbreviations stand for farmers' attitudes toward the behavior (AttB) with respect to the ecosystem services biomass production (Bio), soil erosion reduction (SE), and water quality (WQ), as well as farmers' perceived behavioral control (PBC) over money availability (MA), and skills and knowledge (SaK).

Looking at the confusion matrix for the five-fold cross validation procedure revealed error rates between 28% and 40%, and AUC values between 0.76 and 0.79. The error rate of the full model amounted to 37% with an AUC value of 0.78 (table 3.2).

Table 3.2: Confusion matrix showing number of observed versus number of predicted values for each crop category, percentage of false predictions (Error rate), and area under the receiver operating characteristic curve (AUC). The results for all test groups of the five-fold cross validation (Group 1 to 5), as well as for the full model with all available data (Full model) are displayed.

		Observed values [n]			**Error rate**	**AUC**
		Rice	Annual crops	Perennial crops		
	Predicted values [n]					
	Rice	16	8	3		
Group 1	Annual crops	8	18	5	38%	0.78
	Perennial crops	1	2	9		
	Rice	12	8	4		
Group 2	Annual crops	13	19	2	40%	0.79
	Perennial crops	0	1	11		
	Rice	14	6	2		
Group 3	Annual crops	10	20	7	35%	0.79
	Perennial crops	1	2	8		
	Rice	20	9	1		
Group 4	Annual crops	3	19	5	28%	0.76
	Perennial crops	2	0	11		
	Rice	15	3	1		
Group 5	Annual crops	8	25	4	28%	0.76
	Perennial crops	2	3	14		
	Rice	72	34	12		
Full model	Annual crops	51	103	27	37%	0.78
	Perennial crops	2	6	48		

Using 'Crop_Choice' as hypothesis variable for evidence sensitivity analysis revealed that both AHP nodes ('Crop_AttB' and 'Crop_PBC') had the greatest influence on the posterior probability distributions for all crop types. They were followed by nodes describing farmers' crop choice based on their perceived restrictions by money availability ('Crop_MA'), their attitudes toward producing biomass ('AttB_Bio'), and their perceived limitations by skills and knowledge ('PBC_SaK') (figure 3.3).

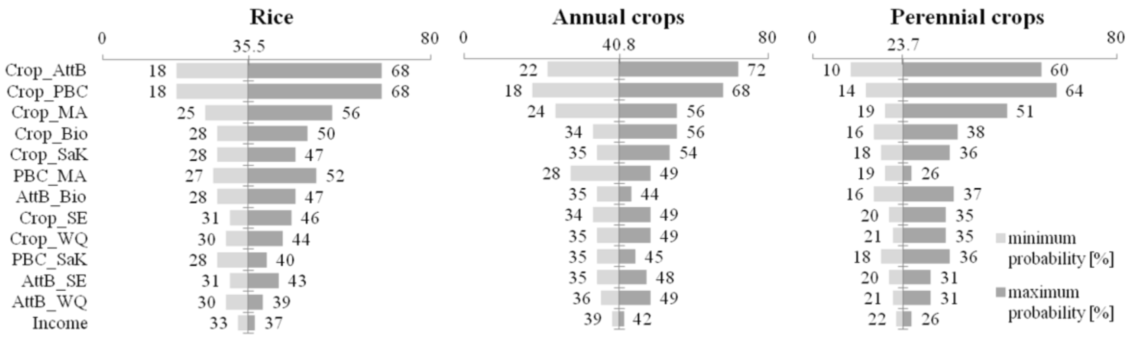

Figure 3.3: Evidence sensitivity analysis results for all three crop categories of node 'Crop_Choice'. Minimum and maximum posterior probabilities [%] due to variations in the probability distributions of all other network nodes are shown. Bars indicate changes relative to the initial posterior probability of every crop category.

The top five variables in value of information analysis were the same as in evidence sensitivity analysis. Thus, variables with the greatest contribution to the reduction of entropy in the probability distribution of 'Crop_Choice' were 'Crop_AttB' and 'Crop_PBC', followed by 'Crop_MA', Crop_Bio' and 'Crop_SaK' (figure 3.4).

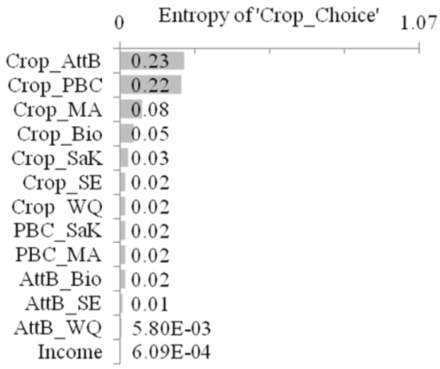

Figure 3.4: Value of information analysis showing the mutual information values of all network nodes in relation to the entropy of 'Crop_Choice' (1.07).

3.5. Discussion

3.5.1. Model validity

Posterior probabilities for crop choice (36% rice, 41% annual crops, 24% perennial crops) are very close to the percentage share of observations from the original interview data (35% rice, 40% annual crops, 25% perennial crops). The model is best at predicting decisions against perennial crops, i.e. it seldom misclassifies rice or annual crops for perennial crops. Its performance with respect to distinguishing between rice and annual crops, however, is less good and contributes most to the error rates between 28% and 40% (see table 3.2). This result confirms the observations in Poppenborg and Koellner (2013) in that socio-psychological factors set apart perennial crop farming from other crop choices. Distinction between rice and annual crops, however, requires additional information and could presumably be improved by extending the network so as to include biophysical data. Using information such as slope, for instance, would facilitate the classification of rice, since a level surface is a crucial prerequisite for its cultivation.

The results of evidence sensitivity and value of information analysis indicate a great influence of the elements from the Analytical Hierarchy Process. Thus, 'Crop_AttB' and 'Crop_PBC' are the most valuable variables to observe in future samplings as they contribute most to entropy reduction, while also being the variables with the highest impact on the posterior probability distribution of 'Crop_Choice'. This large impact is partly due to their immediate adjacency to 'Crop_Choice', as the influence between nodes in a BN decreases with the number of intermediate nodes (Marcot et al., 2006). According to the calculated priority values biomass production was the most important criterion among the investigated attitudes, while money availability had the highest importance among the perceived behavioral control factors. Both results are in line with the trends observed in the multinomial regression analysis in Poppenborg and Koellner (2013).

Looking at the results presented in figure 3.3, the influence of 'Crop_AttB' and 'Crop_PBC' is particularly high for the maximum probabilities of perennial crops, which increase from 24% to approximately 62% (an increase of 160%) compared to an increase from 41% to approximately 70% for annual crops (an increase of 70%). This great importance suggests even closer scrutiny in future research. One way would be to extend the AHP procedure presented in this paper. Thus far, only items within the same category were compared due to restrictions in the maximum length of interviews. Doing pairwise comparisons between items of all categories, however, would allow for evaluating the importance of items from the category of attitudes relative to those from the behavioral control factors. In addition to further improving classification results, this information would also reduce overall model complexity as both nodes on level 4 could be replaced by just one final node that captures the influence of all items on crop choice simultaneously.

As described above, the model in its initial form reasonably represents the underlying interview data in terms of percentage share of observations per crop category.

Yet it does not depict the actual percentage share of agricultural plots in Haean watershed (23% rice, 65% annual crops, and 12% perennial crops). This discrepancy is due to the nature of the interview questions, which investigated socio-psychological factors of farmers' decision-making with respect to every crop category they cultivated. In doing so the questions were not related to specific information on the location and number of plots the decision may be made for. Thus, the model does not allow for allocating the results in a spatially-explicit manner. The uncertainty associated with this lack of geo-spatial reference is mitigated to some degree by the 'average attitude' scenario. By disregarding the more unlikely attitudes, the scenario models crop choice of one hypothetical farmer who represents the most likely observed attitudes. If this average farmer was to decide about crop choice in the watershed, the probability of him choosing perennial crops equals the exact percentage of plots for perennial crops in Haean.

This result indicates the network's capability of reflecting the results from Poppenborg and Koellner (2013) in the sense that it allows for modeling perennial crop choice as a function of farmers' attitudes toward ES. The overall good performance with respect to perennial crops makes the model a powerful tool for political decision-makers in Haean, as the increase of perennial crops is one of their main objectives. The model can provide them with crucial information as to which factors they need to gear their programs toward, as well as to how different scenarios change the percentage share of perennial crops. The less good results for rice and annual crops, on the other hand, point toward the limitations of the approach. Using only socio-psychological information to classify crop choice decisions does not suffice for every crop category. Therefore, the presented work should best be used as an extension to conventional ecosystem management networks, which supplements classification rules based on biophysical information by those capturing socio-psychological factors of decision-making.

3.5.2. Modelling expected benefits from ecosystem services

Measuring attitudes as defined by the theory of planned behaviour reflects the expected benefits an individual associates with the behaviour under consideration. When geared toward benefits associated with ecosystem services, the approach is capable of characterizing the importance of ES for farmers' decision-making (Poppenborg and Koellner, 2013). As indicated by the results presented here, this information can be used to effectively model the influence of expected benefits from ES on ecosystem management decisions in a Bayesian network. One of the approach's distinctive advantages is that it is not restricted to the use of monetary scales for evaluating ES benefits at the decision-making level, which offers the kind of flexibility that is necessary for meeting the multidisciplinary aspects of the ecosystem service concept (Daily et al., 2009). Thus, it allows for incorporating benefits derived from services both tangible as well as intangible in the same modelling environment, possibly even services associated with more abstract sociological and political themes such as those discussed by Fish (2011).

The relative importance between different ecosystem services was handled effectively by using elements from the Analytical Hierarchy Process. In contrast to using only the theory of planned behaviour, adding AHP elements allows for remedying possible effects of a social desirability bias (Handfield et al., 2002). For instance, farmers might state that they care about the reduction of soil loss as it benefits everyone in the watershed. However, when it comes to trading soil loss reduction off against biomass production, its relative importance can be much lower. The AHP can be particularly helpful in situations like that observed in interviews by Mislimshoeva et al. (2012), where farmers attributed the same level of importance to every ecosystem service investigated. Thus, services constituting farmers' means of livelihood like provision of fuelwood or livestock fodder were given the same importance as services such as landscape aesthetics and recreation. Using pairwise comparisons like in the AHP motivates interviewees to reflect critically on their opinions, which can help to reduce uncertainty in the elicitation process (Kuhnert et al., 2010).

Since the ecosystem services covered in this study were selected according to their importance for the decision-makers involved, the approach presented ensures a high level of stakeholder involvement as called for by Daily et al. (2009). Furthermore, using benefits from ecosystem services as a driver for ecosystem management has shown how links between well-being and decisions influencing service provision can be operationalised by means of a Bayesian network. More work, however, would be required to determine the actual influence of the investigated crop categories on the level of service provision. Therefore, the model would need to be coupled with networks covering the biophysical impacts associated with the investigated crop choices. This would make it possible to compare the expected benefits from management decisions with the benefits they actually generate. Being able to identify differences between expected and actual benefits can be a valuable kind of feedback mechanism, which constitutes a basis for stakeholders to discuss possible explanations. Thus, the model can serve as a tool to inform stakeholders of possible misconceptions about the cause-effect relations between intentions and outcome of their management decisions.

As presented in this paper, socio-psychological measurements can be used to model how expected benefits from ecosystem services influence the decisions that determine service provision. In combination with the elements from AHP, this kind of model can be particularly useful for policy-makers interested in fostering specific ecosystem services. Are ecosystem managers interested in the same ecosystem service benefits that are desirable from a societal point of view? Are these benefits important enough for them to guide their management decisions? If not, is it because their interest is simply too low overall, or is it only too low in comparison to benefits from other services? Being able to address such questions can be of great assistance in delivering the starting points for the formulation of effective policy programs.

3.6. Conclusion

The paper at hand illustrates how Bayesian networks can be used to model the role of expected benefits from ecosystem services as drivers for farmers' crop choice decision-making. Drawing upon socio-psychological measurements from the theory of planned behaviour, the applied methodology is capable of addressing diverse ecosystem services in various decision contexts, which makes it a powerful tool for multidisciplinary approaches and political scenario analysis. The combination of elements from Analytical Hierarchy Process also weights the importance of different decision-making criteria, which makes the presented approach capable of dealing with decisions that need to trade-off several ecosystem services. Given the great flexibility of Bayesian networks, it presents itself as a promising approach to expand upon conventional ecosystem management networks with socio-psychological decision factors.

3.7. Acknowledgment

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3.8. Literature

Aguilera, P.A., Fernández, A., Fernández, R., Rumí, R., Salmerón, A., 2011. Bayesian networks in environmental modelling. Environmental Modelling & Software 26(12) 1376-1388.

Ajzen, I., 1991. The theory of planned behavior. Organizational behavior and human decision processes 50(2) 179-211.

Barton, D.N., Saloranta, T., Moe, S.J., Eggestad, H.O., Kuikka, S., 2008. Bayesian belief networks as a meta-modelling tool in integrated river basin management - Pros and cons in evaluating nutrient abatement decisions under uncertainty in a Norwegian river basin. Ecological Economics 66(1) 91-104.

Bromley, J., Jackson, N.A., Clymer, O.J., Giacomello, A.M., Jensen, F.V., 2005. The use of Hugin® to develop Bayesian networks as an aid to integrated water resource planning. Environmental Modelling & Software 20(2) 231-242.

Cain, J., 2001. Planning improvements in natural resource management. Guidelines for using Bayesian networks to support the planning and management of development programmes in the water sector and beyond. Centre for Ecology and Hydrology, Wallingford, UK.

Castelletti, A., Soncini-Sessa, R., 2007. Coupling real-time control and socio-economic issues in participatory river basin planning. Environmental Modelling & Software 22(8) 1114-1128.

Celio, E., Brunner, S.H., Grêt-Regamey, A., 2012. Participatory Land Use Modeling with Bayesian Networks: a Focus on Subjective Validation, In: Seppelt, R., Voinov, A.A., Lange, S., Bankamp, D. (Eds.), International Environmental Modelling & Software Society (iEMSs). 2012 International Congress on Environmental Modelling & Software. Managing Resources of a Limited Planet, Sixth Biennial Meeting: Leipzig, Germany.

Chan, T., Ross, H., Hoverman, S., Powell, B., 2010. Participatory development of a Bayesian network model for catchment-based water resource management. Water Resources Research 46(7).

Chan, T.U., Hart, B.T., Kennard, M.J., Pusey, B.J., Shenton, W., Douglas, M.M., Valentine, E., Patel, S., 2012. Bayesian network models for environmental flow decision making in the Daly River, Northern Territory, Australia. River Research and Applications 28(3) 283-301.

Chen, S.H., Pollino, C.A., 2012. Good practice in Bayesian network modelling. Environmental Modelling & Software 37 134-145.

Daily, G.C., Polasky, S., Goldstein, J., Kareiva, P.M., Mooney, H.A., Pejchar, L., Ricketts, T.H., Salzman, J., Shallenberger, R., 2009. Ecosystem services in decision making: time to deliver. Frontiers in Ecology and the Environment 7(1) 21-28.

Fish, R.D., 2011. Environmental decision making and an ecosystems approach: Some challenges from the perspective of social science. Progress in Physical Geography 35(5) 671-680.

Haines-Young, R., 2011. Exploring ecosystem service issues across diverse knowledge domains using Bayesian belief networks. Progress in Physical Geography 35(5) 681-699.

Haines-Young, R., Potschin, M., 2010. The links between biodiversity, ecosystem services and human well-being, In: Raffaelli, D., Frid, C. (Eds.), Ecosystem Ecology: a New Synthesis. BES Ecological Review Series. Cambridge University Press, Cambridge, pp. 110-139.

Handfield, R., Walton, S.V., Sroufe, R., Melnyk, S.A., 2002. Applying environmental criteria to supplier assessment: A study in the application of the Analytical Hierarchy Process. European Journal of Operational Research 141(1) 70-87.

Kjaerulff, U.B., Madsen, A.L., 2008. Bayesian networks and influence diagrams: a guide to construction and analysis. Springer, New York, USA.

Kuhnert, P.M., Martin, T.G., Griffiths, S.P., 2010. A guide to eliciting and using expert knowledge in Bayesian ecological models. Ecology Letters 13(7) 900-914.

Landuyt, D., Broekx, S., D'Hondt, R., Engelen, G., Aertsens, J., Goethals, P.L.M., 2013. A review of Bayesian belief networks in ecosystem service modelling. Environmental Modelling & Software 46(0) 1-11.

MA, 2005. Millennium Ecosystem Assessment. Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC.

Marcot, B.G., Steventon, J.D., Sutherland, G.D., McCann, R.K., 2006. Guidelines for developing and updating Bayesian belief networks applied to ecological modeling and conservation. Canadian Journal of Forest Research 36(12) 3063-3074.

McCann, R.K., Marcot, B.G., Ellis, R., 2006. Bayesian belief networks: applications in ecology and natural resource management. Canadian Journal of Forest Research 36(12) 3053-3062.

Mislimshoeva, B., Samimi, C., Kirchhoff, J.-F., Koellner, T., 2012. Analysis of costs and people's willingness to enroll in forest rehabilitation in Gorno Badakhshan, Tajikistan. Forest Policy and Economics (in press).

Pearl, J., 2009. Causality: Models, Reasoning and Inference, 2nd ed. Cambridge University Press, Cambridge.

Poppenborg, P., Koellner, T., 2013. Do attitudes toward ecosystem services determine agricultural land use practices? An analysis of farmers' decision-making in a South Korean watershed. Land Use Policy 31(0) 422-429.

Saaty, T., 2008. Decision making with the analytic hierarchy process. International Journal of Services Sciences 1(1) 83-98.

Smith, R.I., Dick, J.M., Scott, E.M., 2011. The role of statistics in the analysis of ecosystem services. Environmetrics 22(5) 608-617.

Ticehurst, J.L., Curtis, A., Merritt, W.S., 2011. Using Bayesian networks to complement conventional analyses to explore landholder management of native vegetation. Environmental Modelling & Software 26(1) 52-65.

Varis, O., Lahtela, V., 2002. Integrated water resources management along the Senegal River: introducing an analytical framework. International Journal of Water Resources Development 18(4) 501-521.

Zorrilla, P., Carmona Garcia, G., De la Hera, A., Varela Ortega, C., Martinez Santos, P., Bromley, J., Henriksen, H.J., 2010. Evaluation of Bayesian networks in participatory water resources management, Upper Guadiana Basin, Spain. Ecology and Society 15(3) 12.

4. Paper 3: Linking benefits from ecosystem services to ecosystem functions and service provision: An integrated Bayesian network modelling approach

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4.1. Abstract

Models about ecosystem services typically consider benefits as a derivative of service provision, which is determined as a function of changes in ecosystem processes resulting from different management decisions. This understanding of the ecosystem services concept implies quite a restricted perception of the relation between service provision and well-being, as it neglects how benefits from ecosystem services influence ecosystem management decisions. This study presents an integrated Bayesian network approach that models land use decisions based on socio-psychological measurements of benefits from the ecosystem services biomass production, soil erosion prevention, and water quality improvement. Land use decisions are then linked to deterministic variables influencing the provision of these very services. The presented findings indicate that Bayesian networks are capable of modelling land use decisions as a function of expected benefits from ecosystem services. Furthermore, they deliver reliable results for service provision, while at the same time they offer the possibility of integrating data from natural and social science disciplines. Our results recommend the use of Bayesian networks not only

for multidisciplinary approaches, but also for variegating the understanding of the socio-ecological couplings between benefits from ecosystem services and their impact on environmental decision-making.

Keywords: Ecosystem service benefits; Land use decision-making; Soil erosion modelling, Water quality modelling; Biomass production modelling

4.2. Introduction

Ecosystem services (ESS) are beneficial ecosystem processes and functions that contribute to human well-being. Propelled by a formal introduction by the Millennium Ecosystem Assessment in 2005 (MA, 2005), they have been subject of an increasing number of research articles (Seppelt et al., 2011). The existing literature embraces contributions from ecological, economic as well as social disciplines, as ESS can be derived from both material and non-material benefits.

In addition to being rooted in a multidisciplinary field of research, the concept of ESS is also characterized by intricate relations between ecosystem functions, services and benefits (Haines-Young and Potschin, 2010). This inherent complexity involves a high level of uncertainty, which imposes considerable challenges on ESS modelling approaches (Haines-Young, 2011).

An increasingly efficient technique is the use of Bayesian network (BN) models. Their growing popularity in ESS research is mainly due to their capability of (i) handling uncertainty in an explicit manner, (ii) allowing for integrated and participatory modelling approaches, (iii) incorporating information from different data sources and measurement scales, and (iv) dealing with missing data (Chan et al., 2012; Smith et al., 2011; Uusitalo, 2007).

Originally used for machine learning and classification tasks, BNs were later introduced in the field of environmental sciences where they are mostly applied in studies about ecology, water resources, and agriculture (Aguilera et al., 2011). Similar areas of application can be found in ESS related research. The majority of publications deals with aquatic ecosystems, while the most addressed services are water regulation, water supply, recreation and food provision (Landuyt et al., 2013).

Very few of the BNs in ESS research, however, are used as a platform for integrated, multidisciplinary ESS modelling. Most studies originate from natural science disciplines and concentrate on investigating a single service, thereby forgoing to consider potential trade-offs between several services. Also, BN models that do integrate several services seldom address well-understood mechanistic ESS such as soil erosion prevention (Landuyt et al., 2013), as these are typically investigated by means of alternative approaches like process-based models (Merritt et al., 2003).

Arising from this lack of multidisciplinary BN models, the aspect of how stakeholders' benefits from ESS relate to decisions about ecosystem management, and thus to ecosystem service provision is often neglected (Daily et al., 2009; Haines-Young and Potschin, 2010). In general, stakeholder information has been used extensively for all steps in BN modelling; from model parameterization (e.g. Bromley et al., 2005; Chan et al., 2010; Zorrilla et al., 2010) and population (e.g. Nash et al., 2010; Newton et al., 2007; Zorrilla et al., 2010), to model validation (e.g. Henriksen et al., 2007; Molina et al., 2010; Wang et al., 2009).

This stakeholder information is usually applied to better understand an ecosystem's capacity of delivering specific services as a function of its structures and processes. Yet, while it has proven valuable for stakeholder participation and communication (Zorrilla et al., 2010), the elicited information is seldom used to investigate the socio-ecological couplings underlying the ESS concept (Haines-Young, 2011).

In a more multidisciplinary approach, Haines-Young (2011) presented two case studies where different elements of the cascaded ESS production chain (Haines-Young and Potschin, 2010) were addressed in separate BNs. The first investigated the impact of land-cover change scenarios on vegetational carbon storage, while the second explored stakeholders' collective evaluation of landscape as a cultural service based on the impact of different scenarios on landscape characteristics. In conclusion, BNs were considered an effective analytical-deliberative tool for combining quantitative facts and qualitative values in multidisciplinary ESS research (Haines-Young, 2011).

In this paper, an integrated BN model is presented that explicitly links stakeholders' benefits, ecosystem functions, and services for a case study region in a South Korean watershed. Thus, farmers' crop choice is modelled as a function of psychological and biophysical input parameters, including expected benefits from the ecosystem services production of marketable biomass, prevention of soil erosion, and improvement of water quality. Land use is then related to variables influencing ecosystem functions, which determine the provision of the very services considered in the land use decision-making part.

The purpose of this paper is to expand upon the use of BNs in ESS modelling by showing how multidisciplinary data can be used to fully grasp the integrated nature of the ESS concept. This is done for several ESS, including well-documented ones like soil erosion prevention, thus allowing for trade-off considerations.

4.3. Methods

4.3.1. Bayesian networks

Bayesian networks are probabilistic multivariate models representing sets of random variables[2] and their conditional dependencies based on two components. First, the model is parameterised qualitatively by means of a directed acyclic graph that uses nodes to represent each variable. Causal or correlative relations between variables are indicated by directed arcs such that the starting node of an arc is defined as parent node, while the node it is connected to becomes its child node (Landuyt et al., 2013).

Second, the model is specified quantitatively by populating tables with probability distributions that define the strength of relationship between parent and child nodes. Probabilities of realizing the states of a parent node are defined by tables with unconditioned (marginal) probability distributions. Child nodes require a conditional probability table, which quantifies the probabilities of realizing the states of the variable given the states of its parent node(s) (Aguilera et al., 2011).

Given a fully specified BN, statistical inference exploiting Bayes' theorem allows for calculating the probability distribution of a child node given the values of their parents, as well as of a parent given the values of their child nodes (Uusitalo, 2007). More detailed mathematical descriptions of BNs and their functionalities are given by Kjaerulff and Madsen (2008) or Pearl (2009).

[2] Although progress on algorithms capable of dealing with continuous data is being made, most BNs are based on discrete variables. Unless stated otherwise, use of discrete or discretised continuous variables is assumed in this paper.

4.3.2. Model parameterisation and population

The model presented in this paper was programmed with the commercial software Hugin Expert A/S version 7.3 (www.hugin.com). Only discrete or discretised continuous variables were being used. Most of the data originated from projects of the research programme TERRECO (www.bayceer.uni-bayreuth.de/terreco), a multidisciplinary graduate school where several ecological and socio-economic work packages have collected information from Haean catchment, a 64 km^2 watershed in Yanggu County, South Korea. In the following, each part of the model is explained with focus on its qualitative aspects as displayed in figure 4.1. Detailed descriptions of the quantitative specifications are given in table 4.2 in the supporting information section.

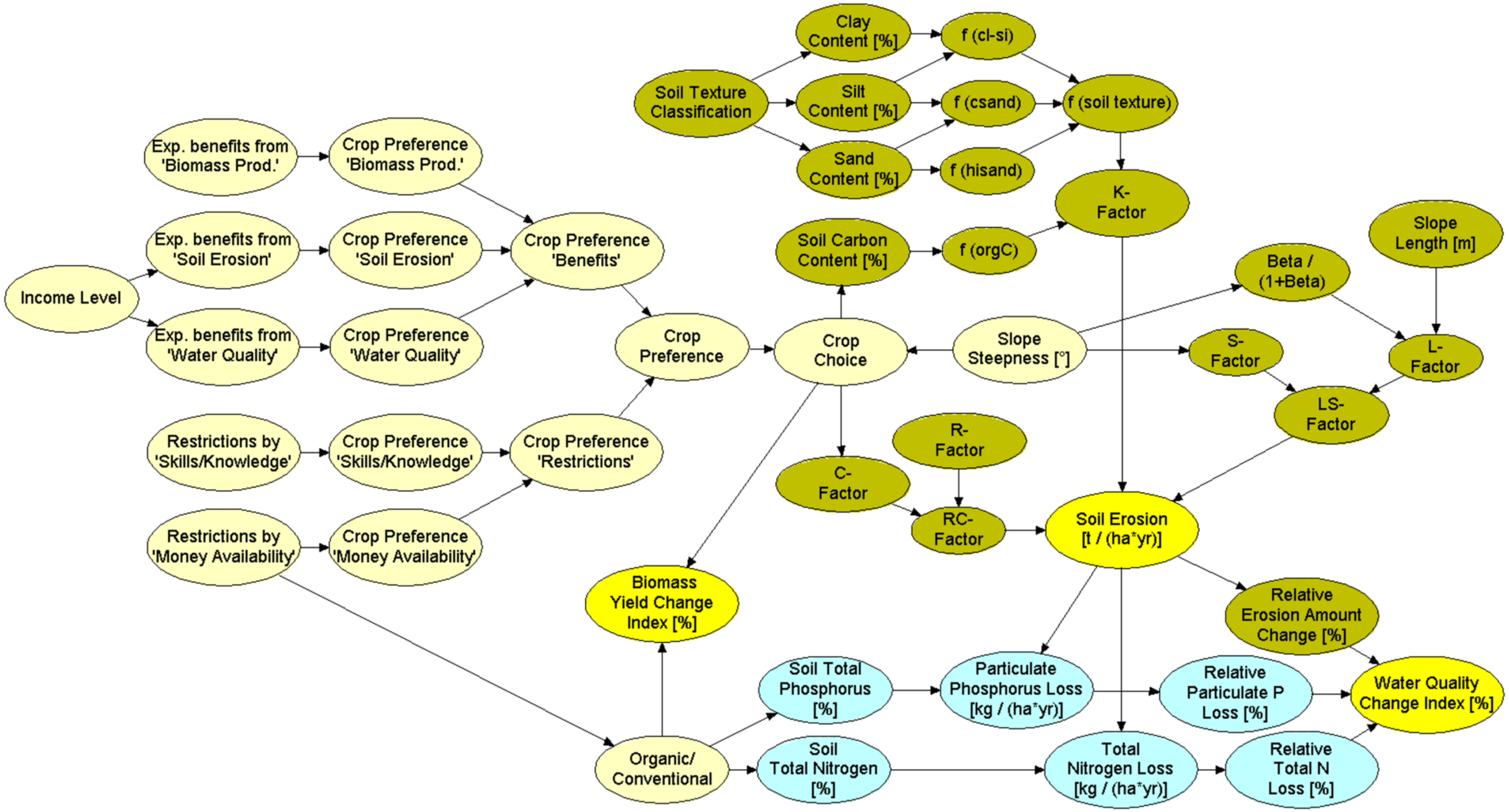

Figure 4.1: Integrated Bayesian network linking decisions based on benefits from ecosystem services to ecosystem functions and provision of ecosystem services. Dependency relationships of all variables are defined as shown by the directed acyclic graph. The modelled ecosystem services soil erosion prevention, water quality improvement, and biomass production are displayed in bright yellow. Pale yellow nodes belong to the decision-making modelling part, green nodes to the soil erosion part, and blue to the water quality part.

Case study area and decision-making modelling

Haean catchment has a kettle-like topography and is dominated by agricultural land use. Rice paddies cover most of the flat core zone, while mostly annual crops and a few plots of perennial crops are grown on the steeper outskirt areas of the catchment. Resulting from crop cultivation on the slopes of the catchment, high amounts of soil erode and charge the rivers with particles and nutrients. Policy measures to mitigate these environmental problems aim at fostering the cultivation of more perennial crops, as their permanent rooting is supposed to stabilize the soil on sloped fields. Also, conversion to organic agriculture is endorsed to reduce chemical fertilizer loads.

The decision-making modelling part of this paper built upon a BN study by Poppenborg and Koellner (under review), where crop preferences of Haean farmers have been modelled based on socio-psychological factors investigated in interviews by Poppenborg and Koellner (2013). Thus, decisions between planting rice, annual crops or perennial crops have been modelled as a function of (i) expected benefits from the ESS production of marketable biomass, prevention of soil erosion, and improvement of water quality, as well as (ii) perceived restrictions by money availability, and skills and knowledge.

The model in Poppenborg and Koellner (under review) had effectively reflected the influence of psychological factors on crop preference, but had not included geo-spatial variables that would have had allowed for modelling decisions under the influence of their biophysical context. The decision-making modelling part in this paper expanded upon using crop preference as explained by psychological factors and introduced slope steepness as an additional input variable for determining actual crop choice. Slope steepness was chosen as explaining factor since the model presented in Poppenborg and Koellner (under review) performed well at predicting farmers' crop choice of perennial crops, but less good for distinguishing between rice and annual crops. As the cultivation of paddy rice requires a level surface, the inclusion of slope steepness was supposed to improve model performance in terms of predicting crop choice.

Conditional probabilities for crop choice in dependence on slope steepness were derived from land use maps and digital elevation models of the case study area. This data was linked to crop preference via slope steepness information provided by 105 of the interviewed farmers (cf. Poppenborg and Koellner, 2013). The conditional probability table for crop choice was populated using an Expectation-Maximisation (EM) algorithm, which approximated the required probability distribution based on given data and model structure using Dirichlet distributions (Lauritzen, 1995). The rest of the decision-making modelling part followed procedures described in Poppenborg and Koellner (under review).

Soil erosion modelling

The soil erosion modelling part largely followed results by Arnhold et al. (under review), who had applied the Revised Universal Soil Loss Equation (RUSLE) to model soil erosion in Haean. Thus, the presented BN included rainfall erosivity factor R, cover-management factor C, slope steepness factor S, slope length factor L, and soil erodibility factor K (Renard et al., 1997). The support practices factor P was not included as conservation management in Haean catchment had turned out to have no mitigating effect on soil erosion (Arnhold et al., 2013).

Deterministic variables associated with the RUSLE were calculated according to the formulas provided by Renard et al. (1997). Data for empirical input variables mostly stemmed from observations that were being made as part of the work of Arnhold et al. (under review). Only C factors for rice and perennial crops originated from external literature sources (Chen et al., 2012; Fu et al., 2005; Kim et al., 2008; Lee and Choi, 2010; Park et al., 2011; Shi et al., 2002; Shi et al., 2004; Yang et al., 2003).

The effects of R and C factor were modelled using one joint parent node (RC factor) for erosion; a technique known as parent divorcing that allowed for improving model efficiency. By introducing this intermediate node that captured the impact of its parent nodes on erosion, the state space of erosion could be reduced and computation times decreased (Kjaerulff and Madsen, 2008).

Erosion output was expressed as tonnes per hectare and year. Additionally, relative percentage changes in erosion amounts were calculated using the mean erosion output of the model as baseline.

Water quality modelling

The water quality modelling part predicted losses of particulate P and N based on soil loss and nutrient enrichment ratios as presented by Sharpley (1985) and Auerswald (1989), respectively. While amounts of soil loss were provided by the erosion modelling part, P and N concentrations were modelled as a function of conventional and organic farming, respectively. Probabilities of implementing conventional or organic farming were conditioned on farmers' perceived restrictions by their money availability according to results presented in Poppenborg and Koellner (2013).

Particulate P and total N losses were given in kilograms per hectare and year. They were furthermore expressed in relative terms as percentage change from their respective baselines, which were determined as the mean P and N losses predicted by the model. Finally, overall changes in water quality were reflected by a node that summed up the relative changes of soil erosion and nutrient losses, thus describing water quality in terms of both chemical as well as sedimentation loads.

Biomass production modelling

Production of marketable biomass was modelled in dependence on the joint probability of crop choice and cultivation method, i.e. conventional or organic. Produced biomass was not expressed in absolute terms as the categories of annual and perennial crops were too diversified to allow for comparisons of crop weights. Instead, only relative changes of biomass were given based on mean absolute values as a baseline to calculate percentage changes.

Unlike as for erosion and water quality however, these mean values had to be calculated externally since they were not provided by the presented model. Therefore, yield data from the statistical database of the Korean Statistical Information Service (KOSIS) (www.kosis.kr) was used, which provided yield information for Yanggu County divided by organic and conventional production, respectively. The selected data considered the years 2009 to 2011 and comprised paddy rice, the annual crops bean, radish, potato and cabbage, as well as the perennial crops orange, peach, persimmon, grape, pear and apple.

The baselines were calculated per crop category (rice, annual crops, perennial crops) using values of both organic and conventional yields. Subsequently, relative changes were expressed as differences between these baselines and the respective mean yields of organic and conventional farming.

4.3.3. Model analysis and validation

Prediction performance of the decision-making modelling part was characterized by percentage of false predictions (error rate), and area under the receiver operating characteristics curve (AUC) for node crop choice (Fawcett, 2006). Furthermore, four scenarios were used to illustrate model performance. Therefore, evidence was entered into the network by assigning a 100% probability to a specific state of a node, which allowed for observing how the probability distributions of related nodes changed as a result.

For the first two scenarios, the node slope steepness was instantiated at 7°, slope length at 30 meters, and the R-factor at 6500 MJ mm ha^{-1} h^{-1} yr^{-1}, which corresponds to the general set-up found in Arnhold et al. (under review). As only annual crops had been considered in the latter study, one of the scenarios instantiated crop choice at state 'annual' (scenario 'Annual crops'), while the other assumed crop choice to be in state 'perennial' (scenario 'Perennial crops'). The 'Annual crop' scenario allowed for comparing the results of the soil erosion modelling part to those observed by Arnhold et al. (under review). The 'Perennial crop' scenario served as an example of how the BN could be used to show the different effects of crop choice on the modelled ESS.

For the other two scenarios, node organic/conventional was instantiated at state 'organic' (scenario 'Organic') and 'conventional' (scenario 'Conventional'), respectively, to illustrate how this affected the modelled ESS. In addition to model validation the scenarios were also chosen to demonstrate how the presented BN can support practical management decision-making, as both the introduction of perennial crops and the fostering of organic farming are initiatives endorsed in the case study area.

4.4. Results

Without entering evidence into the network, predicted probabilities for crop choice equalled 22% for rice, 65% for annual crops and 13% for perennial crops. Predicting crop choice as a function of crop preference and slope steepness produced an error rate of 26% with an AUC of 0.85. The share of organic versus conventional farming was 26% to 74%, respectively. Mean soil erosion amounted to 27 $t*ha^{-1}*yr^{-1}$. Mean nutrient losses equalled 15 $kg*ha^{-1}*yr^{-1}$ for particulate P and 29 $kg*ha^{-1}*yr^{-1}$ for total N, which resulted in an increase of the water quality index by an average of 16%. The biomass production index was slightly above average with a mean increase of 5%. More results of the model without evidence are illustrated in figure 4.2.

Under the 'Annual crops' scenario mean soil erosion amounted to 37 $t*ha^{-1}*yr^{-1}$, while particulate P and total N losses equalled 17 and 33 $kg*ha^{-1}*yr^{-1}$, respectively. As a result, water quality deteriorated by -110% on average. Biomass production amounted to a mean increase of 5%. On the other hand, the ‘Perennial crops’ scenario resulted in an average soil erosion of 31 $t*ha^{-1}*yr^{-1}$. P and N losses amounted to 17 and 33 $kg*ha^{-1}*yr^{-1}$, respectively. Mean biomass production was predicted to increase by 8%.

Modelling the ‘Organic’ scenario resulted in 27 $t*ha^{-1}*yr^{-1}$ soil erosion and nutrient losses of 17 and 33 $kg*ha^{-1}*yr^{-1}$ for particulate P and total N, respectively. Water quality improved by 29%, while biomass production decreased by an average of -10%. The ‘Conventional’ scenario yielded a mean erosion amount of 27 $t*ha^{-1}*yr^{-1}$. Particulate P losses averaged 16 $kg*ha^{-1}*yr^{-1}$, losses of total N amounted to 29 $kg*ha^{-1}*yr^{-1}$. The water quality index showed an increase slightly above average with 11%, while biomass production increased by 10%. Predicted probabilities and mean values of the most important input/output nodes for the model without evidence as well as for all four scenarios are summarized in table 4.1.

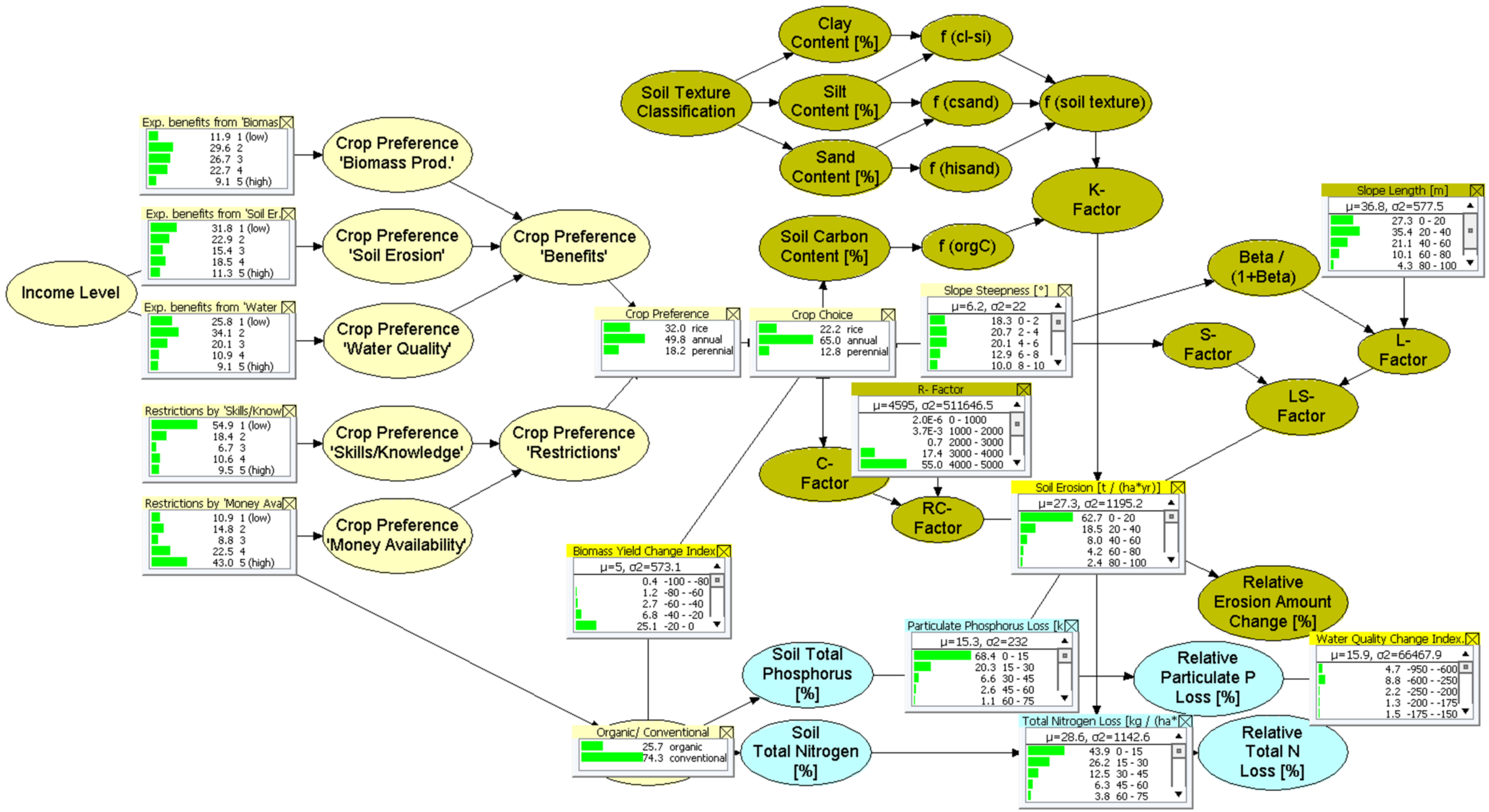

Figure 4.2: Probability distributions [%] of important input/output nodes in the model without further evidence. A maximum of 5 states is displayed for each node. Mean value (μ) and variance (σ²) are given for numeric nodes.

Table 4.1: Probabilities [%] of discrete nodes as well as mean values (μ) and variances (σ²) of discretised continuous nodes for the model without evidence and all scenarios. Displayed are the most important input/output nodes for each scenario. Nodes instantiated under respective scenario are marked in grey.

Variable	Model without evidence		Scenario 'Annual crops'		Scenario 'Perennial crops'		Scenario 'Organic'		Scenario 'Conventional'	
	Probability [%]	Mean (Variance)	Probability [%]	Mean (Variance)	Probability [%]	Mean (Variance)	Probability [%]	Mean (Variance)	Probability [%]	Mean (Variance)
Decision-making factors										
Crop choice										
Rice	22	---	0	---	0	---	22	---	22	---
Annual crops	65	---	100	---	0	---	65	---	65	---
Perennial crops	13	---	0	---	100	---	13	---	13	---
Organic/Conventional										
Organic	26	---	26	---	26	---	100	---	0	---
Conventional	74	---	74	---	74	---	0	---	100	---
Biophysical factors										
Slope Steepness [°]	---	6 (22)	---	7 (0)	---	7 (0)	---	6 (22)	---	6 (22)
Slope length [m]	---	37 (578)	---	30 (0)	---	30 (0)	---	37 (578)	---	37 (578)
R-Factor	---	4595 (511647)	---	6500 (0)	---	6500 (0)	---	4595 (511647)	---	4595 (511647)
Ecosystem services										
Soil erosion [t ha^{-1} yr^{-1}]	---	27 (1195)	---	37 (456)	---	31 (382)	---	27 (1194)	---	27 (1195)
Particulate P loss [kg ha^{-1} yr^{-1}]	---	15 (232)	---	20 (153)	---	17 (128)	---	14 (175)	---	16 (250)
Total N loss [kg ha^{-1} yr^{-1}]	---	29 (1143)	---	38 (821)	---	33 (664)	---	27 (1086)	---	29 (1161)
Water quality change [%]	---	16 (66468)	---	-110 (54689)	---	-46 (47805)	---	29 (61371)	---	11 (68145)
Biomass yield change [%]	---	5 (573)	---	5 (672)	---	8 (852)	---	-10 (997)	---	10 (328)

4.5. Discussion

Predicted probabilities for crop choice in the model without evidence are almost identical to the actual land use distribution in Haean catchment (23% rice, 65% annual crops, 12% perennial crops). Furthermore, adding slope steepness for modelling farmers' decision-making decreases the prediction error rate and increases the AUC value in comparison to using only socio-psychological factors as demonstrated in Poppenborg and Koellner (2013). These results make the presented approach advisable when decisions are to be modelled in the context of their biophysical circumstances. Using slope steepness also offers a potential interface to geographical information systems, which would allow for interpreting the results in a spatially explicit manner (Celio et al., 2013; Grêt-Regamey and Straub, 2006; Stassopoulou et al., 1998).

Under the 'Annual crops' scenario, soil erosion amounts are well within the range of values reported by Arnhold et al. (under review), thus indicating reliable performance of the soil erosion modelling part. Cultivation of annual crops produces higher amounts of soil erosion in comparison to the 'Perennial crops' scenario. This is mainly due to the higher C factor and lower soil carbon content associated with annual crops (see table 4.2). As a result of higher erosion amounts, annual crops also cause higher particulate P and N losses. A direct comparison of both scenarios in terms of biomass production is of limited value as the percentage changes of the biomass index refer to baselines of conventional and organic yields per crop category.

Thus, the results of the organic and conventional scenarios are more informative with respect to biomass yield changes. Given the same crop choice probability for both scenarios, biomass yields drop by an average of -10% if all crops were cultivated organically, in comparison to an average increase of 10% under conventional production. Almost no changes are observed in soil erosion, since node organic/conventional only remotely affects erosion via its impact on the decision-making modelling part. Water quality, on the other hand, improves under the 'Organic' scenario as a result of lower P and N soil concentrations (see table 4.2).

The interpretation of these outputs has to be made with the model's limitations in mind. Thus, especially the water quality and biomass modelling parts are based on simplified assumptions in comparison to more specialized models (e.g. Neitsch et al., 2005). Furthermore, predictions cannot be as precise as results obtained from mechanistic, process-based models due to the information loss associated with discretising continuous variables (Aguilera et al., 2011; Jensen and Nielsen, 2007).

From a single scientific discipline's point of view the simplifications and information loss often involved in BN applications make them seem unfavourable for investigating well-documented ESS (Landuyt et al., 2013). If applied in a multidisciplinary context, however, these limitations can be outweighed by the capability of providing an integrated framework that allows for assessing several ESS, which can greatly support decision-making about multilayered ecosystem management options. Furthermore, simplifying model elements can foster social learning in participatory modelling processes, as it helps participants to comprehend the interrelations and uncertainties involved in the given system (Zorrilla et al., 2010).

According to the results presented in this paper, endeavours to foster perennial crops in the research area seem beneficial in terms of providing the considered ESS. On the other hand, organic farming improves water quality, but also comes along with a trade-off in biomass production. Concluding recommendations about optimal solutions for such a trade-off situation however, would require evaluations that reflect stakeholders' utilities associated with the management outcomes under consideration. Biomass production for instance, is lower under organic cultivation in comparison to conventional farming. However, organic products are likely to achieve higher selling prices, which might make them preferable in terms of economic revenues from a farmer's perspective (Dasgupta et al., 2007). At the same time, higher amounts of biomass in conventional farming might be more beneficial from a societal perspective, as they would nourish a larger number of people.

Thus, taking into account utilities associated with the modelled ESS provisions would allow for viewing the produced results from the perspectives of differing stakeholders' interests. Appropriate techniques have been implemented successfully in several BN studies. Monetary cost/benefit considerations were often evaluated by investigating stakeholders' willingness to pay (e.g. Barton et al., 2008; Gawne et al., 2012; Kragt et al., 2011). Non-monetary evaluation methods were usually based on importance scores derived from stakeholders' preferences to different ESS provision scenarios (e.g. Haines-Young, 2011). While such evaluations have proven useful for assessing the ESS benefits associated with the outcomes of management options, their focus on ecosystems as providers of benefits also implies quite a narrow perception of how natural environments and well-being are related (Fish, 2011). Thus, benefits from ESS are not solely a derivative of service provision, but they also influence the ecosystem management decisions that determine service provision in the first place (Poppenborg and Koellner, 2013).

As demonstrated in this paper, Bayesian networks offer the potential of elaborating on this variegated understanding of the ESS concept. Being able to model the immediate influence of ESS benefits on ecosystem management decisions provides direct insight into the relationship between ESS and well-being, which helps to leverage the formulation of effective management strategies. Without such ability the postulated role of ESS in constituting well-being runs the risk of becoming sort of a 'black box', which obfuscates how and why ESS matter in decision-making (Fish, 2011). Furthermore, the capability of BNs to combine qualitative information about ESS benefits with quantitative data on ecosystem processes and functions represents a crucial advantage for integrated modelling approaches in the framework of ESS (Busch et al., 2012; Smith et al., 2011). Such properties are an indispensable prerequisite if the concept of ecosystem services is to be operationalised in a practical manner that embraces the concept's inter- and multidisciplinary nature.

4.6. Conclusion

The purpose of this paper has been to link decisions based on benefits from ecosystem services to ecosystem functions and finally service provision by means of a multidisciplinary Bayesian network modelling approach. The presented network successfully combines socio-psychological measurements of decision-making factors with natural science data on ecosystem functions and processes. Farmers' land use decisions are modelled effectively as a function of expected benefits from ecosystem services and slope steepness. Although afflicted with information loss in comparison to specialized disciplinary models, the modelled provisions of ecosystem services lie within realistic ranges. These results emphasise the usefulness of Bayesian networks for integrated modelling approaches in the field of ecosystem services. Furthermore, they allow for explicitly incorporating expected benefits from ecosystem services into environmental decision-making, which makes them an appropriate platform for jointly interpreting the interrelations between value-based management decisions and their factual impact on ecosystem functions. Thus, besides presenting themselves as an efficient tool for decision-making support in practical ecosystem management, Bayesian networks can also make valuable contributions to a more holistic understanding of the ecosystem services concept.

4.7. Acknowledgment

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4.8. Literature

Aguilera, P.A., Fernández, A., Fernández, R., Rumí, R., Salmerón, A., 2011. Bayesian networks in environmental modelling. Environmental Modelling & Software 26(12) 1376-1388.

Arnhold, S., Ruidisch, M., Bartsch, S., Shope, C., Huwe, B., 2013. Simulation of runoff patterns and soil erosion on mountainous farmland with and without plastic-covered ridge-furrow cultivation in South Korea. Transactions of the ASABE 56(2) 667-679.

Arnhold, S., Lindner, S., Lee, B., Martin, E., Kettering, J., Seo, B., Nguyen, T.T., Koellner, T., Ok, Y.S., Huwe, B., under review. Conventional and organic farming: Soil erosion and conservation potential for row crop cultivation. Geoderma (under review).

Auerswald, K., 1989. Predicting nutrient enrichment from long-term average soil loss. Soil Technology 2(3) 271-277.

Barton, D.N., Saloranta, T., Moe, S.J., Eggestad, H.O., Kuikka, S., 2008. Bayesian belief networks as a meta-modelling tool in integrated river basin management - Pros and cons in evaluating nutrient abatement decisions under uncertainty in a Norwegian river basin. Ecological Economics 66(1) 91-104.

Bromley, J., Jackson, N.A., Clymer, O.J., Giacomello, A.M., Jensen, F.V., 2005. The use of Hugin® to develop Bayesian networks as an aid to integrated water resource planning. Environmental Modelling & Software 20(2) 231-242.

Busch, M., La Notte, A., Laporte, V.r., Erhard, M., 2012. Potentials of quantitative and qualitative approaches to assessing ecosystem services. Ecological Indicators 21(0) 89-103.

Celio, E., Koellner, T., Grêt-Regamey, A., 2013. Modeling land use decisions with Bayesian networks: Spatially explicit analysis of driving forces. Environmental Modelling & Software (in press).

Chan, T., Ross, H., Hoverman, S., Powell, B., 2010. Participatory development of a Bayesian network model for catchment-based water resource management. Water Resources Research 46(7).

Chan, T.U., Hart, B.T., Kennard, M.J., Pusey, B.J., Shenton, W., Douglas, M.M., Valentine, E., Patel, S., 2012. Bayesian network models for environmental flow decision making in the Daly River, Northern Territory, Australia. River Research and Applications 28(3) 283-301.

Chen, S.-K., Liu, C.-W., Chen, Y.-R., 2012. Assessing soil erosion in a terraced paddy field using experimental measurements and universal soil loss equation. CATENA 95(0) 131-141.

Daily, G.C., Polasky, S., Goldstein, J., Kareiva, P.M., Mooney, H.A., Pejchar, L., Ricketts, T.H., Salzman, J., Shallenberger, R., 2009. Ecosystem services in decision making: time to deliver. Frontiers in Ecology and the Environment 7(1) 21-28.

Dasgupta, S., Meisner, C., Wheeler, D., 2007. Is environmentally friendly agriculture less profitable for farmers? Evidence on integrated pest management in Bangladesh. Applied Economic Perspectives and Policy 29(1) 103-118.

Fawcett, T., 2006. An introduction to ROC analysis. Pattern recognition letters 27(8) 861-874.

Fish, R.D., 2011. Environmental decision making and an ecosystems approach: Some challenges from the perspective of social science. Progress in Physical Geography 35(5) 671-680.

Fu, B.J., Zhao, W.W., Chen, L.D., Zhang, Q.J., Lü, Y.H., Gulinck, H., Poesen, J., 2005. Assessment of soil erosion at large watershed scale using RUSLE and GIS: a case study in the Loess Plateau of China. Land Degradation & Development 16(1) 73-85.

Gawne, B., Price, A., Koehn, J.D., King, A.J., Nielsen, D.L., Meredith, S., Beesley, L., Vilizzi, L., 2012. A Bayesian belief network decision support tool for watering wetlands to maximise native fish outcomes. Wetlands 32(2) 277-287.

Grêt-Regamey, A., Straub, D., 2006. Spatially explicit avalanche risk assessment linking Bayesian networks to a GIS. Natural Hazards and Earth System Sciences 6(6) 911-926.

Haines-Young, R., 2011. Exploring ecosystem service issues across diverse knowledge domains using Bayesian belief networks. Progress in Physical Geography 35(5) 681-699.

Haines-Young, R., Potschin, M., 2010. The links between biodiversity, ecosystem services and human well-being, In: Raffaelli, D., Frid, C. (Eds.), Ecosystem Ecology: a New Synthesis. BES Ecological Review Series. Cambridge University Press, Cambridge, pp. 110-139.

Henriksen, H.J.r., Rasmussen, P., Brandt, G., von Bülow, D., Jensen, F.V., 2007. Public participation modelling using Bayesian networks in management of groundwater contamination. Environmental Modelling & Software 22(8) 1101-1113.

Jensen, F.V., Nielsen, T.D., 2007. Bayesian networks and decision graphs. Springer, New York.

Kim, S., Im, S., Park, S., Lee, J., Benham, B., Jang, T., 2008. Assessment of Wastewater Reuse Effects on Nutrient Loads from Paddy Field Using Field-Scale Water Quality Model. Environmental Modeling & Assessment 13(2) 305-313.

Kjaerulff, U.B., Madsen, A.L., 2008. Bayesian networks and influence diagrams: a guide to construction and analysis. Springer, New York, USA.

Kragt, M., Newham, L.T., Bennett, J., Jakeman, A.J., 2011. An integrated approach to linking economic valuation and catchment modelling. Environmental Modelling & Software 26(1) 92-102.

Landuyt, D., Broekx, S., D'Hondt, R., Engelen, G., Aertsens, J., Goethals, P.L.M., 2013. A review of Bayesian belief networks in ecosystem service modelling. Environmental Modelling & Software 46(0) 1-11.

Lauritzen, S.L., 1995. The EM algorithm for graphical association models with missing data. Computational Statistics & Data Analysis 19(2) 191-201.

Lee, G., Choi, I., 2010. Scaling effect for the quantification of soil loss using GIS spatial analysis. KSCE Journal of Civil Engineering 14(6) 897-904.

MA, 2005. Millennium Ecosystem Assessment. Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC.

Merritt, W.S., Letcher, R.A., Jakeman, A.J., 2003. A review of erosion and sediment transport models. Environmental Modelling & Software 18(8-9) 761-799.

Molina, J.L., Bromley, J., GarcÃ-a-ArÃ³stegui, J.L., Sullivan, C., Benavente, J., 2010. Integrated water resources management of overexploited hydrogeological systems using Object-Oriented Bayesian Networks. Environmental Modelling & Software 25(4) 383-397.

Nash, D., Hannah, M., Robertson, F., Rifkin, P., 2010. A Bayesian Network for Comparing Dissolved Nitrogen Exports from High Rainfall Cropping in Southeastern Australia. Journal of Environmental Quality 39(5) 1699-1710.

Neitsch, S., Arnold, J., Kiniry, J., Williams, J., King, K., 2005. Soil and water assessment tool: theoretical documentation, version 2005. Texas, USA.

Newton, A.C., Stewart, G.B., Diaz, A., Golicher, D., Pullin, A.S., 2007. Bayesian Belief Networks as a tool for evidence-based conservation management. Journal for Nature Conservation 15(2) 144-160.

Park, S., Oh, C., Jeon, S., Jung, H., Choi, C., 2011. Soil erosion risk in Korean watersheds, assessed using the revised universal soil loss equation. Journal of Hydrology 399(3-4) 263-273.

Pearl, J., 2009. Causality: Models, Reasoning and Inference, 2nd ed. Cambridge University Press, Cambridge.

Poppenborg, P., Koellner, T., 2013. Do attitudes toward ecosystem services determine agricultural land use practices? An analysis of farmers' decision-making in a South Korean watershed. Land Use Policy 31(0) 422-429.

Poppenborg, P., Koellner, T., under review. A Bayesian network approach to model farmers' crop choice using expected benefits fom ecosystem services. Environmental Modelling&Software (under review).

Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D., Yoder, D., 1997. Predicting soil erosion by water: a guide to conservation planning with the revised universal soil loss equation (RUSLE). Agriculture Handbook No. 703, USDA, Washington, D.C.

Seppelt, R., Dormann, C.F., Eppink, F.V., Lautenbach, S., Schmidt, S., 2011. A quantitative review of ecosystem service studies: approaches, shortcomings and the road ahead. Journal of Applied Ecology 48(3) 630-636.

Sharpley, A.N., Smith, S.J., Berg, W.A., Williams, J.R., 1985. Nutrient Runoff Losses as Predicted by Annual and Monthly Soil Sampling. Journal of Environmental Quality 14(3) 354-360.

Shi, Z., Cai, C., Ding, S., Li, Z., Wang, T., Sun, Z., 2002. Assessment of erosion risk with the rusle and Gis in the middle and lower reaches of Hanjiang River, 12th ISCO Conference Beijing, China.

Shi, Z.H., Cai, C.F., Ding, S.W., Wang, T.W., Chow, T.L., 2004. Soil conservation planning at the small watershed level using RUSLE with GIS: a case study in the Three Gorge Area of China. CATENA 55(1) 33-48.

Smith, R.I., Dick, J.M., Scott, E.M., 2011. The role of statistics in the analysis of ecosystem services. Environmetrics 22(5) 608-617.

Stassopoulou, A., Petrou, M., Kittler, J., 1998. Application of a Bayesian network in a GIS based decision making system. International Journal of Geographical Information Science 12(1) 23-46.

Uusitalo, L., 2007. Advantages and challenges of Bayesian networks in environmental modelling. Ecological Modelling 203(3-4) 312-318.

Wang, Q.J., Robertson, D.E., Haines, C.L., 2009. A Bayesian network approach to knowledge integration and representation of farm irrigation: 1. Model development. Water Resources Research 45(2) W02409.

Yang, D., Kanae, S., Oki, T., Koike, T., Musiake, K., 2003. Global potential soil erosion with reference to land use and climate changes. Hydrological Processes 17(14) 2913-2928.

Zorrilla, P., Carmona Garcia, G., De la Hera, A., Varela Ortega, C., Martinez Santos, P., Bromley, J., Henriksen, H.J., 2010. Evaluation of Bayesian networks in participatory water resources management, Upper Guadiana Basin, Spain. Ecology and Society 15(3) 12.

4.9. Supporting information

Table 4.2: Specifications of all network nodes with indications of variable labels (used in figures of the network), variable names (used for calculations), node type ('Labelled' for discrete variables, 'Interval' for discretised continuous variables), no. of states (total number of variable's states), value range (range covered by variable's states), unit, specification (method used for populating variable's probability table), and data source.

Variable label	**Variable name**	**Node type**	**No. of states**	**Value range**	**Unit**	**Specification**	**Data source**
Income level	Income	Labelled	6	1 to 6	Very low (1) to very high (6)	EM-algorithm	Interviews (Poppenborg and Koellner (under review))
Expected benefits from 'Biomass Production'	AttB_Bio	Labelled	5	1 to 5	Very low (1) to very high (5)	EM-algorithm	Interviews (Poppenborg and Koellner (under review))
Expected benefits from 'Soil Erosion'	AttB_SE	Labelled	5	1 to 5	Very low (1) to very high (5)	EM-algorithm	Interviews (Poppenborg and Koellner (under review))
Expected benefits from 'Water Quality'	AttB_WQ	Labelled	5	1 to 5	Very low (1) to very high (5)	EM-algorithm	Interviews (Poppenborg and Koellner (under review))
Restrictions by 'Skills and Knowledge'	PBC_SaK	Labelled	5	1 to 5	Very low (1) to very high (5)	EM-algorithm	Interviews (Poppenborg and Koellner (under review))
Restrictions by 'Money Availability'	PBC_MA	Labelled	5	1 to 5	Very low (1) to very high (5)	EM-algorithm	Interviews (Poppenborg and Koellner (under review))
Crop preference 'Biomass'	Crop_Bio	Labelled	3	Rice, Annual, Perennial	N/A	EM-algorithm	Interviews (Poppenborg and

							Koellner (under review))
Crop preference 'Soil Erosion'	Crop_SE	Labelled	3	Rice, Annual, Perennial	N/A	EM-algorithm	Interviews (Poppenborg and Koellner (under review))
Crop preference 'Water Quality'	Crop_WQ	Labelled	3	Rice, Annual, Perennial	N/A	EM-algorithm	Interviews (Poppenborg and Koellner (under review))
Crop preference 'Skills and Knowledge'	Crop_SaK	Labelled	3	Rice, Annual, Perennial	N/A	EM-algorithm	Interviews (Poppenborg and Koellner (under review))
Crop preference 'Money Availability'	Crop_MA	Labelled	3	Rice, Annual, Perennial	N/A	EM-algorithm	Interviews (Poppenborg and Koellner (under review))
Crop preference 'Benefits'	Crop_AttB	Labelled	3	Rice, Annual, Perennial	N/A	AHP analysis	Interviews (Poppenborg and Koellner (under review))
Crop preference 'Restrictions'	Crop_PBC	Labelled	3	Rice, Annual, Perennial	N/A	AHP analysis	Interviews (Poppenborg and Koellner (under review))
Crop preference	Crop_Preference	Labelled	3	Rice, Annual, Perennial	N/A	AHP analysis	Interviews (Poppenborg and Koellner (under review))
Crop choice	Crop_Choice	Labelled	3	Rice, Annual, Perennial	N/A	EM-algorithm	Interviews (Poppenborg and Koellner (under review))
Slope steepness	Slope_Steepness	Interval	13	0 to 26	Degrees	EM-algorithm	Interviews (Poppenborg and Koellner (under

							review)); Digital elevation model
Soil carbon content	Soil_C	Interval	5	0 to 6	Percentage	Truncated normal distribution with mean=0.8688, variance=0.0461 for rice; mean=0.7552, variance=0.4243 for annuals; mean=2.4147, variance=7.0598 for perennials	Soil map (Arnhold, personal communication (2013))
f (orgC)	orgC	Interval	26	0.974 to 1	N/A	1 - 0.0256 * Soil_C / (Soil_C + exp (3.72 - 2.95 * Soil_C))	*Deterministic*
Soil texture classification	Soil_Tex	Labelled	2	Loamy sand, Sandy loam	N/A	Count data with n=34 for loamy sand, and n=60 for sandy loam	Soil map (Arnhold, personal communication (2013))
Clay content	clay	Interval	10	0 to 20	Percentage	Truncated normal distribution with mean=3.5058, variance=0.7186 for loamy sand; mean=6.5568, variance=2.3762 for sandy loam	Soil map (Arnhold, personal communication (2013))
Silt content	silt	Interval	10	0 to 50	Percentage	Truncated normal distribution with mean=17.1757, variance=5.1158 for loamy sand; mean=26.1842, variance=12.958 for sandy loam	Soil map (Arnhold, personal communication (2013))
Sand content	sand	Interval	8	50 to 90	Percentage	Truncated normal distribution with mean=79.3184, variance=8.3288 for loamy sand; mean=67.2589, variance=22.0441 for sandy loam	Soil map (Arnhold, personal communication (2013))
f(cl-si)	cl_si	Interval	8	0 to 1	N/A	(silt / (clay + silt)) ^ 0.3	*Deterministic*
f(csand)	csand	Interval	5	0.2 to 0.2005	N/A	0.2 + 0.3 * exp (-0.256 * sand * (1 - silt / 100))	*Deterministic*
f(hisand)	hisand	Interval	11	0.5 to 1	N/A	1 - 0.7 * (1 - sand / 100) / (1 - sand / 100 + exp (-5.51 + 22.9 * (1 - sand / 100)))	*Deterministic*
f(soil texture)	st	Interval	11	0 to 0.22	N/A	hisand * csand * cl_si	*Deterministic*
K-Factor	K	Interval	15	0 to 0.03	N/A	orgC * st * 0.1317	*Deterministic*
S-Factor	S	Interval	14	0 to 7	N/A	Slope_Steepness <6:	*Deterministic*

						10.8 * sin (Slope_Steepness / 57.2957) + 0.03; Slope_Steepness >=6: 16.8 * sin (Slope_Steepness / 57.2957) - 0.5	
Beta / (1+Beta)	Beta	Interval	8	0 to 0.8	N/A	sin (Slope_Steepness / 57.2957) / 0.0896 / (3 * sin (Slope_Steepness / 57.2957) ^ 0.8 + 0.56) / (1 + sin (Slope_Steepness / 57.2957) / 0.0896 / (3 * sin (Slope_Steepness / 57.2957) ^ 0.8 + 0.56))	*Deterministic*
Slope Length	Slope_Length	Interval	25	1 to 125	Meter	Truncated Gamma distribution with shape=2.16, scale=17.54	Arnhold et al. (under review)
L-Factor	L	Interval	12	0 to 4	N/A	(3.2808 * Slope_Length / 72.6) ^ Beta	*Deterministic*
LS-Factor	LS	Interval	34	0 to 28	N/A	L * S	*Deterministic*
R-Factor	R	Interval	40	0 to 20000	N/A	Truncated normal distribution with mean=6599, variance=22742900	Arnhold et al. (under review)
C-Factor	C	Interval	20	0 to 0.4	N/A	Truncated normal distribution with mean=0.13, variance=0.0013 for rice; mean=0.1417, variance=0.0045 for annuals; mean=0.1257, variance=0.0101 for perennials	Arnhold et al. (under review); Kim et al. 2005; Yang et al. 2003; Liu and Luo 2005; Chen et al. 2012; Shi et al. 2002; Park et al. 2011; Jung et al. 2003; Lee and Choi 2009; Fu et al. 2005
RC-Factor	RC	Interval	32	0 to 8000	N/A	R * C	*Deterministic*
Soil Erosion	Erosion	Interval	54	0 to 7000	Tons / (Hectare * Year)	RC * LS * K	*Deterministic*
Relative Erosion Amount Change	RE	Interval	19	-100 to +infinity	Percentage	-1 * (100 - Erosion / 53 * 100)	*Deterministic*
Biomass Yield Change Index	Biomass	Interval	19	-100 to +infinity	Percentage	Truncated normal distribution with mean=-5.82, variance=72.34 for organic rice; mean=-1.25, variance=1904.39 for organic annuals;	Yield statistics from KOSIS (www.kosis.kr)

						mean=-10.29, variance=1274.41 for organic perennials;
						mean=5.82, variance=51.02 for conventional rice;
						mean=10.29, variance=335.63 for conventional annuals;
						mean=15.57, variance=470.13 for conventional perennials;	

Organic/Conventional	Cultivation	Labelled	2	Organic, Conventional	N/A	EM-algorithm	Interviews (Poppenborg and Koellner (under review))
Soil Total Phosphorus	STP	Interval	10	0 to 0.2	Percentage	Truncated normal distribution with mean=0.04022, variance=0.00013728 for organic; mean=0.04842, variance=0.00014707 for conventional	Soil map (Arnhold, personal communication (2013))
Particulate Phosphorus Loss	PPL	Interval	29	0 to 6200	Kilograms / (Hectare * Year)	STP / 100 * Erosion * 1000 * (2.53 * Erosion ^ (-0.21))	*Deterministic*
Relative Particulate P Loss	RPPL	Interval	19	-100 to +infinity	Percentage	-1 * (100 - PPL / 24 * 100)	*Deterministic*
Soil Total Nitrogen	STN	Interval	10	0 to 0.2	Percentage	Truncated normal distribution with mean=0.0762, variance=0.0032 for organic; mean=0.0864, variance=0.0026 for conventional	Soil map (Arnhold, personal communication (2013))
Total Nitrogen Loss	TNL	Interval	29	0 to 6200	Kilograms / (Hectare * Year)	STN / 100 * Erosion * 1000 * (2.53 * Erosion ^ (-0.21))	*Deterministic*
Relative Total N Loss	RTNL	Interval	19	-100 to +infinity	Percentage	-1 * (100 - TNL / 44 * 100)	*Deterministic*
Water Quality Change Index	WQ	Interval	20	-950 to 300	Percentage	-1 * (RTNL + RE + RPPL)	*Deterministic*

Declaration/Erklärung

I hereby declare, to the best of my knowledge and belief, that this thesis does not contain any material previously published or written by another person, except where due reference has been made in the text. This thesis contains no material, which has been previously accepted or definitely rejected for award of any other doctoral degree at any university or equivalent institution.

Bayreuth, 15.01.2014 ____________________________________

Patrick Poppenborg

Hiermit erkläre ich, dass ich die vorliegende Doktorarbeit selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

Bayreuth, 15.01.2014 ____________________________________

Patrick Poppenborg

Hiermit erkläre ich, dass ich nicht bereits anderweitig versucht habe, diese Dissertation ohne Erfolg einzureichen oder mich einer Doktorprüfung zu unterziehen.

Bayreuth, 15.01.2014 ____________________________________

Patrick Poppenborg

Hiermit erkläre ich, dass ich die Hilfe von gewerblichen Promotionsberatern bzw. Promotionsvermittlern weder bisher in Anspruch genommen habe, noch künftig in Anspruch nehmen werde.

Bayreuth, 15.01.2014 ____________________________________

Patrick Poppenborg