

The Institute for Natural Resource Conservation
of the Christian-Albrechts-Universität zu Kiel

**Assessing and Mapping
Rice Provisioning Ecosystem Services**

Dissertation submitted for the Doctoral Degree
awarded by the Faculty of Agricultural and Nutritional Sciences
of the Christian-Albrechts-Universität zu Kiel

Submitted by

M.Sc. Kinh Bac Dang

Born in Hanoi, Vietnam

Kiel, 2018

Dean: Prof. Dr. Christian Henning

Examiners: Prof. Dr. Benjamin Burkhard

Prof. Dr. Felix Müller

Day of oral examination: July 4th 2018

**Assessing and Mapping
Rice Provisioning Ecosystem Services**

Submitted by

M.Sc. Kinh Bac Dang

Faculty of Agricultural and Nutritional Sciences

Christian-Albrechts-Universität zu Kiel

Printed with the approval
of the Faculty of Agricultural and Nutritional Sciences
in the Christian-Albrechts-Universität zu Kiel

Acknowledgements

I wish to express my gratitude to all those who have contributed to the completion of this thesis.

First of all, I would like to express my deepest appreciation to my supervisors Prof. Dr. Benjamin Burkhard and Prof. Dr. Felix Müller for their valuable idea, motivation, enthusiasm and continuous support. Their guidance helped me in all the time of research and writing of this thesis. I have been learnt from them many things, not only their tremendous academic knowledge but also their kind personality. This work would of course not have been possible without their assistance.

I would also like to thank Dr. Wilhelm Windhorst for agreeing to serve as additional reviewers of my dissertation. All of his continuous encouragement and support, for helpful advice and discussions and for the critical review of my manuscripts, helpful scientific advice, good cooperation and of course for their supporting friendliness and inspiring motivation.

I gratefully acknowledge financial support by the Ministry of Education and Training in Viet Nam (911 scholarship) during four years and LEGATO (Land-use intensity and Ecological EnGineering – Assessment Tools for risks and Opportunities in annual crop based production systems), funded by the German Ministry of Research and Education (BMBF) project for supporting data and an interesting trip to project conference in Indonesia (March 2015).

Thanks to Dr. Claus Schimming, Dr. Marion Kruse, Dr. Liwei Ma, Dr. Peter Wangai and Sabine Bicking for a friendly working atmosphere in Institute for Natural Resource Conservation, University of Kiel. Many special thanks to my dear friends Mr. Nguyen Quang Anh, Mr. Nguyen Van Phuong and Mrs. Vu Thi Tinh for sharing a great time in and outside the university. Furthermore, I thank Dr. Isoda Yuzuru, Dr. Vu Kim Chi and Dr. Hoang Thi Thu Huong for data support. Thanks to Dr. Georg Hormann for R programing support and to Mrs. Angie Faust for polishing the English of my articles.

Nhân dịp này con muốn gửi lời cảm ơn chân thành nhất tới bố mẹ - người đã sinh ra và dạy dỗ con. 4 năm trôi qua với nhiều biến cố trong gia đình nhưng bố mẹ vẫn luôn ủng hộ và động viên con vượt qua những khó khăn trong cuộc sống xa nhà. Con rất may mắn khi có bố mẹ vợ đã luôn lo lắng và giúp đỡ gia đình con. Bố mẹ thường xuyên thăm hỏi, động viên khiến cuộc sống xa nhà trở nên gần gũi hơn, đặc biệt là thời gian bé Kiên ra đời. Con biết ơn bố mẹ rất nhiều. Cảm ơn anh Vũ, chị Hội, anh Trung và chị Vân đã luôn thấu hiểu và động viên tôi để hoàn thành luận án này.

Đóng góp không thể thiếu trong luận văn này là sự giúp đỡ của vợ và con trai. Anh cảm ơn vợ đã là hậu phương vững chắc cho anh tập trung hoàn thành luận văn này.

Thank you!

Declarations

M.Sc. Kinh Bac Dang

Statutory Declaration:

Herewith I declare on oath that the submitted dissertation under the title “Assessing and mapping rice provisioning ecosystem services” has been authored independently and without illegitimate external help and that it has not been formerly submitted to another university department.

Kiel, 12. 08. 2018

Signature

Herewith I declare, that I am not subject to any pending case of public prosecution.

Kiel, 12. 08. 2018

Signature

Herewith I declare, that the dissertation complies with the conventions of proper academic practices as defined by the DFG.

Kiel, 12. 08. 2018

Signature

Table of Contents

Acknowledgements	I
Declarations	II
List of Figures	V
List of Tables.....	V
Zusammenfassung	1
Summary	3
Chapter 1. Introduction.....	5
1.1. Ecosystem services (ES).....	6
1.1.1. Background concepts	6
1.1.2. Classification of ecosystem services (ES).....	8
1.1.3. Interdependences of ecosystem services in social-ecological systems	9
1.1.4. Ecosystem service assessment	11
1.1.5. Ecosystem service assessments in Asia and Vietnam	12
1.2. Rice provisioning ecosystem service.....	15
1.2.1. Background rice ecosystems.....	16
1.2.2. Classification of rice ecosystems	17
1.2.3. Rice provision based on the ecosystem service approach	19
1.3. Methodologies in ecosystem service assessments.....	20
1.4. Research area	22
1.5. Research questions and outline of the thesis.....	26
Chapter 2. Modelling and Mapping Natural Hazard Regulating Ecosystem Services in Sapa, Lao Cai Province, Vietnam	31
Chapter 3. Application of hybrid neural-fuzzy inference system for mapping crop suitability areas and predicting rice yields	47
Chapter 4. A Bayesian Belief Network – based approach to link ecosystem functions with rice provisioning ecosystem services	84

Chapter 5. Potential, flow and demand of rice provisioning ecosystem services – Case study in Sapa district, Vietnam	102
Chapter 6. Synthesis	135
6.1. Summarizing answers to research questions.....	136
6.1.1. Natural hazard regulating ecosystem services (RES).....	136
6.1.2. Mapping crop suitability areas and predicting rice yields	137
6.1.3. A Bayesian Belief Network – based approach to understand rice provisioning ecosystem services.....	138
6.1.4. Ecosystem service supply chain for rice products	139
6.2. Conclusions.....	140
6.2.1. How are erosion and landslides regulated in terraced rice ecosystems?	140
6.2.2. How can farmers improve rice production in mountainous areas?	140
6.2.3. What are differences in the use of Bayesian Belief Networks in ecosystem service assessments in comparison with other formal models, particularly in neural networks?	141
6.3. Outlook	144
6.4. Highlights of the dissertation	145
References	146
Chapter 7. Curriculum Vitae	156

List of Figures

(Not include figures in chapters 2, 3, 4, 5)

Figure 1. Classification of main ecosystem services (dark yellow color) according to Kandziora et al. (2013a). The light yellow color represents supporting services and abiotic resources.....	8
Figure 2. Conceptual model showing the relations of ecosystem functions, services and human benefits (adapted from Burkhard et al. (2014)).....	10
Figure 3. Distribution of four rice ecosystems in the landscape based on the classification of IRRI (2006).....	17
Figure 4. Simplified hierarchy of data mining commonly used in ecological studies.....	21
Figure 5. Location of the Sapa district, Lao Cai province, Vietnam and the different research scales mentioned in the next chapters. Photo credit: Tu Trung Dang, 2014.	23
Figure 6. Rice agriculture landscapes in the Sapa district, Lao Cai province, Vietnam. (a) An agricultural landscape captured from the Cat Cat village; (b) The use of buffalo for rice cultivation on terraces; (c) A poor household containing seven kids in the case study. Photo credits: Dang Kinh Bac, 2015.....	24
Figure 7: Conceptual framework to assess rice provisioning ecosystem services based on a Bayesian approach	84
Figure 8. A general framework of Rice Provisioning Ecosystem service supply chain from service providing areas to service benefiting areas; Grey arrows present the movements of material, energy or information related to rice provision across space; Dark arrows present the one or two ways relations between components.	102

List of tables

(Not include tables in chapters 2, 3, 4, 5)

Table 1. Definitions of ecosystem services.....	7
Table 2. A comparison between the use of Bayesian Belief Networks (BBN) and the Hybrid Neural-Fuzzy Inference System (HyFIS) for ecosystem service assessments.	143

Zusammenfassung

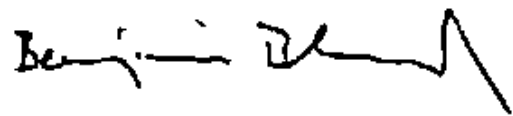
Reisproduktion und damit verbundene Ökosystemleistungen sind abhängig von ökologischen und sozio-ökonomischen Faktoren. Auf wissenschaftlicher sowie auf politischer Ebene bestehen immer noch Wissenslücken zum Thema Entwicklung nachhaltiger Strategien für die Landwirtschaft und zur Verbesserung der Nahrungsmittelsicherheit. Landnutzer verstehen oftmals nicht die Probleme bezüglich Angebot und Nachfrage von Reisprodukten und Ökonomen können nicht alle landwirtschaftlichen Aspekte nachvollziehen. Diese Lücken haben zu einer Steigerung ökologischer Risiken (z.B. Dürre, Erosion und Verschmutzung) und zu Hungersnöten in Entwicklungsländern beigetragen. Darum ist es zwingend notwendig, einen integrativen Ansatz zu erarbeiten, welcher die Vorteile und das Wissen der verschiedenen Stakeholder, wie z.B. Landwirte, Politiker, Zwischenhändler und Konsumenten, integriert und eine ausbalancierte Bewertung ermöglicht.

In dieser Dissertation wird das Konzept der Ökosystemleistungen (ÖSL; englisch „Ecosystem Services“ - ES) als vielversprechender Lösungsansatz für die Kommunikation mit Entscheidungsträgern vorgestellt. Verschiedene ökologische und sozioökonomische Aspekte werden in dieser Studie diskutiert, darunter: (1) Die Komplexität der Reis-produzierenden sozial-ökologischen Systeme; (2) der Beitrag von regulierenden Ökosystemleistungen zur Reisproduktion, mit besonderem Fokus auf die Regulation von Naturkatastrophen; (3) Potentiale, Flüsse und Nachfragen von/nach Reis-Versorgungs-ÖSL; (4) die räumlichen Beziehungen zwischen Reis-ÖSL-bereitstellenden und -nutzenden Gebieten und Gemeinden und (5) ÖSL-Angebots-/Nachfrageketten in der Reisproduktion. Um die Ökosystemleistung Reisproduktion zu quantifizieren, wurden verschiedene Methoden angewendet, darunter: Geographische Informationssysteme (GIS), Fernerkundung, Modellierung, maschinelles Lernen, Datenerfassung durch teilstandardisierte Interviews, statistische Berichte und frei verfügbare GIS-Datenquellen. Zwei quantitative Modelle wurden hierbei benutzt: Das Hybrid Neural-Fuzzy Inference System (HyFIS) und ein Bayesian Belief Network (BBN), um geeignete Anbaugelände für Reis zu finden, Reisernten vorherzusagen und die Reisproduktion zu bestimmen. Um die Qualität der angewendeten Methoden und des allgemeinen Forschungsansatzes zu demonstrieren, wurde die Sapa Region in der Lao Cai Provinz in Nordvietnam als Fallstudiengebiet ausgewählt.

Drei konzeptionelle Modelle wurden hierbei entwickelt, um (i) den Einfluss von bewässerten Reisfeldern und anderen Landnutzungstypen auf Erosions- und Erdbeben-regulierende ÖSL zu analysieren; (ii) den Beitrag von ökologischen Strukturen und Prozessen (basierend auf ökologischen Faktoren) und zusätzlichen anthropogenen Einträgen zur Reisproduktion zu bestimmen, und (iii) die Beziehung zwischen Potential, Fluss und Nachfrage nach der ÖSL Reisproduktion zu verstehen. Die Ergebnisse beweisen, dass erstens Reisanbau auf Terrassen nicht immer eine nachhaltige Methode ist, um Erosion und Erdbeben zu verhindern. Zweitens, mithilfe quantitativer Beziehungen zwischen den

Potential-, Fluss- und Nachfrage-Komponenten der Reisproduktion die Notwendigkeit von Reimporten und Optionen für Reis-Exporte zeitlich und räumlich vorhergesagt werden und die Effizienz der ÖSL-Bereitstellungsketten für die Reisproduktion beurteilen werden können. Drittens konnte festgestellt werden, dass derzeit ineffektive ÖSL-Bereitstellungsketten in Vietnam vorherrschen, insbesondere im Untersuchungsgebiet. Die Landwirte in der Sapa-Region produzieren im Allgemeinen einen Überschuss an Reis. Dieser wird jedoch meist an Touristen verkauft oder in andere Gebiete exportiert, anstatt als Nahrungsquelle für die lokale Bevölkerung zu dienen. Infolgedessen entstehen regelmäßig Hungersnöte, insbesondere in den ärmeren Gemeinden. Um die ÖSL-Bereitstellungskette zu verbessern, sollte die Politik die Landwirte dazu animieren, ihren Reis in den benachbarten, insbesondere den ärmeren Gemeinden, zu verkaufen anstatt ihn in andere Regionen zu exportieren. Diese politische Strategie benötigt eine größere Beteiligung der Entscheidungsträger, vor allem von Verantwortlichen auf Gemeinde- und Regionalebene. Die Ergebnisse dieser Studie können von politischen Entscheidungsträgern genutzt werden, um Veränderungen der Reisproduktions-ÖSL zu beurteilen, zu quantifizieren und flächenhaft im Kontext von Störungen der sozial-ökologischen Systemkomponenten darzustellen.

Bestätigung des Gutachters:



Hannover, 18.04.2018

Prof. Dr. Benjamin Burkhard

Summary

Rice production and related ecosystem services provision are strongly dependent on environmental characteristics and socio-economic factors. There are still various knowledge gaps among decision makers for the development of sustainable agriculture strategies and to improve food security. Farmers can often not clearly understand issues related to rice supply chains, while economists can often not clearly understand farming issues. These gaps have led to the increase of environmental risks (e.g. droughts, erosion and pollution), as well as famine threats in developing countries. Therefore, it is necessary to find out an integrated approach to balance the benefits and knowledge between stakeholders such as farmers, politicians, intermediate traders and consumers.

In this dissertation, the approach of ecosystem services (ES) is proposed as a promising solution to communicate with decision makers. Various environmental and socio-economic issues are discussed in this study including: (1) the complexity of the rice-producing social-ecological systems; (2) the contribution of regulating ES to rice production and provision, especially regarding natural hazard regulation; (3) the potentials, flows, demand and budgets of rice provisioning ES; (4) the spatial relations between rice ES providing and benefiting areas and communities; and (5) ES supply chains of rice products. In order to quantify rice provisioning ES, a bundle of methods was applied, including: Geographical Information Systems (GIS), remote sensing, modelling, machine learning and data collection from semi-structured interviews, statistical reports and free-GIS-data sources. Two quantitative models were used: the Hybrid Neural-Fuzzy Inference System (HyFIS) and the Bayesian Belief Network (BBN) approach to locate crop suitability areas, predict rice yields and assess rice provisioning ES. To demonstrate the quality of the proposed methods and the general approach, a case study in the Sapa district in the Lao Cai province in northern Vietnam was chosen.

As a result, three conceptual models developed in order to understand (i) the impacts of irrigated rice fields and other forms of land use/land cover on erosion and landslide regulating ES, (ii) the contribution of ecological structures and processes (based on environmental characteristics) and additional anthropogenic inputs to rice provisioning ES, and (iii) the relations between potential, flow and demand of rice provisioning ES. The results proved firstly that rice cultivation on terraces is not

always a sustainable method to prevent soil erosion and landslides. Secondly, quantitative relations between potential, flow and demand components of rice provisioning ES can predict the demand of rice import/export in a particular time and region, and assess the efficiency of ES supply chains of rice products. Thirdly, ineffective ES supply chains are currently at place in Vietnam, particularly in the case study area. Farmers in the Sapa district produce in general a surplus of rice, but it is often sold for tourists and exported to other regions, instead of being used as a food source for the local people. This is regularly resulting in hunger periods in the poorer communities. To improve the ES supply chains, policies should encourage farmers to sell their rice products to neighboring communities, especially to poorer communities, before exporting them to outside regions. These policies need a deeper participation of decision makers, especially officers from community/regional levels. Finally, the results of this study can be used by decision makers to assess, quantify and map changes of rice provisioning ES in the context of disturbances of socio-ecological system components.

Chapter 1.

Introduction

1.1. Ecosystem services

In this section, a general background of the ecosystem services (ES) concept, its definition and classification is presented. Various quantitative and qualitative methods to assess ES are listed. Lastly, studies about ecosystem service assessments in Asian countries, particularly in Vietnam, are summarized.

1.1.1. Background concepts

The term ecosystem services has entered scientific studies since the 1980s as a consideration of benefits from biodiversity, nature and ecosystems to support human well-being (Potschin et al., 2016). The ES approach does not only focus on biodiversity conservation, but also institutional management (United Nations, 1992). Earliest, Sears (1956) draws attention to the important role of ecosystems in waste treatment and nutrient cycling. The earliest documents related to services, functions and values of ecosystems were written from the mid-1960s to the early 1970s (De Groot et al., 2002). The term "environmental services" was firstly proposed in the "Study of Critical Environmental Problems" (SCEP, 1970), which focuses on pollination, fisheries and flood mitigation.

Over time, many different terms have been used, such as "public-services", "nature's services", "natural solutions" and "ecological services" as listed in Burkhard et al. (2012a); Eckholm (1978); Ehrlich and Holdren (1973) and Westman (1977). The IUCN (1980) emphasized that "goods and services provided by ecosystems" need to be attended in biodiversity conservation and sustainable development. Already in the publication "Man and Nature" (Marsh, 1864), the authors have mentioned the limitations of benefits provided to people from nature related to the excessive use of environmental resources. Over four decades, different values of nature for people, as well as trade-offs between ecosystem services, climate change and biodiversity have been understood more clearly (Millennium Ecosystem Assessment, 2005).

The Millennium Ecosystem Assessment (2005) has defined ES as "the benefits obtained from ecosystems". According to this assessment, ES refer to different contributions from natural capital to human benefits, with the participation of three other forms of capital (including social, human and build forms) (Potschin et al., 2016). In these concepts, the natural capital refers to the natural potential of ecosystems to provide ES, without contributions of human activities, whereas the social capital includes additional inputs by humans to optimize ES supply. Related benefits can be useable, non-useable, limited or optional based on the type of ES.

Other ES definitions have been proposed over time on the base of different ecological and/or economic approaches (Table 1). The arguments between benefits of natural ecosystems and the human society have led to the variety in defining this terminology. Many efforts to demonstrate the importance of ecosystem services to humans have been embedded in developing classification systems and frameworks for assessing and quantifying ES (De Groot et al., 2002; Kumar et al., 2010;

Millennium Ecosystem Assessment, 2005). In this process, the distinctions between the ecological processes and structures, ecosystem functions and ecosystem services have become more clear. For example, Bastian et al. (2012) identified the differences between ecosystem properties, potentials and services, whereas Burkhard et al. (2012b) explicitly distinguished between ES potential, supply, demand and flows. According to these definitions, ecosystem services seem to be broad and vague because the term contains benefits people can or cannot perceive. Concerning some ecosystem services, Crossman et al. (2013); Haines-Young and Potschin (2010a) and Villa et al. (2009) noted that the human benefits are obtained from ecosystem processes and structures (so-called as “intermediate” services), then the “final” services could enable valuation of these final benefits to human. However, it is difficult to distinguish between intermediate and final services (Haines-Young and Potschin, 2013). Some ecological processes and functions are considered as services, whereas some services (such as supporting services in the MA classification) are classified as intermediate/final types. The complex correlations and trade-offs between the different ecosystem services and related ecosystems need further studies, to reduce complexities in developing management strategies based on the ecosystem service approach.

Table 1. Definitions of ecosystem services.

Definition of ecosystem services	Reference
“the contributions of ecosystem structure and function – in combination with other inputs – to human well-being.”	Burkhard et al., 2012b
“the benefits people obtain from ecosystems.”	MEA, 2003
“the aspects of ecosystems utilized (actively or passively) to produce human well-being.”	Fisher et al., 2009
“a range of goods and services generated by ecosystems that are important for human well-being.”	Nelson et al., 2009
“the capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly.”	De Groot et al., 2002
“the benefits human populations derive, directly or indirectly, from ecosystem functions.”	Costanza et al., 1997
“the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life.”	Daily, 1997

The assessment of ecosystem services requires an in-depth understanding of ecology, human well-being and interactions in the social-ecological system. Initially, the concept of ecosystem services was criticized for focusing too much on natural systems and eliminating interactions between the environment and humans (Sun and Müller, 2013). More recently, this concept has gained increasingly widespread recognition as a part of social-ecological systems where different contributions of humans

to the environment have generated artificial ecosystems and related services (Huntsinger and Oviedo, 2014). Hence, the approach of ecosystem services helps to communicate with decision-makers in improving social welfare and at the same time minimizing environmental risks.

1.1.2. Classification of ecosystem services (ES)

The classification of ES depends on definition, geographical conditions, period in time, object and spatial scales and is updated by different organizations such as the Common International Classification of Ecosystem Services (CIESS) (Haines-Young and Potschin, 2018, 2013), National Ecosystem Service Classification system (NESCS) (EPA, 2015) and US EPA Classification System for Final Ecosystem Goods and Services (USEPA) (Freeman, 2014). In general, ES include three main categories: provisioning, regulating and cultural services. Kandziora et al. (2013a) described these three main types of services as follows (Figure 1):

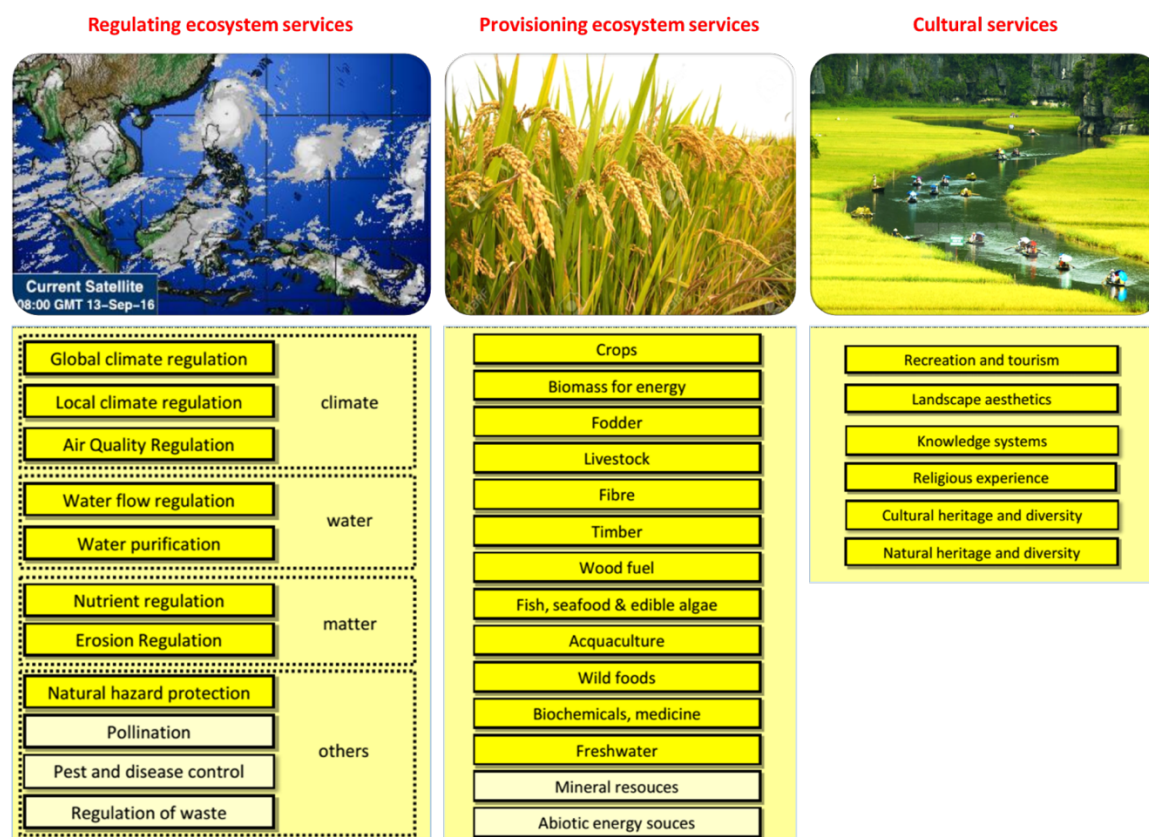


Figure 1. Classification of main ecosystem services (dark yellow color) according to Kandziora et al. (2013a). The light yellow color represents supporting services and abiotic resources.

- *Provisioning ES* are goods/products made or supplied from ecosystems, including nutritional (such as rice, meat and fresh water), material (such as wood and fiber) and energy (such as firewood and

fuel) supplies. The products from these services can usually be traded or directly used by beneficiaries.

- *Regulating ES* are the human benefits achieved from the mitigation of harmful processes, such as climate change and natural catastrophes. Many types of regulating ES are intangible benefits in controlling natural processes, such as natural hazards and global/local climate.
- *Cultural services* are non-material benefits derived from ecosystems, including non-material spiritual benefits, entertainment, knowledge or education.

According to CICES ¹ that was developed for the EEA (European Environment Agency) ², published and widely used, ES are classified into different levels (updated version 5.1 in December 2017). The three categories in the highest level include: provisioning, regulating and maintenance, and cultural services. Each category is classified with more detail in “Division”, “Group” and “Class” levels within a hierarchical structure. For example, erosion regulation represents controls of erosion rates (class) in mass flows (group) of mediation of flows (division) in the “regulation and maintenance” section. Whereas, rice is classified in cultivated crops (class) in biomass (group) of nutrition (division) in the “provisioning ES” section. In addition, supporting (or intermediate) services were excluded from CICES, because these are ecosystem functions that do not provide direct benefit to humans (Haines-Young and Potschin, 2010b). They are, however, needed for the production of all other ES. This decision does not only avoid “double counting” of supporting services, but also helps focusing on the final services benefiting humans in ES assessments (Haines-Young and Potschin, 2013). According to the ecosystem service classification updated in 2017, all classifications contain abiotic ecosystem outputs, such as minerals and hydro/wind power because of their dependences on “natural processes”, instead of “living processes” (Haines-Young and Potschin, 2018).

1.1.3. Interdependences of ecosystem services in social-ecological systems

To foster a better understanding of nature-human-interactions to optimize sustainable development is the main task for the earth sciences (Comberti et al., 2015). As a bridge between human and natural systems, the concept of ecosystem services has proposed to realize the benefits from ecosystems obtained by human (Potschin and Haines-Young, 2011), and to learn about feedback effects of human activities on ecosystems (Mach et al., 2015). In other words, the analysis of ecosystem services is considered as essential part of social-ecological system studies (Carpenter et al., 2009). Hummel et al. (2011) generated a hybrid framework for complex social-ecological systems to structure key factors, concepts and human-nature interactions. The interaction between natural and social structures and processes through ecosystem functions and land management can provide services, but also disservices to beneficiaries. To understand these interactions, knowledge of human-nature

¹ <https://cices.eu/>

² <https://www.eea.europa.eu/>

interactions, social practices and institutions of natural resource use and technologies to exploit natural resources need to be explicitly identified in the process of ecosystem services assessments. The interactions can vary from place to place, and from time to time. Therefore, studies relating this interest require interdisciplinary understandings about natural and social sciences, as well as technical knowledge.

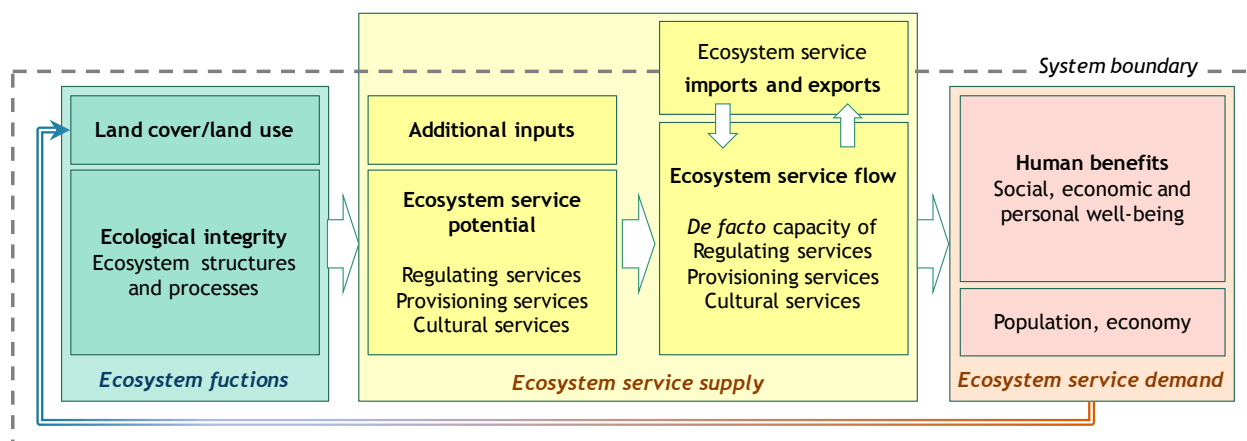


Figure 2. Conceptual model showing the relations of ecosystem functions, services and human benefits (adapted from Burkhard et al. (2014)).

Burkhard et al. (2014) constructed a conceptual model to depict ES potential, flow and demand cycles based on the relationships between the environment and the human society (Figure 2). In this concept, land uses/covers and ecological structures and processes play important roles in the modification of ecosystem functions and the ecosystem service potential. In combination with additional inputs (related to social, human, financial and manufactured capitals), people take full advantages of ecosystem service potentials to produce final services from particular ecosystems. The *de-facto* amount of ES used (or ES flows), which depends on the demand of user/beneficiaries, can provide information for decision makers concerning the demand for ES imports or exports. The definitions of these terminologies will be presented in detail in Chapters 4 and 5 of this dissertation.

Spatial relations between service providing units (SPUs) and service benefiting areas (SBAs) are commonly used to depict the spatial-temporal interactions between social-ecological systems and ecosystem services. A clear understanding of Service Providing Units (SPUs) and Service Benefiting Areas (SBAs) could partly explain these dependences. According to different research scales and spatial relations between areas of ES supply and demand, SPUs can be coincided or different from SBAs. Therefore, Fisher et al. (2009) and Syrbe and Walz (2012) classified the SPU-SBA spatial relations into four types:

- *in situ* - where the SPU is in the same place with SBA,

- *omni-directional* - where the SPU provides services for the surrounding areas (SBA) without directional bias,
- *directional* - where the SPU benefits an exact location based on the flow direction, and
- *decoupled* - where the SPU provided a service to SBA over long distances and complex networks.

Based on ecological and social characteristics, information on SPUs and SBAs can be useful for understanding ecosystem functions and trade-offs between biodiversity conservation and ecosystem services (Potschin et al., 2016). In contrast, understanding trade-offs involved in each SPU helps to value multi-benefits obtained from different ecosystems.

1.1.4. Ecosystem service assessment

Daily (1997) and Fisher et al. (2007) emphasized the important roles of identification and monitoring of ES, their changes in ecosystems and their effects on humans. Over time, various conceptual frameworks to assess ES have been developed as a basis for action, such as the framework of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES). These frameworks help to connect experts, decision-makers and the public by simplifying complex systems and clarify relationships between interdisciplinary studies (Potschin et al., 2016). Due to the complexities of social-ecological systems, credible frameworks that were developed based on expert knowledge need to be testable by qualitative and/or quantitative methods. Haines-Young and Potschin (2009) proposed three approaches commonly used in ES assessments, including “habitat”, “system” or “place-based” approaches. The selection of an approach depends on different interests, such as the type of ecosystem service, trade-offs to be considered and research scales. The three approaches are not mutually exclusive and can support each other toward a better understanding of the links between the environment and humans based on the ES concept (Potschin et al., 2016).

The habitat approach, as the most widely used concept in ES assessments. It focuses on observations in ecological habitats (land use/cover or biomes in some assessments) to evaluate the relationships between nature and humans. Because of the flexibility in the use of available data, this approach is commonly selected for studies at regional, national and local scales. Land use/cover data and expert judgments are effectively employed in presenting different services in maps and matrices. For example, Burkhard et al. (2014, 2012b and 2009) developed easily applicable matrices assessing ecosystem services supply, demand and flows in different geospatial units (such as different land use and land cover (LULC) types). This approach can show multifunctional land use/cover and trade-offs between related ES (Kandziora et al., 2013a). The capacity of services is often assessed based on the contribution of whole landscapes, instead of considering individual habitats. This can lead to uncertainties in ES assessments at different scales (Potschin et al., 2016).

The system- (or process-) orientated approach provides a more integrative picture in ecosystem service assessments through modelling-based developments. The modelling process can simplify relationships within social-ecological systems and helps to identify ecosystem functions, service outputs, service providing units and benefiting areas. Additionally, influences of initial factors of ES supply, demand and flows can be analyzed at different scales and by using scenarios (Grêt-Regamey et al., 2017). Some models have been widely used, such as InVEST, ARIES and LUCI (Bagstad et al., 2013). Bayesian Belief Networks (BBN) have become an increasingly popular modelling tool for simulating uncertain and complex issues in ES assessments (Uusitalo, 2007). Various Bayesian networks based on cascade models have proved the advantages of the system approach in understanding trade-offs between different choices of strategic planning (Burkhard and Maes, 2017). Nevertheless, the calibration and testing processes of these models seem to be difficult in some complex models due to a lack of data, time and other resources.

The place-based approaches evaluate “bundles” of ecosystem services through an integrated understanding in a particular “place”. Discussions between different groups of people, who know and use the area, are carried out to value ES and their changes. This approach starts from social perspectives to define people’s priorities and values (Potschin et al., 2016). After deliberative processes, sustainable solutions relating to ecological, social and economic terms can be proposed. Observations at the landscape scale help to clearly understand values of each ES in local contexts as well as to avoid conflicts and trade-offs of ES bundles. The development of participatory mapping is an important method in place-based approaches (Palomo et al., 2013; Plieninger et al., 2013) with combination of analyses of stakeholder perspectives (Raymond et al., 2009). However, results from this approach seem to be difficult to be generalized or measured in other places because of uncertainties and lacks of data. A complete model-based place-based approach needs interdisciplinary knowledge, is time- and resource-consuming if complexities of social-ecological systems are to be simulated.

1.1.5. Ecosystem services assessments in Asia and Vietnam

In Asia, the approach of ecosystem services has been seriously arrived since the year 2010. It has focused on assessments related to changes in ecosystems and influences of climate change on biodiversity and ecosystem services (Brander, 2000; Kubiszewski et al., 2016; Maniatis, 2007). According to the Policy Brief written by Mukhopadhyay and Shyamsundar (2015), four priorities of the ecosystem service approach in South Asia include: (1) Understanding contributions of ecosystem services to humans, especially poor people; (2) Developing biodiversity conservation strategies as well as threatened and irreplaceable services; (3) Investigating conflicts between service benefiting units at different scales; (4) Training and testing applicable policies to conserve biodiversity and ecosystem services. Kubiszewski et al. (2016) indicated that about \$US 14 trillion per year of terrestrial ecosystem services have not shown up in the GDP in 47 Asian and Pacific countries.

Regarding major threats and opportunities of ecosystem services in southeast Asian countries, Maniatis (2007) indicated the significant degradation of related services obtained from forest ecosystems due to the highly intensive exploitation of mineral, petroleum and other related resources in Southeast Asian countries. The rapid population and economic growths are considered as main drivers for this degradation. According to this project, all area of natural forest in the ASEAN countries could be transformed into agricultural and other non-forested lands before 2050.

The Economics and Ecosystem and Biodiversity (TEEB) has pursued a green growth economy in Southeast Asian countries through the assessment and valuation of ecosystem services (Brander, 2000; Brander and Eppink, 2012). Different types of ecosystems and their services were assessed in 182 case studies in Indonesia, Philippines, Thailand, Malaysia and Vietnam during the years 1986-2012. The reviews indicated a high number of scientific studies focusing on forest ecosystems, followed by wetlands, coastal and mangrove ecosystems. The most intensively valued type of ecosystem services are provisioning services, followed by some types of cultural services. Although attention for regulating ecosystem services (e.g. erosion and landslide regulating ecosystem services) is less, Brander and Eppink (2012) emphasized the important roles of careful assessments of regulating ecosystem services in the context of climate change and sustainable development.

In Vietnam, the term “environmental services” is more commonly used than “ecosystem services”. The use of these two terms has focused on protections of forest ecosystems and biodiversity conservation. Studies and policy relating to environmental services in Vietnam over the last decades have focused on benefits obtained from forest ecosystems. The Vietnamese government and the international communities have paid great attention and investments to programs in upstream forest conservation, in particular with respect to the Decision No.661/QDTTg dated July 29th 1998 from the Prime Minister in Vietnam. The goal of this program is to increase the country's forest area by 5 million hectares; with funding of about 31.858 billion VND - equivalent to 1.2 billion EUR (the current exchange is updated in 27th March 2018) till the end of 2010. Recently, forest environmental services provided in Decision No.99/2010/ND-CP dated 24th September 2010 of the Government of Vietnam – related to payment for forest environment services – are defined as values obtained from the use of forest ecosystem to meet the needs of the society and to support human life. Here, the forest environmental services include: a) soil conservation through mitigating erosion and sedimentation in lakes, rivers and streams; b) regulating and maintaining water sources for production and social life; c) improvement of carbon sequestration and reduction of greenhouse gas emissions through preventing deforestation; d) protection of the natural landscapes and preservation of biodiversity of forest ecosystems supporting cultural services; e) services related to spawning grounds, food security and breeding animals from nature, using water from forests for aquaculture. Based on this approach, article 5 of this Decree mentions two clauses of payment for environmental services as following: i) organizations and individuals benefiting from the forest environment services (or service benefiting

areas) must pay to the owners of forests (or service providing units); and ii) payment for forest environmental services must be done in cash through direct or indirect payments. These regulations are an important legal basis for payments for forest environmental services in Vietnam (VNFF, 2014).

The “environmental services” term was mentioned in the Biodiversity Law in 2008 (Decision No.20/2008/QH12) of the Government of Vietnam. Accordingly, article 74 about "Environmental services related to biodiversity" stipulates that organizations and individuals using related environmental services (from forest ecosystems in particular) need to pay for service providing units. Article 150 in the “Environmental Protection Law” (Decision No.55/2014/QH13, 2014) stipulates that environmental services need to be connected closely with the some of the following interests: a) Waste management (including collection, transportation, and disposal of all waste products); b) Monitoring and analyzing environmental indices, in combination with environmental impact assessment; and c) Environmentally-friendly technology transfer. Although the “Environmental Protection Law” seems to be closer to the approach of ecosystem services compared to the Biodiversity Law, this law is too narrow because it only focuses on forest ecosystems. In the Master Plan for Biodiversity Conservation throughout the country up to 2020, orientation to 2030 (Decision No.45/QD-TTg, 2014), ecosystem services were considered as a main objective of the master plan. Its content focuses on sustainable development with the purpose of preserving important natural ecosystems, endangered species and genomes; maintaining and developing ecosystem services; and adaptation to climate change. According to this content, the term “environmental services” was not mentioned in this document. In the Decision No.1250/QD-TTg (2012), the Prime Minister approved a national strategy, related to “biodiversity conservation up to 2020, vision to 2030”, that mentions the necessity to investigate and evaluate important ecosystem services, supporting payments for ecosystem services and biodiversity .

Additionally, significant contributions in ecosystem services assessments have come from international organizations such as the Winrock International organization; the German Corporation for International Cooperation GmbH (GIZ); World Agroforestry Centre (ICRAF); Center for International Forestry Research (CIFOR); World Wildlife Fund (WWF); The International Union for Conservation of Nature (IUCN); Asian Development Bank (ADB). Publications commonly focus on the payment of ecosystem services (Loft et al., 2017; Pham et al., 2015; Phan et al., 2017; Suhardiman et al., 2013; Tran et al., 2016) and indicator selections for ecosystem service assessments (Ho Huu et al., 2017; Loc et al., 2018; McDonough et al., 2014; Quoc Vo et al., 2015; Quyen et al., 2017). In the Asia Regional Biodiversity Conservation Program (ARBCP), scientists assessed the potential of forest environmental services and experimented a model for payment of these services in the Lam Dong and Son La provinces (Chiramba et al., 2011). Afterwards, the Ministry of Agriculture and Rural Development (MARD), in collaboration with the Winrock International organization, implemented this program from 2006 to 2009. The result of this program is a foundation to generate the

Government issued Decision No.99/2010/ND-CP (2010), formally extending the policy relating to Payment for Forest Environmental Services throughout the country. Other projects were developed in the same period, such as the project to identify corridors for biodiversity conservation run by the Asian Development Bank (ADB) from 2006-2010 (ADB, 2010); the project to develop a payment method for carbon sequestration in forestry experimented in Cao Phong district, Hoa Binh province funded by the Ministry of Foreign Affairs of Denmark (DANIDA) and the World Wildlife Fund (WWF) (Nguyen et al., 2009); the project to provide an initial strategic orientation for Mangrove for the Future (MFF) in Vietnam in identifying, designing, and planning appropriate activities for the use of ecosystem services in coastal areas of Vietnam over periods 2011 – 2013 and 2014 – 2018 supported by IUCN (MFF, 2015, 2012).

As a part of the framework programme “FONA—Research for Sustainability” funded by the German Ministry of Education and Research BMBF ³, the LEGATO project ⁴ (abbreviated from “Land-use intensity and Ecological enGineering—Assessment Tools for risks and Opportunities in irrigated rice based production systems”) contributed useful results in the assessment of rice provisioning ecosystem services. The project aimed to provide long-term sustainable solutions for irrigated rice landscapes adapting to different aspects of global change. The dependences of the rice-dominated landscapes on ecosystem functions and services were quantified based on three main drivers: (i) socio- economic and cultural drivers, (ii) land use intensity and biodiversity loss on different scales, and (iii) climate change in the future (Burkhard et al., 2015; Langerwisch et al., 2016; Settele et al., 2015). The project analyzed the potential of ecological engineering methods as well as threats and opportunities of the ecosystem services approach to optimize crop productivity and diversification of landscapes and land uses in Southeast Asian countries (Klotzbücher et al., 2014; Settele et al., 2015; Spangenberg et al., 2017). In Vietnam, four regions have been chosen as case studies of LEGATO, including the Hai Duong, Vinh Phuc, Lao Cai and Tien Giang provinces. Two partners in Vietnam participated directly: the Southern Regional Plant Protection Center (SRPPC/MARD) in the Tien Giang province - southern Vietnam, and the Center for Policy Studies and Analysis (CEPSTA) in the capital Hanoi - northern Vietnam (Spangenberg et al., 2017).

1.2. Rice provisioning ecosystem service

According to the background described above, it is vital to note that comprehensive literature about rice provisioning ES that accounts for the complexity of the social-ecological system is still lacking. In order to prepare for quantitative assessments of rice provisioning ES, this section shows a general background of rice ecosystems and the approach of ES in the case of rice production.

³ <http://www.fona.de/en/index.php>

⁴ <http://www.legato-project.net/>

1.2.1. Background rice ecosystems

The history of rice domestication and cultivation is closely connected to human evolution (GRiSP, 2013). At the dawn of the rice farming, many typical types of terrains such as terraces were exploited in irrigation canals. The first domestication of rice was found 10.000 years ago in the mainland of Southeast Asia and China known as “ladder fields” (Levetin and McMahon, 2008). Since the development of bunds, the leveling fields have guaranteed water supply based on natural characteristics such as slope and rill formation. At first, these rice ecosystems developed on the higher terraces of the major rivers and their tributaries, then spreading quickly into valleys and mountainous areas (IRRI, 2006), such as in Sapa (in Vietnam) and Manila (in Philippines) (Burkhard et al., 2015). Rice is still cultivated through traditional techniques, but the face of rice farming has changed extremely in the rice landscapes. Recently, the “green revolution” in Asia and India marked a new step of rice production in floodplains (IRRI, 2006). Different technologies help farmers attaining a higher productivity on less land and with less time efforts. However, Ericksen et al. (2009) claimed that environmental-based solutions need to go along with biotechnological developments if the ultimate goal is a sustainable agriculture. Especially biotechnological methods have met many obstacles in mountainous regions.

Population growth, overexploitation of resources and increasing social inequality are challenging sustainable agriculture in the developing countries, especially in Southeast Asia. Until the beginning of the 21st century, 2,5 billion people in the world and 557 million people in Southeast Asia need rice as an essential staple food (Manzanilla et al., 2011). To satisfy these demands, the world rice production has reached 700 million tons in 2010, whereas nearly 30% of this number were produced in Southeast Asia (FAO, 2013). Nevertheless, the rice supply cannot meet the demand in many regions, especially in mountainous areas. The intensive use of fertilizers and pesticides caused a significant rise in yield per hectare (Bottrell and Schoenly, 2012). It has also resulted in a serious decline of biodiversity in rice agro-ecosystems (IRRI, 2006) and further negative impacts on other natural ecosystems (Sanchez-Bayo, 2011; Zacharia, 2007). Rice farming is facing today nutrient and water shortages and needs to develop resistances against pests and has to reduce fertilizer applications in order to become more sustainable (IRRI, 2006). Agricultural development does not only focus on present needs, but also needs to meet the needs of future generations. Therefore, agriculturists need a new approach that enables a sustainable management of rice farming systems, satisfies future demands for rice production and minimizes negative impacts on the environment.

Over time, four rice farming systems, including animal-, tree-, water- and fertilizer-based systems, have developed (IRRI, 2006). Particularly, the fertilizer- and pest regulation-based systems in upland rice production have brought positive impacts on the yield to more than five ton/ha per year (IRRI, 1985). Sustainable farming systems have been investigated for the maintenance and enhancement of soil quality through nutrient and water provision and considering soil degradation mitigation.

However, environmental and social developments related to rice farming are causing a rise in polluted waters, uncontrollable rice expansion and the rapid increase in food demand (Bray, 1986; IRRI, 1984). In upland rice, the biotechnological methods are facing challenges related to extreme weather and natural hazards, leading to the reduction of rice yields by more than one ton/ha per year compared to other agricultural regions (Catling et al., 1983). Therefore, nature-based solutions in rice cultivation need to be developed to improve ES potential and the actual rice provision.

1.2.2. Classification of rice ecosystems

Rice has grown in different kinds of environments, from hot and humid floodplains to high ranges of mountains (about 2700 m) and from the equator to high latitudes (about 53 degrees) (IRRI, 2006). With the extensive geographical spread of rice farming, intensive efforts have been devoted to classify rice production systems based on understandings of environmental factors. Various land classifications have been developed, such as the productivity-based classification proposed by Kassam et al. (1991) in the “Agro-ecological Land Resources Assessment for Agricultural Development Planning”, a soil-based classification for rice cultivation proposed by the Windmeijer and Andriess (1993) in Agro-ecological characterization of the land resources in West Africa, or the land-based characterization/classification for agricultural development initiated from the Ecological Program for the Humid and Sub-humid Tropics of Sub-Saharan Africa (EPHTA) by the Consultative Group on International Agricultural Research (CGIAR). As an international agricultural research and training organization, the International Rice Research Institute (IRRI) updated a comprehensive and simple classification in 2006 with four rice farming systems (flood-prone, rain-fed lowland, irrigated and upland rice) that is widely used in science (IRRI, 2006) as shown in Figure 3.

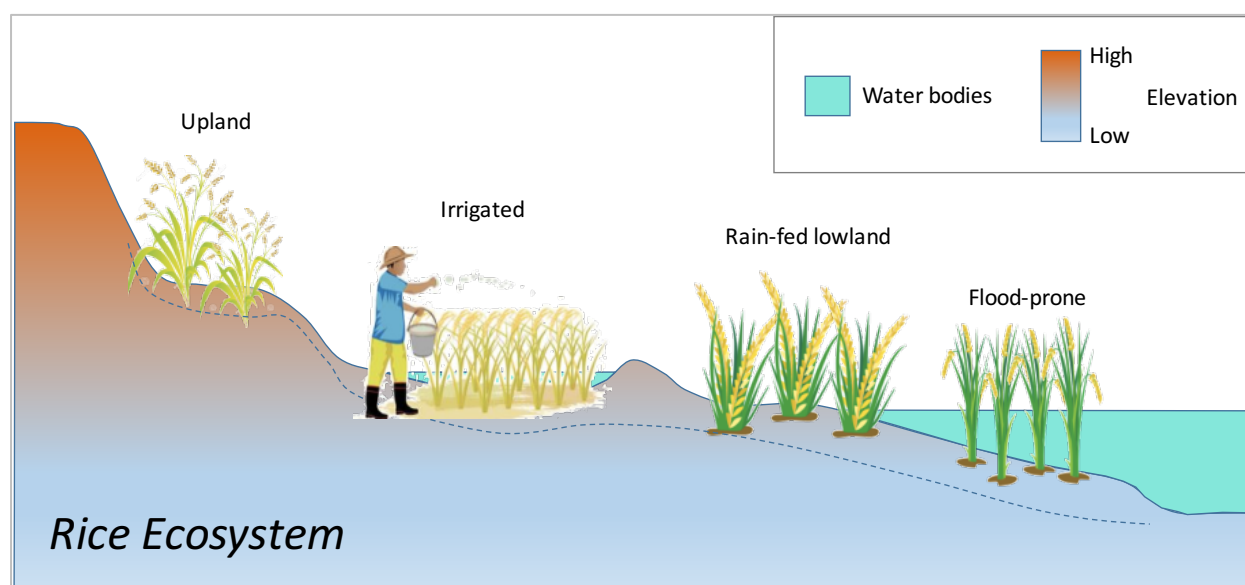


Figure 3. Distribution of four rice ecosystems in the landscape based on the classification of IRRI (2006).

The flood-prone rice environment can be found in areas favorable for the growth of deep-water and “floating” rice, such as the Mekong delta (in Vietnam and Cambodia) and the Chao Phraya delta (in Thailand) (IRRI, 2006). These environments include the regularly flooded parts of river basins, back-swamp areas and river floodplains where slight slopes and more than 10 continuous days of natural floods (from 50 to 300cm) during the rice growth period are described. The common growing cycle of the flood-prone rice is six months or more. The growth height of flood-prone rice depends on water levels and flooding time length. Thus the rice plants need to adapt to deeply flooded areas by floating their panicles on the surface. Their roots hold in the soil to absorb nutrients directly (IRRI, 2006). Because of the dependence on flooding periods, sowing and harvesting periods need to be effectively controlled, avoiding poor crops by the rapid rise of floodwater. Although the yield of the flood-prone rice in Southeast Asian countries can be recorded as more than 4 tons per hectare in average, the global yield is only 1.5 ton per hectare (according to IPAD's Agricultural Production⁵). Some flood-prone rice transplanted in tidal swamp, such as coastal plains of Southeast Asia, is influenced by the high salinity of the sea water and by the occurrence of acid sulphate soils, leading to reductions of rice yields and unsustainable conditions in this environment (CGIAR, 2016).

The rain-fed lowland rice environment is described as deeply flooded areas with water control and the depth of floodwaters less than one meter. The deep and soft topsoil layer in this environment is suitable for terraced rice cultivation that can retain floodwater and rainwater during the growing season. Because of their locations in the back-swamps, paddy fields could not be supported by many drainages, leading to the rise of organic matters and other toxins in the soils. The global average yield of rice in the rain-fed lowland environment reaches 2.3 tons per hectare in 1990s (IRRI, 2006). Nevertheless, this number is very variable from year to year and site to site because of the use of fertilizers and manures.

The irrigated rice environment is a landscape of alluvial river terraces which are flooded when the water level of rivers reaches at its peak. The bunds and outlets are constructed to impound irrigated water from higher to lower fields, leading to low water levels in each terrace. Because these irrigated paddy fields are located in slightly sloping and non-continuous flooding areas, different natural hazards can influence them during the rainy season (IRRI, 2006). Water and nutrient shortages can also limit the use of the irrigated rice fields in the monsoon period (IRRI, 2006). Nevertheless, the water supplemented from rainfall can be retained by the bund systems during the rainy season. The groundwater originating from upstream areas could be effectively used for irrigation through using pump systems, for example in eastern India and Bangladesh (Fujita, 2013; Herdt and Capule, 1983). Manures, pesticides and weed control is common practice in these paddy fields. According to IRRI (2006), the well-controlled irrigated systems can produce between five to eight tons per hectare per year.

⁵ <https://ipad.fas.usda.gov/>

The upland rice environment is an important cropping system in Africa and South-east Asia. According to (IRRI, 2006), the dry-land is generally mentioned as land of high elevation and arid areas. The upland rice, however, is grown in steeply sloping fields which are rarely flooded and cannot impound irrigated water (Garrity, 1984). Therefore, the upland environments are always drier than the other forms of rice cultivation mentioned above. Due to their typical natural conditions, the upland rice ecosystems are influenced by different natural hazards, such as erosion and landslides. Population pressure and commercial rice demand are challenging farmers to practice shifting cultivation. Rice is intercropped with maize or legumes in some mountainous regions such as the North-eastern part of Vietnam. Because of water and nutrient deficiencies and weed competition, yields of upland rice are generally low (less than one ton per hectare per year). If farmers use a sufficient amount of fertilization and pest control, yields can be higher than 3.5 tons per hectare per year (IRRI, 2006).

1.2.3. Rice provision based on the ecosystem service approach

In general, ecosystem services are defined as the benefits obtained from ecosystem structures and functions and additional inputs to human well-being (Burkhard et al., 2012a), in which provisioning ES are all natural products achieved from ecosystems. The provisioning ES can provide nutritional and energetic values to humans (Kandziora et al., 2013b). The ES approach for rice provision provides a promising method to improve the understanding of ecological and socio-economic knowledge about rice production by decision makers (Burkhard et al., 2015). Based on the ES approach, rice is investigated as a natural product achieved from arable ecosystems and providing nutrition and energy to humans. Although the approach has been applied in different contexts (Burkhard et al., 2014), comprehensive literature sources related to mapping and quantification of rice provisioning ES are still lacking, partly due to the complexity of the social-ecological systems. This study does not only focus on impacts of additional inputs (such as fertilizer and pesticide inputs) from farming practices (as e.g. in Heong and Escalada, 2015; Kubo and Purevdorj, 2004), but also analyzes the impacts of environmental components on rice ecosystems. Moreover, mapping rice provisioning ES helps to identify effective/ineffective service providing units, benefiting areas and the potential of rice expansion in a given area.

According to Burkhard et al. (2014) and Kandziora et al. (2013b), yield and productivity have commonly been used as *indicators* to quantify crop provisioning ES, also in the case of rice production. To understand the variance of yields and productivity under different environmental conditions helps to explain the impacts of ecological cycles and socio-economic effects on rice ecosystems. Hence, the potential of rice provisioning ES, which is determined by related ecosystem functions, can be defined as the maximum (hypothetical) rice yield (Burkhard et al., 2014).

In social-ecological systems, different natural and anthropogenic components are co-producing rice provisioning ES. *Regarding the natural components*, the ecological cycles affect the water supply (i.e. the hydrological cycle) and the nutrient supply (i.e. the nitrogen cycle) through different ways, which need to be considered to find suitable areas for rice cultivation. For example, radiation intensity and temperature limit processes of photosynthesis and evapotranspiration (Gupta and Toole, 1986; IRRI, 1982). Meanwhile, other natural components such as slope, flow lengths, rock weathering crusts and bedrock nutrient are playing crucial roles in distributing soil water and nutrients (Meylan et al., 2013). The high amount of the sand-sized material deposited during erosion processes could lead to a decrease of the soil nutrient availability (Ren, 2015). Burkhard et al. (2014) assessed the potential of crop provisioning ES in different ecosystems, of which agricultural lands such as arable lands, irrigated lands and pastures have the highest potentials for rice provision, whereas discontinuous urban fabrics and agro-forestry areas were indicated as unsuitable service providing units for rice. The role of anthropogenic components is clearly demonstrated in the concept of ES supply, flow and demand (Burkhard et al., 2014; Jones et al., 2016). Especially degraded soils in many paddy fields nowadays require nutrient supplementation (e.g. inorganic fertilizer inputs) and water (e.g. through irrigation processes) by humans. The other anthropogenic components can be related to the land management, knowledge, developed seed types, or pesticides inputs. Due to the lack of data, it is very difficult for scientists to differentiate between natural and human effects in rice ecosystems (Remme et al., 2014). Glavan et al. (2014) recommended a better combination of suitable site selection (based on natural capitals) and farming practices (based on human-derived capitals) to control continuous water and nutrient availabilities and to safeguard a stable supply of rice provisioning ES. Such concepts will be discussed in detail in Chapters 4 and 5 of this dissertation.

1.3. Methodologies of ecosystem service assessments

Data mining is well-known as a central step in the discovery of knowledge in databases. It is based on an analysis of specific algorithms to find out patterns (a statement depicting certain relationships in a subset of the data set through linear/nonlinear equations and predictive rules) in data (Fred et al., 2011). A discovered pattern needs to be applicable for new data with high certainty and understandably represent the knowledge (or correlations) between related variables. Compared to common statistical analysis, data mining with powerful, flexible and efficient techniques using descriptive and predictive models (Hochachka et al., 2007) has affirmed important roles in the development of artificial intelligence. The use of data-mining methods brings different benefits in analyzing correlations between predictor variables and response variables (such as through correlation matrixes), visualizing clearly a large number of predictor variables, identifying the most important predictors (such as through principal component analysis and sensitivity powers) and predicting

accurately scenarios from observed data (such as neural networks and Bayesian networks) (Bauer and Kohavi, 1999; Breiman, 1996; Hastie et al., 2001).

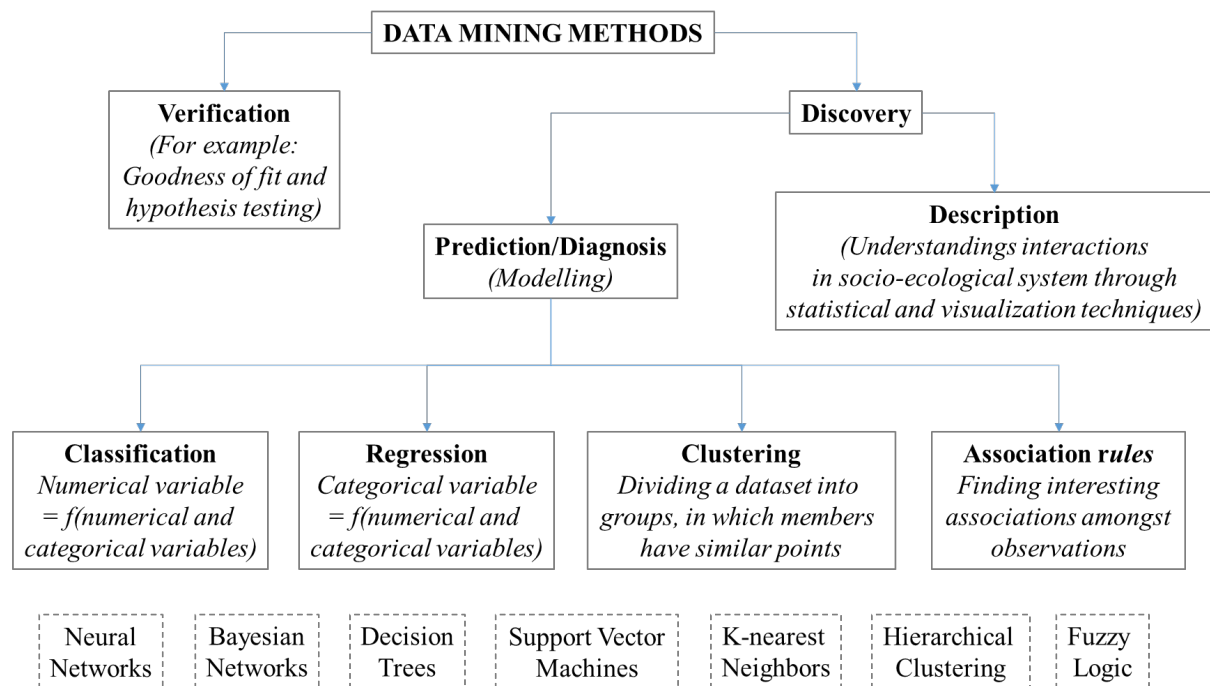


Figure 4. Simplified hierarchy of data mining commonly used in ecological studies.

During the last decade, data mining has been more widely used by ecologists (De'ath and Fracricius, 2000; Elith et al., 2006). Data mining has become a powerful tool in analyzing big data from many different ecological and environmental aspects and scales to understand the structure, dynamics and functional relationships between ecological and social elements (Hastie et al., 2001). Complexities of social-ecological systems are leading to the development of data-mining methods, especially in describing data, generating predictive/diagnosis models and developing calibration and validation processes (Figure 4). For example, non-linear relationships between rice yields and environmental elements as well as anthropogenic inputs need further studies in modeling to represent the impacts of social-ecological systems on rice production. Different data-mining methods have been used in ecological studies such as general linear/logistic regressions (Blaschke et al., 2016; Coomes and Allen, 2007; Sattaka et al., 2017), decision trees (Estoque, 2011; Hochachka et al., 2007), neural networks (Le et al., 2017; Liu et al., 2010; Prieto et al., 2016) and predictive rules (Bui et al., 2012). These methods seem, however, not to be successful in communicating their results with decision makers. The next parts of this thesis will introduce in general two powerful data-mining approaches, that are hybrid neural-fuzzy inference systems and Bayesian Belief Networks. These concepts have been developed as useful solutions to understand non-linear correlations in nature and society.

Difficulties of multiple regression models in analyzing non-linear relationships between rice yields and environmental and anthropogenic variables have been solved through the use of **artificial neural networks** (Le et al., 2017; Lek et al., 1996; Liu et al., 2010; Mihajlović et al., 2010). Lek et al. (1996) demonstrated the advantages of neural networks for ecological process modeling, compared to multiple regressions. In neural networks, a preliminary transformation is implemented through different hidden layers to minimize non-linearity. Hence, neural networks are able to effectively work with raw data, instead of transformed data and easily to be used. The neural networks using a back-propagation algorithm (McClelland et al., 1988; Rumelhart et al., 1986) have become a popular tool for the classification of satellite images in remote sensing (Liu et al., 2010), studies related to global climate change (such as in the study of Liu et al. (2010), drought mitigation (Le et al. 2017), soil carbon stocks (Aitkenhead and Coull 2016)), hydrology (such as DeWeber and Wagner (2014); Siou et al. (2011)) and agriculture (such as Palomares-Salas et al. (2014) and Gu et al.(2017)). Three parts of the back-propagation algorithm include an input layer, one or several hidden layers and an output layer (Lek et al., 1996), in which the number of hidden layers is chosen by users, resulting from difficulties in selecting suitable parameters and functions. Today, many optimization methods have been developed to identify these parameters, such as the use of simple iterations and particle swarm optimization (Bui et al., 2017). Therefore, the selection of neural networks and a suitable optimization method for data analysis is in great demand. The application of this model for assessments of rice provisioning ecosystem services will be discussed in detail in Chapters 3 and 5 of this dissertation.

The approach of **Bayesian Belief Networks** was initiated from artificial intelligence researches and has become an increasingly popular method for simulating uncertain and complex issues in environmental management (Uusitalo, 2007). The terminology of “Bayesian networks” or “Bayes nets” was named after Bayes (1763), who developed a theorem relating to the fluctuation of probabilities in given new evidences. Recently, this theorem has been commonly used in environmental management publications (Barton et al., 2016). The term of “Bayesian Belief Networks” (BBN) has been used in this paper to clearly emphasize the integration of calculated data and data observed by farmers and researchers about rice production in data analysis. The application of this network for assessments of rice provisioning ecosystem services will be discussed in detail in Chapters 4 and 5 of this dissertation.

1.4. Research area

The Sapa district in the Lao Cai province in northern Vietnam was selected in the LEGATO project⁶ as a typical agricultural landscape for terraced rice ecosystems. The case study is located in the North-eastern part of Vietnam with diverse landscape types, such as river valleys, high mountain ranges and

⁶ <http://legato-project.net/>

waterfalls (Figure 5). The altitude ranges from 500 m along the Ta Van and Ngoi Dum valleys to the Fansipan peak (3143 m). A high seasonality in Sa Pa can be depicted through changes from subtropical climate in the summer to a temperate one in the winter (Jadin et al., 2013), showing an annual mean temperature of 13.6°C and an annual precipitation of 2790 mm (Li, 2014; Tran and Nguyen, 1986). The unique climatic and the rough topographical characteristics have challenged the development of sustainable agriculture in Sapa (Li, 2014; Nguyen et al., 2011).

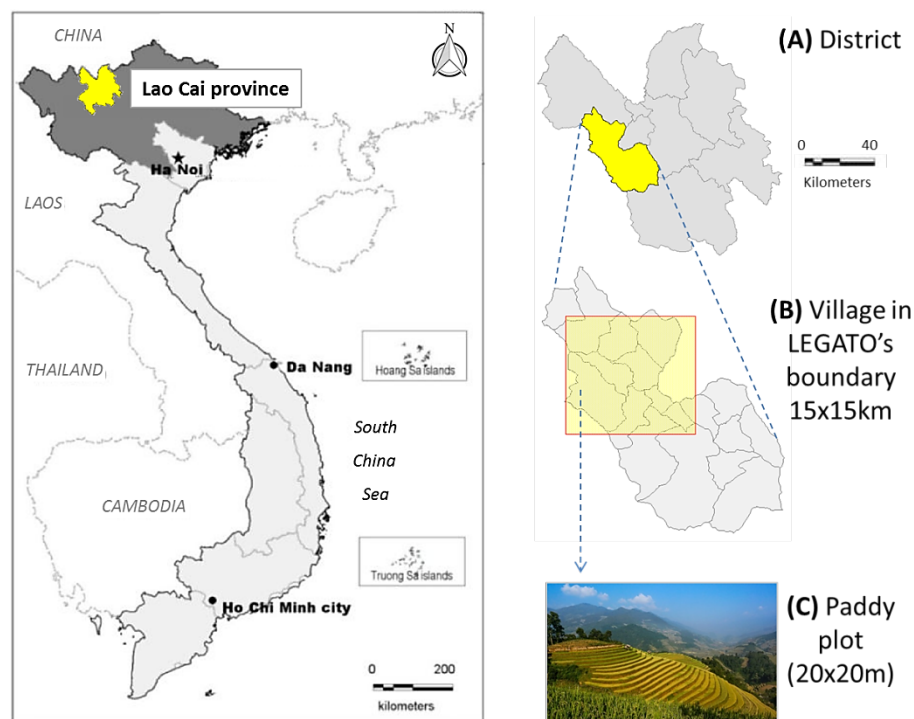


Figure 5. Location of the Sapa district, Lao Cai province, Vietnam and the different research scales mentioned in the next chapters. Photo credit: Tu Trung Dang, 2014.

Under the French Regime (1887-1940), the Sapa district was known as a famous holiday and relaxation resort (Michaud and Turner, 2017, 2000). During the Indochina war (1945-1954), Sapa town was fallen into oblivion, leading to a large emigration process to the surrounding provinces. In the early 1960s, immigration policies stimulated the Vietnamese Kinh people from lowlands to move to the northern Vietnamese highlands (Hardy, 2005). Since 1993, the implemented policy allowing international tourists to visit Sapa has significantly improved the daily life of the local people. From 1995 to 2012, the number of domestic and international tourists has increased to more than 600,000 visitors per year (GSO, 2012, 1995)., Tourism accounted for 58 % of Sapa district's GDP in 2010 (GSO, 2010) and the local poverty rate was reduced by 15 % (about 21 % in 2009) (GSO, 2012, 2001).

The Sapa district is divided into 8 communities and its administrative center (named Sa Pa town). There are five different ethnic groups living in the Sapa district, including Hmong (66 % of households), Dao (19 %), Tay (7 %), Kinh (6 %) (the Vietnamese majority group) and Day (2 %) (Jadin et al., 2013). The Hoang Lien protected area in the western part (Figure 5) was recognized in 1986 as a ‘special use forest’ in Vietnam and was re-named in 1994 as the Hoang Lien Nature Reserve (Hoang et al., 2014a). Since 2002, its name has been changed to Hoang Lien National Park under the management of the Lao Cai’s People’s Committee (Hoang, 2014).



Figure 6. Rice agriculture landscapes in the Sapa district, Lao Cai province, Vietnam. (a) An agricultural landscape captured from the Cat Cat village; (b) The use of buffalo for rice cultivation on terraces; (c) A poor household containing seven kids in the case study. Photo credits: Dang Kinh Bac, 2015.

Agriculture is the major economic item for the local people in the Sapa district. Until 2012, the case study area had about 1700 poor households mostly working in the agricultural sector (GSO, 2012). Burkhard et al. (2015) and Spangenberg et al. (2017) denoted a low agricultural land use intensity, a

high structural diversity and a high cultural identity (related closely to rice cultivation) in the Sapa region during the last four generations. Most minorities have focused on different subsistence agriculture types, whereas the Kinh minority focuses on administration, tourism and education (Tugault-Lafleur, 2007). Nowadays, the transition from agricultural lands to urban lands is leading to the narrowing of paddy fields. Rice is today cultivated by the minority groups on permanent terraced paddy fields among valley bottoms. The extreme environmental conditions generate many difficulties to use modern machines, especially on steep slope lands (Figure 6). For example, many kinds of livestock like horses and buffaloes are used for agricultural purposes (Jadin et al., 2013). Compared to Yao villages, Hmong households show a lower rice productivity due to the use of more traditional practices (Jadin et al., 2013). Due to the easy accessibility to the market of Sapa town, farmers in the Yao villages are able to buy chemical products and new seeds (related to rice farming) easier than the farmers in the Hmong villages using traditional practices. In contrast, the paddy fields of the Hmong group are closer to forested areas where they are commonly used to find irrigated water for rice cultivation. Nevertheless, rice provision in both (Hmong and Yao) groups is not enough to feed farmers and their families and they can provide only little or no surplus for trade (Delisle, 2014).

According to the new approach of the Green Revolution from the 1990s onwards, the Vietnamese government has developed different new hybrid rice seeds in combination with the use of chemical fertilizers and pesticides to increase rice yields in Sapa (Bonnin and Turner, 2012). Consequently, the Government Statistical Organization of Vietnam identified an increase of rice yields in Lao Cai province from 2.3 ton/ha per year in 1990 to 3.3 ton/ha per year in 2000 and 4.3 ton/ha per year in 2014 (GSO, 2012, 2001, 1995). Nevertheless, the increase of yield is still lower than in other agricultural areas of the province (higher than 4 tons/ha per year in average) (Lò Dieu Phu, pers. comm. 2012). The high costs for rice imports and the low rice productivity are endangering the local food security. It has caused the conversion of nearly one thousand hectares of forest and shrub lands into arable land between 1952 and 2012 (Hoang et al., 2014b). Although the local food rice produced annually is barely sufficient to sustain local people, the rapid raising of immigration and tourism has caused the local authorities to claim for expansion of agricultural lands and rice productivity in the future. However, the spatial expansion of agriculture is not an easy solution due to urbanization, limiting climatic and topographic conditions in the study area. Therefore, the clear understandings about (1) crop suitability areas for rice cultivation, (2) positive/negative impacts of farming practices on different kinds of ecosystem services and (3) rice supply chains could be promising methods to stabilize or even to raise the local rice production, avoid famine threats and reduce negative impacts on the environment.

1.5. Research questions and outline of the thesis

From the points mentioned above, several gaps in rice provisioning ecosystem service research can be identified, including:

- The ES approach is limited for crop provision at plot, regional and global scales. Particularly trade-offs between rice provision and other ecosystem services, such as erosion regulation, freshwater provision and recreation have not been clearly understood.
- Despite typical challenges related to social, economic, environmental and political dynamics in mountainous areas, there is limited knowledge on the management of rice producing socio-ecological systems. Interdisciplinary approaches that could offer adaptive management strategies for rice production and provision are lacking in developing countries, particularly in Vietnam.
- Rapid urbanization and economic development have narrowed the area of agricultural lands. The increase of rice yields at plot scales could not fulfill the food demand at larger scales. Decision makers need a new approach to (1) take full advantage of natural productivity, (2) select appropriate farming practices for each particular paddy field and (3) minimize negative impacts on the surrounding environment.
- Although developing countries such as Vietnam, Thailand and India belong to the top ten rice exporters in the world, hunger is still a serious issue in these countries. Rice supply chains are currently not well-implemented. The rice ES providing units and benefiting areas are not yet well-identified at province/regional scales.

These research gaps inspired this thesis to investigate rice provisioning ecosystem services in detail at different spatial scales (plot, field, community and regional scales) in a mountainous area of Vietnam. The first aim of this thesis is to demonstrate the advantage of the ecosystem service approach for a sustainable development of rice agriculture. Second, the thesis wants to propose new knowledge and applicable solutions to fill the gaps mentioned above by the development of various innovative models (such as Bayesian Belief Network and neural network) at different scales. Furthermore, the thesis explores a simple way to shorten the ecosystem service supply chains of rice products at regional scales by identifying spatial-temporal relations between rice ES providing units and benefiting areas and communities.

Besides the individual research questions listed in Chapters 2, 3, 4 and 5, three following research questions were guiding the whole dissertation:

- How are erosion and landslides regulated in terraced rice ecosystems?
- How can farmers improve rice production in mountainous areas?

- What are differences in the use of Bayesian Belief Networks in ecosystem service assessments in comparison with other formal models, particularly in neural networks?

In Chapter 2, the regulating ecosystem services of soil erosion and landslides were assessed and mapped in the case study area based on the “Sediment retention” model of the InVEST tool and the AHP model. Here, the potential of different ecosystems in natural hazard mitigation was compared. Then, paddy fields located in areas with low capacity for these regulating ecosystem services were identified. The three following research questions were guiding Chapter 2:

- a. How do different ecosystems effect the supply of erosion and landslide RES?
- b. How can providing units and benefiting areas of soil erosion and landslide RES be identified, related to different types of land use and land cover?
- c. Can soil erosion and landslide RES effectively be supplied in paddy fields and forest areas?

Main author of this chapter: Kinh Bac Dang. The author’s role was to independently collect and analyze all the required literature data, organize and write the results and discussions, and to compile all other parts of the chapter. Besides, the author was fully in charge as the corresponding author to the “Paddy and Water Environment” journal during the external review process.

Co-authors: Prof. Dr. Benjamin Burkhard, Prof. Dr. Felix Müller and Prof. Dr. Van Bao Dang.

Role of co-authors: Prof. Dr. Benjamin Burkhard provided intellectual knowledge in this chapter, especially in the development of the research idea and the conceptual framework to understand the benefits of erosion regulating ecosystem services to human well-being and the application of the InVEST tool for ecosystem service assessments. He gave the main author a chance to participate in the LEGATO project, go field research trips and communicate with interdisciplinary scientists who have worked in the research case study. Additionally, Prof. Dr. Benjamin Burkhard and Prof. Dr. Felix Müller guide and recommend on certain technical corrections, with the aim of improving readability and ensuring a scientifically sound manuscript before submission to the scientific journal. Lastly, Prof. Dr. Van Bao Dang participated in data collection and field works, and provided expert elucidation in the relations between geological (and) geomorphological characteristics with the risks of erosion and landslides.

State of publication: The article **was accepted** in the “Paddy and water environment” journal and first online in 30th July 2018.

In Chapter 3, a model to predict rice yields (a so-called as I-HyFIS model) and another model to assess crop suitability areas for rice cultivation (a so-called as S-HyFIS model) were proposed based on the combination of hybrid neural-fuzzy inference systems and geographical information systems. The S-HyFIS model was applied for both plot and regional scales, especially for the extrapolation process for the whole Sapa district. The three following research questions were guiding Chapter 3:

- d. Is it feasible and effective to use natural and anthropogenic factors to explain the dynamics of rice production at regional and plot scales?
- e. How can we integrate neural-fuzzy inference system and GIS analysis to map crop suitability areas on the regional scale and predict the potential of rice yields on the plot scale?
- f. How is the potential of agricultural development in other ecosystems in the Sapa region?

Main author of this chapter: Kinh Bac Dang - who is also the author of this dissertation. The author's role was to independently identify the title of the chapter, plan, organize, develop models, contact interdisciplinary scientists and coordinate fieldworks in the study area, collect and analyze the entire required primary and secondary data, organize and write the methods, results and discussions, and to compile all other parts of the chapter. Besides, the author is fully in charge as the corresponding author of the manuscript submitted in the "Environmental Modelling and Software" journal.

Co-authors: Prof. Dr. Benjamin Burkhard, Dr. Wilhelm Windhorst and Prof. Dr. Felix Müller.

Role of co-authors: The role of the co-authors of this chapter was to guide and recommend on certain corrections, with an aim of improving readability and ensuring a scientifically sound manuscript before submission to the scientific journal.

State of publication: The article **was submitted** to the "Environmental Modelling and Software" journal in 19th April 2018.

In Chapter 4, the complex interactions between the environmental and anthropogenic components with rice production were simplified in a Bayesian Belief Network (BBN) assessing rice provisioning ecosystem services. The network contains all issues related to rice production and the environmental problems mentioned above. The balance between RPES supply and demand was predicted in eight scenarios depending on the efficiency of site selection for rice cultivation and farming practices used by farmers. Hence, this Chapter also suggests options for farmers to select suitable areas for rice cultivation and to effectively use farming practices. The three following research questions were guiding Chapter 4:

- g. Is it feasible and effective to model the interactions between a regional social-ecological system and rice provisioning ecosystem services by developing a Bayesian Belief Network?
- h. Which are effective and ineffective choices on the local level for farmers to cultivate rice in a remote mountainous region?
- i. Is it possible to equip stakeholders on the regional level with information to foster a sustainable regional development plan by supporting sustainable rice cropping?

Main author of this chapter: Kinh Bac Dang, who is also the author of this dissertation. The author's role was to independently plan, organize, execute and coordinate fieldworks and interviews in the

study area, contact interdisciplinary scientists, collect and analyze the entire required data, organize and write the methods, results and discussions, and to compile all other parts of the chapter. Besides, the author was fully in charge as the corresponding author during the external review by the “Ecological Indicators” journal.

Co-authors: Dr. Wilhelm Windhorst, Prof. Dr. Benjamin Burkhard and Prof. Dr. Felix Müller.

Role of co-authors: Dr. Wilhelm Windhorst participated in the scenario development. Prof. Dr. Benjamin Burkhard and Prof. Dr. Felix Müller participated in the discussion/selection of appropriate variables for the Bayesian Belief Network to study rice provisioning ecosystem services. Additionally, Prof. Dr. Benjamin Burkhard introduced to main author different scientists who have worked in the field of rice agriculture to develop the Bayesian Belief Network. All three co-authors guided and recommended on certain corrections, with an aim of improving readability and ensuring a scientifically sound manuscript before submission to the scientific journal.

State of publication: The article **was accepted** in the “Ecological Indicators” journal in 23rd April 2018.

In Chapter 5, (1) the S-HyFIS and BBN models were used to quantify and map the capacity of RPES potentials; (2) inventory data was used to identify the capacity of RPES flows and (3) rice consumption per capital and population were used to estimate RPES demand. The potential, flow and demand of RPES in the case study area were compared throughout 25 years at district levels. Additionally, the balance between RPES supply (potential and flow) and demand in 18 communities of the Sapa district was estimated to identify service providing units and benefiting areas. The Chapter tries to demonstrate that the surplus of RPES has not been supplied to suitable service benefiting areas and some suggestions were proposed to improve the local rice supply chain. The three following research questions were guiding Chapter 5:

- j. How are RPES potential, supply and demand related to rice imports and exports?
- k. Can the agricultural regions in the mountainous provinces of northern Vietnam provide sufficient rice for local people to avoid hungers and reduce poverty?
- l. How could managers at community/regional levels improve the RPES supply chains?

Main author of this chapter: Kinh Bac Dang as the author of this dissertation. The author’s role was to independently identify the title of the chapter, plan, organize, execute and coordinate fieldworks and interviews in the study area, collect and analyze all the required data, organize and write the results and discussions, and to compile all other parts of the chapter. Besides, the author will be fully in charge as the corresponding author during the external review by the “Landscape Online” journal.

Co-authors: Prof. Dr. Benjamin Burkhard, Prof. Dr. Felix Müller, Dr. Wilhelm Windhorst and Prof. Dr. Van Bao Dang.

Role of co-authors: Prof. Dr. Benjamin Burkhard provided intellectual input in this chapter, especially in the application of a Bayesian Belief Network to calculate rice productivity at regional scales and the selection of suitable indicators for potential, flow and demand of rice provisioning ecosystem services. Prof. Dr. Felix Müller and Dr. Wilhelm Windhorst contributed to idea development. Additionally, the role of the first three co-authors for this chapter was to guide and recommend on certain corrections in results, with an aim of improving readability and ensuring a scientifically sound manuscript before submission to the scientific journal. Lastly, Prof. Dr. Van Bao Dang participated in field work (and interview) process in the years 2015 and 2017 and data collection, especially in local statistical reports related to annual rice productivity and the number of population and tourists.

State of publication: The article **will be submitted** to the “Landscape Online” journal in September 2018.

The above research sub-questions are answered in Chapter 6 “Synthesis” before coming to the three main research questions in the “Conclusions” Section. Then, a short outlook and some take-home-messages are provided at the end of the dissertation.

Chapter 2.

Modelling and Mapping Natural Hazard Regulating Ecosystem Services in Sapa, Lao Cai Province, Vietnam

Kinh Bac Dang, Benjamin Burkhard, Felix Müller, Van Bao Dang

(Published in “Paddy and Water Environment” journal

on July 30th 2018)



Modelling and mapping natural hazard regulating ecosystem services in Sapa, Lao Cai province, Vietnam

Kinh Bac Dang^{1,4} · Benjamin Burkhard^{2,3} · Felix Müller¹ · Van Bao Dang⁴

Received: 17 May 2017 / Revised: 19 March 2018 / Accepted: 23 July 2018

© The International Society of Paddy and Water Environment Engineering and Springer Japan KK, part of Springer Nature 2018

Abstract

Land use change due to the development of agriculture and community-based tourism has resulted in an increase in natural hazards (e.g. erosion and landslides) that affect sustainability in the Sapa mountainous area in northern Vietnam. Natural hazard regulating ecosystem services have protected the local people from the destruction of their villages, goods and natural resources, especially in the rainy season. However, it is difficult to identify which kinds of anthropogenic constructions support a co-production of regulating services in human-influenced social–ecological systems and in which specific types of land use and land cover the supply of such services takes place, especially in heterogeneous mountainous areas. Therefore, this research attempts to (1) distinguish between the potential and actual use (flow) of natural hazard regulating ecosystem services and (2) understand how soil erosion and landslide regulating ecosystem services can contribute to a sustainable management of different ecosystems, especially in rice fields and forest areas. Two models (InVEST for soil erosion, Analytic Hierarchy Process for landslide analysis) were used to analyze and map the contributions of natural versus anthropogenic components for regulating natural hazards in Sapa. The results show the incoherent distribution of erosion regulating services and low capacities of landslide regulating services in areas that have seriously been affected by human activities, especially forestry and agricultural development. The contribution of rice ecosystems to soil erosion mitigation is higher than in the case of landslides. Nevertheless, one-third of the area of paddy fields in the case study area have “no” capacity to supply natural hazard regulating ecosystem services and should therefore be re-forested.

Keywords Landslide · Erosion · Regulation ecosystem services · Landscape · InVEST · Analytic Hierarchy Process

Introduction

Humans receive many types of benefits from various ecosystem services in direct and indirect ways (Costanza et al. 1997; De Groot et al. 2002; MEA 2003). More recently, the ecosystem services approach has become a significant tool

to improve the communication and understanding between science, policy and practice (Maes et al. 2012; Schulp et al. 2014). According to the “Salzau Message” on Sustaining Ecosystem Services and Natural Capital, ecosystem services are “the contributions of ecosystem structure and function—in combination with other inputs—to human well-being” (Burkhard et al. 2012a; P. 2). Ecosystem services are classified as ecological phenomena, and their indicators have been logically derived by the properties of the investigated ecosystems (Müller and Burkhard 2012). The Common International Classification of Ecosystem Services (CICES¹) has divided ecosystem services into provisioning, regulating and maintenance, and cultural services (Haines-Young and Potschin 2012). Regulating ecosystem services (RES) include human benefits resulting from the prevention of harmful processes, natural hazards in particular (Kandziora et al. 2013; TEEB 2010). The mediation of mass flows, as a major group of RES, includes all types of solid, liquid

✉ Kinh Bac Dang
kinhbachus@gmail.com

¹ Department of Ecosystem Management, Institute for Natural Resource Conservation, Christian Albrechts University Kiel, Olshausenstr. 40, 24098 Kiel, Germany

² Institute of Physical Geography and Landscape Ecology, Leibniz Universität Hannover, Schneiderberg 50, 30167 Hannover, Germany

³ Leibniz Centre for Agricultural Landscape Research ZALF, Eberswalder Straße 84, 15374 Müncheberg, Germany

⁴ Faculty of Geography, VNU University of Science, 334 Nguyen Trai, Thanh Xuan, Hanoi, Vietnam

¹ <http://cices.eu/>.

and gaseous movements providing benefits to human beings (Haines-Young and Potschin 2012). However, the understanding of soil erosion and other natural hazard mitigation services is still limited (TEEB 2010).

The impact of natural hazards on human development, prosperity and poverty has increased in many regions around the world, especially over the past four centuries (Arouri et al. 2015; Gill and Malamud 2017; Islam and Ryan 2016). The reported number of people that were affected by natural disasters has increased globally from over 700 million in the 1970s to nearly 2 billion people in the 1990s (MEA 2003). In Vietnam, many geological and geomorphological investigations about natural hazards have been conducted (Bui et al. 2012; Meinhardt et al. 2015; Nguyen et al. 2011). However, most of them focus on assessing the risk at a certain location and providing support for appropriate protection methods. Only a few studies focus on the question of how humans benefit from natural hazard mitigation as it is usually done in ecosystem service-based approaches (Shoyama et al. 2017). Additionally, various studies revealed that natural hazards do not necessarily have only negative effects (Benda and Dunne 1997; Geertsema et al. 2009). For example, rice cultivation on terraces often takes advantage of the vestiges of hazards (such as alluvial fans), in which nutrient-rich sediments are accumulated by floods. Therefore, whether and how damages or benefits are obtained from natural hazards need to be better understood and quantified related to different forms of land use, land cover and further socio-ecological system conditions.

Assessments of RES are often complicated due to less clear ecosystem function–service–benefit relations compared, for example, to provisioning ecosystem services. In mountainous areas such as the Sapa region in the Lao Cai province in northern Vietnam, many ecosystems are highly modified by human land use activities such as terraced paddy fields as well as regularly occurring natural hazards (i.e. erosion and landslides). Thus, ecosystem function–service–benefit relations are relatively complex. Natural hazards do not only have direct effects on local human well-being, they also cause indirect harm by influencing numerous other ecosystem services such as rice provisioning ecosystem services (Le 2014) and cultural services (Dang et al. 2017). Therefore, it is necessary to safeguard a constant supply of RES in order to protect human interests and to prevent people from extreme events (Lelys Bravo de Guenni 2005). The costs for damage and mitigation of natural hazards were mentioned in various international studies (e.g. in Meyer et al. 2013; Pielke and Downton 2000). However, little has been done so far in Vietnam. Additionally, there is no universal solution for natural hazard treatment. Instead, scientists and decision-makers have to work out how humans can sustainably optimize the profit from nature, such as by man-made protection

constructions, which lead to an improved ecosystem services supply (Kumar et al. 2010).

The ecosystem services “matrix” (Burkhard et al. 2009, 2012b, 2014) has been used to assess the capacities of different geospatial units to supply different ecosystem services with a regional focus mostly on Europe (such as different land use and land cover (LULC) types). Therefore, one research question is whether it is possible to apply this method to subtropical countries and the Sapa region, Vietnam, in particular, where a significant increase in soil erosion and landslides has been recorded during the last decades (Häring et al. 2014; Mai et al. 2013). The ES matrix concept helps to illustrate and assess the diverse benefits humans receive from ecosystems. The ecosystem services supply (including potential supply and actual ecosystem services flow) usually shows higher scores for RES in the matrices in near-natural land cover types (such as forests or natural grasslands) than in human-influenced or inhabited land cover types (such as urbanized areas). However, the distinction between ecosystem service potential, flow and demand is not trivial in regard to the regulation of ecosystem services (Zhou et al. 2013) because the actual quantification depends strongly on the chosen indicators and the investigated land cover (Müller and Burkhard 2012).

The aim of this study is to spatially quantify the capacity of erosion and landslide RES under the rapid growth of tourism and urbanization in different land use and land cover types with a special focus on terraced rice fields and forest areas in Sapa. A conceptual framework to understand the impacts of human activities on natural hazard RES is proposed in “Natural hazard RES assessment” section. Hence, in order to assess the supply of and demand for erosion and landslide RES, appropriate landscapes, which act as ES-providing units and benefiting areas, are identified, quantified and mapped. Maps are chosen to spatially visualize complex natural or human phenomena and are therefore powerful tools for decision-making (Burkhard et al. 2012a; Wood 2010). However, proper identification and mapping of those structures and processes that support erosion and landslide RES are challenging, especially in a mountainous area such as the Sapa district. This information can be used to improve landscape planning, monitoring and sustainable environmental resources and land use management (Crossman et al. 2012; Swetnam et al. 2011). In this study, two models to quantify and map erosion and landslide RES were used. One model is based on “sediment retention” calculation developed in the InVEST tool, and the second one is based on Analytic Hierarchy Process (AHP) models. Both are presented in detail in “Modelling soil erosion and landslide regulation ecosystem services” section.

Referring to the issues described above, the following three research questions are answered in this study:

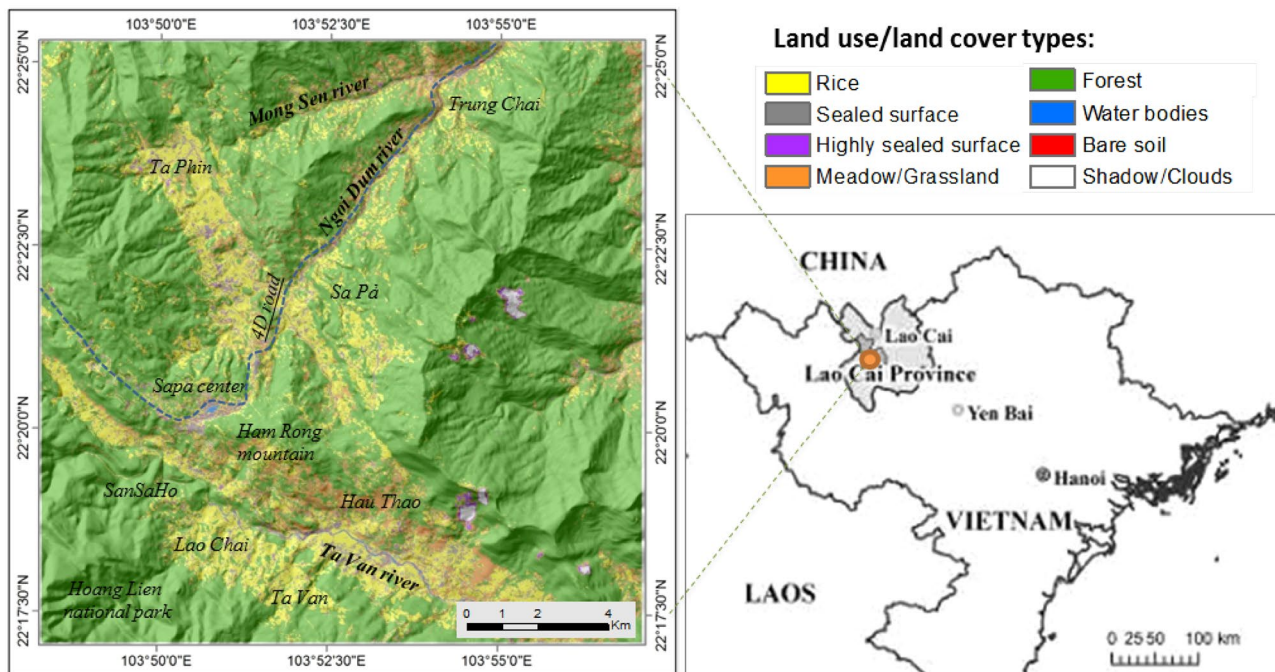


Fig. 1 Land use/land cover in Sapa, Lao Cai province, Vietnam. Classification based on SPOT5—satellite image taken on 21/10/2010, provided by the LEGATO (<http://legato-project.net/>) project

- How do different ecosystems affect the supply of erosion and landslide RES?
- How can providing units and benefiting areas of soil erosion and landslide RES be identified, related to different types of land use and land cover?
- Can soil erosion and landslide RES effectively be supplied in paddy fields and forest areas?

Materials and methods

Case study area

Sapa is a mountainous district in the western part of the Lao Cai province in Vietnam. The research area, which has a size of 15 km × 15 km in mountainous terrain, can be divided into three main basins: Mong Sen, Ngoi Dum and Ta Van (Fig. 1). The altitude fluctuates from 500 to 2.800 m, with many slopes greater than 25°. The average annual rainfall is very high with an average of about 1500 mm per year and maxima of more than 3500 mm. The wet season in Sapa is in the summer and lasts from June to September (Leisz 2017). A stable cool season occurs throughout the year although frost and snow are also recorded in winter. Rice agriculture, which is one of the main livelihoods in this region, has developed over centuries with terraced rice ecosystems (Hoang 2014).

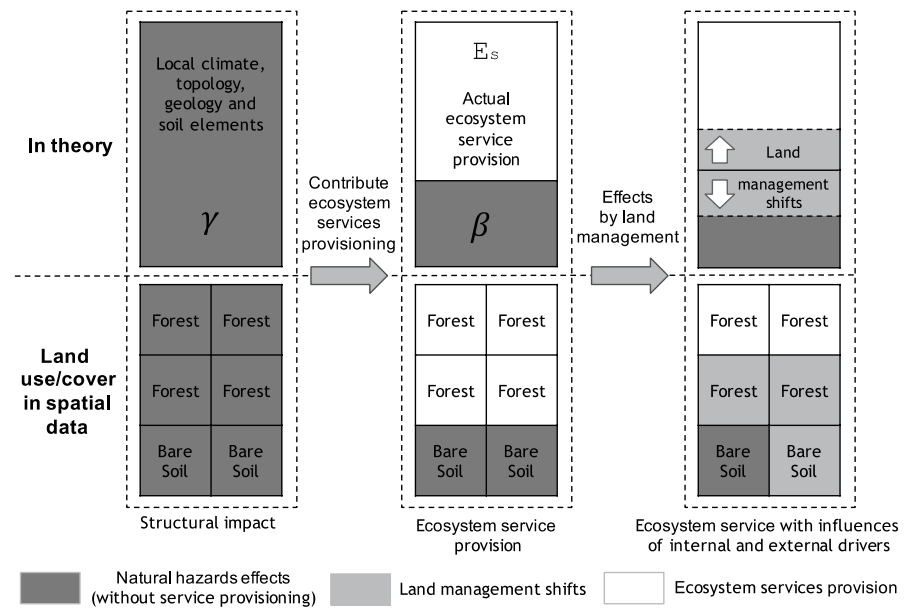
The dynamics of land use and tourism in Sapa have created imbalances with respect to agricultural development and natural hazard prevention during the last years (Jadin et al. 2013). The area has experienced a high number of landslides and soil erosion events, compared with other regions in northern Vietnam. Some large landslides and soil erosion events were recorded during the last few years (such as along the national road 4D, Lao Chai and Mong Sen villages). At least 62 landslides, soil erosion and flash flood events have happened since 1998 in the whole province of Sapa (Tran 2013). The Mong Sen phenomenon is the most famous landslide in Sapa, occurred in 2009 (Nguyen et al. 2011). After 15 years, some of these landslide surfaces are still moving on slopes with more than 30°, and plants have not recovered yet.

The lack of knowledge about natural hazard RES has caused the destruction of many villages, the loss of goods and natural resources and threaten human well-being, especially during the rainy season. Exploring the relationships between natural hazards and ecosystem services can provide significant information and thereby help to improve the quality of life in this region.

Natural hazard RES assessment

Different approaches were used and combined in this study to assess erosion and landslide regulating ecosystem services. Landslides are a type of mass movements, such as

Fig. 2 Framework for erosion regulating ecosystem services (RES) assessment in particular land use/land cover types (γ as the total natural hazards impact in the absence of RES, β as the remaining ES mitigated impact). Adapted from Guerra et al. (2014, 2016)



rock fall and debris flow (Anderson and Holcombe 2013). Soil erosion is described as the loss of the top soil layer by wind or water (Pimentel 2006). In serious events, both of these hazards can occur alternately, which makes it difficult to identify them. Although many publications have discussed the risk of soil erosion and landslide at different scales (Chen et al. 2012; Kayastha et al. 2013), only a few papers studied the supply capacities of natural hazard RES. These ecosystem services have recently been assessed and quantified, for example, by Guerra et al. (2014, 2016; soil erosion RES) or Nedkov and Burkhard (2012; flood RES). The latter study, which was based on the ecosystem service “matrix” approach (after Burkhard et al. 2009), shows the distinct potentials of different LULC types for ecosystem services supply and demand. The more comprehensive matrix approach (Burkhard et al. 2014) differentiates between ES potential (available ecosystem services), flow (actually used ecosystem services) and demand (all ecosystem services used/consumed by people in a certain area). Such differentiation is not trivial for natural hazard RES, which mostly focus on avoided events. This means that the supply (flow) of these RES is highest in areas where no such events take place (Guerra et al. 2014). This again needs to be combined with demands for hazard RES, which is highest in areas with a high hazard risk. We can assume that, for example, in an old forest in a flat area with stable soils, dense vegetation cover and sufficient water infiltration, the risk for soil erosion is rather low. Thus, the demand for erosion regulating ecosystem services would also be low.

Guerra et al. (2016) have proposed a framework for the assessment of erosion RES, which describes the relationships between structural impacts (without ES provision), actual ecosystem services provision and actual ecosystem

services loss by soil erosion (Fig. 2). Adapting this concept, the soil erosion and landslide regulating ecosystem services (E_s) could be identified by the gradient between structural impact (γ) and actual natural hazard risk (β). With structural impact (γ), the natural hazards happen without protective vegetation cover and no ecosystem service is supplied. In this case, γ is influenced by natural conditions (such as local climate, topology and soil) and determines the potential of a natural hazard. As a key fraction to assess the quantity of the structural impact (γ) that is mitigated by human impacts, the actual ecosystem services provision (E_s) can be defined by the capacity of RES in a given place and time. Meanwhile, the rest of γ relates to the remaining natural hazards (β). In a particular place and time, the high capacity of E_s can reduce the amount of β . Therefore, both fractions have a negative correlation with each other. In fact, land management could modify the risk of natural hazards (β). The regulating ecosystem services might be expanded by appropriate land use policies but might also be destroyed by unsustainable development.

Natural hazards have been prevented to different degrees in different LULC types depending on respective actions/inactions of the land users and inhabitants. In Fig. 2, the forest cover (in white colour) would, for example, provide a higher capacity of natural hazard RES supply than bare soil (in black colour). However, under some negative conditions (such as deforestation, forest fires or climate change), certain forest regions (in grey colour) could not be protected from natural hazards, resulting in a reduction in RES. In contrast, under some positively consolidated conditions, areas with bare soil (in grey colour) could be protected from natural hazards. According to the framework of Guerra et al. (2014; Fig. 2), calculating the actual regulating ecosystem service

supply requires the understanding of the different levels of risk of natural hazards (β) in each LULC type. It also helps to understand the potential of natural hazard RES (Es) in each LULC. The RES supply in each LULC can be assessed and compared using the ES matrix approach by Burkhard et al. (2014). Then, the potential RES supply (Es) can be overlaid with the management of different LULC to quantify the actual RES use.

Modelling soil erosion and landslide regulation ecosystem services

This section presents the methods that were used to assess natural hazard RES in three steps based on 13 natural and human components. The sources of input data are presented in “Database” section. In the first two steps, the risks of soil erosion and landslides were simulated by applying the model InVEST (Sharp et al. 2014) and the AHP approach (Ishizaka and Labib 2009). The soil erosion RES, that were calculated based on the amount of sediment retained in the different land cover types, were assessed. The capacities of landslide RES supply were calculated in the third step by using a risk map and a LULC regionalization. Modelling was supported by field work in order to update new natural hazard events and to detect extraordinary points (or outliers) of events.

Step 1 Modelling soil erosion risk and RES by using the “sediment retention” model

Natural phenomena like erosion and sedimentation contribute to the evolution of landscapes and cause severe consequences for ecosystems (Sharp et al. 2014). Sediment retention is one key element in soil erosion investigations and can be described by the Universal Soil Loss Equation (USLE) as a potential indicator (Kandziora et al. 2013). The InVEST tool, which has been used in 102 countries including the USA, the UK, Germany and Colombia (Posner et al. 2016), also applies USLE (Eq. 1) to assess the sediment retention service:

$$USLE = R * K * LS * C * P \quad (1)$$

in which, R is the rainfall erosivity factor, K is the soil erodibility factor, LS is the slope length factor, C is the land cover factor and P is the land management factor (Wischmeier and Smith 1978). The erosivity factor (R) is assessed through the intensity and duration of rainfall in each grid cell (Sharp et al. 2014). The higher the amount of precipitation is, the more serious the erosion potential becomes. The soil erodibility factor (K) assesses the detachment and movement of soil particles by rainfall and surface run-off. The erodibility value of each soil type is determined through its texture (percentages of silt, sand and organic matters, soil structure and permeability) and the soil erodibility nomograph generated

by Wischmeier and Smith (1978). Using a digital elevation model (DEM), the geomorphological factors slope, flow direction and flow length can be simulated. These three factors are input variables of the LS function—generated by Govers and Desmet (1996)—to calculate the slope length factor. Lastly, the LULC and normalized difference vegetation index (NDVI) maps, respectively, determine the P and C factors by evaluating the influences of human activity on erosion.

The sediment, which is trapped in a particular region, is calculated by the run-off and the incoming sediment flowing from upstream regions. Land cover plays an important role in trapping materials. Therefore, the model simulates the process of soil erosion for two cases (with and without land cover and land management) (Keller et al. 2015). The difference between these two cases is the actual amount of sediment retention which is then used to indicate soil erosion RES. Meanwhile, the amount of sediment, which is exported from upstream areas and reaches downstream areas, is used to indicate soil erosion risk.

Step 2 Modelling landslide risk by using the Analytic Hierarchy Process (AHP) model

In this step, the AHP, which is a semi-quantitative method, is used to assess the weights of independent variables (e.g. natural and anthropogenic components in this study) on the dependent variable (e.g. landslide risks) (Saaty 2008). Each independent variable was compared with the other variables to assess their own weights. Firstly, the prioritized values are consigned into pairwise comparison matrices by assigning values from one (for the less important variable) to nine (for the most important variable) for direct comparison; from 1/2 to 1/9 for inverse comparison. Secondly, each eigenvalue of the variables was calculated based on a set of pairwise ratings in a consistent reciprocal matrix. Finally, the weight of each variable was calculated by each eigenvalue, following the study of Saaty and Vargas (2012). In this study, two AHP models were created for assessing landslide (1) potential and (2) risk.

1. The first AHP model was used for analyzing the landslide potential without human impacts. Choosing natural variables for analyzing landslide potentials has been described in many research studies (Kayastha et al. 2013; Pham et al. 2016; Pradhan and Kim 2016). In this study, ten natural variables to determine the landslide potential were used, including slope (F_1), lithology (F_2), weathering crust (F_3), bedrock orientation (F_4), rainfall (F_5), fault density (F_6), curvature (F_7), sediment retention (F_8), relief amplitude (F_9) and drainage density (F_{10}). With these variables, the landslide potential (LP) was simulated by the following function:

$$\begin{aligned}
 LP = & 0.26 * F_1 + 0.18 * F_2 + 0.18 \\
 & * F_3 + 0.12 * F_4 + 0.09 * F_5 \\
 & + 0.06 * F_6 + 0.04 * F_7 + 0.03 \\
 & * F_8 + 0.03 * F_9 + 0.02 * F_{10}
 \end{aligned} \quad (2)$$

According to Eq. 2 generated from the first AHP model, the lithology (F_2) is considered as an important influencing variable for the occurrence of weathering processes and faults, as well as for the stabilization of terrains. The bedrock orientation (F_4) is constructed based on the differences between bedrock direction and topological aspects (as downslope directions for grid cells calculated from 0° to 360°). Three geomorphological variables which are important for landslide analyses were extracted by the use of DEM. These include slope (F_1), curvature (F_7) and relief amplitude (F_9). In case of a sufficiently thick weathering crust, the higher the local slope is, the more the terrain is threatened by landslides. The variable “relief amplitude” (the difference between the highest and lowest altitudes in a topological unit) assesses mass movements in vertical direction. Lastly, the variation of hydrologic and climatic factors is considered through two variables: rainfall (F_5) and drainage density (F_{10}). Detailed information of these input variables for the case study is presented in Chapter 2.4.

- The second AHP model was generated to assess the actual risk of landslide under human impacts. Anthropogenic impacts are a part of the environment, and human activities have changed the potential of natural hazards in different ways. Human actions that contribute in a positive way to landslide risk regulation increase the capacity of erosion RES provision. In contrast, negative impacts, which can be generated by unsustainable local land management, can maintain or intensify landslide risks. Therefore, human variables are used in landslide risk quantifications as additional components that impact the landslide potential. In the second AHP model, human-derived variables, which include land cover (F_{11}), road density (F_{12}) and population density (F_{13}), are analyzed. Therefore, the landslide risk (LR) was computed by the following function:

$$LR = 0.56 * LP + 0.26 * F_{11} + 0.12 * F_{12} + 0.06 * F_{13} \quad (3)$$

Because the various input data do not all have the same ranks and units, all (natural and anthropogenic) variables need to be normalized into a common scale. With the numerical variables, this conversion process resized the original values into a continuous range of values from 1 (lowest impact on landslide risk) to 5 (highest impact

on landslide risk). With the categorical variables (such as geology and weathering crust), expert experience was used to assign discrete values from 1 to 5 for each class of variables.

Step 3 Modelling landslide RES

In this step, the effectiveness of various “service providing units” in reducing the landslide risk was assessed before mapping landslide RES supply. The contribution of these units can be analyzed by calculating what percentage of each LULC has been protected effectively or ineffectively. All percentages were drawn in scatterplots to easily observe the distribution of risk levels in the different LULC types. These percentages were then compared with each other to evaluate the capacity of landslide RES supply in all LULC types. LULC types with higher percentages at the low-risk level supply more landslide RES than the other LULC types with higher percentages at the high-risk level. According to this evaluation, capacities of the different LULC types (or service providing units) to mitigate landslides were listed.

In general, the balance between the landslide risk and RES supply depends on their locations and capacities of the service providing units and demands in the benefiting areas. If the service providing units do not overlap with the benefiting areas, humans cannot receive benefits from landslide RES. Consequently, the landslide risk remains high in areas of landslide RES demand. Environmental managers need to know how RES supply and demand are distributed over space in order to target their actions accordingly. Spatial differences of actual RES supply can be shown in respective distribution maps. It can be assumed that areas with lower risks for landslides have a higher supply of RES and vice versa. The map of landslide RES potential was created by “reversing” the risk map.

Lastly, the LULC (seven types) and potential RES map (five levels) were overlaid. With this step, the potential RES map was divided into a maximum of 35 classes. The number of classes depends on the appearance of LULC in each level of the landslide risk. Then, the evaluation of the service providing units was used to sort the seven LULC types inside each capacity of the landslide RES potential. Accordingly, objects that are well protected from landslides could be distinguished from unprotected ones. In order to simplify the results, the actual landslide RES supply was reclassified into six classes (from zero to five) in the outcome map, corresponding to six classes of landslide RES supply capacities. The level “zero” represents no relevant and the level “five” represents the maximum relevant capacity of landslide RES supply.

Database

All data used for the spatial analyses needed to be transformed into an appropriate format and had to be georeferenced into the WGS84 coordinate system (48N). The topographic and hydrologic maps, the map of residential areas and transportation data were supplied by the FICHE project BL/10/V26.² A digital elevation model (DEM) was interpolated at 10-m resolution based on elevation data provided by the Vietnamese Ministry of Natural Resources and Environment. Hydrologic and climatic data were acquired from eight stations located around Sapa (Nguyen et al. 2011). Field work was carried out in 2015 in order to update the road network, to detect changes in land use and land cover and to map landslides. With respect to the landslide inventories, 22 events were found in 2015. Additional 16 events were recorded during the last 10 years in reports and other scientific studies (Tran 2013) from the Lao Cai province.

The geology, geomorphology and soil maps were acquired from different sources. The geological map with a scale of 1:50.000 was created by the Centre for Information and Archives of Geology at the General Department of Geology and Minerals of Vietnam. The geological map also shows information about slope, faults, formations, ages and bedrock directions. Such information is useful to analyze bedrock orientation and fault density. The soil map with a scale of 1:50.000 (from the Department of Geography at the Hanoi University of Science) illustrates five main types of soil including “humic alisols”, “plinthic alisols”, “dystric gleysols”, “humic alisols” and “humic ferralsols”. In addition, the soil map also provides information about soil thickness and particle sizes in the different soil types.

Satellite images of the SPOT5-series were used to create the NDVI map and the LULC types. The latter ones were classified by partners from the LEGATO³ project from Europe and Southeast Asia (Burkhard et al. 2015). The LULC map is based on a satellite image from 2010 and was used as the main source for modelling and mapping the natural hazard RES. The image classification resulted in a map with eight classes (seven LULC types: rice, bare soil, highly sealed surface, sealed surface, grassland, forest and water bodies) based on an interpretation of SPOT5-panchromatic and SPOT5-multispectral data (Müller 2013). Areas that were covered by clouds and shadows were assigned as “no data”.

² <http://www.belspo.be/>.

³ <http://legato-project.net/>.

Verification of simulation methods

To assess the soil erosion risk, the N-SPECT tool, which was developed by the NOAA Coastal Services Centre (NOAA 2008), was used to find the relationships between land cover, pollution and erosion. The Revised Universal Soil Loss Equation (RUSLE) and the Modified Universal Soil Loss Equation (MUSLE) were used to analyze these relationships. The InVEST and the N-SPECT tools were run in parallel to compare their results and to assess related uncertainties. The N-SPECT tool changes the weight and equation of predicting rainfall erosivity and soil erodibility factors (NOAA 2008). The InVEST tool calculates the sediment that is trapped by each land cover type and the sediment that is exported from each pixel afterwards. Therefore, the results of InVEST may be more precise in this case than those from the N-SPECT tool.

Based on the landslide inventories from the fieldwork in 2015, this study used the Kappa index with 30 landslide and 30 locations without landslide to verify related results. The Kappa value is an index, which quantitatively measures the magnitude of agreement among observations (Viera and Garrett 2005) as follows:

$$\text{Cohen's Kappa} = \frac{p_0 - p_e}{1 - p_e} \quad (4)$$

with p_0 as the observed proportional agreement and p_e as the overall probability of random agreement. In predicting the precision of landslide results, the Kappa index calculates the difference between actually true agreements (or “observed” agreement) and faulty agreements (or “expected” agreement). The results are acceptable if the Kappa index is higher than 0.75.

For the landslide assessment with AHP, an index of consistency, known as the consistency ratio, was used to randomly indicate the probability:

$$\text{Consistency ratio (CR)} = \frac{\text{CI}}{\text{RI}} \quad (5)$$

where RI is the average of the resulting consistency index depending on the order of the matrix given by Saaty (2008) and CI is the consistency index expressed by the following equation:

$$\text{Consistency index (CI)} = (\lambda_{\text{Max}} - n) / (n - 1) \quad (6)$$

where λ_{Max} is the largest eigenvalue, and n is the size of comparison matrix. Saaty (2008) explained that if the value of the CR is smaller or equal to 10%, the inconsistency is acceptable, but if CR is greater than 10%, the subjective value judgments need to be revised.

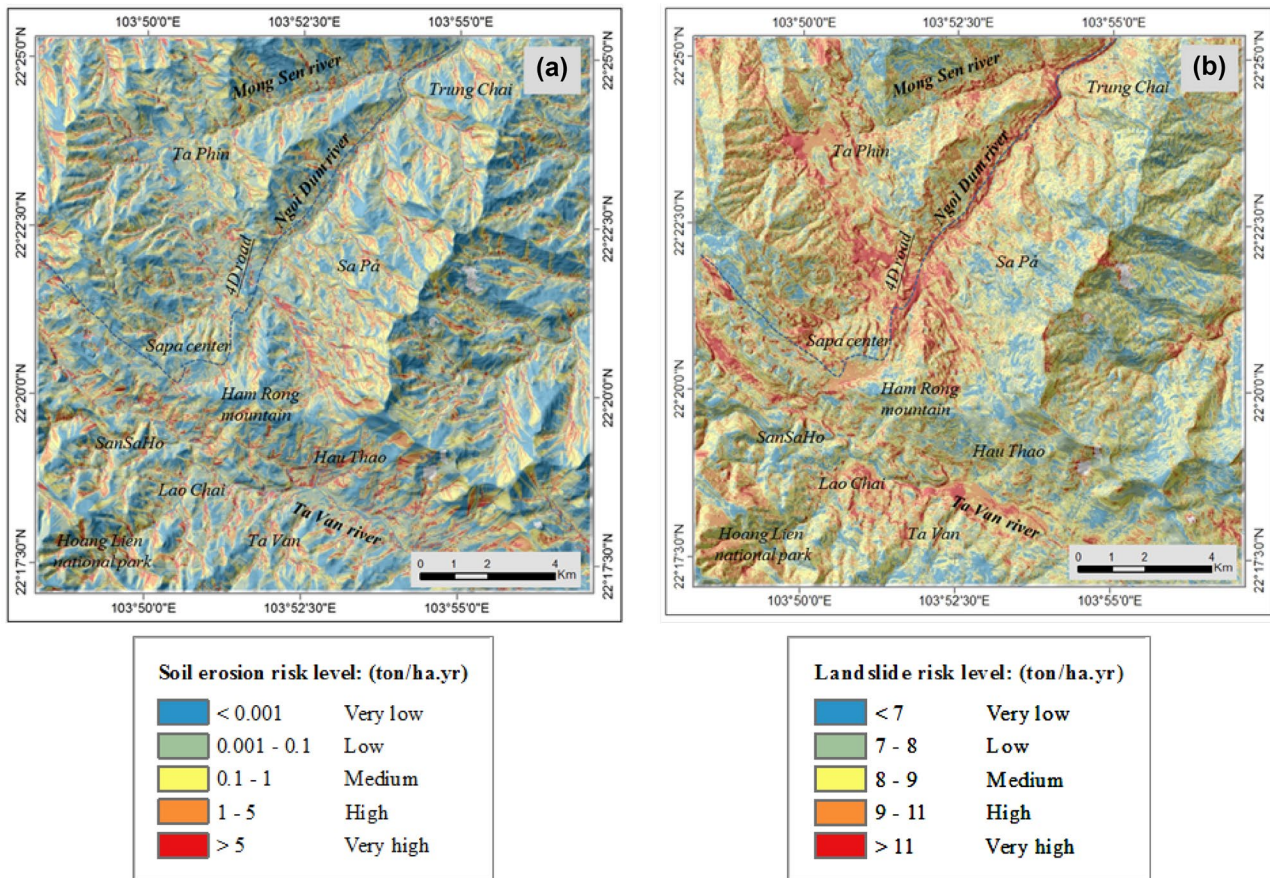


Fig. 3 Soil erosion risk map **a** based on InVEST and landslide risk map **b** based on AHP assessment

Results

Risk of soil erosion and landslides

Figure 3a shows the distribution of soil erosion in Sapa based on InVEST. The results were calculated based on exported sediment values that can reach to downstream areas from the original sediment positions. The map shows that erosion is mainly scattered along small streams. The “high” and “very high” levels of soil erosion reached 15% of the total area, especially around Ham Rong and the Hoang Lien National Park. Nearly one-third of terraced rice fields coincides with the locations of the “very high” and “high” risk levels. Moreover, continuous “very high” levels of soil erosion risk are predicted for the precipitous cliffs reaching from the Hau Thao village to the national road 4D in an eastern part of the Ham Rong mountain. The risk of soil erosion is considerably reduced in the flat terrain where most of the local people live, such as Sapa centre and the Ta Phin village. In contrast, an irregular distribution of soil erosion was modelled in the forest areas, especially in the Ta Van basin.

Based on the AHP model for potential landslides, the prioritized weights were calculated for each component in the LP function (see Eq. 2). The highest contribution to this function belongs to slopes of 26% or higher. With a total contribution of about 8%, the drainage density, height and sediment retention play less important roles for this function. According to the LR function (see Eq. 3), land covers, roads and population densities control about 26, 12 and 6%, respectively, while the variable of landslide potential contributes about 56% to risk prediction. The consistency indices of the two AHP models, which are about 6.6% (smaller than 10%), have validated the model results.

The different risk levels of landslide events can be seen in Fig. 3b. The Kappa index reaches about 0.77. In contrast to the results of soil erosion risk, the landslide risk in the Ta Van basin is mostly at a medium level. One-third of the area of the Ngoi Dum basin seems to be strongly impacted by landslide risk, such as in the north-eastern part of Sapa centre, the western part of Ta Phin village and along the national road 4D. A large area of forests was assessed at “low” and “medium” landslide risk levels. Compared with

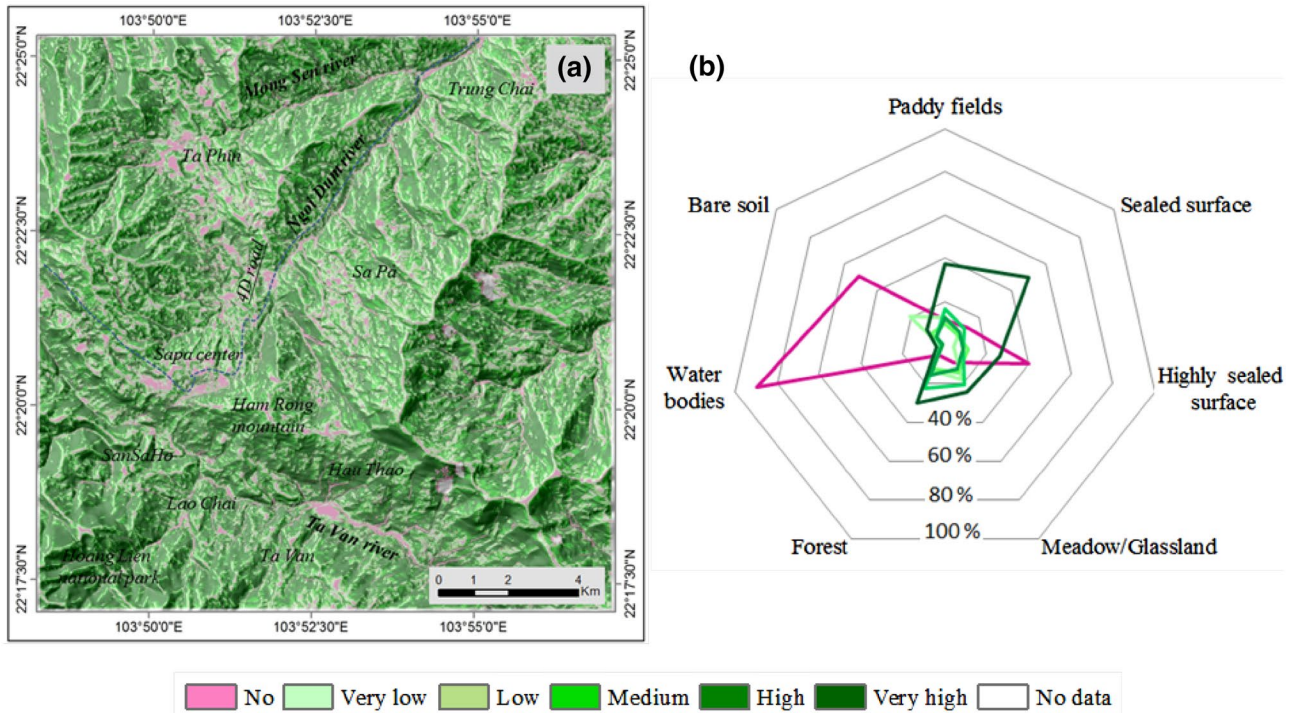


Fig. 4 Soil erosion regulating ecosystem services (RES) supply map (a) and distribution in each LULC type (b)

the soil erosion risk, the residential areas seem to be more vulnerable to landslide risk.

Landslide and soil erosion RES in Sapa

Figure 4a shows the soil erosion RES supply based on InVEST. The results were calculated based on retained sediment that originates from upstream regions and from the area (the modelled cell) itself. Similar to the erosion risk map, the distribution of soil erosion RES is very complex. About 45% of the area show efficient soil erosion regulation. “No relevant” soil erosion RES supply occurs in the eastern part of the Ngoi Dum basin, as well as in the Ta Phin and Sapa villages (about 10% of the total area). The residential areas show different levels of soil erosion RES supply, and more than 20% of the sealed surfaces do not benefit from the soil erosion RES.

Figure 4b illustrates the percentages of soil erosion RES in the different supply classes for each LULC type. “No relevant capacities” can be found in “water bodies” (such as lakes, rivers and ponds) and “bare soils” (such as sandbanks), which compose about 90%, and 50% in each type, respectively. “Sealed surfaces” (urban areas), “paddy fields” and “forests” show the highest percentages in the “very high relevant capacity” class, reaching 50, 37 and 30%, respectively. Accounting

for three-fourth of the protected areas in Sapa, forests can prevent erosion at higher levels than paddy fields.

The resulting landslide RES map is presented in Fig. 5a. After comparing the risk map and the land management, the landslide RES supply was separated into 27 classes before reclassifying it into six classes. Most forest ecosystems are effectively protected from landslide risk. The “no relevant” and “very low” supply classes were observed in the northern centre of Sapa, the western Ta Phin village, the downstream regions of the Ta Van basin and along the national road 4D. In contrast to the soil erosion RES, nearly 40% of the residential areas do not receive any benefit from landslide RES.

The distribution of the landslide RES supply classes in each LULC type is shown in Fig. 5b. The “very high” and “high” landslide RES supply capacities make up about 40 and 35% of the “forest” area. These capacities account for 30% of the “meadow/grassland” area. Regarding the “paddy fields” and the “sealed surfaces”, about 20% of these areas benefit from “high” landslide RES supply, while more than 40% do not supply landslide RES. Accounting for more than 68% in the “no relevant capacity” class, “bare soils” are not well protected from landslides.

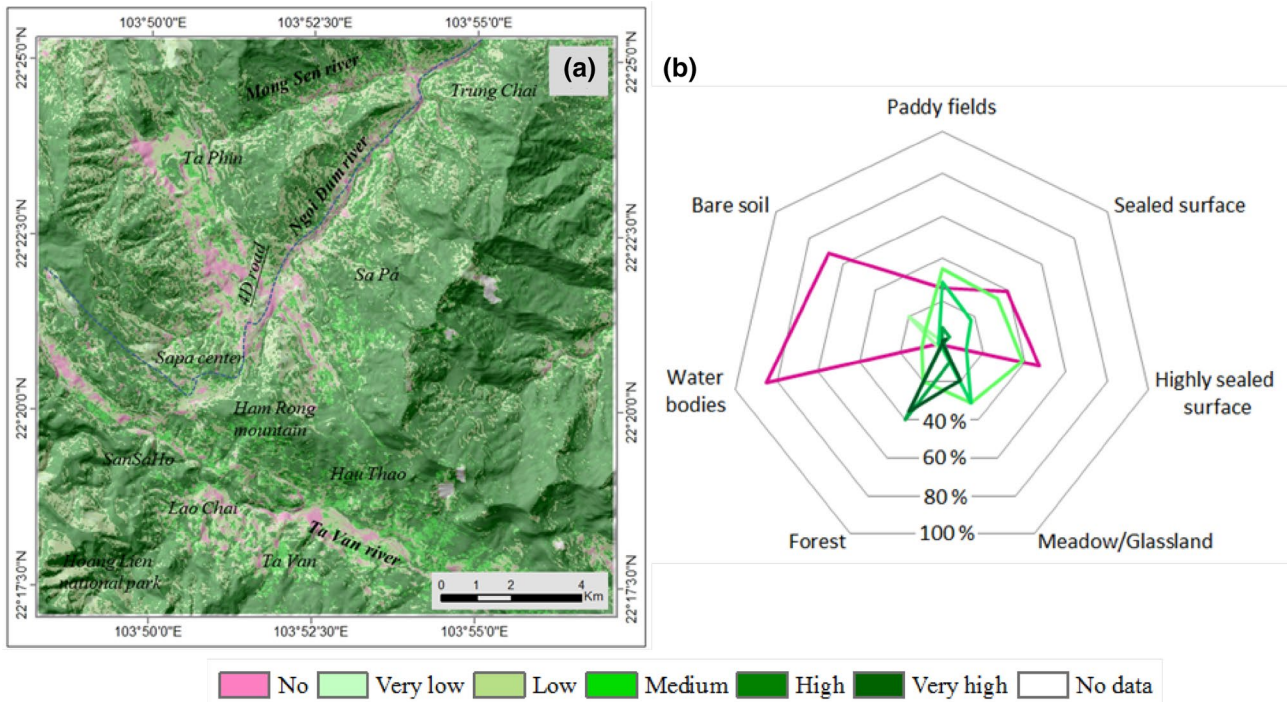
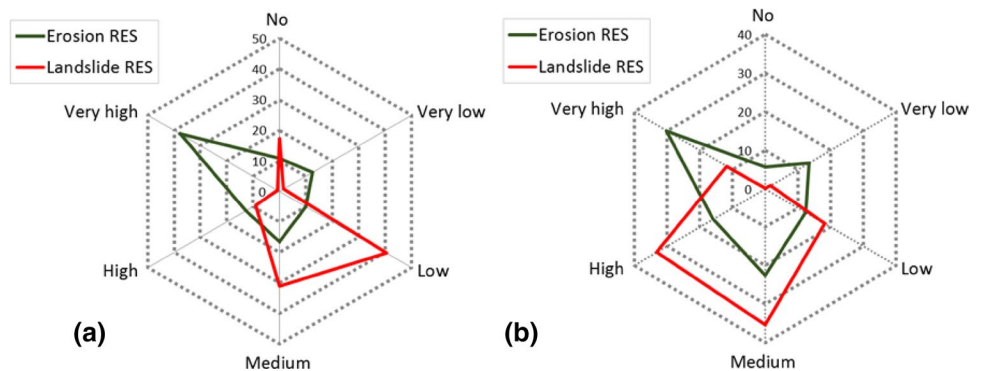


Fig. 5 Landslide regulating ecosystem services (RES) supply map (a) and distribution in each LULC type (b)

Fig. 6 Areal percentage of paddy fields (a) and forests (b) in relationship to soil erosion and landslide regulating ecosystem services (RES) supply capacities



Natural hazard RES supply in paddy fields and forest areas

Soil erosion and landslide RES bring heterogeneously distributed benefits to rice ecosystems. Figure 6a illustrates that nearly 20% (or 500 ha) of the paddy fields are located in areas of “no” capacity of landslide RES supply. This is far higher compared to the soil erosion RES, which account for about 10% of area with no relevant supply. In the “very low” landslide RES supply class, the area of paddy fields is ten times lower than in the erosion RES supply. Nevertheless, paddy field areas of altogether 1500 ha (approximately 50%) are well protected from soil erosion within areas of “high” and “very high” RES

supply. In summary, paddy fields benefit more effectively from soil erosion RES than from landslide RES.

The positive contributions of natural hazard RES in forest ecosystems are illustrated by a varying RES supply distribution (Fig. 6b). In contrast to the paddy fields, the area of forests within the “no” capacity of erosion RES supply is approximately 5% (or 1000 ha) larger than the respective area in the landslide RES. About 25% of the forest area (about 4000 ha) are threatened within the “very low” and “low” erosion and landslide RES supply capacity classes. To sum it up, both types of natural hazards seem to be effectively regulated in the forest ecosystems in Sapa.

Discussion

The natural hazard RES assessment

The achieved results show interesting patterns of landslide and soil erosion RES supply in the research area. Compared with existing “ecosystem services matrix” assessments (e.g. in Burkhard et al. 2014), both assessments prove that forest areas supply soil erosion RES more efficiently than any other LULC type. The residential areas, which usually are located in more flat areas than other LULC, are well protected by soil erosion RES. However, landslides threaten many transport-related constructions. Soil erosion RES supply is comparably higher in agricultural areas than in meadow and bare soil areas, although paddy fields cultivated on slope terraces (with slopes of 15–25%) are more sensitive to landslides.

Although Nguyen et al. (2011) and Do et al. (2013) predicted and warned about landslide phenomena in the research area, perception or appreciation of benefits from the natural hazard RES capacity are still inadequate. In the study presented here, several aspects of soil erosion and landslide RES were analyzed based on the framework for RES assessment provided by Guerra et al. (2016). The maps of soil erosion potential and landslide potential were used as structural impacts (γ). The negative environmental effects associated with soil degradation, urban expansion or mining could increase the risks of natural hazards (β), leading to the degradation of RES provision (E_s). In theory, γ , which is separated into β and E_s , is modified by land management. In the Sapa case study, this process is clearly represented by the six classes of soil erosion and landslide RES supply capacities. These RES are supplied differently in each LULC type due to heterogeneous management measures and variation of climatic, hydrologic and topologic factors.

According to this study, the identification of effective/ineffective service providing units has become more efficient. On the one hand, the RES providing units supply services to the benefiting areas based on demands and following a specific service flow direction. Firstly, the effective service providing units in upstream areas (as identified mostly in forests and meadows in the case study) often overlap with the service benefiting areas (in situ service supply; after Syrbe and Walz (2012)). Secondly, these units additionally protect various objects (such as sealed surfaces and paddy fields) in downstream areas from natural hazards (*directional* service supply; after Syrbe and Walz (2012)), especially in the centre of villages and in the Lao Cai province (Nguyen and Dao 2007). On the other hand, after the occurrences of natural hazards in ineffective service providing units, for example, in more than

500 ha of paddy fields or about 1000 ha of forest located in areas of “no” capacity of natural hazard RES (Fig. 6), the run-off from upstream areas can transport enormous volumes of debris to downstream areas (Kean et al. 2013). Consequently, the functions of service providing units in the downstream areas to regulate natural hazards can be gradually reduced due to the loss of land cover, creating various unprotected surfaces, such as bare soils in the Mong Sen bridge and the Hau Thao village as predicted by Nguyen et al. (2011).

Contributions of natural hazard regulating ecosystem services to rice agricultural development

As shown by Lelys Bravo de Guenni (2005), landslides and soil erosion do not necessarily only have negative effects on agro-ecosystem functions and services. This could, at least for some areas, be proven in this case study. As reported in 2015 by local farmers from the Sapa region, several communities take advantage of landslides and soil erosion vestiges for rice cultivation in terraced fields in the Hau Thao and Ta Van villages. The erosion and landslide risks in these fields are at “low” to “medium” levels (Fig. 3). Following the process of mass movement, landslides and soil erosion can create fertile regions by providing nutrients to the soil that otherwise may be lacking. These areas are actually often considered to be the best places for farming terraced rice fields in combination with controlling water supply from upland forests. This has especially been the case for terraced rice fields in places with a “very high” capacity of erosion and landslide RES identified in Figs. 4 and 5.

Nevertheless, unsuitable crop selection—e.g. about 500 ha of paddy fields located in areas of “no” capacity of landslide RES supply (Fig. 6a)—and intensive farming in the mountainous regions can destroy the natural cycles and provide an impulse for subsequent erosion (Mai et al. 2013). The sediment retained has been continuously removed from these areas and deposited in downstream regions (such as in the centre of Lao Cai province) (Nguyen et al. 2011; Nguyen and Dao 2007). Consequently, the RES supply capacities, which may be reduced dramatically, can lead to an increasing occurrence of natural hazards, especially in the case of landslides. In Sapa, many human-made installations such as dams and agricultural lands were destroyed in the last few years. As reported by a local farmer in the Trung Chai village, the 2014 landslide occurred in a former landslide area, which was reclaimed for agricultural purposes. After long-lasting rain, a large amount of water was stored in the soil and eventually swept away everything, including the national road 4D, down to the valley. This was confirmed by results shown in Fig. 5a.

As shown in Figs. 4b and 5b, the class “no” capacity to provide erosion and landslide RES was mainly defined for

ivers, streams and bare soils. In spite of lacking capacity to supply RES in those ecosystems, it is difficult to identify the exact time of erosion or landslide occurrences (as analyzed by Bui et al. 2016). Especially the structural impacts of natural hazards in the Sapa region depend on various temporary factors, such as rainfall dynamics or other extreme weather. Regarding the rainy season in mountainous areas (from June to September in Sapa), the high precipitation leads to an increase in surface water levels, causing erosion in riverbeds and banks where paddy fields are located. Although about 50% (about 1500 ha) and 10% (about 300 ha) of the paddy fields have, respectively, provided the erosion and landslide RES, most crops can become more vulnerable to both natural hazards if the local rainfall intensity suddenly increases within a short period. The coincidence of rainy season and harvesting season (September and October) in Sapa also results in the reduction in local rice production. This relationship needs to be understood further in order to reduce the negative trade-offs between natural hazards RES and rice production (food provision ecosystem service).

Uncertainties

Uncertainties related to limited knowledge of the assessed human-environmental system, data, modelling and technical issues are important challenges when analyzing regulating ecosystem services (Hou et al. 2013). RES assessments integrate environmental and human systems and are highly complex. Therefore, verification indices such as the Kappa index and the consistence index for the AHP model were used in this study. Nevertheless, the understanding and calculation of the landslide and soil erosion RES supply involved several uncertainties, which are discussed in the following.

Key uncertainties of this study relate to the spatial interpretation of the LULC map and the quantification of the different components of RES supply. The complexity of the local landscape was simplified in the LULC map in $10\text{ m} \times 10\text{ m}$ pixels derived from the SPOT satellite images. This means that objects smaller than 100 m^2 (such as self-contained houses) may not be visible in the LULC map. Moreover, clouds and shadows of different objects were included in the satellite image. They can cover some areas and make the classification process more difficult, especially in the mountainous regions. However, the area of clouds and shadows accounts only for about 0.4% of the whole case study area.

Further uncertainties are related to the application of the different simulation models. Especially the combination of expert valuations and models needs to be improved. For the quantification of soil erosion, Sharp et al. (2014) claimed that the “sediment retention” model has been used for the identification of rill/inter-rill erosion, excluding gully and stream banks. In addition, the simplification of the model

using the USLE as a main equation makes the erosion outcome more sensitive to the input variables (such as rainfall, soil types and land cover). Consequently, the weight of each input variable in the equation would need to be changed for studying soil erosion in mountainous areas. The analysis of landslides is quite complex due to the combination of quantitative and qualitative methods. In the landscape field inventories, some areas relevant for soil erosion and landslides could not be clearly identified in the topologic map. Some facilities for landslide prevention were indicated on the topologic map, but did not exist in reality or had been destroyed. In the validation process, the number of testing data did not cover all types of land uses/covers. Testing data were mostly collected near man-made land uses such as paddy fields and building constructions. Therefore, they did not represent well landslide regulation effects in more natural ecosystems, such as forests.

Finally, the simplification of natural and human-derived factors may increase the uncertainty of the outcomes. By normalizing the ten natural and three human-derived factors into the 1–5 classes, their importance for the RES supply capacities could be compared using the same scale instead of using the original values. This normalization process can avoid bias in magnitude differences of the input factors. Some factors, including complex data of lithology, weathering crust and land uses that originally were collected in categorical data format, were transformed to discrete values based on expert experience. Meanwhile, other factors (such as DEM and precipitation data) were calculated in continuous values. The combination of categorical and continuous data could regionalize the output maps and cause the loss of spatial information about direction, distance and area. The influence of regionalization on the outcomes depends on the weight assigned for the categorical data in the AHP model. As shown in Eqs. 2 and 3, the important roles of three categorical factors on landslide risk (as well as the landslide RES supply) were assessed based on semi-quantitative models (AHP). Thus, these assessments were also partly influenced by subjective factors from expert knowledge.

Conclusions

In order to answer the three research questions raised in the introduction, this study explicitly analyzed spatial soil erosion and landslide regulating ecosystem services supply in various ecosystems in the Sapa region. Firstly, it was shown that the current land management in different LULC type units plays an important role in determining the capacity of natural hazard RES supply. Regarding soil erosion RES, forest and urban areas show, as it could be expected, higher capacities of RES supply than meadow and bare soil areas. Landslide RES supply capacities are higher in forest and

meadow areas compared to urban and bare soil areas. Natural hazard risk and RES supply maps are promising tools for decision-makers to safeguard a constant flow of ES between service providing units and service benefiting areas. Service benefiting areas can, for example, be identified in residential areas or planning units, whereas service providing units can be identified in forest or meadow/grassland areas. Two spatial relations between RES providing units and benefiting areas were identified, including in situ and *directional* ones (“The natural hazard RES assessment” section). The spatially explicit prediction of risks through natural hazards can be used to identify regions that need to be better protected, i.e. service benefitting areas with a high demand for landslide RES. More than one-third of the paddy field areas are not well protected from soil erosion and landslides, whereas more than two-third of the forest areas are well protected from both natural hazards.

The identification of areas without sufficient RES supply can help decision-makers to guide respective investments and to protect prioritized environmental and human resources. The current, in many aspects rather unsustainable, policy and land management regimes reduce the natural hazard mitigation capacities in the Sapa area. Local and national monitoring systems should focus on information that is relevant for the understanding of ecosystem functions and related ecosystem services. Thereby, local people could be better informed and more in time about areas threatened by landslides and initiate suitable prevention procedures. Especially the relations between the amount of sediment retention and erosion and landslide risks with rice provisioning ecosystem services should be quantitatively assessed to understand the (often indirect) contributions of natural hazard RES to agricultural development.

Erosion and landslide RES supply requires surfaces covered by vegetation such as forest or meadow/grassland areas, protective landscape structures or can be based on man-made constructions. As an effective nature-based solution, afforestation could help to improve the natural hazard RES supply capacities. Areas including bare soils, which contain very low capacities of natural hazard RES supply, should be recovered by forests, suitable vegetation or protective constructions such as bio-engineering measures (e.g. erosion control blankets, silt fences or geotextiles) and engineering techniques (such as diversion drains and rocky barriers). Mainstreaming of natural hazard RES into policy and decision-making requires a better understanding of the essential controlling components and the links between environmental and societal systems.

Acknowledgements This paper is a contribution to the LEGATO project which is funded by the German Ministry of Research and Education (BMBF) within their funding measure Sustainable Land Management; Funding No. 01LL0917A-O. This study was co-financed by the Vietnamese Government Scholarship (911). Furthermore, we would

like to thank our colleagues at the Institute for Natural Resource Conservation, Department of Ecosystem Management at Kiel University and the LEGATO colleagues for the constructive cooperation. The authors want to thank Mrs. Angie Faust for language corrections of the manuscript.

References

- Anderson MG, Holcombe E (2013) Community-based landslide risk reduction. The World Bank, Washington. <https://doi.org/10.1596/978-0-8213-9456-4>
- Aroui M, Nguyen C, Ben Youssef A (2015) Natural disasters, household welfare, and resilience: evidence from rural Vietnam. *World Dev* 70:59–77. <https://doi.org/10.1016/j.worlddev.2014.12.017>
- Benda L, Dunne T (1997) Stochastic forcing of sediment supply to channel networks from landsliding and debris flow. *Water Resour Res* 33:2849–2863. <https://doi.org/10.1029/97WR02388>
- Bui DT, Pradhan B, Lofman O, Revhaug I, Dick OB (2012) Landslide susceptibility assessment in the Hoa Binh province of Vietnam: a comparison of the Levenberg–Marquardt and Bayesian regularized neural networks. *Geomorphology* 171–172:12–29. <https://doi.org/10.1016/j.geomorph.2012.04.023>
- Bui TD, Tuan TA, Hoang ND, Thanh NQ, Nguyen DB, Van Liem N, Pradhan B (2016) Spatial prediction of rainfall-induced landslides for the Lao Cai area (Vietnam) using a hybrid intelligent approach of least squares support vector machines inference model and artificial bee colony optimization. *Landslides*. <https://doi.org/10.1007/s10346-016-0711-9>
- Burkhard B, Kroll F, Müller F (2009) Landscape’s capacities to provide ecosystem services—a concept for land-cover based assessments. *Landsc Online*. <https://doi.org/10.3097/LO.200915>
- Burkhard B, De Groot R, Costanza R, Seppelt R, Jørgensen SE, Potschin M (2012a) Solutions for sustaining natural capital and ecosystem services. *Ecol Indic* 21:1–6. <https://doi.org/10.1016/j.ecolind.2012.03.008>
- Burkhard B, Kroll F, Nedkov S, Müller F (2012b) Mapping ecosystem service supply, demand and budgets. *Ecol Indic* 21:17–29. <https://doi.org/10.1016/j.ecolind.2011.06.019>
- Burkhard B, Kandziora M, Hou Y, Müller F (2014) Ecosystem service potentials, flows and demands—concepts for spatial localisation, indication and quantification. *Landsc Online* 32:1–32. <https://doi.org/10.3097/LO.201434>
- Burkhard B, Müller A, Müller F, Grescho V, Anh Q, Arida G, Bustamante JV, Van Chien H, Heong KL, Escalada M, Marquez L, Thanh Truong D, Villareal S, Settele J (2015) Land cover-based ecosystem service assessment of irrigated rice cropping systems in southeast Asia—an explorative study. *Ecosyst Serv* 14:76–87. <https://doi.org/10.1016/j.ecoser.2015.05.005>
- Chen SK, Liu CW, Chen YR (2012) Assessing soil erosion in a terraced paddy field using experimental measurements and universal soil loss equation. *CATENA* 95:131–141. <https://doi.org/10.1016/j.catena.2012.02.013>
- Costanza R, D’Arge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O’Neill RV, Paruelo J, Raskin RG, Sutton P, van den Belt M (1997) The value of the world’s ecosystem services and natural capital. *Nature* 387:253–260. <https://doi.org/10.1038/387253a0>
- Crossman ND, Burkhard B, Nedkov S (2012) Quantifying and mapping ecosystem services. *Int J Biodivers Sci Ecosyst Serv Manag* 8:1–4. <https://doi.org/10.1080/21513732.2012.695229>
- Dang KB, Dang VB, Burkhard B, Müller F, Giang TL (2017) Cultural ecosystem services assessment based on geomorphological approach—case study in Sapa, Lao Cai province. *VNU J Sci Earth Environ Sci* 33:92–102. <https://doi.org/10.22144/ctu.jsi.2017.055>

- De Groot RS, Wilson MA, Boumans RMJ (2002) A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecol Econ* 41:393–408. [https://doi.org/10.1016/S0921-8009\(02\)00089-7](https://doi.org/10.1016/S0921-8009(02)00089-7)
- Do T, Nguyen C, Phung T (2013) Assessment of natural disasters in Vietnam's northern mountains. Munich Personal PePec Archive
- Geertsema M, Highland L, Vaugeouis L (2009) Environmental impact of landslides. In: Sassa K, Canuti P (eds) *Landslides—disaster risk reduction*. Springer, Berlin, pp 589–607. https://doi.org/10.1007/978-3-540-69970-5_31
- Gill JC, Malamud BD (2017) Anthropogenic processes, natural hazards, and interactions in a multi-hazard framework. *Earth Sci Rev* 166:246–269. <https://doi.org/10.1016/j.earscirev.2017.01.002>
- Govers G, Desmet PJJ (1996) A GIS procedure for automatically calculating the USLE LS factor on topographically complex landscape units. *J Soil* 51:427–433
- Guerra CA, Pinto-Correia T, Metzger MJ (2014) Mapping soil erosion prevention using an ecosystem service modeling framework for integrated land management and policy ecosystems 17:878–889. <https://doi.org/10.1007/s10021-014-9766-4>
- Guerra CA, Maes J, Geijzendorffer I, Metzger MJ (2016) An assessment of soil erosion prevention by vegetation in Mediterranean Europe: current trends of ecosystem service provision. *Ecol Indic* 60:213–222. <https://doi.org/10.1016/j.ecolind.2015.06.043>
- Haines-Young R, Potschin M (2012) CICES Version 4: Response to Consultation. Centre for Environmental Management, University of Nottingham
- Häring V, Fischer H, Stahr K (2014) Erosion of bulk soil and soil organic carbon after land use change in northwest Vietnam. *CATENA* 122:111–119. <https://doi.org/10.1016/j.catena.2014.06.015>
- Hoang HTT (2014) Multi-scale analysis of human–environment interactions. A case-study in the Northern Vietnamese mountains. Katholieke Universiteit Leuven, Leuven
- Hou Y, Burkhard B, Müller F (2013) Uncertainties in landscape analysis and ecosystem service assessment. *J Environ Manag* 127:S117–S131. <https://doi.org/10.1016/j.jenvman.2012.12.002>
- Ishizaka A, Labib A (2009) Analytic hierarchy process and expert choice: benefits and limitations. *Oper Res Soc* 22:201–220. <https://doi.org/10.1057/ori.2009.10>
- Islam T, Ryan J (2016) Hazard identification—natural hazards. In: Islam T, Ryan J (eds) *Hazard mitigation in emergency management*, chapter 5. Butterworth-Heinemann, Oxford, pp 129–170. <https://doi.org/10.1016/B978-0-12-420134-7.00005-9>
- Jadin I, Vanacker V, Hoang HTT (2013) Drivers of forest cover dynamics in smallholder farming systems: the case of northwestern Vietnam. *Ambio* 42:344–356. <https://doi.org/10.1007/s13280-012-0348-4>
- Kandziora M, Burkhard B, Müller F (2013) Interactions of ecosystem properties, ecosystem integrity and ecosystem service indicators—a theoretical matrix exercise. *Ecol Indic* 28:54–78. <https://doi.org/10.1016/j.ecolind.2012.09.006>
- Kayastha P, Dhital MR, De Smedt F (2013) Application of the analytical hierarchy process (AHP) for landslide susceptibility mapping: a case study from the Tinau watershed, west Nepal. *Comput Geosci* 52:398–408. <https://doi.org/10.1016/j.cageo.2012.11.003>
- Kean JW, McCoy SW, Tucker GE, Staley DM, Coe JA (2013) Runoff-generated debris flows: observations and modeling of surge initiation, magnitude, and frequency. *J Geophys Res Earth Surf* 118:2190–2207. <https://doi.org/10.1002/jgrf.20148>
- Keller AA, Fournier E, Fox J (2015) Minimizing impacts of land use change on ecosystem services using multi-criteria heuristic analysis. *J Environ Manag* 156:23–30. <https://doi.org/10.1016/j.jenvman.2015.03.017>
- Kumar P, Verma M, Wood MD, Negandhi D (2010) *Guidance manual for the valuation of regulating services*. UNEP, Publishing Services Section, UNON, Nairobi-Kenya
- Le TD (2014) *Assessing the provisioning ecosystem service food rice and its linkages to human well-being in Lao Cai and Tien Giang Province of Vietnam*. Master thesis. Faculty of Agricultural and Nutritional Sciences, Christian-Albrechts-Universität zu Kiel
- Leisz SJ (2017) Land-cover and land-use transitions in northern Vietnam From the early 1990s to 2012 BT. In: Shivakoti G, Pradhan U, Helmi H (eds) *Redefining diversity and dynamics of natural resources management in Asia*, chapter 6, vol 2. Elsevier, Amsterdam, pp 77–86. <https://doi.org/10.1016/B978-0-12-805453-6.00006-1>
- Lelys Bravo de Guenni (2005) *Ecosystems and human well-being: current state and trends: regulation of natural hazards: floods and fires*, chapter 16. Millennium Ecosystem Assessment
- Maes J, Egoh B, Willemen L, Lique C, Vihervaara P, Schägner JP, Grizzetti B, Drakou EG, Notte AL, Zulian G, Bouraoui F, Luisa Paracchini M, Braat L, Bidoglio G (2012) Mapping ecosystem services for policy support and decision making in the European Union. *Ecosyst Serv* 1:31–39. <https://doi.org/10.1016/j.ecose.2012.06.004>
- Mai VT, van Keulen H, Hessel R, Ritsema C, Roetter R, Phien T (2013) Influence of paddy rice terraces on soil erosion of a small watershed in a hilly area of Northern Vietnam. *Paddy Water Environ*, 11:285–298. <https://doi.org/10.1007/s10333-012-0318-2>
- MEA (2003) *Ecosystems and human well-being: a framework for assessment*. Millennium Ecosystem Assessment, pp 1–25
- Meinhardt M, Fink M, Tünschel H (2015) Landslide susceptibility analysis in central Vietnam based on an incomplete landslide inventory: comparison of a new method to calculate weighting factors by means of bivariate statistics. *Geomorphology* 234:80–97. <https://doi.org/10.1016/j.geomorph.2014.12.042>
- Meyer V, Becker N, Markantonis V, Schwarze R, van den Bergh CJJM, Bouwer LM, Bubeck P, Ciavola P, Genovese E, Green C, Halle-gatte S, Kreibich H, Lequeux Q, Logar I, Papyrakis E, Pfurtscheller C, Poussin J, Przulski V, Thieken AH, Viavattene C (2013) Review article: assessing the costs of natural hazards—state of the art and knowledge gaps. *Nat Hazards Earth Syst Sci* 13:1351–1373. <https://doi.org/10.5194/nhess-13-1351-2013>
- Müller F (2013) An application of the ecosystem service concept in different cropping systems and related production intensities. Kiel University, Kiel
- Müller F, Burkhard B (2012) The indicator side of ecosystem services. *Ecosyst Serv* 1:26–30. <https://doi.org/10.1016/j.ecose.2012.06.001>
- Nedkov S, Burkhard B (2012) Flood regulating ecosystem services—Mapping supply and demand in the Etropole municipality Bulgaria. *Ecol Indic* 21:67–79. <https://doi.org/10.1016/j.ecolind.2011.06.022>
- Nguyen VC, Dao VT (2007) Investigation and research of landslide geohazard in north-western part of Vietnam for the sustainable development of the territory. *Osaka Univ. Knowl. Arch. OUKA*, Osaka, pp 269–280
- Nguyen H, Dang KB, Dang VB (2011) Application of N-SPECT model and GIS for soil erosion assessment in Sapa district Lao Cai province. *J Earth Sci* 27(04):199–207
- NOAA (2008) *Nonpoint-source pollution and erosion comparison tool (N-SPECT): technical guide 15*
- Pham BT, Pradhan B, Tien Bui D, Prakash I, Dholakia MB (2016) A comparative study of different machine learning methods for landslide susceptibility assessment: a case study of Uttarakhand area (India). *Environ Model Softw* 84:240–250. <https://doi.org/10.1016/j.envsoft.2016.07.005>
- Pielke RA, Downton MW (2000) Precipitation and damaging floods: trends in the United States. *J Clim*. [https://doi.org/10.1175/1520-0442\(2000\)013<3625:PADFTI>2CO;2](https://doi.org/10.1175/1520-0442(2000)013<3625:PADFTI>2CO;2)

- Pimentel D (2006) Soil erosion: a food and environmental threat. *Environ Dev Sustain* 8:119–137. <https://doi.org/10.1007/s10668-005-1262-8>
- Posner S, Verutes G, Koh I, Denu D, Ricketts T (2016) Global use of ecosystem service models. *Ecosyst Serv* 17:131–141. <https://doi.org/10.1016/j.ecoser.2015.12.003>
- Pradhan AMS, Kim YT (2016) Evaluation of a combined spatial multi-criteria evaluation model and deterministic model for landslide susceptibility mapping. *CATENA*. <https://doi.org/10.1016/j.catena.2016.01.022>
- Saaty TL (2008) Decision making with the analytic hierarchy process. *Int J Serv Sci*. <https://doi.org/10.1504/IJSSCI.2008.017590>
- Saaty TL, Vargas LG (2012) Models methods concepts & applications of the analytic hierarchy process. Springer, New York
- Schulp CJE, Burkhard B, Maes J, Van Vliet J, Verburg PH (2014) Uncertainties in ecosystem service maps: a comparison on the European scale. *PLoS ONE*. <https://doi.org/10.1371/journal.pone.0109643>
- Sharp R, Tallis H, Ricketts T, Guerry A, Wood S, Chaplin-kramer R, Nelson E, Ennaanay D, Wolny S, Olwero N, Vigerstol K, Pennington D, Mendoza G, Aukema J, Foster J, Forrest J, Cameron D, Arkema K, Lonsdorf E, Kennedy C, Verutes G, Kim C, Guannel G, Papenfus M, Toft J, Marsik M, Bernhardt J, Griffin R, Glowinski K, Chaumont N, Perelman A, Lacayo M, Mandle L, Griffin R, Hamel P (2014) InVEST 301: user's guide the natural capital project, Stanford
- Shoyama K, Kamiyama C, Morimoto J, Ooba M, Okuro T (2017) A review of modeling approaches for ecosystem services assessment in the Asian region. *Ecosyst Serv* 26:316–328. <https://doi.org/10.1016/j.ecoser.2017.03.013>
- Swetnam RD, Fisher B, Mbilinyi BP, Munishi PKT, Willcock S, Ricketts T, Mwakalila S, Balmford A, Burgess ND, Marshall AR, Lewis SL (2011) Mapping socio-economic scenarios of land cover change: a GIS method to enable ecosystem service modelling. *J Environ Manag* 92:563–574. <https://doi.org/10.1016/j.jenvman.2010.09.007>
- Syrbe RU, Walz U (2012) Spatial indicators for the assessment of ecosystem services: providing benefiting and connecting areas and landscape metrics. *Ecol Indic* 21:80–88. <https://doi.org/10.1016/j.ecolind.2012.02.013>
- TEEB (2010) The economics of ecosystems and biodiversity. TEEB Ecological and Economic Foundations, London
- Tran TH (2013) Relationship between geomorphology and landslide in Lao Cai province. *VNU J Sci* 3:35–44
- Viera AJ, Garrett JM (2005) Understanding inter-observer agreement: the kappa statistic. *Fam Med* 37:360–370
- Wischmeier WH, Smith DD (1978) Predicting rainfall erosion losses: a guide to conservation planning. US Department of Agriculture. Handbook no. 537, pp 1–69. <https://doi.org/10.1029/tr039i002p00285>
- Wood D (2010) Rethinking the Power of Maps. Guilford Press, p 335
- Zhou S, Mueller F, Burkhard B, Cao X, Hou Y (2013) Assessing agricultural sustainable development based on the DPSIR approach: case study in Jiangsu China. *J Integr Agric* 12:1292–1299. [https://doi.org/10.1016/S2095-3119\(13\)60434-7](https://doi.org/10.1016/S2095-3119(13)60434-7)

Chapter 3.

Application of hybrid neural-fuzzy inference system or mapping crop suitability areas and predicting rice yields

Kinh Bac Dang, Benjamin Burkhard, Wilhelm Windhorst, Felix Müller

*(Submitted to “Environmental Modelling and Software” journal
in 19th April 2018)*

Abstract:

Climate change, growing population numbers and environmental stressors have significantly affected the terraced rice ecosystems in mountainous areas, such as the Sapa district in northern Vietnam. The dependence of rice ecosystems on the local social-ecological system is challenging farmers and scientists in predicting the variation of rice yields. The question arises how natural and socio-economic components determine the amount of rice yields. This study combines a hybrid neural-fuzzy inference system (HyFIS) with GIS-based methods to generate two models that can map suitability areas for rice cultivation and predict actual rice yields. Semi-structured interviews, the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) tool and different statistical models were used to investigate the impacts of natural and anthropogenic components on rice production. Eight environmental variables (elevation, slope, erosion, sediment retention, length of flow, water yield, ratio of evapotranspiration to precipitation and topological wetness index) and three socio-economic variables (investment of farmer, compound fertilizer and straight fertilizer uses) were collected to train two HyFIS models. The first model (with 88 % accuracy) for mapping the crop suitability areas at a regional scale requires eight environmental variables as input data, whereas the second model (90 % accuracy) to predict the actual rice yields at a plot scale requires besides eight environmental additionally three socio-economic variables as input data. Because the predictive power values of the two proposed models are higher than those of two benchmark models (Support Vector Machine and General Logistic Regression), the two HyFIS models are considered as alternative models for decision makers to optimize land use and related rice productivity.

Keywords: agriculture; crop; HyFIS; neural network; regional scale; plot scale.

Abbreviations: HyFIS - Hybrid neural-Fuzzy Inference System; SVM - Support Vector Machine; GLM - General Logistic Regression; GIS - Geographical Information System; LULC - Land Use and Land Cover; GSO - General Statistics Office of Vietnam; fractp - ratio of evapotranspiration to precipitation; TWI - Topographic Wetness Index; IRRI – International Rice Research Institute.

Highlights

- Hybrid models integrating neural network, fuzzy logic and geographical information system approaches were developed to find areas suitable for rice cultivation (a so-called S-HyFIS model) and to predict rice yields (a so-called I-HyFIS model).
- Impacts of environmental characteristics and additional human inputs on rice production were quantified.
- The S-HyFIS model can extrapolate results from plot to regional scales in order to generate a map representing crop suitability areas for rice cultivation.
- The potential of conversion from different land uses/covers to arable lands and vice versa were analyzed in the Sapa district, Lao Cai province, Vietnam.

1. Introduction

Different nature-based and technological solutions have significantly reduced the dependency of rice agriculture on the vagaries of weather, water and floods (IRRI, 2006). However, especially the rice production in mountainous communities still faces many variations in rice yields due to environmental impacts (Dobermann and Fairhurst, 2000). Meanwhile, the area of agricultural lands is decreasing due to urbanization, leading to land use conflicts in regard to paddy fields (Samranpong and Pollino, 2009). Therefore, more efforts from spatial planning and effective use of farming practices are needed in order to select appropriate areas for rice cultivation and improve yields in terraced paddy fields (IRRI, 2015; Maddahi et al., 2016).

Based on the rapid development of new mathematical and geographical methods, agricultural managers can be equipped with decision-supporting tools and models to optimize rice production (Khairunniza-Bejo et al., 2014). In the past, many yield prediction models at regional and plot scales were commonly based on statistical and machine learning methods. Especially at the plot scale, the statistical methods, such as generalized linear/logistic regression models (GLM), are more common in bio-agricultural analyses such as the influence of organic farming on rice plants (Datta, 1981; Dobermann and Fairhurst, 2000). Recently, the application of machine learning methods seems to become more effective for yield prediction, such as the use of support vector machines (SVM) (Jaikla et al., 2008; Were et al., 2015) and neural networks (Dahikar et al., 2015; Jabjone and Wannasang, 2014; Liu et al., 2005; Rahman et al., 2012). Other publications integrated statistical methods and remote sensing in Geographical Information Systems (GIS) to assess the rice suitability of areas on a regional scale (Maddahi et al., 2016; Samanta et al., 2011) and to estimate potential rice yields on a plot scale (Huang et al., 2013; Noureldin et al., 2013; Pirmoradian and Sepaskhah, 2006). However, these models using simple and non-spatial input variables cannot represent non-linear effects of the

social-ecological system on rice growth and hence are limited to extrapolating the overall suitability of areas for rice cultivation.

In order to account for nonlinear correlations of rice yields with environmental and social components, we use the hybrid neural-fuzzy inference system (HyFIS) developed by Kim and Kasabov (1999) in this study. This system uses a combination of fuzzy logic and the artificial neural network (ANN) approach. The fuzzy modeling system uses IF-THEN rules to separate a linear correlation between a response variable (such as rice yields) and related predictor variables (such as environmental variables) into separated independent correlations based on linguistic terms (Tung and Quek, 2009). Hereby the predictor variables with crisp values are transferred into different sets of linguistic terms corresponding to IF-THEN rules, thus each linguistic term provides a membership value to better adapt complex models (Bergmeir and Ben, 2015; Thessen, 2016). Hence, in contrast to “general linear models” (GLM) and “support vector machine” (SVM) models, the HyFIS universally uses linguistic and crisp values in parallel for prognosis and diagnosis application (Bui et al., 2017; Kothamasu and Huang, 2007; Thessen, 2016). In order to evaluate potential advantages of the HyFIS system, the yield predictions calculated with the HyFIS approach are compared with GLM and SVM models in this study.

The nominated concepts are applied here to help solve the following general issues: The rice yield to be expected depends on two major factors: i) the “natural productivity”, determined by environmental components and ecosystem functions in cropping areas, and ii) different socio-economic (e.g. agricultural management) options used to optimize rice yields (IRRI, 2006). In order to take full advantage of environmental conditions for rice growth, the identification of sites and areas best suited for rice cropping becomes a prerequisite in agricultural management (Gupta and Toole, 1986). The yields harvested from areas with high crop suitability can be up to 50 % higher than those harvested from unsuitable areas (Dang et al., 2017, submitted). Once the rice is cropped in favorable areas, the farmers can accordingly apply appropriate farming practices to take full advantage of the maximum potential of rice yields (Balbi et al., 2015). Thus, a map depicting the crop suitability areas at different levels on regional scales would be useful for agricultural planning and optimized land use decisions (Maddahi et al., 2016; Ye et al., 2015). Predictions for the potential of rice yields at plot scales can help farmers to assess their farming practices during each cropping season (Glavan et al., 2014; IRRI, 2006). A better interrelation of suitable site selection procedures (based on environmental components) and farming practices (based on socio-economic components) can help to control continuous water and nutrient availabilities and thus safeguard a sustainable supply of rice products (Dang et al., 2017, submitted).

By integration of the HyFIS system with GIS-based systems, this study develops two models for mapping rice suitability areas and predicting the potential of rice yields, corresponding to two scales of investigation (regional and plot scales, respectively). The mountainous area of the Sapa district in

the Lao Cai province in Vietnam was chosen as a case study area. The aims of this study are i) to indicate the suitability of areas for agricultural development on the regional scale, ii) to identify those ecosystems which potentially could be converted into arable lands, and iii) to better predict the potential of rice yields of particular plots. Eight environmental variables (with their spatial databases) have been chosen to assess the suitability conditions of areas for rice cropping at the regional scale. Additionally to these environmental variables, three socio-economic variables have been identified to predict the overall potential for rice yields on the plot scale. In the next sections, we present the methods related to data collection and the subsequent steps of the model developments based on the HyFIS approach.

The three following research questions are presented in this study:

- Is it feasible and effective to use natural and anthropogenic factors to explain the dynamics of rice production at regional and plot scales?
- How can we integrate the neural-fuzzy inference system and the GIS analysis to map crop suitability areas on the regional scale and to predict the potential of rice yields on the plot scale?
- How is the potential of agricultural development in other ecosystems in the Sapa region?

2. Study area

The study area is located in the Sapa district, a narrow 15 km x 15 km valley in the north-west mountain range of Vietnam (Figure 1). The altitude of this area ranges between 500 and 2,800 m. Besides extreme weather events with frost and snow recorded in winter, the climate stays comparably cool throughout the year. According to the National Center of the Hydro-Meteorological Forecast Service in Vietnam, the mean sunshine hours of the research area reach 1,400 hours annually, which is lower than in other agricultural regions (about 2,500 hours annually). The annual humidity in Sapa is always higher than 85 % while the temperature is lower than 24 degrees Celsius. The typical weather with high frequencies of fog reduces the extent to which solar energy can drive photosynthesis of rice plants as basic process of rice growth. Furthermore, due to the snow and low temperatures in winter, rice harvesting in this region is only possible once a year. The rice yields of 2 - 3 tons/ha per year in Sapa are usually lower than that in other agricultural regions of the Lao Cai province (Lò Dieu Phu, pers. comm. 2012).

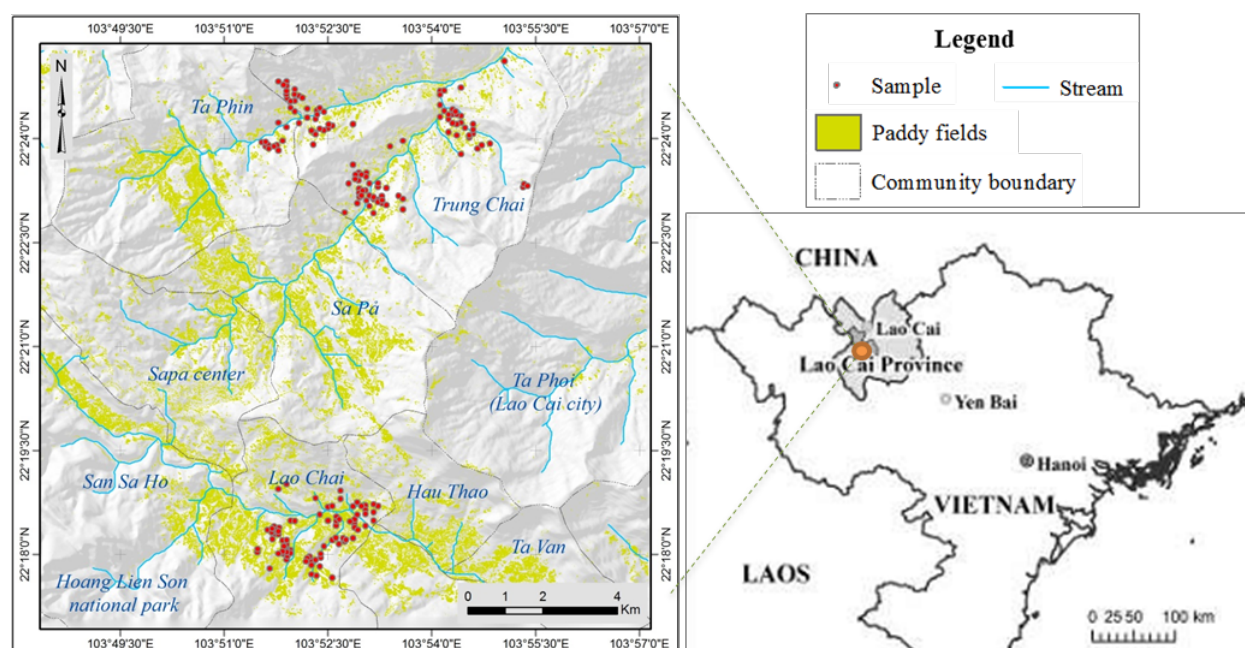


Figure 1. Location of 200 sample plots in six communities in the Sa Pa District, Lao Cai Province, Vietnam (paddy field identification based on SPOT 5 satellite image taken on 21/10/2010, provided by the LEGATO project; see text).

According to the Land Use Land Cover (LULC) map interpreted from SPOT 5 satellite image in 2010 and provided by partners from Europe and Southeast Asia (Burkhard et al., 2015), the area of paddy fields in the research area is about 2,700 hectares. This equals to 12 % of the whole study area (Figure 1). In the San Sa Ho, Hang Lao Chai and Ly Lao Chai communities (in Ngoi Dum basin), the paddy fields have been expanded to the colluvium and alluvial regions (Hoang, 2014). In the Chu Lin, Mong Sen and Vu Lung Sung communities (in the Ta Van basin), the distribution of paddy fields is more heterogeneous. Nevertheless, the area of paddy fields in the Ta Van basin has nearly doubled since the year 1993 (Hoang, 2014).

Recently, the increase of food demand has put pressure on the rice supply in Sapa (Dang et al., 2017, submitted). In order to meet the growing demands for food, farmers can either expand the rice cropping areas or increase rice yields by implementing suitable farm management measures. However, narrow valleys a challenge to the local people (local authorities as well as farmers) when it comes to identifying additional and suitable crop areas. As the number of additional farming areas is generally low, farmers usually reduce the times for shifting cultivation and use more fertilizers and pesticides instead. Local farmers have a belief in biotechnology to optimize crop yields and they trust especially the application of fertilizers and pesticides (Isoda, pers. comm. 2015). Additionally, farmers put less attention on environmental conditions when selecting additional sites for rice cropping, which leads to an increase of soil degradation (Nguyen et al., 2011) and an instability in rice yields (Isoda, pers. comm. 2015). Therefore, the mapping of suitable rice cropping areas can minimize

environmental risks and provide complementary knowledge and supporting tools for local farmers to stabilize rice yields.

3. Environmental and socio-economic variables affecting rice growth

3.1. The fluctuation of rice yields in Sapa

Rice yields for 200 paddy plots have been collated in a research project carried out by Yuzuru Isoda (pers. comm. 2015). The area of each sample plot equals 100 square meters and they are located in six communities (shown in Figure 1), The data were collected by interviews and revealed a fluctuation of rice yields between 2010 and 2012 from 1.28 to 9.56 tons/ha per year. Other rice yield data from the Sapa region showed lower average values for the same time period: 0.4 tons/ha per year less according to data from the LEGATO ⁷ project and 0.6 tons/ha per year lower according to inventories published by the General Statistics Office⁸ of Vietnam (GSO) (Table 1). Nevertheless, it is important to emphasize that in the Sapa district, rice is cultivated on slope lands where nutrient-rich soils are more scarce and the local climate is more extreme than in agricultural lands in the downstream areas of the Lao Cai province (Nguyen et al., 2011). It is obvious that the rice production here is lower than the mean rice yield values in the rest of the Lao Cai province. The rice yield data based on interviews represents the fluctuations of the upland rice production in the Sapa district.

Table 1. Rice yields based on interview data compared with data from the LEGATO project and the province report.

Sources	Rice yield (tons/ha per year)			Information
	<i>Min</i>	<i>Mean</i>	<i>Max</i>	
Interviews (Sapa)	1.28	3.73	9.56	200 plots in years 2010 - 2012
LEGATO project (Sapa)	1.7	4.10	7.7	17 samples in years 2012 and 2014
Yield inventory in the Lao Cai province	<i>Years 2010 - 2012</i>			http://www.gso.gov.vn/SLTK
	4.26 (mean)			

According to the inventory data of IRRI (2006), the mean of rice yields in Sapa corresponds with the rice yields in mountainous areas recorded in Asian countries with fluctuations from 1.5 to 4 tons/ha per year in average. Compared to the inventory data of GSO, the yields recorded in 10 paddy plots in the case study area are higher than the average yield (7.2 tons/ha per year) in other agricultural regions in Vietnam. The increase is based on the use of more intensive farming methods, such as

⁷ Land-use intensity and Ecological Engineering – Assessment Tools for risks and Opportunities in irrigated rice based production systems: <http://legato-project.net/>

⁸ <https://www.gso.gov.vn/>

fertilization and new seed choices. It is assumed that nearly 50 % of the 200 paddy sample plots (Figure 1) with yields lower than 3.5 tons/ha per year are related to poor site selection and/or ineffective farm management methods.

3.2. Environmental variables

In order to generate effective models to predict areas suitable for rice cultivation on different scales, the most effective predictor variables related to environmental and socio-economic conditions need to be selected. This process should eliminate non-relevant variables and improve the interpretability of final models (Bui et al., 2017). The correlations of relevant/non-relevant variables with rice yields have been identified by a Pearson comparison before any variable was used in the prediction models. The eight environmental variables considered in this study include: elevation (meter), slope (degree), soil erosion (ton/ha per year), sediment retention (ton/ha per year), length of flow (meter), water yield (millimeter), ratio of evapotranspiration (AET) to precipitation (P) and topological wetness index (TWI) (Table 2). The topographical variables (including elevation, slope, erosion and sediment retention) determine the distribution of soil nutrients. The hydrological variables (water yield, ratio of evapotranspiration to precipitation, TWI and length of flow) describe the water resources potentially available from irrigation activities (Dang et al., submitted. 2017). These eight environmental variables were used to define crop suitability areas **at regional scales** and to predict potential rice yields **at plot scales**.

Table 2: Data sources and descriptions of available environmental and socio-economic variables at regional and plot scales.

No.	Variable	Research scale	Source	Variance of data collected
1	Rice yields	Regional and plot	Collected in 200 paddy plots (10 m x 10 m) by Isoda et al. (pers. comm. 2015)	From 1.28 to 9.56 tons/ha per year
Environmental variables				
2	Elevation	Regional and plot	Provided by Ministry of Natural Resources and Environment of Vietnam at scale of 1:25.000	From 500 to 2800 m (above sea level)
3	Soil erosion	Regional and plot	Provided by Dang et al. (submitted 2017)	From 0 to 5 tons/ha per year
4	Sediment retention	Regional and plot	Provided by Dang et al. (submitted 2017)	From 0 to 5 tons/ha per year
5	Soil	Regional and plot	Soil map from the Department of Geography at the Hanoi University of Science in Vietnam	Plinthic Acrisols, Humic Acrisols, Humic Ferrasols
6	Temperature	Regional and plot	Downloaded from WorldClim ⁹ website - Free global climate data (period of 1960-1990)	From 18 to 25 degree Celsius
7	Precipitation	Regional and plot	Recorded in eight weather stations of the Meteorological Service in the Lao Cai province (period of 1990-2006)	From 1600 to 2300 mm
Socio-economic variables				
8	Compound fertilizers	Plot	Interviews in 2010-2011 (Unit: kg/ha per year)	From 0 to 300 kg/ha per year
9	Straight fertilizers	Plot	Interviews in 2010-2011 (Unit: kg/ha per year)	From 0 to 250 kg/ha per year
10	Investments	Plot	Interviews in 2010-2011 (Unit: Million VND/ha per year)	From 0 to 20 million VND per year

⁹ <http://www.worldclim.org/>

The three topological variables **elevation**, **slope** and **length of flow** (Figure 2) were calculated from a Digital Elevation Model (DEM) of the research area. The DEM is based on four topographical maps with a resolution of 10 meters. The topographical maps were collected in digital format from the VN-2000 national coordinate system. The contour lines were extracted from these maps and converted to the WGS-84 coordinate system before being used to extrapolate the DEM for the whole case study region. Three variables with special relevance in mountainous areas like the Sapa region are i) the high variances of elevation, ii) slope and iii) length of flow. All three variables strongly influence the climatic (such as temperature, precipitation and humidity) and topographic characteristics. This again leads to indirect changes in water and nutrient availability for rice (IRRI, 1978).

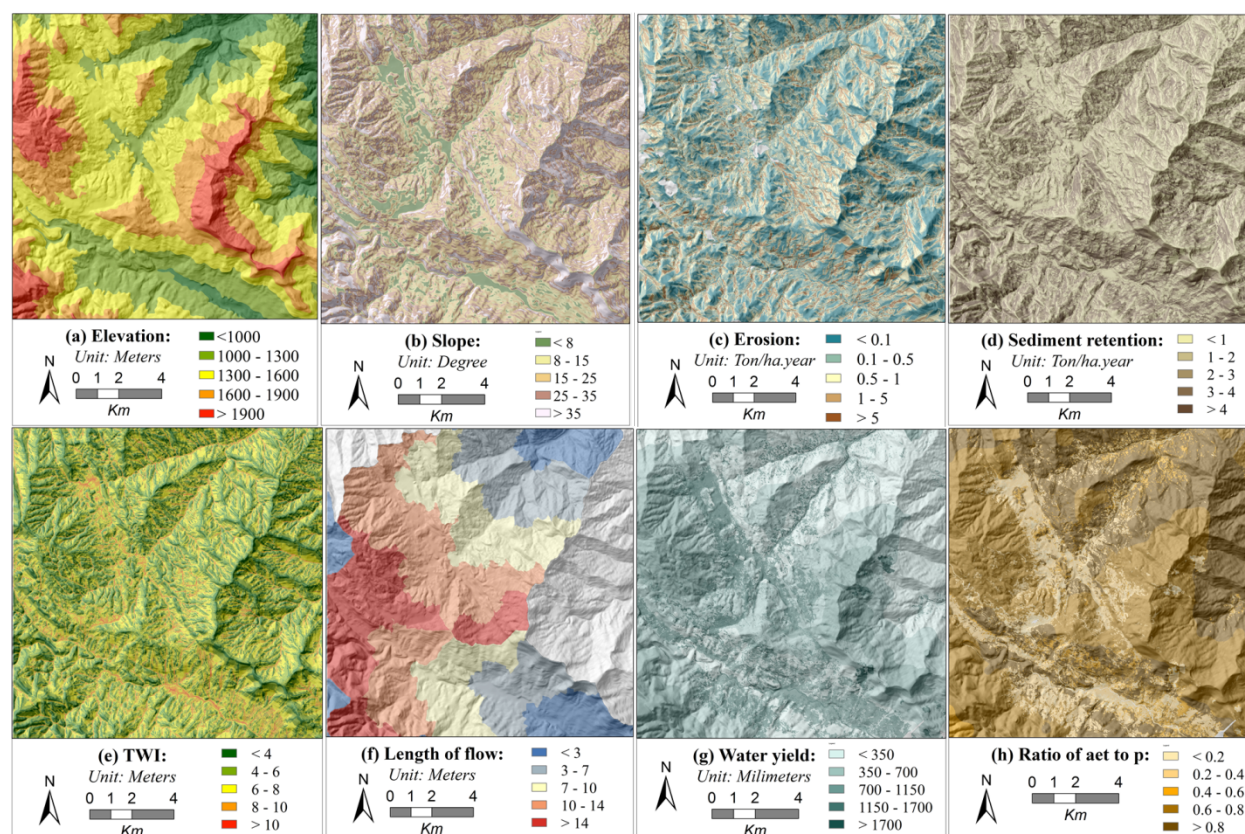


Figure 2. Maps of environmental variables used to develop the two HyFIS models, including elevation (a), slope (b), soil erosion (c), sediment retention (d), length of flow (e), ratio of evapotranspiration (AET) to precipitation (P) (f), water yield (g) and TWI (h). Calculations are based on a DEM derived from topographic maps of the region with 10 m resolution.

The variable length of flow determines the downhill runoff distance from each plot to the nearest reservoir in downstream areas (Tesfa et al., 2009). High values of flow length indicate plots which are located in upstream areas (far from downstream reservoirs), They are characterized by high flow

intensities, steep slopes and shallow soils mixed with pebbles and gravel (Chang, 2003). Soil nutrient enrichment in the upstream areas can be slower than those in downstream areas (Renaud and Kuenzer, 2012). Thus, nutrient and water availabilities in areas used as paddy plots could be inversely proportional to the length of flow. In order to demonstrate the important role of this variable, its correlation with rice yields is presented and discussed in detail in the result section.

Regarding the nutrient availability in soils, **erosion** and **sediment retention** (Figure 2) are crucial processes that strongly influence the deposition of fertile material on paddy fields. In detail, soil erosion is defined as the loss of top soil by wind or runoff (Pimentel, 2006), resulting in soil degradation. Erosion processes can detach and move soil particles to downstream areas, leading to the reduction of fertile materials in upstream areas (Wischmeier and Smith, 1958). For example, steep areas with sandy soils and high precipitation become more vulnerable to erosion, compared to flat areas with clay soils and low precipitation (Wischmeier and Smith, 1978). These variables have been determined by simulating the “sediment retention” with a sub-model developed as part of the tool InVEST 3.0 (Integrated Valuation of Ecosystem Services and Tradeoffs) (Sharp et al., 2014) by Dang et al. (submitted, 2017). The two resulting data sets have a resolution of 20 m.

Sediment retention is the amount of materials trapped on topsoil layers. Retention is affected by topographical factors and land covers (Sharp et al., 2014). Because of its important role in determining the quality and quantity of nutrients in the topsoil, this variable has been selected for the prediction models. The amount of sediment retained can be quantified as the gap between the incoming and exported sediment on each plot (Vigerstol and Aukema, 2011). The quantity of soil nutrients retained is noticeably dependent on the type and volume of materials in the deposited sediment (Schmitter et al., 2010). Therefore, the correlation of sediment retention with rice yields can be positive or negative, depending on the type of incoming materials (Slaets et al., 2015). If the amount of unfertile materials trapped in a plot is higher than the fertile ones, the level of suitability for rice cultivation in that plot is lower. In contrast, the plots retaining more fertile materials might be more suitable for cropping rice. In the research area, the high amount of un-weathered geologic materials maintained from the depositional processes (Nguyen et al., 2011) can reduce the fertility of soils, leading to changes in rice yields.

Regarding hydrologic and climatic variables, the **water yield** represents the amount of water unavailable for rice growth through both ground and surface water, whereas the **ratio of evapotranspiration to precipitation (fractp)** partly explains the quality of water and nutrient transports in rice plants. Two variables have been simulated with a spatial resolution of 20 m x 20 m with the “reservoir hydropower production” model in the InVEST 3.0 tool (Sharp et al., 2014). Water yield is known as the water extracted from a landscape that also contributes to other landscapes in downstream areas (Sharp et al., 2014). The increase of water yield does not only erode alluvium from

the topsoil, but also reduces the water uptake of rice plants. The amount of water yield in the whole region was calculated through a Budyko curve (1974) based on the following equation:

$$\text{Water yield (x)} = \left(1 - \frac{AET(x)}{P(x)}\right) \cdot P(x) \quad (\text{Eq. 1})$$

where *AET* is the actual evapotranspiration and *P* is precipitation.

In the “reservoir hydropower production” model of InVEST, the ratio (*fractp*) of actual annual evapotranspiration (AET) to precipitation (P) is calculated based on the following equation proposed by Fu (1981) and Zhang et al. (2004):

$$fractp = \frac{AET(x)}{P(x)} = 1 + \frac{PET(x)}{P(x)} - \left[1 + \left(\frac{PET(x)}{P(x)}\right)^w\right]^{1/w} \quad (\text{Eq. 2})$$

where *PET* is the potential evapotranspiration of different land cover types according to local climatic conditions and *w* is an empirical parameter related to soil properties. The potential evapotranspiration was calculated through the use of a temperature and soil database (Table 2). The database of soil thickness and particle sizes extracted from the soil map was used to identify the *w* parameter based on the expression of Donohue et al. (2012), integrated in the “reservoir hydropower production” model.

Through the aggregation of two important climatic factors, the “fractp” ratio has been commonly used as an indicator to assess the water-energy balance in a particular land use/cover over a long-term timescale (Budyko, 1974; Lu et al., 2005). Firstly, the evapotranspiration factor represents the loss of water from the soil surface by evaporation and from crop by transpiration that contributes to the transportation process of nutrients from the roots to other plant tissues (Allen et al., 1998). Doorenbos and Kassam (1979) have described the positive correlation between rice yields and evapotranspiration. Recently, various studies demonstrate that the reduction of evapotranspiration can prevent water and nutrient transports through plants, leading to the reduction of rice yield in different time scales (Alberto et al., 2011; Steduto et al., 2012). Secondly, the precipitation factor plays an important role in triggering soil erosion in slope lands (Sharp et al., 2014). In upland-rice production, irrigation water from rainfalls is commonly kept in upstream reservoirs and directed toward paddy plots in downstream areas. Raindrops falling down in a particular paddy plot can detach and move soil particles, leading to the increase of soil erosion and the decrease of topsoil nutrients (Wischmeier and Smith, 1978). According to relations between rice production and climatic factors, the “fractp” variable was used to develop yield prediction models.

As an indicator of soil moisture, the **topographic wetness index (TWI)** has been proposed by Sørensen et al. (2006). This variable can represent the flow accumulation of corresponding landscapes and assesses the amount of water available for rice production in a whole region. Therefore, it was chosen for this analysis. The TWI was calculated based on the following equation:

$$TWI = \ln\left(\frac{a}{\tan\beta}\right) \quad (\text{Eq. 3})$$

where a is the accumulated flow; β is the slope. Wetlands or floodplains have higher values of TWI, whereas lower values are found for example in ridges. In contrast with water yields known as amount of water outputted/extracted from a particular plot, the flow accumulation (a) is the amount of water inflows from upstream regions to each downstream plot. One hypothesis would be that the higher the TWI is, the higher the rice yield is.

According to the GIS analysis and the InVEST model application, the calculations of eight variables (No.2 until No.7 as listed in Table 2) were converted to a spatial resolution of 20 m x 20 m for the whole Sapa region.

3.3. Socio-economic variables

During the semi-structured interviews, further production-related data (besides rice yields) were collected for the 200 sample plots (Figure 1). Based on the interview results, three significant variables related to human activities were identified: (financial) **investments** of each household and the amount of **compound** and **straight fertilizers** used. In order to improve nutrient availability, NPK fertilizers (compound fertilizers) containing all three primary components (nitrogen, phosphorus and potassium) and straight fertilizers (such as nitrogen, phosphorus and potassium separately) that are required for healthy rice growth (Bi et al., 2014), are applied. Due to extreme nitrogen shortages in the soils, urea is spread as a main straight fertilizer in the case study region. Other types of straight fertilizers used in a few paddy plots were not considered in this study.

The socio-economic data collected at the 200 paddy plots could only be used to predict the yield potentials **at plot scales**. The details of using such data in yield assessments will be discussed in the next sections. The location information of the paddy plots was used to link the plots to the environmental information from available spatial data. The efficiency of farming practices highly depends on the amount of fertilizers, pesticides, seeds and equipment used. However, the farmers could unfortunately not provide sufficiently detailed information on their management inputs. Therefore, the variable ‘financial investment’ was used as a bulk indicator (for all kinds of additional inputs) to represent the management efforts of local farmers on their paddy plots.

4. Modelling process

The study aimed at creating a joint homogenous indicator dataset covering the whole Sapa region with a spatial resolution of 20 m x 20 m. This dataset was used to identify sites of naturally high productivity (e.g. indicators 2 until 8, Table 2). These sites were expected to be promising for an efficient use of farming methods (i.e. indicators 9 until 11, Table 2), ensuring high probabilities for high rice yields (i.e. indicator 1, Table 2). This homogenous dataset was available for the 200 sample plots with a size of 100 m². The data were used as a basis to develop linguistic rules for the creation of

a homogenous database for the whole Sapa region. Altogether 75 % of the basic data set was used to develop the linguistic rules and 25 % of the basic data set was reserved for the validation process.

4.1. Background of model validation

The model validation process was performed in different steps complementary to the HyFIS development (see Section 4.2). The prediction models always need to be trained, especially with the use of neural networks in machine learning processes (Jabjone and Wannasang, 2014). In order to assess the performance/quality of trained models, different kinds of testing indices have been developed for the validation process. The combination between neural networks and fuzzy logic can be developed from statistical measures (Bergmeir and Ben, 2015). Various goodness-of-fit tests and prediction-power assessments, such as overall accuracy, positive predictive value (PPV), negative predictive value (NPV), specificity (true positivity rate) or sensitivity (false negative rate) (in equations 4, 5 and 6 below), can be used.

$$\text{Overall Accuracy (ACC)} = \frac{TP + TN}{TP + TN + FP + FN} \quad (\text{Eq. 4})$$

$$\text{Sensitivity} = \frac{TP}{TP + FN} \quad ; \quad \text{Specificity} = \frac{TN}{TN + FP} \quad (\text{Eq. 5})$$

$$\text{PPV} = \frac{TP}{TP + FP} \quad ; \quad \text{NPV} = \frac{TN}{FN + TN} \quad (\text{Eq. 6})$$

where TP is the number of correct/true positive points and TN is the number of correct/true negative points between predicted and observed data; FP is the number of incorrect/false positive points and FN is the number of incorrect/false negative points between predicted and observed data.

These values can assess the performance of a prediction model in “positive” (value of “1”) or “negative” (value of “0”) cases (Fawcett, 2006). In detail, the value of ACC represents the probability of successful predictions and is calculated as the number of points where both “0” and “1” values are predicted correctly, divided by the total number of testing points. Compared to the total number of predicted points, the Positive Predictive Value (PPV) is the successful probability of prediction corresponding to the points with the “1” value, whereas the Negative Predictive Value (NPV) is the successful probability of prediction corresponding to the points with the “0” value. Compared to the total number of observed points, Sensitivity is the probability of correct points with the “1” value, whereas Specificity is the probability of correct points with the “0” value (Newlands et al., 2016).

To assess the efficiency of iterative processes (Bui et al., 2016), the Receiver Operating Characteristic (ROC) curve and Area Under the Curve (AUC) values have recently been used to validate machine learning models (Ajaz and Campus, 2015). In detail, the ROC curve and AUC values can partly measure the predictive power of model outcomes. Both of them refer to the sensitivity and specificity of model outcomes. That means that for example good AUC values fluctuate between 0.5 and 1. AUC values of 0.5–0.7 indicate a poor model, AUC values of 0.7–0.8 indicate a moderate model and AUC

values of 0.8–0.9 indicate a good model. AUC values of 0.9–1 indicate excellent models (Fawcett, 2006).

4.2. The training process of hybrid neural-fuzzy inference systems using GIS

This section explains the artificial intelligence approach based on a neural-fuzzy inference system that was used to define areas suitable for rice cultivation on the regional scale and to estimate potential rice yields on the plot scale. Corresponding to the two spatial scales of this study, two HyFIS models were developed. On the regional scale, a site-selection HyFIS model (abbreviated by S-HyFIS) considers eight environmental input variables (as listed in Table 2) to map areas suitable for rice cultivation. On the plot scale, a complementary, integrated HyFIS model (abbreviated by I-HyFIS) considers, besides the eight environmental input variables used in the S-HyFIS model, additionally three socio-economic variables (as listed in Table 2) to predict potential rice yields.

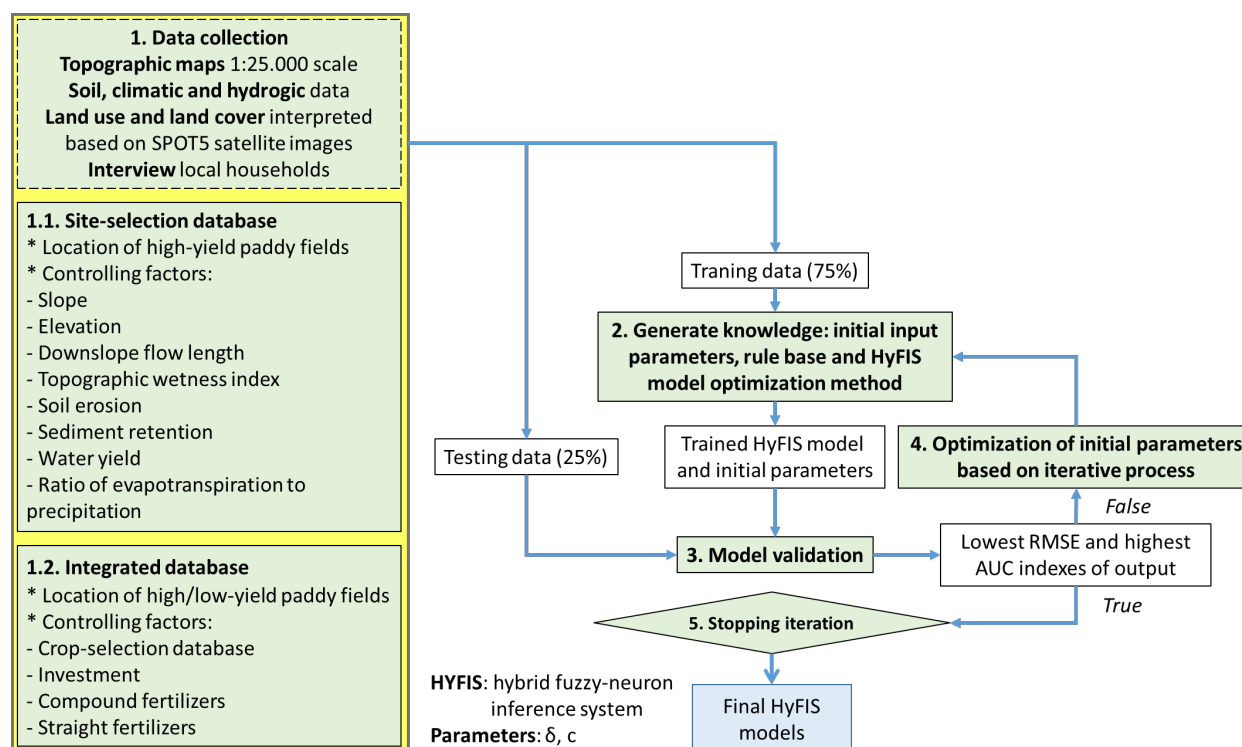


Figure 3. The structure of the HyFIS model development, showing the integrated iterative process and the GIS-based analysis.

The structure of the two proposed models is shown in Figure 3. The modeling procedure was carried out in five steps, including: database preparation (1), training (2), optimizing (3), validating models (4) and assessing the performance (5) of final models. The formal HyFIS models were implemented via the *frbs* package (Bergmeir and Ben, 2015) in the R-Studio environment, Version 1.0.136. The

optimization process was based on iteration and programmed by the authors. The spatial analysis was carried out in ArcGIS 10.2.

4.2.1. Step 1: Preparation of site-selection and set up of an integrated database for the training and testing processes

In the first step, the predictor variables mentioned in Sections 3.2 and 3.3 (covering eight environmental and three socio-economic variables) need to be analyzed by their Pearson correlations with the target variable “rice yields”. If the predictor variables have statistical significance to explain the variance of “rice yields”, these variables are selected for the next step after normalization to values ranging from 0.01 to 1.00. The normalization reduces the bias between the input variables used in the prediction models. The correlations were analyzed with data for 200 sample plots collected in the years 2010 - 2012. Based on the coordinates for these 200 plots, all data could be linked to the maps of the eight environmental variables as described in Section 3.2. Hence, 200 plots containing full environmental and socio-economic data were analyzed to check their correlations with rice yields.

For the proposed modeling process based on fuzzy logic, a binary classification for the “rice yields” variable in the two values “0” and “1” is required. “0” indicates unsuitability of areas for rice cultivation in the S-HyFIS model and low potential for high rice yields in the I-HyFIS model. “1” indicates suitability of areas for rice cultivation in the S-HyFIS model and high potential for high rice yields in the I-HyFIS model. According to IRRI (2006), if farming practices (such as fertilization and pesticide use) are not applied, the potential of yields for upland rice in Asian countries is estimated to range from 3 to 3.5 tons/ha per year. Hence, the locations of 102 paddy plots where recorded yields were higher than 3.5 tons/ha per year were classified by the value of “1”, whereas the 98 plots with lower yields were classified with the value “0”. Therefore, the output of the two models ranges from 0 to 1. The outcomes near “1” indicate the suitability of areas for rice cultivation (in the S-HyFIS model) or the potential for high rice yields (in the I-HyFIS model). Values near “0” represent areas unsuitable for rice cultivation (in the S-HyFIS model) or low potential for high rice yields (in the I-HyFIS model).

In order to test the performance of the developed models, the 200 plots, for which complete datasets were compiled, were randomly divided into two data sets (training and testing). The testing data set consists of 25 % (or 50 plots) of all plots, while the training data set consists of the remaining 75 % (or 150 plots). The testing dataset was used during the validation process because it has not been used to train the models. This allowed us to compare the trained model outcomes with observations in the testing data set in order to assess the accuracy of the results (Liu et al., 2010).

4.2.2. Step 2: Knowledge learning and design of the neural-fuzzy inference system

This step focused on constructing a conceptual HyFIS model for training purposes. In this study, the IF-THEN rules of the fuzzy structure followed the Mamdani inference model - proposed by Mamdani (1977). The neural fuzzy structure contains four layers corresponding to four components of the

Mamdani model (Figure 4). The first layer is designed to transform input data from crisp values to linguistic ones, whereas the fourth layer produces numerous outcomes from linguistic values. The two layers in the middle compose fuzzy rules and membership functions. The inference engine of the S-HyFIS can be explained in detail as follows:

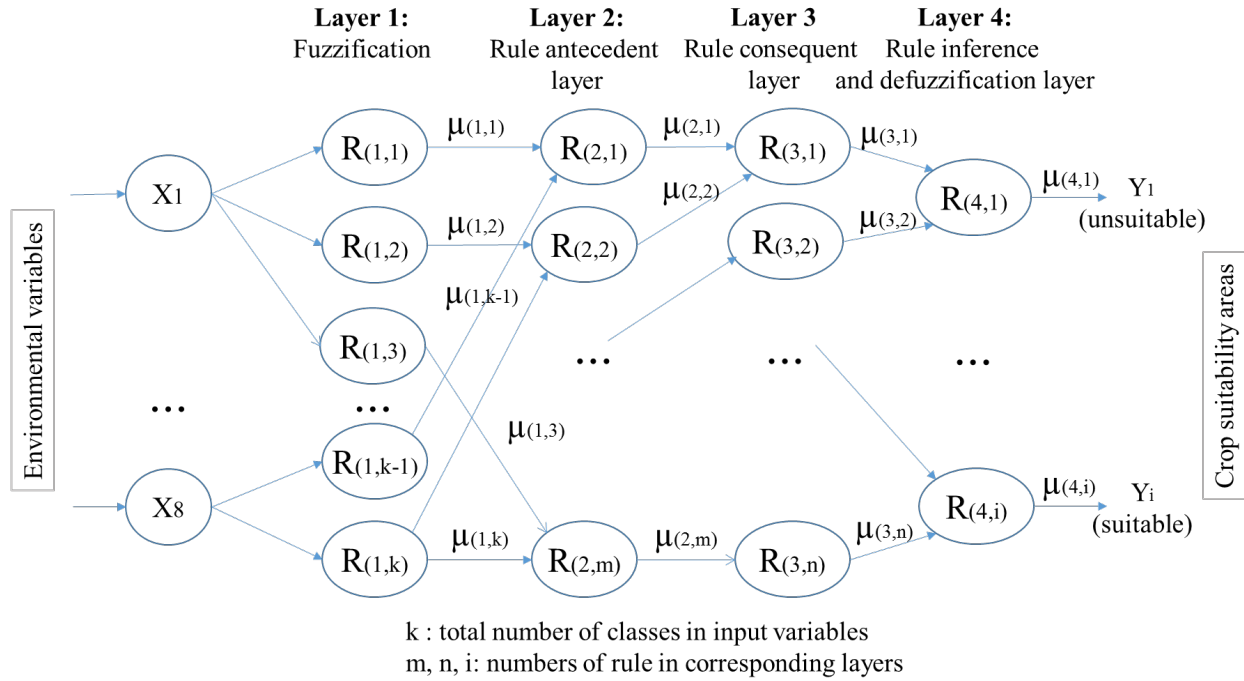


Figure 4. Structure of the site-selection hybrid fuzzy-neural network (S-HyFIS) with participation of the eight environmental variables (see Table 2).

Layer 1 (Fuzzification layer): In this layer, the input environmental variables of the given numerical data were separated into fuzzy regions associated with linguistic terms. The number of linguistic terms depends on the length of the fuzzy regions and represents the variance of rice yields. Then, the linguistic terms were assigned to fuzzy membership values in the fuzzification process. In this process, the Gaussian membership function in equation 7 was implemented for each input variable with two initial parameters (variance and standard deviation).

$$\mu_{(1,k)} = \exp \frac{-(x-c)^2}{2\delta^2} \tag{Eq. 7}$$

where μ is the Gaussian membership function for input variables; δ is the variance parameter and c is the standard deviation of the function; k is the total number of linguistic terms for eight input variables.

Two initial parameters (δ and c) were adjusted by using gradient descent-based learning algorithms (Bergmeir and Ben, 2015). These parameters converge to local optima and are more sensitive to membership values. In the end of this layer, the membership functions and values were calculated for

all training data. In order to minimize the number of IF-THEN rules in layer 2 and to maximize the accuracy of outcome models, the number of linguistic terms was optimized through an iterative process (presented in step 3).

Layer 2 (Rule antecedence layer): This layer performs the appropriate fuzzy rules between input and output in training data and determines a strength value for each rule (or the relative membership values). The number of nodes in this layer equals the number of fuzzy IF-THEN rules generated for the training data in the preceding step. For instance in Layer 1 of Figure 4, the input variable X_1 has three linguistic terms ($R_{(1,1)}$, $R_{(1,2)}$ and $R_{(1,3)}$), whereas the input variable X_8 has two linguistic terms ($R_{(1,k-1)}$ and $R_{(1,k)}$). In this case, the nodes $R_{(1,1)}$ and $R_{(1,k-1)}$ decide on the membership function for node $R_{(2,1)}$ in layer 2 which represents “the outcome y_1 is unsuitability areas”. Then, their connections represent the rules “IF X_1 is $R_{(1,1)}$ and X_8 is $R_{(1,k-1)}$ THEN y_1 is unsuitability areas” and “IF X_1 is $R_{(1,3)}$ and X_8 is $R_{(1,k)}$ THEN y_1 is unsuitability areas”. The process was repeated for each instance of the training data to generate fuzzy rules. The strengths of these rules were calculated based on the Hamacher operation (Bergmeir and Ben, 2015). For instance, the membership function for the first rule of Layer 2 in Figure 4 was as follows:

$$\mu_{(2,1)} = \frac{\mu_{(1,1)}\mu_{(1,k-1)}}{\mu_{(1,1)} + \mu_{(1,k-1)} - \mu_{(1,1)}\mu_{(1,k-1)}} \quad (\text{Eq. 8})$$

Layer 3 (Rule consequent layer): This layer yields final rules by removing redundant rules. The distinct concept in this layer is the aggregation of rules created in the second layer. The strength of each rule concept is decided by aggregating the strengths of membership functions in the antecedent layer. In this case, the maximum operation was used to delete the redundant rules having lower strengths. For example in Figure 4, the first two nodes ($R_{(2,1)}$ and $R_{(2,2)}$) in the second layer determine the rule and the membership function of the node $R_{(3,1)}$ in the third layer, then its activation function will be:

$$\mu_{(3,1)} = \max \{ \mu_{(2,1)}, \mu_{(2,2)} \} \quad (\text{Eq. 9})$$

Layer 4 (Rule inference and defuzzification layer): This process transforms linguistic terms into numerical values to create the final model output values by using the modified Center Of Gravity (COG) method. It also determines the final linguistic terms for the output variables. For example, the first two nodes ($R_{(3,1)}$ and $R_{(3,2)}$) in the third layer decide the first node ($R_{(4,1)}$) in the fourth layer, then the strength of the first fourth-layer node is calculated by following equation:

$$\mu_{(4,1)} = \frac{\mu_{(3,1)}y_{(2,1)} + \mu_{(3,2)}y_{(2,1)}}{\mu_{(3,1)} + \mu_{(3,2)}} \quad (\text{Eq. 10})$$

where the y_i is value of each rule consequent node.

The inference engine of the I-HyFIS model operates with the same layers. In four layers of the HyFIS models, the number of linguistic terms (k) and the values of two initial parameters (variance and standard deviation) can impact the weights of antecedent and consequent rules (in layers 3 and 4), and

then the accuracy of the outcome (Kim and Kasabov, 1999). In other words, the values of the membership functions in four layers are dependent on the variance of two initial parameters and the number of linguistic terms and need to be learned/optimized, in order to obtain well-designed IF-THEN rules.

4.2.3. Step 3 and 4: Modeling optimization based on iterative processes and model evaluation

Once the framework of the neural-fuzzy network was constructed, the iterative and testing processes were launched to identify the best position and length for fuzzy regions in the first layer of step 2. In the iterative process, the number of linguistic terms was tested from three to nine in order to find out the optimal value that can minimize the number of IF-THEN rules and maximize the performance of HyFIS models (Bergmeir and Ben, 2015). The lower the number of IF-THEN rules, the better is the performance of outcome models (Bui et al., 2017). Regarding the two initial parameters, their values were changed based on the fluctuations of initialized fuzzy regions in each iteration, leading to changes in the values of membership functions and IF-THEN rules (Bergmeir and Ben, 2015). Then, the testing dataset was used to assess the goodness-of-fit of the trained HyFIS models by calculating the mean square errors and the AUC values.

The values of Mean Square Errors (MSE), which are commonly used to assess the iteration process (Omez et al., 2010), were calculated with the following equation:

$$MSE = \frac{1}{n} \sum_{i=1}^n (Pre_i - Obs_i)^2 \quad (\text{Eq. 11})$$

where n is number of plots considered in the training data or the testing data; Obs_i indicates observed values in the testing data and Pre_i are the predicted values produced by the trained models.

In the optimal position of initial parameters and numbers of linguistic terms, the gap between predicted outcomes and observed values is smallest. Moreover, the AUC value was used for assessing the accuracy of the trained models in parallel with the MSE value in each iteration. The final model needed to have the highest AUC value and the lowest MSE value. Based on the MSE and AUC values, the number of iterations was terminated at 500 to fully represent the fluctuation of the two initial parameters (Benmiloud, 2012). In the testing process, the authors could not find more accurate models in cases of higher numbers of iteration.

4.2.4. Step 5: Assessment of final HyFIS models

In this step, the final S-HyFIS and I-HyFIS models with the highest AUC values and lowest MSE values were evaluated to estimate their goodness-of-fit using testing data and calculating seven statistical values (ACC, sensitivity, specificity, PPV, NPV, MSE and AUC). In order to demonstrate the advantage of the developed HyFIS models, these models were benchmarked with alternative models/methods. This included a Support Vector Machine (SVM) and a logistic regression model (simulated as Generalized Linear Models (GLM) and programmed in R). Both models are known as powerful tools in machine learning used in agricultural and social studies (Ajaz and Campus, 2015;

Were et al., 2015) to explain the probability of a binary variables (“1” and “0”) depending on explanatory variables. Eight environmental explaining variables and the target variable “rice yields” selected from the training data were used to generate the benchmark SVM and GLM models. All goodness-of-fit tests and the prediction-power assessment, which were used for the developed HyFIS models, were also applied for the SVM and GLM models, in order to indicate the efficiency of the different models to map areas suitable for rice cultivation in the Sapa region.

Whereas the logistic regression model is commonly used to estimate the probability of binary variables in agricultural fields (Ali et al., 2012; Sattaka et al., 2017), SVMs have been recognized as robust supervised learning models in classification and regression analysis during the last decade (Armstrong, 2016; Balakrishnan and Muthukumarasamy, 2016; Su et al., 2017). In particular, the outcome of SVM models depends on parameters of C-classification (c) and specific kernel width (γ) (Karatzoglou et al., 2006). Therefore, the testing process based on the changes of AUC and MSE values was implemented. Finally, the values of γ and c were chosen respectively at eight and three for the most effective SVM model. The performance of these models is shown in the results section.

Based on the comparison between the four models, the study identified two optimal models with the best goodness-of-fit to predict the potential of rice yields on the plot scale and to map areas suitable for rice cropping at the regional scale. Based on the eight environmental variables as input data (Table 2), the S-HyFIS model has extrapolated the suitability of areas from the plot scale to the regional scale. The extrapolation process of the S-HyFIS model identified the suitability/unsuitability of areas based on the similarity of environmental characteristics in the whole case study area. The map of crop suitability areas was validated by 17 independent plots provided by the LEGATO project (as mentioned in Section 3.1). In this project, scientists collected straws and grains from 17 paddy plots and then weighed the amount of dried rice grains to calculate rice yields at each plot. 14 high-yield and 3 low-yield plots were recorded. The locations of these plots provide important data to cross-check the accuracy of the S-HyFIS model. If the outcomes of the S-HyFIS model is correct, the high-yield plots collected from the LEGATO project need to be located in suitable areas and the low-yield plots need to be located in unsuitable areas. Socio-economic data were not collected at these plots. Therefore, these plots can only be used to check the accuracy of the S-HyFIS model. Finally, in order to assess the potential of rice expansion in the case study area, the areal percentage of areas suitable/unsuitable for rice cultivation predicted from the S-HyFIS model were counted in seven different land use/cover types (including the paddy fields). Land uses/cover types having highly suitable environmental characteristics for rice cultivation can be suggested for agricultural conversion. Regarding the potential of rice yields predicted through the I-HyFIS model at the plot scale, the accuracies of results were only assessed at the 200 observed plots through percent-error values following this equation:

$$\text{Percent – error value} = (\text{Predicted value} - \text{observed value}) / 100 \quad (\text{Eq. 12})$$

Percent-error values higher than 50 % could identify plots predicted incorrectly from the I-HyFIS model. To make the results easy-to-observe, each paddy plot is conveniently visualized within a single point on the map.

5. Results

5.1. Pearson correlation between predictor variables and rice yields

The input data were analyzed in order to eliminate non-statistical significant variables of the chosen predictor variables to explain the rice yield as a response variable. The high-yield paddy plots were compared with the low-yield ones by eight environmental variables and three socio-economic variables through boxplots and by calculating the Pearson correlation values (shown in Figure 5). Out of the eight spatial input variables, used as main inputs for the S-HyFIS model (see Table 2), the “slope”, “length of flow” and “sediment retention” variables have the strongest correlation values of -0.4, -0.34 and -0.3, respectively. The variables “soil erosion”, “elevation” and “water yield” follow with correlation values of about 0.2. The ratio of evapotranspiration to precipitation (fractp) and the Topological Wetness Index (TWI) were the poorest predictive variables with low correlation values of 0.16 and 0.11.

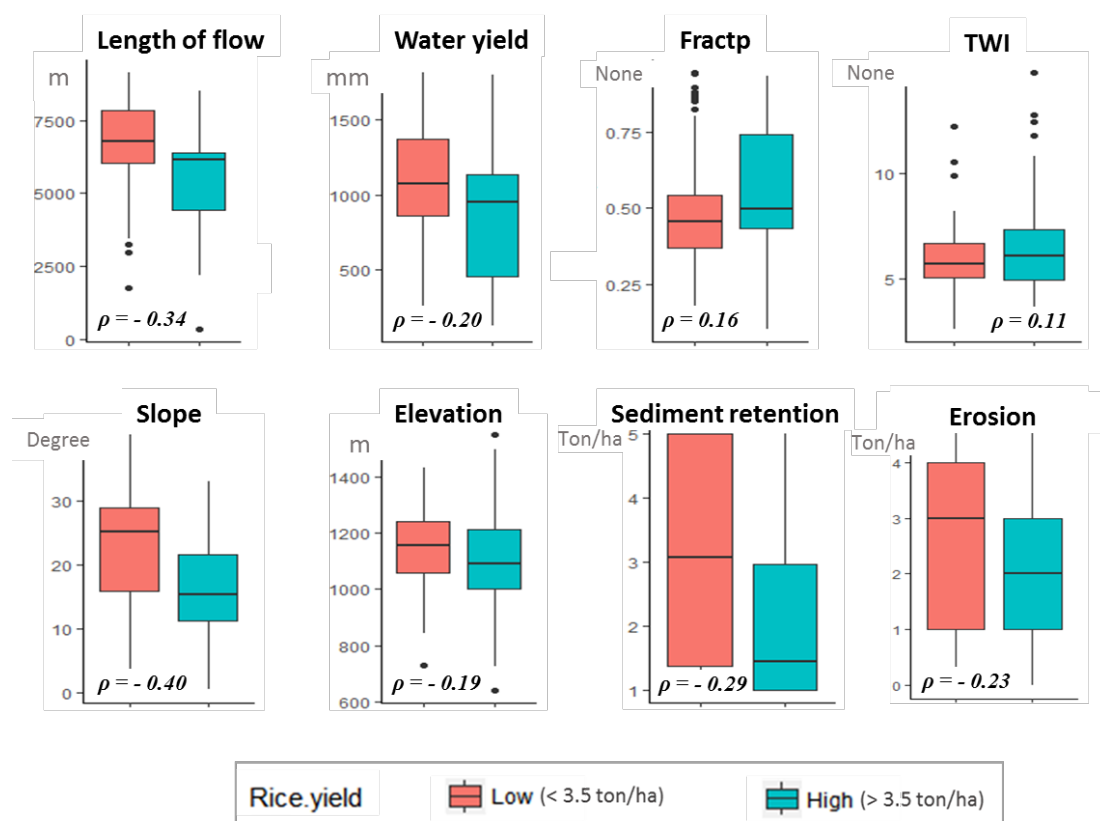


Figure 5. Comparison of rice yields in dependence on different environmental variables based on Pearson correlations.

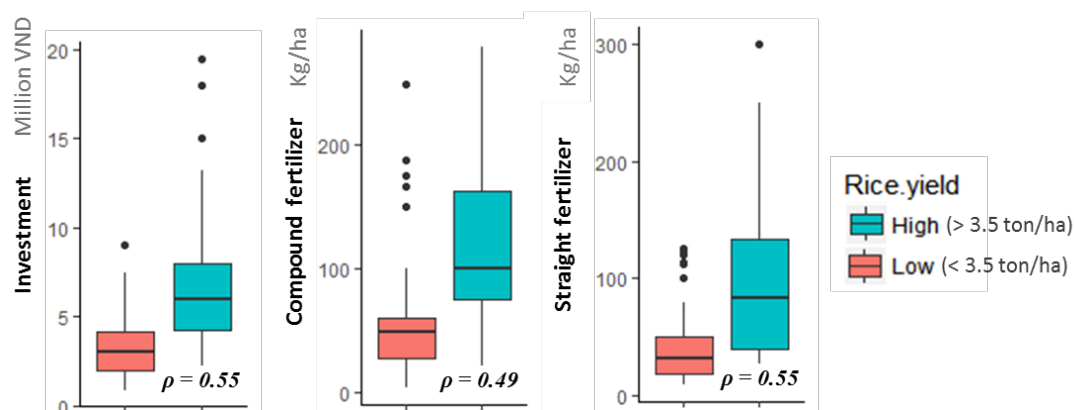


Figure 6. Comparison of rice yield under different socio-economic variables using Pearson correlation.

The indicated low yield areas appeared in cases where rice was cropped on sites with high erosion susceptibility, situated on steep terrains, and/or on high altitudes. Although a higher altitude for agricultural lands can be identified at 1,100 m, the contribution of the variable “elevation” does not fully and adequately explain the increase of rice yields with decreasing altitude. Hence farmers need to consider further environmental variables, such as slope (lower than 13 degrees), water yields (lower than 700 mm) and length of flow (less than 6 km) to have high probabilities to harvest higher rice yields.

The three socio-economic variables used in the I-HyFIS model correlate to about 0.5 with rice yields (Figure 6). According to this result, the additional inputs (related to farm management practices) have remarkably influenced the rice production, especially in the case of fertilizers. Nevertheless, the amount of investment should range from 5 to 6 million VND (equal to more than 200 EUR) per hectare to achieve high yields on suitable plots. However, the effective amount of fertilizers should be limited to 180 kg of compound fertilizers and 130 kg of urea for one hectare for high-yield plots in the case study (Figure 6).

5.2. Final S-HyFIS and I-HyFIS models

Table 3 depicts the structure of the two final HyFIS models in the case study area. Eight environmental variables were considered as the inputs for the S-HyFIS model to assess the suitability of areas for rice cultivation. Three socio-economic variables were added to develop the I-HyFIS model to predict the potential of rice yields. In the iterative process, the optimal number of linguistic terms in both HyFIS models was chosen to be eight. If the number of linguistic terms is lower/higher than eight, the performance of HyFIS models assessed through the AUC and MSE values is reduced.

Hence, the S-HyFIS model generated 148 IF-THEN rules based on 128 initial parameters, whereas the I-HyFIS model had 149 rules based on 176 initial parameters (see more in Section 4.2.2).

Table 3. The structure of the proposed HyFIS models in the optimization process.

Model	Number of input variables	Number of initial parameters	Number of IF-THEN rules	Outcome
S-HyFIS	8	128	148	Areas suitable for cropping
I-HyFIS	11	176	149	Rice yields

According to the iterative processes described in Section 4.2.3 and in Figure 7, the optimal values of initial parameters were chosen through the values of AUC and MSE. The MSE mean of the I-HyFIS model (from 0.07 to 0.35) in the iteration process was lower than the one of the S-HyFIS (from 0.15 to 0.55). As shown as a linear fluctuation of the AUC values, the predictive ability of the I-HyFIS model was higher than the S-HyFIS model from 3 % to 6 %.

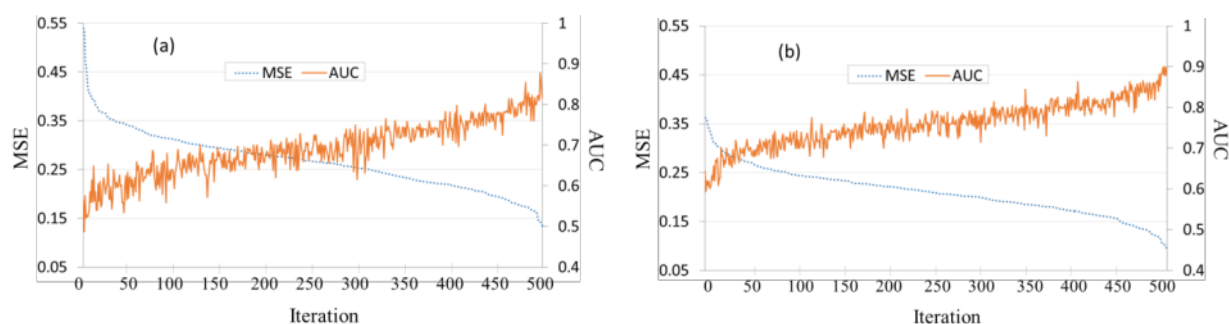


Figure 7. Fluctuation of MSE and AUC values in iterative processes for the S-HyFIS (a) and I-HyFIS (b) models.

Based on the goodness-of-fit test, the chosen S-HyFIS model has an AUC value of 0.88 and a MSE value of 0.14 (see Table 4). The positive predictive value (PPV) of this model reaches 0.74 or, in other words, the probability of finding a suitable plot for crop cultivation (value of “1”) is 74 %. Complementarily, the negative predictive value (NPV) reaches 0.96, explaining that the probability of finding a plot unsuitable for crop cultivation (value of “0”) is 96 %. The accuracy of the suitable plots was 94 % as shown by the value of sensitivity, whereas the accuracy in predicting unsuitable plots was 81 % as shown in the value of specificity. The predictive power of the S-HyFIS model was also illustrated by the ACC value of 0.86 and the Kappa index of 0.71.

The best I-HyFIS model chosen from the iterative process has the overall accuracy (ACC) value of 90 % (with an AUC value of 0.9 and a MSE value of 0.1), which is higher than the accuracy of the S-HyFIS model. The probabilities of finding a plot with a high (value of “1”) or low (value of “0”) yield potential are both 88 % (shown in PPV and NPV values of 0.88). The accuracy of each finding is 92 % (shown in the values of sensitivity and specificity). Besides, the overall predictive power of the I-HyFIS model estimated through the ACC value of 0.9 and the Kappa index of 0.8 was higher than for the S-HyFIS model. The I-HyFIS model can be run for the whole region (or for regional scales) if the socio-economic variables are provided for the same scale. In this study, the three socio-economic variables were not available for the whole Sapa region. Therefore, the I-HyFIS model could only predict potential rice yields at the plot scale.

Table 4. Comparison of the prediction models using neural-fuzzy network (S-HyFIS and I-HyFIS) with GLM and SVM methods (using 8 environmental input variables).

No	Validation values	S-HyFIS	I-HyFIS	GLM	SVM
1	True positive	26	22	23	28
2	True negative	17	23	17	15
3	False positive	1	2	1	3
4	False negative	6	3	9	4
5	Positive predictive value	0.74	0.88	0.65	0.79
6	Negative predictive value	0.96	0.88	0.96	0.90
7	Sensitivity	0.94	0.92	0.94	0.83
8	Specificity	0.81	0.92	0.72	0.87
9	ACC	0.86	0.9	0.8	0.84
10	MSE	0.14	0.10	0.14	0.13
11	Kappa statistic	0.71	0.80	0.60	0.69
12	AUC	0.88	0.90	0.83	0.85

For the mapping of the areas suitable for crop farming at the regional scale, the accuracy of the final S-HyFIS model was compared with the accuracies of the SVM and GLM models. The accuracies of the two benchmark models are illustrated in Table 4. The predictive powers of the GLM and SVM models (shown in the values of PPV, NPV, ACC and AUC) seem to be lower than those of the S-HyFIS model. The Kappa indices in the S-HyFIS model and the SVM model were almost the same with about 0.7 in average, whereas the Kappa index of the GLM model was 0.6. Although the three models are applicable to map areas suitable for rice cropping in the whole case study area, the proposed S-HyFIS model seemed to be the most reliable model due to its high accuracy.

5.3. Mapping areas suitable for rice cropping in Sapa

The areas suitable for rice cropping are shown in Figure 8. The areas were mapped based on the application of the final S-HyFIS model for the whole case study area. To distinguish between areas that are suitable/unsuitable for rice cultivation, the outcomes of the S-HyFIS model ranging from 0 to 1 were classified into four classes. These classes include low (values lower than 0.5, corresponding to 30 % of the total area), medium (values from 0.5-0.7 or 20 % of the total area), high (values from 0.7-0.9 or 25 % of the total area) and very high (values higher than 0.9 or 25 % of the total area) suitability for rice cultivation. In order to validate the results, 17 independent plots provided by the LEGATO project were used. Within these plots, 14 high-yield plots were located correctly at high and very high suitability plots, whereas 3 low-yield plots were located at medium and low suitability plots.

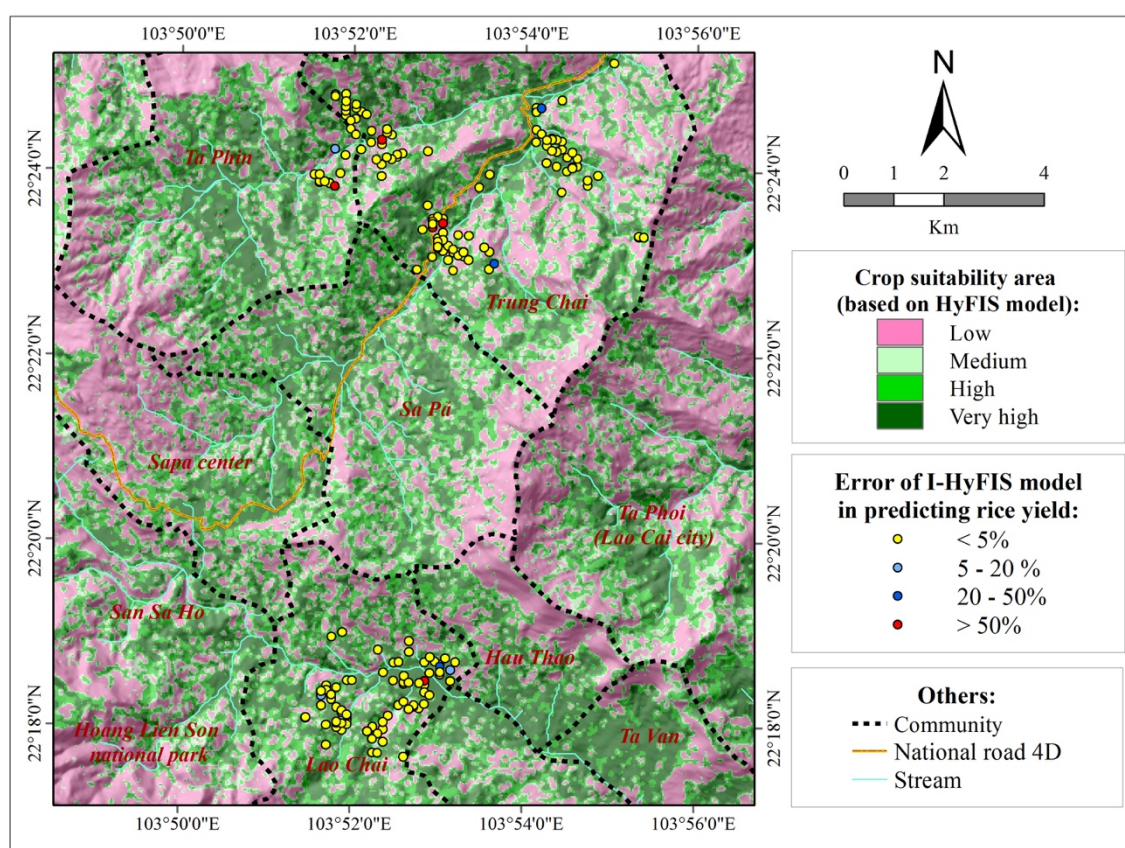


Figure 8. Map of areas suitable for rice cultivation (based on S-HyFIS model) and predictions of potential rice yields (based on I-HyFIS models) in the Sapa region.

According to this result, the areal percentage of high and very high suitability areas in the Ta Van basin seems to be equal to those in the Ngoi Dum basin. The high and very high potential areas for agricultural development were found along rivers and streams in the Ta Van, Lao Chai and Ta Phin

communities. Areas with low potentials were found in more than 4,000 ha of upstream areas in Sapa center, Trung Chai, Sa Pả, Hau Thao and San Sa Ho communities (corresponding to 35 % of the total area in these communities). Accordingly, agricultural development should not be expanded to upstream areas of the mountainous communities.

The potentials of predicted rice yields based on the final I-HyFIS model were compared at 200 observed plots as shown in Figure 8. Because the three socio-economic variables were only recorded for these 200 plots, the I-HyFIS model was not used to estimate the potential rice yields at the regional scale. Potential yields at eight plots were predicted by the I-HyFIS model with the percent-error values higher than 50 %, while other eight plots have errors from 5 to 50 %. Nearly 94 % of all paddy plots could be correctly identified by this model with errors lower than 5 %, especially with plots in the Ta Van basin. The high percent-error values (more than 50 %) were mostly found in the Ngoi Dum basin. According to the performance of the I-HyFIS model, farmers can consider an appropriate amount of fertilizer (about 180 kg/ha per year of compound fertilizers and 130 kg/ha per year of urea) and investments of about 5 to 6 million VND required to have good chances for high yields on high-suitability plots.

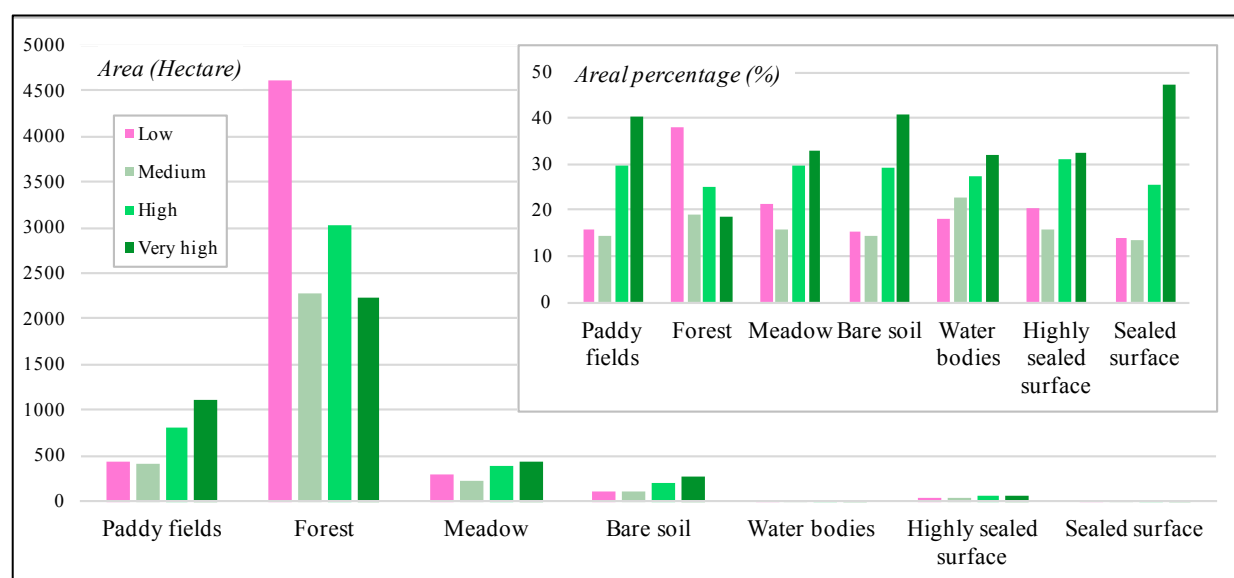


Figure 9. Areas suitable for rice cultivation (in area and areal percentage) measured in each land use/land cover type in the Sapa region.

Figure 9 depicts the suitability of current paddy plots and the potential of future agricultural development in other LULC types based on the calculations with the S-HyFIS model. Accordingly, about 16 % (or 430 hectares) of current sites cropped with rice were classified as areas with a low suitability. While about 70 % (or 1,900 hectares) of the current rice fields were characterized as areas with a high and very high suitability for the production of rice.

Though there are still areas with a size of 4,100 ha classified as areas with high suitability for cropping rice, the transformation of these land uses to rice cultivation should be analyzed carefully. The suitability areas were identified particularly in 40 % (about 4,600 hectares) of forest areas. This addresses also highly/low sealed surfaces, where about 50 % of these areas have been indicated as highly suitable for rice production. These areas include houses that are distributed heterogeneously among paddy fields. However, the area of highly/low sealed surfaces is not so large (nearly 250 hectares in total), leading to uncertainties in the assessment that will be discussed in the next sections. Different rationales concerning the conversion of the land use types bare soil and meadow (40 % respectively 30 % classified as highly suitable) are to be expected. The 700 ha of meadows and bare soils could be used for agricultural development. Their extension is larger than the total area of water bodies, highly sealed surfaces and sealed surfaces. In total, more than 3,200 hectares (including the “high and very high suitability” areas of current paddy plots, meadow and bare soil) could be used for rice cultivation. In comparison to the present situation with more than 2,700 hectares paddy fields, nearly 1,900 hectares with high and very high suitability were identified for rice cropping. The areas with low suitability calculated with the S-HyFIS model cover more than 5,500 hectares of the research area, in which the forest areas occupy about 4,500 hectares.

6. Discussion

6.1. Application of HyFIS models

Compared to previous prediction models (such as neural networks; e.g. by Dahikar et al. (2015) and SVM model by Jaikla et al. (2008)), the hybrid neural-fuzzy inference system is highly applicable for users to map areas suitable for rice cropping at the regional scale and to predict potential rice yields at the plot scale. However, it seems to be more complicated than other models due to the training process and the use of the high number of IF-THEN rules. Although different optimization methods developed in mathematics (Bui et al., 2017) have been used to optimize the two developed HyFIS models, the traditional iterative method chosen in this study made the training process more effective and simple as only a low number of parameters needed to be trained. However, the quality of the iterative process needs to be assessed by both AUC and MSE values, allowing to determine optimal values of 0.9 and 0.1 respectively for the final models. According to the calculated goodness-of-fit tests and prediction-power values, the two proposed HyFIS models provide more precise results than other benchmark methods (such as SVM and GLM). The main limitation of HyFIS models is the requirement of many kinds of input data, such as topographic, hydrologic, climatic and soil databases, as well as the information of farming practices. However, these databases can represent multidimensional impacts of the social-ecological system on rice ecosystems (Arnáez et al., 2015; Hoang, 2014; Li et al., 2015).

Both HyFIS models can be used to predict potential rice yields **at plot scales**, but the results from the I-HyFIS model seem to be more precise. The potential of rice yields – as shown in the outcome of the I-HyFIS model - is a result of the rice cultivation in suitable/unsuitable cropping areas (based on environmental variables) and the effective/ineffective use of farming practices (based on socio-economic variables). Nevertheless, both HyFIS models have not fully demonstrated whether or not the farmers can reduce financial investments and fertilizer inputs if they choose more suitable areas for rice cultivation; or whether they need to use more supplemental nutrients for fertilization if they want to cultivate rice plants in unsuitable areas.

Land suitability evaluation for rice cropping mapped **at the regional scale** - as done using the outcomes of the S-HyFIS model – can provide better land-use strategies to local farmers (IRRI, 1982). According to the results, the locations of other land uses/cover types can provide a lot of useful information related to water and nutrient supplies in agricultural development – and sometimes even much more than those of paddy fields. Many parts of the case study area that are characterized by sealed surfaces, bare soils and water bodies could for instance take full advantage of rice cultivation. For example, more than 1,200 hectares of meadow and bare soil areas (in the “high” and “very high” classes – Figure 8 and 9) could be considered as suitable rice farming places, replacing more than 400 hectares of paddy in the “low suitability” class. This would not only protect the green mountainous land, but also help prevent erosion and balance ecological functions. The potential of land use/cover change will be discussed in the following Section.

So far, the application of the I-HyFIS model is restricted to the 200 plots used as training and testing sites in this study. Therefore, the I-HyFIS model could only be powerful in a small number of plots. An extrapolation from the plot scale to the regional scale would require more information about farming practices (or related socio-economic data), which depend on financial conditions of each household and tradition and behavior of farmers under certain environmental conditions. It would however, be a time-consuming work for managers to collect socio-economic data at every paddy plot from the farmers. In this case, managers need to consider other ways to receive better information, such as the use of the Bayesian Belief Network approach (Dang et al., 2017, submitted).

6.2. Potential of land use/cover change in Sapa

Urbanization processes with the expansion of sealed surfaces have decreased the number of suitable areas for cropping (Kamoshita, 2007). If local managers would like to take full advantage of favorable environmental conditions in the study area, bare soils in the sealed surface land use areas could be changed to appropriate urban agricultural systems, focusing on rice production as proposed by Sharp and Smith (2003) and Kamoshita (2007). The key point of the urban agricultural systems is the selection and creation of areas that have environmental characteristics favorable for crop cultivation around and within urban areas. It does not only provide more rice for urban residents, but also reduces

costs of food transportation from outside regions to urban areas (Midmore and Jansen, 2003; Mita, 1993). These systems have been developed in Tokyo, Since the 1900's Japan (Kamoshita, 2007). Muñoz-Vallés et al. (2013) has demonstrated that a suitable urban agricultural system can help to improve food security in highly densely populated areas, to decrease air temperature in urban areas and to provide recreational and educational ecosystem services. Nevertheless, trade-offs between urbanization and agricultural development need further studies using an integrated approach if urban agricultural systems are to become more likely in the case study area.

Regarding water bodies and forest areas, the study has identified high/low suitability areas for rice cultivation that were distributed rather heterogeneously. Rice can be well cultivated in narrow areas around water bodies, such as riverbeds and riverbanks, because of the high potential of water availability. However, rice cultivation in such types of land cover contains high risks of erosion due to increasing water levels during the rainy season, especially in narrow valleys (Nguyen et al., 2011). The allocation of forest lands for agricultural purposes needs to be done very carefully and large forest areas are actually unsuitable for rice cultivation. Additionally, the national law in Vietnam related to forest protection restricts the conversion of forest land to other land uses. Hence quite the contrary, regulations and incentives for reforestation need to be implemented. For example, a conversion of nearly 500 ha unsuitable agricultural lands to forests in related communities could be a sustainable solution in the case of the current rapid urbanization in the Sapa region.

Additionally, the conversion of other land use/cover types to arable lands and vice versa need to consider environmental issues such as climate and erosion regulation as well as wood and freshwater provision. Dang et al. (2018) demonstrated that many paddy fields on terraces have not been an appropriate land use to mitigate risks of soil erosion and landslides in mountainous areas. The excessive use of pesticides/fertilizers in rice cultivation can increase the amount of nitrate and toxic products leaching into the soil and groundwater. Groundwater is commonly used as a freshwater source by Vietnamese people living in mountainous areas (Erik Lichtenberg, 2013; Heong et al., 2015). Forest areas have been ranked as ecosystems with a high potential to slow down processes of climate change and soil degradation (FAO, 2010; IPCC, 2006). Urban areas such as the town of Sapa have mainly been developed for tourist and administrative purposes (Hoang, 2014). The local people there have usually enough money to import rice, instead of implementing rice expansion. Hence, trade-offs between benefits obtained from forest and urban ecosystems and rice production in mountainous areas are often not strongly considered. Particularly in the Sapa district, the local people working on areas that are unsuitable for rice cultivation can find better fields in the meadows and the bare soils or, alternatively, choose to import rice from other regions.

6.3. Uncertainties of the study

This study included several assumptions as well as model and data shortcomings, which need to be mentioned here and should be considered in comparable future studies. The socio-economic variables used in this study have not depicted all types of additional anthropogenic inputs. For example, effects of seed choices and pesticide uses as well as other environmental impact factors need to be quantified in order to better understand variances of rice yields. The models were trained on data collected in upland and irrigated rice ecosystems, commonly found in the mountainous areas of the Sapa region. Thus, these data are applicable only to a limited extent for lowland and flood-prone rice ecosystems. Impacts of topographical and hydrological characteristics on rice production vary from plot to plot, thus the prediction of suitable cropping areas based on the S-HyFIS model can be less certain in regions in which no training data for rice cultivation was available. This is especially problematic in lowlands with lengths of flow less than 5 km and elevations lower than 900 m as well as in upstream regions with lengths of flow higher than 8 km and elevations lower than 1300 m.

In addition, some primary data were used twice to calculate input variables for the HyFIS models. The interaction effects between these input variables could reduce the accuracy of the prediction results. The correlations analyzed in step 1 (shown in Section 4.2.1) ensure that these interaction effects were very low. For example, the “precipitation” data was used to estimate the two input variables including the soil erosion and the fractp ratio. This did not generate interaction effects between two input variables. The other chosen variables make significant additions to the developed HyFIS models. It is demonstrated through the lower accuracy of HyFIS models trained without one in two variables, compared to the accuracy of the final models, from 15 to 20 %. Although the correlation between the “precipitation” and the “yields” variables was not recorded, the intensity of rainfalls indirectly affects the water and nutrient supplies for the rice plants. In this case, the application of Bayesian Belief Networks could provide a graph representing complex causal relations, such as links from the “precipitation” to the “soil erosion” or to the “fractp ratio” and the “rice yields” (Dang et al., 2017, submitted).

7. Conclusions

The variances of rice yields at regional and plot scales can be well explained by eight environmental and three socio-economic variables through the Pearson correlation. The environmental variables analyzed in this study determine the quality of ecosystem functions including photosynthesis processes, water availability and nutrient availability at each paddy plot. Rice yields could be improved if more paddy plots would be located in appropriate regions for agricultural development, such as in downstream areas with low values of water yields, low slopes, low sediment retention and low erosion. These analyses could be extrapolated to the whole region in order to select areas suitable for rice cultivation and to provide information for a more sustainable agricultural planning at different

administrative levels. Additional anthropogenic inputs were analyzed based on three socio-economic variables, which in general have contributed positively to rice production at the plot scale. The use of the socio-economic variables could be applied for the whole region if we would assume that the other plots having the same environmental characteristics would also have the same amounts of additional anthropogenic inputs. This should be addressed more in future applications.

This study successfully integrated the fuzzy logic in two neural networks and then applied GIS analysis to map crop suitability areas (by the S-HyFIS model) and predict the potential of rice yields (by the I-HyFIS model) at both regional and plot scales. Four layers of the fuzzy logic were replaced for hidden layers in traditional neural networks. The training process with the participation of iterative processes helped to optimize the overall accuracy of the S-HyFIS model up to 86 % and of the I-HyFIS model up to 90 %. The goodness-of-fit and prediction-power values of these models are higher than two benchmark models (SVM and GLM).

The results of the two models applied in the Sapa region showed that paddy fields, meadows and bare-soil areas hold high potentials for rice agricultural developments. The conversion from meadows and bare soils to paddy fields should be considered, because the extension of meadow and bare soil areas suitable for rice cultivation is equal (same areal extension) to the extension of areas unsuitable for rice cultivation, that are presently used as paddy fields. In contrast, the conversion of forest and water-body areas to arable lands should not be encouraged. Areas of upstream forests should be expanded instead of rice field expansion, if the ultimate goal is to support natural water and nutrient supplies for downstream paddy fields.

The HyFIS models seem to be promising tools to find suitable areas for agricultural development and to predict rice yields. However, there seem to be limitations in the case of scarce data, especially with regard to deficient socio-economic data. In this case, the data collection is time-consuming. The Bayesian Belief Network approach can be a promising solution by using expert experiments to clearly represent uncertainties of the impacts of social-ecological system dynamics on rice ecosystems. An integration of the HyFIS models with a Bayesian Belief Network can provide better information for decision making, such as assessments related to the balance between rice supply and demand. Additionally, scientific results from modelling, mapping and expert knowledge should be communicated to relevant stakeholders in order to be taken up on various levels for improved and evidence-based decision making.

Acknowledgements

The study was embedded in the LEGATO (Land-use intensity and Ecological EnGineering – Assessment Tools for risks and Opportunities in annual crop based production systems) project, funded by the German Ministry of Research and Education within their funding program Sustainable Land Management; Funding No. 01LL0917. We want to thank all our LEGATO colleagues,

especially Anika Klotzbücher and Isoda Yuzuru, for providing relevant information and data. This study was co-financed by the Vietnamese Government Scholarship (911). Furthermore, we would like to thank our colleagues at the Institute for Natural Resource Conservation, Department of Ecosystem Management at Kiel University, Germany. We thank Angie Faust for language revision of the manuscript.

Reference

- Ajaz, R.H., Campus, I., 2015. Seed Classification using Machine Learning Techniques. *J. Multidiscip. Eng. Sci. Technol.* 2, 1098–1102.
- Alberto, M.C.R., Wassmann, R., Hirano, T., Miyata, A., Hatano, R., Kumar, A., Padre, A., Amante, M., 2011. Comparisons of energy balance and evapotranspiration between flooded and aerobic rice fields in the Philippines. *Agric. Water Manag.* 98, 1417–1430. doi:10.1016/j.agwat.2011.04.011
- Ali, S., Iyaki, N.O., Llahyari, M.S.A., 2012. Logistic Regression Analysis on Factors Affecting Adoption of Rice- Fish Farming in North Iran. *Rice Sci.* 19, 159–160.
- Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. *Crop Evapotranspiration: guidelines for computing crop water requirements*, FAO Irrigation and Drainage Paper No56. FAO, Rome, Italy.
- Armstrong, L.J., 2016. Rice Crop Yield Prediction in India using Support Vector Machines 11–15.
- Arnáez, J., Lana-Renault, N., Lasanta, T., Ruiz-Flano, P., Castroviejo, J., 2015. Effects of farming terraces on hydrological and geomorphological processes. A review. *Catena* 128, 122–134. doi:10.1016/j.catena.2015.01.021
- Balakrishnan, N., Muthukumarasamy, G., 2016. Crop Production - Ensemble Machine Learning Model for Prediction. *Int. J. Comput. Sci. Softw. Eng.* 5, 148–153.
- Balbi, S., del Prado, A., Gallejones, P., Geevan, C.P., Pardo, G., Perez-Minana, E., Manrique, R., Hernandez-Santiago, C., Villa, F., 2015. Modeling trade-offs among ecosystem services in agricultural production systems. *Environ. Model. Softw.* 72, 314–326. doi:10.1016/j.envsoft.2014.12.017
- Benmiloud, T., 2012. Improved adaptive neuro-fuzzy inference system. *Springer* 575–582.
- Bergmeir, C., Ben, M., 2015. *frbs : Fuzzy Rule-Based Systems for Classification* 65.
- Bi, L., Xia, J., Liu, K., Li, D., Yu, X., 2014. Effects of long-term chemical fertilization on trends of rice yield and nutrient use efficiency under double rice cultivation in subtropical China. *Plant Soil Environ.* 60, 537–543.
- Budyko, M.I., 1974. *Climate and Life*. Academic Press, New York.
- Bui, K.-T.T., Bui, D.T., Zou, J., Van Doan, C., Revhaug, I., 2016. A novel hybrid artificial intelligent approach based on neural fuzzy inference model and particle swarm optimization for horizontal displacement modeling of hydropower dam. *Neural Comput. Appl.* 1–12. doi:10.1007/s00521-016-2666-0

- Bui, T.D., Bui, Q.-T.T., Nguyen, Q.-P.P., Pradhan, B., Nampak, H., Trinh, P.T., 2017. A hybrid artificial intelligence approach using GIS-based neural-fuzzy inference system and particle swarm optimization for forest fire susceptibility modeling at a tropical area. *Agric. For. Meteorol.* 233, 32–44. doi:10.1016/j.agrformet.2016.11.002
- Burkhard, B., Müller, A., Müller, F., Grescho, V., Anh, Q., Arida, G., Bustamante, J.V. (Japan), Van Chien, H., Heong, K.L., Escalada, M., Marquez, L., Thanh Truong, D., Villareal, S. (Bong), Settele, J., 2015. Land cover-based ecosystem service assessment of irrigated rice cropping systems in southeast Asia—An explorative study. *Ecosyst. Serv.* 14, 76–87. doi:10.1016/j.ecoser.2015.05.005
- Chang, M., 2003. Forest hydrology: an introduction to water and forests. *Vasa* 388. doi:10.1016/0378-1127(80)90025-0
- Dahikar, S.S., Extc, P.G.S., College, S., 2015. An Artificial Neural Network Approach for Agricultural Crop Yield Prediction Based on Various Parameters. *Int. J. Adv. Res. Electron. Commun. Eng.* 4, 94–98.
- Dang, K.B., Burkhard, B., Müller, F., Dang, V.B., 2018. Modelling and Mapping Natural Hazard Regulating Ecosystem Services in Sapa, Lao Cai Province, Vietnam. *Paddy Water Environ.* xxx, xxx.
- Datta, S.K. De, 1981. Principles and practices of rice production, A Wiley-Interscience publication. doi:10.1007/s13398-014-0173-7.2
- Dobermann, A., Fairhurst, T., 2000. Rice: nutrient disorders & nutrient management, Handbook Series.
- Donohue, R.J., Roderick, M.L., McVicar, T.R., 2012. Roots, storms and soil pores: Incorporating key ecohydrological processes into Budyko's hydrological model. *J. Hydrol.* 436–437, 35–50. doi:10.1016/j.jhydrol.2012.02.033
- Doorenbos, J., Kassam, A., 1979. Yield response to water, FAO Irrigation and Drainage Paper No 33. FAO, Rome, Italy.
- Erik Lichtenberg, 2013. Pesticide Productivity in Green Revolution Rice Production: A Case Study of Vietnam. *J. Chem. Inf. Model.* 53, 1689–1699. doi:10.1017/CBO9781107415324.004
- FAO, 2010. The role of forests and forestry in the prevention and rehabilitation of landslides in Asia. For. ans landslides, Cent. people For. FAO.
- Fawcett, T., 2006. An introduction to ROC analysis. *Irbm* 27, 861–874. doi:10.1016/j.patrec.2005.10.010
- Fu, B.P., 1981. On the calculation of the evaporation from land surface (in Chinese). *Sci. Atmos. Sin.* 5, 23–31.
- Glavan, M., Pintar, M., Urbanc, J., 2014. Spatial variation of crop rotations and their impacts on provisioning ecosystem services on the river Drava alluvial plain. *Sustain. Water Qual. Ecol.* 5, 31–48. doi:10.1016/j.swaqe.2015.01.004
- Gupta, P.C., Toole, J.C.O., 1986. Upland Rice: A Global Perspective. International rice research institute, Philippines.
- Heong, K.L., Wong, L., Reyes, J.H.D., 2015. Addressing planthopper threats to Asian rice farming

- and food security: Fixing insecticide misuse. *Rice Planthoppers Ecol. Manag. Socio Econ. Policy* 65–76. doi:10.1007/978-94-017-9535-7_3
- Hoang, H.T.T., 2014. *Multi-scale Analysis of Human-Environment Interactions. A Case-study in the Northern Vietnamese Mountains*. Katholieke Universiteit Leuven.
- Huang, J., Wang, X., Li, X., Tian, H., Pan, Z., 2013. Remotely Sensed Rice Yield Prediction Using Multi-Temporal NDVI Data Derived from NOAA's-AVHRR. *PLoS One* 8, 1–13. doi:10.1371/journal.pone.0070816
- IPCC, 2006. *IPCC Guidelines for National Greenhouse Gas Inventories - Volume 4 Agriculture, Forestry and Other Land Use - Chapter 4 forest land*, in: *Forestry*. pp. 41–69. doi:10.1016/j.phrs.2011.03.002
- IRRI, 2015. *Steps to Successful Rice Production*.
- IRRI, 2006. *The sustainability of rice farming*, International Rice Research Institute, CAB International Publishing. International rice research institute, Philippines. doi:10.5860/CHOICE.35-3847
- IRRI, 1982. *Rice research strategies for the future*. International rice research institute, Philippines.
- IRRI, 1978. *Irrigation policy and management in Southeast Asia*, International Rice Research Institute, CAB International Publishing. International rice research institute, Philippines, Los Baños, Laguna, Philippines.
- Jabjone, S., Wannasang, S., 2014. Decision support system using artificial neural network to predict rice production in Phimai district, Thailand. *Int. J. Comput. Electr. Eng.* 6, 162–166. doi:10.7763/IJCEE.2014.V6.814
- Jaikla, R., Auephanwiryakul, S., Jintrawet, A., 2008. Rice Yield Prediction using a Support Vector Regression method 29–32.
- Kamoshita, A., 2007. Historical Changes in Urban Rice Production Systems in Tokyo, Japan. *Plant Prod. Sci.* 10, 245–269. doi:10.1626/pp.10.245
- Karatzoglou, A., Meyer, D., Hornik, K., 2006. Support Vector Algorithm in R. *J. Stat. Softw.* 15, 1–28.
- Khairunniza-Bejo, S., Mustaffha, S., Ishak, W., Ismail, W., 2014. Application of Artificial Neural Network in Predicting Crop Yield: A Review. *J. Food Science Eng.* 4, 1–9.
- Kim, J., Kasabov, N., 1999. HyFIS: Adaptive neuro-fuzzy inference systems and their application to nonlinear dynamical systems. *Neural Networks* 12, 1301–1319. doi:10.1016/S0893-6080(99)00067-2
- Kothamasu, R., Huang, S.H., 2007. Adaptive Mamdani fuzzy model for condition-based maintenance. *Fuzzy Sets Syst.* 158, 2715–2733. doi:10.1016/j.fss.2007.07.004
- Li, F.B., Lu, G. De, Zhou, X.Y., Ni, H.X., Xu, C.C., Yue, C., Yang, X.M., Feng, J.F., Fang, F.P., 2015. Elevation and Land Use Types Have Significant Impacts on Spatial Variability of Soil Organic Matter Content in Hani Terraced Field of Yuanyang County, China. *Rice Sci.* 22, 27–34. doi:10.1016/j.rsci.2015.05.005
- Liu, G., Yang, X.H., Li, M.Z., 2005. An artificial neural network model for crop yield responding to

- soil parameters. *Adv. Neural Networks - Isnn 2005, Pt 3, Proc.* 3498, 1017–1021.
- Liu, Z., Peng, C., Xiang, W., Tian, D., Deng, X., Zhao, M., 2010. Application of artificial neural networks in global climate change and ecological research: An overview. *Chinese Sci. Bull.* 55, 3853–3863. doi:10.1007/s11434-010-4183-3
- Lu, J., Sun, G., McNulty, S.G., Armatya, D.M., 2005. A comparison of six potential evapotranspiration methods for regional use in the southeastern United States. *J. Am. Water Resour. Assoc.* 41, 621–633.
- Maddahi, Z., Jalalian, A., Kheirkhah Zarkesh, M.M., Honarjo, N., 2016. Land suitability analysis for rice cultivation using a GIS-based fuzzy multi-criteria decision making approach: central part of Amol District, Iran. *Soil Water Res.* 2017, 1–10. doi:10.17221/1/2016-SWR
- Mamdani, E.H., 1977. Application of fuzzy logic to approximate reasoning using linguistic synthesis. *IEEE Trans. Comput. C-26*, 1182–1191. doi:10.1109/TC.1977.1674779
- Midmore, D.J., Jansen, H.G.P., 2003. Supplying vegetables to Asian cities: is there a case for peri-urban production? *Food Pol.* 28, 13–27.
- Mita, K., 1993. Present condition and problems on agriculture in urban area under low conserving agriculture land etc. Reserved in the urbanization promotion area. *Bull. Tokyo Metro. Agric. Exp. Stn.* 25 43–57.
- Muñoz-Vallés, S., Cambrollé, J., Figueroa-Luque, E., Luque, T., Niell, F.X., Figueroa, M.E., 2013. An approach to the evaluation and management of natural carbon sinks: From plant species to urban green systems. *Urban For. Urban Green.* 12, 450–453. doi:10.1016/j.ufug.2013.06.007
- Newlands, N.K., Newlands, N.K., Townley-smith, L., 2016. Predicting energy crop yield using bayesian networks 795–799.
- Nguyen, H., Dang, K.B., Dang, V.B., 2011. Application of N-SPECT model and GIS for soil erosion assessment in Sapa district, Lao Cai province. *J. Earth Sci. Vietnam Natl. Univ. Publ.* 27, 199–207.
- Noureldin, N.A., Aboelghar, M.A., Saady, H.S., Ali, A.M., 2013. Rice yield forecasting models using satellite imagery in Egypt. *Egypt. J. Remote Sens. Sp. Sci.* 16, 125–131. doi:10.1016/j.ejrs.2013.04.005
- Omez, N.G., Mingo, L.F., Bobadilla, J., Serradilla, F., Polit, U., Monte, B., 2010. Particle Swarm Optimization models applied to Neural Networks using the R language 9.
- Pimentel, D., 2006. Soil Erosion: A Food and Environmental Threat. *Environ. Dev. Sustain.* 8, 119–137. doi:10.1007/s10668-005-1262-8
- Pirmoradian, N., Sepaskhah, A.R., 2006. A very simple model for yield prediction of rice under different water and nitrogen applications. *Biosyst. Eng.* 93, 25–34. doi:10.1016/j.biosystemseng.2005.09.004
- Rahman, M.S., Rashid, M.M., Hussain, M.A., 2012. Thermal conductivity prediction of foods by Neural Network and Fuzzy (ANFIS) modeling techniques. *Food Bioprod. Process.* 90, 333–340. doi:10.1016/j.fbp.2011.07.001
- Renaud, F.G., Kuenzer, C., 2012. *The Mekong Delta System: Interdisciplinary Analyses of a River Delta.* Springer 463. doi:10.1073/pnas.0703993104

- Samanta, S., Pal, B., Pal, D.K., 2011. Land Suitability Analysis for Rice Cultivation Based on Multi-Criteria Decision Approach through GIS. *Int. J. Sci. Emerg. Technol.* 12–20.
- Samranpong, C., Pollino, C., 2009. Comparison of two modelling approaches for an integrated crop economic model. 18th World IMACS Congr. *Int. Congr. Model. Simul. Interfacing Model. Simul. with Math. Comput. Sci. MODSIM09* 595–601.
- Sattaka, P., Pattaratuma, S., Attawipakpaisan, G., 2017. Agricultural extension services to foster production sustainability for food and cultural security of glutinous rice farmers in Vietnam. *Kasetsart J. Soc. Sci.* 38, 74–80. doi:10.1016/j.kjss.2016.05.003
- Schmitter, P., Dercon, G., Hilger, T., Thi Le Ha, T., Huu Thanh, N., Lam, N., Duc Vien, T., Cadisch, G., 2010. Sediment induced soil spatial variation in paddy fields of Northwest Vietnam. *Geoderma* 155, 298–307. doi:10.1016/j.geoderma.2009.12.014
- Sharp, J.S., Smith, M.B., 2003. Social capital and farming at the rural-urban interface: The importance of nonfarmer and farmer relations. *Agric. Syst.* 76, 913–927. doi:10.1016/S0883-2927(02)00083-5
- Sharp, R., Tallis, H., Ricketts, T., Guerry, A., Wood, S., Chaplin-kramer, R., Nelson, E., Ennaanay, D., Wolny, S., Olwero, N., Vigerstol, K., Pennington, D., Mendoza, G., Aukema, J., Foster, J., Forrest, J., Cameron, D., Arkema, K., Lonsdorf, E., Kennedy, C., Verutes, G., Kim, C., Guannel, G., Papenfus, M., Toft, J., Marsik, M., Bernhardt, J., Griffin, R., Glowinski, K., Chaumont, N., Perelman, A., Lacayo, M., Mandle, L., Griffin, R., Hamel, P., 2014. InVEST 3.0.1 User's Guide, The Natural Capital Project, Stanford.
- Slaets, J.I.F., Schmitter, P., Hilger, T., Vien, T.D., Cadisch, G., 2015. Sediment trap efficiency of paddy fields at the watershed scale in a mountainous catchment in Northwest Vietnam. *Biogeosciences Discuss.* 12, 20437–20473. doi:10.5194/bgd-12-20437-2015
- Sørensen, R., Zinko, U., Seibert, J., 2006. On the calculation of the topographic wetness index: evaluation of different methods based on field observations. *Hydrol. Earth Syst. Sci.* 10, 101–112. doi:10.5194/hess-10-101-2006
- Steduto, P., Hsiao, T.C., Fereres, E., Raes, D., 2012. Crop yield response to water, Fao Irrigation and Drainage Paper Issn.
- Su, Y., Xu, H., Yan, L., 2017. Support vector machine-based open crop model (SBOCM): Case of rice production in China. *Saudi J. Biol. Sci.* 24, 537–547. doi:10.1016/j.sjbs.2017.01.024
- Tesfa, T.K., Tarboton, D.G., Chandler, D.G., McNamara, J.P., 2009. Modeling soil depth from topographic and land cover attributes. *Water Resour. Res.* 45, 1–16. doi:10.1029/2008WR007474
- Thessen, A., 2016. Adoption of Machine Learning Techniques in Ecology and Earth Science. *One Ecosyst.* 1, e8621. doi:10.3897/oneco.1.e8621
- Tung, W.L., Quek, C., 2009. A Mamdani-Takagi-Sugeno based linguistic neural-fuzzy inference system for improved interpretability-accuracy representation. *IEEE Int. Conf. Fuzzy Syst.* 367–372. doi:10.1109/FUZZY.2009.5277194
- Vigerstol, K.L., Aukema, J.E., 2011. A comparison of tools for modeling freshwater ecosystem services. *J. Environ. Manage.* 92, 2403–2409. doi:10.1016/j.jenvman.2011.06.040
- Were, K., Bui, D.T., Dick, Ø.B., Singh, B.R., 2015. A comparative assessment of support vector

regression, artificial neural networks, and random forests for predicting and mapping soil organic carbon stocks across an Afromontane landscape. *Ecol. Indic.* 52, 394–403. doi:10.1016/j.ecolind.2014.12.028

Wischmeier, W.H., Smith, D., 1978. Predicting rainfall erosion losses: a guide to conservation planning. U.S. Dep. Agric. Handb. No. 537 1–69. doi:10.1029/TR039i002p00285

Wischmeier, W.H., Smith, D.D., 1958. Rainfall energy and its relation to soil loss. *Trans. Am. Geophys. Union* 285–291. doi:10.1029/TR039i002p00285

Ye, Q., Yang, X., Dai, S., Chen, G., Li, Y., Zhang, C., 2015. Effects of climate change on suitable rice cropping areas, cropping systems and crop water requirements in southern China. *Agric. Water Manag.* 159, 35–44. doi:10.1016/j.agwat.2015.05.022

Zhang, L., Hickel, K., Dawes, W.R., Chiew, F.H.S., Western, A.W., Briggs, P.R., 2004. A rational function approach for estimating mean annual evapotranspiration. *Water Resour. Res.* 40, W025021–W02502114. doi:10.1029/2003WR002710

Chapter 4.

A Bayesian Belief Network - based approach to link ecosystem functions with rice provisioning ecosystem services

Kinh Bac Dang, Wilhelm Windhorst, Benjamin Burkhard, Felix Müller

(Accepted in "Ecological Indicators" journal in 23rd April 2018)

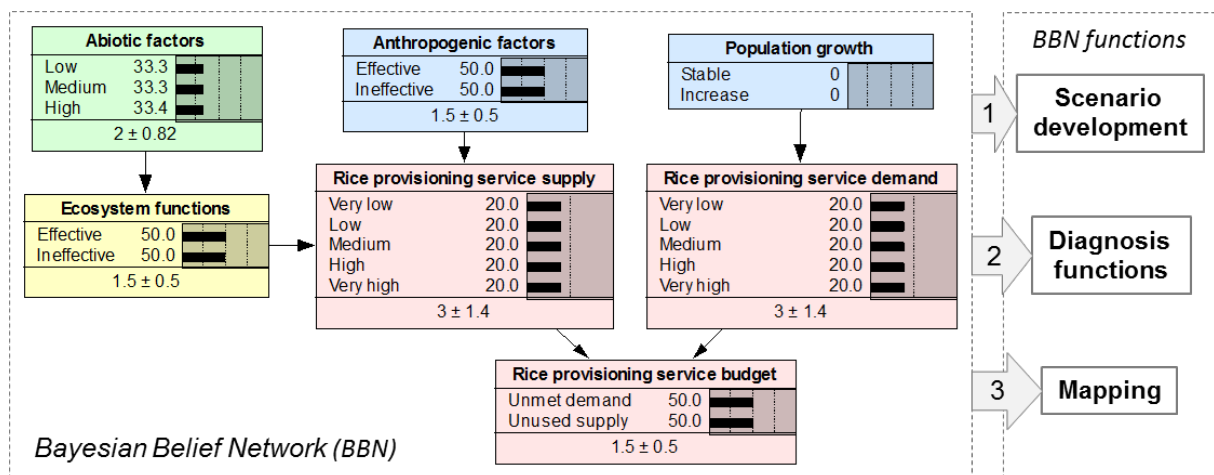
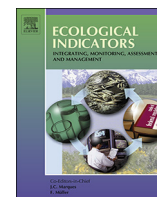


Figure 7 (Graphical abstract): Conceptual framework to assess rice provisioning ecosystem services based on a Bayesian approach

Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Original Articles

A Bayesian Belief Network – Based approach to link ecosystem functions with rice provisioning ecosystem services

Kinh Bac Dang^{a,d,*}, Wilhelm Windhorst^a, Benjamin Burkhard^{b,c}, Felix Müller^a^a Institute for Natural Resource Conservation, Department of Ecosystem Management, Christian Albrechts University Kiel, Olshausenstr. 40, 24098 Kiel, Germany^b Institute of Physical Geography and Landscape Ecology, Leibniz Universität Hannover, Schneiderberg 50, 30167 Hannover, Germany^c Leibniz Centre for Agricultural Landscape Research ZALF, Eberswalder Straße 84, 15374 Müncheberg, Germany^d Faculty of Geography, VNU University of Science, 334 Nguyen Trai, Thanh Xuan, Hanoi, Viet Nam

ARTICLE INFO

Keywords:

Agriculture
Ecosystem service demand
Ecosystem service supply
Ecosystem service budget
Socio-ecological system
Scenario

ABSTRACT

The complex interactions between environmental and anthropogenic components have significantly influenced rice cultivation. The clear understanding of these interactions is important to (i) optimize rice provisioning ecosystem service (ES) supply, (ii) minimize negative impacts on other ES and (iii) choose suitable strategies for sustainable agriculture. Impacts of environmental and anthropogenic components on rice provisioning ES supply largely depend on site selection and farming practices. The demand for rice can be determined by the size of the population and imports/exports of rice products. Rice provisioning ES supply and demand need to be balanced if the goal is an import-independent and sustainable agriculture. As a decision support tool, Bayesian Belief Networks (BBN) are used for quantifying various ES supply types, demands as well as their budgets. The BBN network presented in this study was developed through interviews, expert knowledge, geographical information systems and statistical models. The results show that the capacity of rice provision can be optimized through site selection and farming practice. The results can help to reduce crop failures and to choose suitable areas for the use of new practices and technologies. Moreover, the presented BBN has been used to forecast future patterns of rice provision through effective or ineffective options of the environmental and human-derived components in eight scenarios. Thereby, the BBN turns out to be a promising decision support tool for agricultural managers in predicting probabilities of success in scenarios of agricultural planning.

This paper is part of a special volume which is dedicated to our friend and colleague Sven-Erik Jørgensen. For the authors it is an honor to describe a study which strongly correlates with Sven's ideas and concepts in this journal, which he has co-founded and for which he has invested a lot of personal exergy and time as an associated editor. We are seriously sad that Sven has passed away, and therefore we feel that many items within this paper show that his ideas keep on flourishing. As in the following pages, Sven-Erik Jørgensen used models to improve the human nutrition situation around the world and to make food production sustainable and compatible with environmental targets. Sven integrated ecological structures and functions in models and simulations, and he carried out assessments of ecosystem services, based upon his bright thermodynamic concepts. We are proud and grateful that we have had the favor of working together with Sven-Erik Jørgensen, and we wish to thank him for his friendship, enthusiasm and support.

1. Introduction

The ongoing global population growth has led to a rapidly increasing food demand that has required a more intensified rice production (FAO, 2000). Recently, the Food and Agriculture Organization (FAO) recognized an increase in Asian per capita rice consumption by nearly 20 kilograms and a double increase in global rice consumption since the 1960s (Kubo and Purevdorj, 2004). In order to ensure a satisfactory food security for 9.6 billion people in 2050 (Tim Searchinger, 2013), the Millennium Ecosystem Assessment (2005) estimated a growing demand of 70–85 percent in the next five decades. Recently, the expansion of agricultural lands and a more intensive cultivation have been considered as solutions for rice yield maximization (IRRI, 1985; Virmani et al., 1996). However, these potential drivers of change play a crucial role in global environmental destruction (Jørgensen et al., 2015a,b), especially by diminishing the fresh water quality and by

* Corresponding author at: Institute for Natural Resource Conservation, Department of Ecosystem Management, Christian Albrechts University Kiel, Olshausenstr. 40, 24098 Kiel, Germany.

E-mail addresses: kinhbachus@gmail.com (K.B. Dang), wwindhorst@ecology.uni-kiel.de (W. Windhorst), burkhard@phygeo.uni-hannover.de (B. Burkhard), fmueller@ecology.uni-kiel.de (F. Müller).

<https://doi.org/10.1016/j.ecolind.2018.04.055>

Received 27 June 2017; Received in revised form 20 April 2018; Accepted 23 April 2018
1470-160X/ © 2018 Elsevier Ltd. All rights reserved.

increasing erosion (Gupta and Toole, 1986). In mountainous regions, the area of terraced rice fields is expanding but the yields are instable and paralleled by a rapid increase of rice demand (IRRI, 2006). Unexpected low rice yields can be attributed to the selection of unsuitable crop varieties and poor land management resulting in wasting the investments and efforts of farmers. Thus, the dynamics of rice provision within the social-ecological system need to be deeply understood if the ultimate purpose is a sustainable agriculture.

1.1. Research background

Jørgensen et al. (1997) have developed a conceptual network related to the relationship between rice and crayfish growth, in which the weight and density of rice were mentioned in detail. The impact of crayfish on rice production was assessed through connections in one-way direction between different nodes have a close relation with Bayesian Belief Network. The outcome of the network provides important information related to rice yields and growth. On the other hand, Anastácio et al., (1995) proposed a sustainable method to keep crayfish together with rice by using surfactants and reducing the use of toxic chemicals as tested in Portugal. As a result, this method can reduce the damages on the rice. It was also emphasized that the role of the spraying time in the use of pesticides (such as dimethoate and parathion) could be a promising method to optimize rice yields and minimize the environmental disadvantages (Jørgensen et al., 1997).

Realizing such indirect and cumulative effects, a fundamental component of the demonstrated concept is based upon the systems comprehension of the ecosystem service approach. The provision of all services, their potentials and flows, their dynamics and resilience, can be understood as a clear output of ecosystem functions, and these are results of the linked ecosystem processes, ecosystem structures and the respective developmental dynamics. Therefore, a deep knowledge in ecosystem theoretical ideas will be extremely helpful in understanding ecosystem service dynamics. Again, Sven-Erik Jørgensen has provided several basic and theoretical conceptions to understand the fundamentals of ecosystem service creation (e.g. (Jørgensen, 2002; Jørgensen et al., 2011; Jørgensen and Svirezhev, 2004; Müller and Joergensen, 2000). He has described models as tools to improve the comprehension of ecosystems dynamics (Jørgensen and Fath, 2011; Jørgensen and Nielsen, 2015, 2014, 2007), and he has developed indicators to inform decision makers about the potentials and risks of environmental variables (e.g. Jørgensen, 2006a,b, Jørgensen et al., 2016, 2013). Basing upon the concept of eco-exergy, Jørgensen has also developed thermodynamic indicators for an overall assessment of ecosystem services (Burkhard et al., 2012b; Jørgensen, 2010). Therefore, we understand this contribution as a continuation of Jørgensen's work, applying his fundamentals in serious socio-ecological problem fields.

In combination with additional anthropogenic inputs, ecosystem structures and functions deliver various services contributing to human well-being (Burkhard et al., 2012a,b). According to the Common International Classification of Ecosystem Services (CICES¹), ecosystem services (ES) are divided into provisioning, regulating, and cultural ecosystem services (Haines-Young and Potschin, 2012; Jørgensen, 2010). Hereby, the provisioning ES are defined as all natural products obtained from ecosystems that benefit humans through nutrition, processing and energy purposes (Dunbar et al., 2013; Kandziora et al., 2013a).

Compared to other types of ecosystem services, a comprehensive literature about rice provisioning ES that accounts for the complex and dynamic interactions with the social-ecological system is still lacking. The interactions between natural structures and processes with land management (or unintended effects) through ecosystem functions can provide partly services/disservices to beneficiaries (Petter et al., 2013;

Power, 2010). The understanding of these interactions among ecosystem functions as a noticeable challenge for agricultural managers and politicians has required further development in scenarios and practical models (Jørgensen and Fath, 2011; McVittie et al., 2015; Müller et al., 2010). Hereby, the ecosystem service approach is a promising way to counter unsustainable agricultural systems by providing alternative management choices for decision makers (Landuyt et al., 2013; McVittie et al., 2015; Swinton et al., 2007). As interdependences of socio-ecological systems vary from place to place and from time to time, an interdisciplinary understanding of human-nature interactions, social practices in using natural resources and related technologies are required in ES assessments (Potschin et al., 2016). However, publications related to the interdependences between natural and anthropogenic components through the ES concept are rather limited (Balbi et al., 2015; Jacobs et al., 2015). Furthermore, many uncertainties in ES-assessments (such as spatial scale mismatches, data scarcity or functional knowledge gaps) still limit the scientific understanding of ES delivery patterns and processes (Burkhard et al., 2015; Hou et al., 2013; Schulp et al., 2014).

Integrated models for agricultural development need to be examined in various dimensions of social-ecological systems, such as land degradation, pest and disease control, water and nutrient availabilities (Jørgensen, 2012, 2009; Jørgensen and Nielsen, 1996; Palmeri et al., 2013). As a suitable method to analyze uncertain and complex issues in environmental management (Uusitalo, 2007), the Bayesian approach is a promising tool to deal with these challenges (Jørgensen, 2016; Troldborg et al., 2013; Xue et al., 2016). As a useful guideline to develop a Bayesian Belief Network, Cain (2001) introduced a simple network, estimating the probability of crop yields. The proposed Bayesian network by Cain (2001) focused on biological components by qualitatively addressing fertilization, pesticide use, and irrigation in relation to natural water supply and soil types as main factors determining yield. Because of lacking data, previous networks have not been used to represent influences of environmental-societal interactions on rice ecosystems and to develop related scenarios.

In our study, various methods concerning the quantification of rice provisioning ES are harnessed to provide the data needed to develop a Bayesian Belief Network (BBN) accounting also for environmental constraints based on the ES approach. The societal and environmental information related to the three components of ES delivery (supply, demand and budget) and land management have been assembled with interviews of experts as well as local people. The required climatic and geographic data about service providing units to develop the presented BBN have been expanded with Geographical Information System (GIS) models. Statistical methods served to analyze the sensitivity of the related components on rice provisioning ES supply. The overall aim of this research was to develop scenarios revealing the sensitivity of rice production schemes on intensive farming practices and optimal crop selection methods supporting related decision-making processes. This study addresses the interactions between environmental and societal components (related to rice provision), allowing optimization of rice provisioning ES while, at the same time, minimizing negative impacts on other related ecosystem services.

The following research questions – relevant for sustainable development of rice provisioning ecosystem services – guide this study:

- Is it feasible and effective to model the interactions between a regional social-ecological system and rice provisioning ES by developing a Bayesian Belief Network?
- Which are effective and ineffective choices on the local level for farmers to cultivate rice in a remote mountainous region?
- Is it possible to equip stakeholders on the regional level with information to foster a sustainable regional development plan by supporting sustainable rice cropping?

In the following sections, we present the relevant background of

¹ <http://cices.eu/>.

Bayer's theory, the steps of BBN development for estimating probabilities of rice provisioning ES, and scenarios for optimized rice cultivation in a mountainous region characterized by diverse agricultural landscapes in the Sapa region in northern Vietnam. Thereby, this paper summarizes the construction steps of a conceptual BBN for rice provisioning ES and explains relevant data used to develop the presented BBN but will omit details about sampling and GIS analysis.

1.2. BBN theory and development

1.2.1. BBN theory

The BBN approach is based on Bayes' theorem starting from the question how the probability of event A is interlinked with a given event B (Glickman and van Dyk, 2007). In mathematical notation, this idea could be written as the posterior probability $P(A|B)$, and it can be updated by an observed evidence B. The required parameters include the prior probabilities in occurrence of event A ($P(A)$), event B ($P(B)$) and event B with the conditional probability of A ($P(B|A)$) or the likelihood of the evidence, given the hypothesis to be tested (Ji and Marefat, 1995; Kruschke, 2015). Therefore, Bayes' theorem can be formulated as:

$$P(A|B) = P(B|A) \cdot P(A) / P(B) \quad (1)$$

The event B is called a 'parent node' or a causal factor of event A, whereas event A is called a 'child node' of event B (Kragt, 2009). All parent nodes in a BBN need to provide their prior probabilities, at least one child node and a conditional probability table indicating the relation between parent and child nodes. A fundamental table of conditional probability, that incorporates n variables, can be calculated by following the chain rule:

$$P(A_1, A_2, \dots, A_n) = \prod P(A_i | \text{parents}(A_i)) \quad (2)$$

where parents (A_i) are parent nodes of variable A_i . For example, with n binary variables, the required number of probabilities is 2^n (Charniak, 1991; Taalab et al., 2015). In case the complex network of a socio-ecological system is depicted, the number of probabilities can quickly increase to a very large number, especially because various variables have more than two states (Taalab et al., 2015). This practical drawback can be avoided by finding out the probabilistic relationships between variables through quantitative measurements limiting alternative states of nodes. However, it is challenging and critical to translate qualitative variables, e.g. from expert knowledge into the form of numerous probabilities (Uusitalo, 2007).

As a graphical probabilistic model representing cause - effect relationships under uncertain conditions (Barton et al., 2008; Hough et al., 2010), a BBN containing nodes (boxes) and links (arrows) can use field measurements or expert judgments to convert the qualitative and quantitative relationships into a set of probabilities (McCann et al., 2006). The network allows to organize current ideas, to check hypotheses during calibrating, validating and updating processes (Haines-Young, 2011). The arrows represent the influent directions and correlations between nodes. The "parent nodes" do not have incoming arrows; output child nodes do not have outgoing arrows; and intermediate nodes have incoming and outgoing arrows (Cain, 2001; Poppenborg and Koellner, 2014). However, this network will not be a BBN as long as the nodes have no defined unconditional (prior) probability inside parent nodes and a conditional probability table (CPT) to child nodes. Based upon these interactions within the network, the probabilistic tables for the nodes are the basis to calculate the final "posterior probabilities" of the outcomes based on the Bayesian theory (Cain, 2001; Guo and Hsu, 2002).

*Netica*² is a software product designed for creating Bayesian networks on Windows and Mac OS systems. A free version is unlimitedly

provided but is limited to 15 variables. *Netica* can allocate continuous variables into bins with defined network structures, instead of requiring discrete formats for the input variables (Uusitalo, 2007). Input nodes for this software can be classified into three types including "nature" nodes (controlled by actions of decision makers), "decision" nodes (implemented directly by decision makers) and "utility" nodes (decisions or outcomes) (Norsys, 2010).

Conditional probability tables can be constructed when *Netica* identifies the BBN structure, even with incomplete data. Expectation maximization (EM) of an algorithm has been explored in the case of a missing or latent observation (Kragt, 2009). This algorithm, using stepwise iterations, aims to compute sufficient probabilities with the highest likelihood to unobserved variables based on given data (Poppenborg and Koellner, 2014). Firstly, it computes expected log-likelihoods over missing values (E-step), then maximizes the quality of the network found in training data and the initial network (M-step). These steps are iterated until the probabilities converge and no changes occur in the log-likelihoods.

1.2.2. BBN development

BBN development is an intensive and iterative process on the way to a complete practical network (Farmani et al., 2009). The BBN developed in this study followed the five major steps developed by Kragt (2009). In step 1 "model objectives", we defined the network's objective and the scope of the system that should support local councils, landholders and specialists in a mountainous region characterized by diverse agricultural landscapes. In step 2, the "conceptual model development" starts with the identification of crucial system variables (nodes) and the links between them. These chosen variables need to be measurable, observable, predictable and unambiguous for an initial conceptual network. Therefore, suitable environmental and socio-economic variables related to rice provisioning ES have to be quantified by both qualitative and quantitative methods (such as literature and expert elucidation). Supporting interviews were carried out in the years of 2010, 2011, 2015 and 2016 by some of the authors. In step 3, "parameterizing the model", states and probabilities were assigned for each variable depending on type and quality of the available data. The uncertainties in each probability distribution were discussed with various experts representing ecological, geological, and agricultural objects. The three steps can be iterated until positive feedback from experts and stakeholders is received; or from the results of a sensitivity analysis (such as entropy and Shannon's measure of mutual information) in step 4 "model evaluation and testing". After completing the BBN, the network can be used to predict or to optimize the posterior probabilities of final objectives, according to different scenarios or hypotheses in the fifth step. Generally, BBN development is a time-consuming process, especially with a large network comprising complex structures and interactions in a social-ecological system (Norsys, 2010).

1.3. Principles of rice provisioning ecosystem services

Fig. 1 depicts the close relations between rice provisioning ES, ecosystem functions, and agricultural activities. Abiotic variables, including ecosystem structures, control ecosystem functions and are thereby determining the ES supply potentials. ES potentials are constrained by ecological processes, land use/cover and anthropogenic factors, before turning into actual ES supply (Burkhard et al., 2014). The ES budget estimates and indicates the balance between ES supply and the demand for ES (Burkhard et al., 2012c) in a particular region and time. The demand is defined as the amount of ES consumed by users (or beneficiaries) – in this case the population living in the study region. Consequently, the probability of an unmet demand could increase in a particular area in the case of inadequate supply and/or with growing demand. Based on ES budget assessments, stakeholders like farmers, local land-managers, and politicians can reconsider their management strategies in order to avoid supply–demand mismatches.

² <http://www.norsys.com/>.

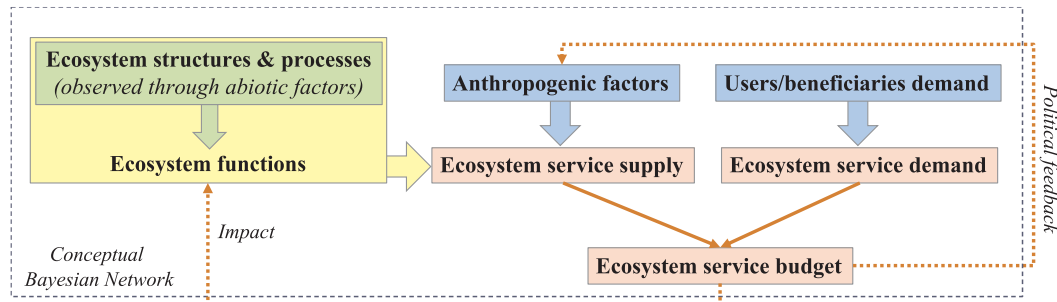


Fig. 1. Concept of the Bayesian Network to study rice provisioning ecosystem services.

Such strategies cause in return impacts on related ecosystems.

The components to model the interactions between abiotic components, ecological processes and ES in this study are listed as initial variables linking to the ecosystem functions (Appendix). The states of each component were named with respect to the characteristics of the related components. The suitability of the conceptual network was tested by a sensitivity analysis and by alternative scenarios (see Sections 2.4 and 3.5).

2. Material and methods

2.1. Case study

To evaluate the suitability of the developed BBN, a narrow valley in the Sapa district in the Lao Cai province in northern Vietnam served as case study. This area was investigated in detail as part of the LEGATO project³ (Burkhard et al., 2015). As one of the main livelihoods in Sapa, rice cultivation has been developed on terraces with water provision strongly regulated by upstream forests. Steep slopes up to 30 degrees in paddy fields and high altitudes from 500 to 2800 m challenge agricultural activities in several ways (Nguyen et al., 2011). Because of the severe climate with fog and snow and extreme cold winters, local farmers can cultivate rice only once per year. The area of terraced paddy fields in the case study area is 2700 hectares large (Fig. 2). In the San Sa Ho, Hang Lao Chai and Ly Lao Chai villages (within the Ngoi Dum basin), the paddy fields are located in colluvium and alluvial regions. In the villages of Chu Lin, Mong Sen and Vu Lung Sung (within the Ta Van basin), the distribution of paddy fields is comparatively heterogeneous (Hoang, 2014).

According to interviews with local farmers carried out in the context of another project (see below), rice yields have been fluctuating from 1.2 to 9.5 tons/ha per year (Yuzuru Isoda, pers.comm. 2015), while on half of the paddy fields the harvest has been lower than 3.5 tons per hectare per year. This average yield has regularly been poorer than in other agricultural areas of the province with average yields higher than 4 tons/ha per year (Lò Dieu Phu, pers. comm. 2012). The costs for rice imports and the low rice productivity are endangering the local food security and have caused the transformation of nearly one thousand hectares of forest and shrub vegetation into arable land in the study area between 1952 and 2012 (Hoang et al., 2014). Though currently the production of food rice is barely sufficient to sustain local people, the significant increases of immigration and tourist development have caused the local authorities to claim for expansion of agricultural lands and rice productivity in the future. Nevertheless, the spatial expansion of agriculture is not an easy solution due to limiting climatic and topographic conditions in the study area. Therefore, site selection, e.g. the identification of plots with a more optimal productivity, and more intensive farming could be promising methods to stabilize or even to raise the local rice production.

2.2. Identification of environmental and social-economic variables

In order to build a functioning Bayesian network, environmental and anthropogenic variables relating to rice farming need to be identified, and respective data for their quantification need to be collected from different sources. This process can help to eliminate non-relevant variables and improve the certainty of the final network. 15 abiotic variables (shown in Appendix) were selected with their spatial data in the whole case study area (except “solar radiation” and “silicon” variables). Nine anthropogenic variables were selected in 200 plots (except “spraying period”, “pest and disease” and “human demand” variables). The study uses rice yields to quantify rice provisioning ES supply and to identify the respective impacts of environmental and anthropogenic variables. The next sub-sections describe how to prepare the input databases for Bayesian Belief Networks.

2.2.1. Indicator of rice provisioning ecosystem service (ES)

Yield has been proposed as an indicator for provisioning ES by CICES and other ES classification systems (Burkhard et al., 2014; Kandziora et al., 2013b). Though yield alone cannot fully reflect the quantity of rice ES provision, it is the most commonly used indicator to represent the productivity and performance of agricultural systems. However, the approach of concentrating the indication on rice yield alone seems to be too narrow. Instead, more integrative assessments of food (rice) provisioning ES broaden the view to potentially negative or positive interactions between related ES relevant for human well-being (Defra, 2007; Kandziora et al., 2013b; Müller et al., 2016). Especially water-related ES determine the quantity and quality of irrigated water and influence rice yields directly and indirectly together with the nutrient availability based on natural geo-ecological dynamics. Moreover, impacts of agricultural practices – often fostered by respective policies – on biodiversity, climate regulation, soil erosion regulation, fresh water quality and nutrient availabilities have become detrimental (Balbi et al., 2015). Regarding water regulation, about 70 percent of the global water resources have been used for irrigation since 1960 (Millennium Ecosystem Assessment, 2005). The massive use of fertilizers has polluted fresh water resources, often resulting in human health problems. Changes of land cover into croplands can intensify soil erosion and land degradation, lowering nutrient supply and water storage in soils and can finally increase the share of surface runoff and hence the likelihood of floods (IRRI, 2006). Therefore, studying rice yields embedded in an ES-approach helps to unveil human-environmental interactions and assesses outcomes of varying land management approaches in a more integrated way.

The rice yield information was collected by conducting interviews in six villages in the Sapa area. The surveys, taken in September 2010, July 2011 and March 2012, identified rice field location, area and other production-related data (detailed explanations in Section 2.2.3). The location was used to delineate the physical site information (such as slope, soil and hydrology) by overlaying topographical, soil, geomorphological and hydrological maps (scale 1:25.000) of the Sapa area, provided by the Geography Faculty, Hanoi University of Science. The

³ <http://legato-project.net/>.

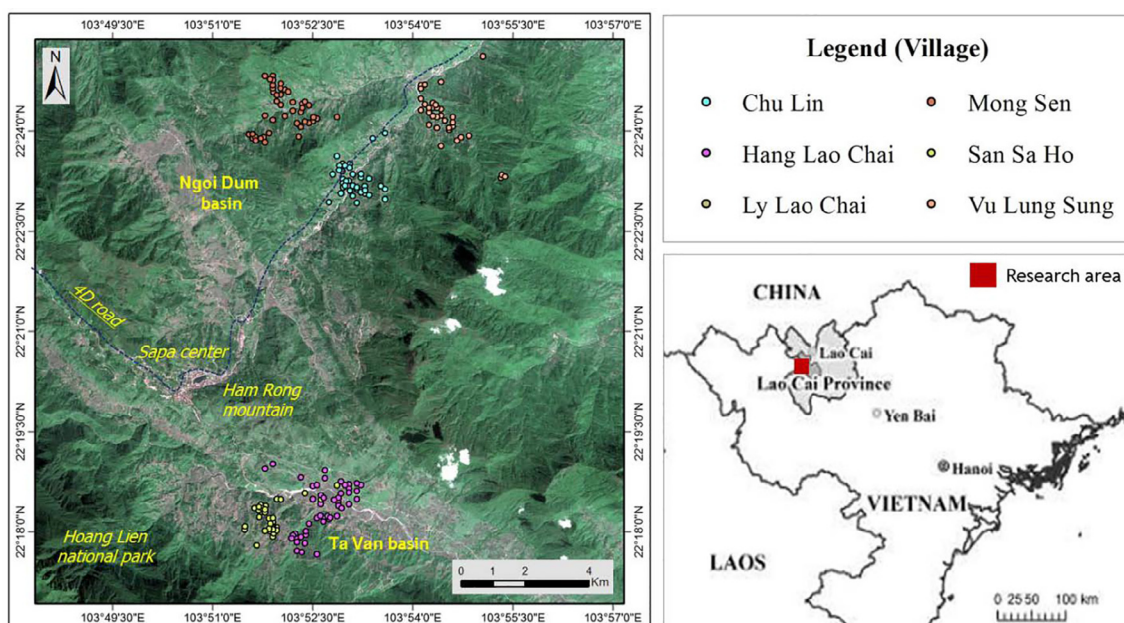


Fig. 2. Location of taken samples in six villages in the Sa Pa District, Lao Cai Province, Vietnam (based on SPOT 5 satellite image taken on 21/10/2010).

final values for rice yields coincided with statistical data from the General Statistics Office of Vietnam (GSO)⁴ and results from the LEGATO project⁵ (Burkhard et al., 2015; Settele et al., 2015). This information allows to assess the site-specific capacity of rice provisioning ES supply and its interactions with abiotic components and ecosystem functions. Detailed characteristics of these components are presented in the next sections. Based on the classification of Burkhard et al. (2014), rice provisioning ES supply and demand were grouped into six states ranging from “no (relevant) capacity” to “very high capacity”. Because all data were calculated for paddy-field areas cropped with rice, the class “no capacity” of rice provisioning ES actually does not exist in the final BBN.

The related nodes described in detail in Appendix calculate the rice provisioning ES supply as a function of farming practice (No. 29), the photosynthesis process (No. 4), water (No. 5) and nutrient (No. 6) availabilities (numbers coincide with numbers shown in the Appendix and Fig. 5 in the results section). The assessment of farming practices depends on investments of different households (No. 24), fertilizer applications (No. 22 and 23), seeds (No. 25), pesticide inputs (No. 26), and disease occurrence (No. 28). The photosynthesis process and the water- and nutrient availabilities were analyzed by 15 physical variables (No. 7 until No. 21). This study will omit the effects of natural hazards or extreme weather, though they were partly accounted via environmental data such as slope, temperature, or erosion.

The rice provisioning ES demand in the research area depends significantly on the number of beneficiaries (such as local population and incoming tourists) and their ecosystem service needs – in this case their demand for food in the form of rice. The population census recorded a steady annual rise by about 10,000 residential people and about 1.5 million tourists per year during last five years for the Sapa region (GSO4). In order to represent this development, the future increase of user demand is set to about 20 percent in scenario C (see Section 2.4). If the rice supply in a particular area during a given time period is higher than the rice demand, the probability to produce an unused supply (e.g. a positive ES budget) will increase, leading to export options for farmers to other regions (Jones et al., 2016). Conversely, low yields at a stable population or stable yields accompanied by a population growth will

cause an unmet demand (e.g. a negative ES budget). In this case, hunger occurs and/or the import of rice from other regions and respective return flows (of money or other goods) are needed. Furthermore, farmers and regional managers would be challenged to optimize rice farming. Therefore, two chosen states of the node “rice provisioning ES budget” (No. 03) in the network were set to “unused supply” and “unmet demand”.

2.2.2. Environmental components for site selection methods

The environmental components impacting rice growth and productivity were determined by the International Rice Research Institute (IRRI) and other scientists (Gupta and Toole, 1986; IRRI, 1985; McLean et al., 2013; Slaets et al., 2015; Soediono, 1989; Wu and Chen, 2013). IRRI (2006) stated that a well-designed rice selection system (e.g. cropping suitable rice varieties with a highly efficient use of solar energy, water and natural nutrients) yields 50 percent higher harvests than common intensive-farming systems. Hence, site selection methods play an important role in minimizing losses of water, soil, and nutrients to adjacent systems and maximizing the provision of rice (Chan et al., 2006; IRRI, 1984).

In the Sapa region, data for 200 locations of paddy fields were collected in interviews. 13 spatial variables were selected to develop the BBN model, including hydrological characteristics (precipitation, evapotranspiration, ratio of evapotranspiration (AET) to precipitation (P), released water, length of flow, solar radiation, temperature and distance to upstream forests), topographic parameters (altitude, slope and height of terraces), and lithological parameter groups (soil types, bedrock and soil erosion). A brief description of these spatial variables is given in the Appendix. A spatial data set with a grid resolution of 10 m was used for simulations in GIS models, e.g. in order to estimate water yield or sediment retention with the InVEST model (Sharp et al., 2016). In the Bayesian network, the discretization of spatial variables like slope and soil erosion were grouped into 3 to 4 classes in order to keep the number of interactions between nodes on a level creating clear distinctions between the outcome variables (Barton et al., 2008). Correlations between the rice provisioning ES supply and all spatial variables have been analyzed with statistical models before being re-classified into three groups of ecosystem functions including photosynthesis processes, water and nutrient availabilities (No. 4, 5 and 6 in Appendix).

⁴ <https://www.gso.gov.vn/>.

⁵ <http://legato-project.net/>.

Information concerning “silicon” (No. 21) and “solar radiation” (No. 7) variables, such as prior probabilities and conditional probability tables (see section 4), have been assigned based on values from expert elucidation. Solar radiation and silicon availability are known to influence the photosynthesis process and nutrient availability, and are hence of key importance, as these parameters are positively correlated with the productivity of rice (IRRI, 2006, 1985, Klotzbücher et al., 2016, 2014). Moreover, silicon (Si) is very important for enhancing the resistance of rice plants against pests and pathogens (Klotzbücher et al., 2016, 2014). The Si availability in the Sapa region is dependent on weathering processes and/or by supplementing straw to the topsoil as a Si source. Therefore, the identification of the bedrock layers is a guide for farmers to assess the available amount of silicon and to locate those paddy fields needing Si fertilization. In this study, the variable “silicon” was included in the “nutrient availability” group and classified as “rich” or “poor”, corresponding to the different bedrock types in the research area. Paddy fields cultivated on the “rich-silicon” bedrock types could provide about 5% higher yields than fields cultivated on the “poor-silicon” types (see Section 3.2).

IRRI (1982) proved that in tropical countries, rice yields strongly depend on the level of solar radiation although their relationship would be curvilinear (Randolph Barker et al., 1986; Youshida, 1981). Solar energy is the key indicator for the photosynthesis process and accumulation of dry matter, from panicle initiation to crop maturation (Datta, 1981; Pirmoradian and Sepaskhah, 2006). However, very strong solar radiation may cause a drought phenomenon in a dry period leading to an extreme reduction of the rice provisioning ES potential. According to above publications, three states of the “solar radiation” variable have been chosen: “weak”, “strong” and “very strong” (listed in Appendix). The contribution of the “solar radiation” variable to the photosynthesis processes of rice decreased respectively from “strong”, “very strong” to “weak” states (see Section 3.2).

2.2.3. Anthropogenic factors and farming practice

Interviews on the individual household level were used to collect agricultural data in the mountainous region, because the “farming practice” (No. 29) is dependent on the situation of each household (such as income or knowledge). Besides rice yields, fertilization (amount and types) and further production-related information was collected in interviews, including investments, types of seed, and the number of households using pesticides. The three seed varieties used in the research area are “Chinese hybrid”, “Vietnamese hybrid”, and “Vietnamese inbred”. These types are assigned in the network as optional states in the “seed” node (No. 25).

Reliable information on fertilizer use at each paddy field is very important for agricultural strategies and for related research activities (FAO, 1991; Schipanski et al., 2014; Virmani et al., 1996). Fertilizers are not only nutrient additives providing sources for plant growth, but can also enhance the soil quality by water maintenance (Catling et al., 1983; Huan et al., 2005). The efficiency of the fertilizer use depends on the knowledge of local farmers and the nutrient dynamics of the soil (especially storage capacity and mineralization rates). Too much fertilization may lead to leaf scorch and complementary damages in the rice plants (Dobermann and Fairhurst, 2000). Hence, decisions on fertilization rates are connected with numerous uncertainties. Nevertheless, under infertile site conditions, the fertilizers are necessary supplements on terraced rice fields (Dawe, 2010). According to their different functions, the application of fertilizer was separated into two nodes (No. 22 and 23) in the BBN. The single nutrients (such as N, P and K) are known as “straight fertilizers” and the combination of two or more nutrients is called “multi-nutrient” or “compound” fertilizers (Dobermann and Fairhurst, 2000; FAO, 1991). Because fertilization varies from field to field, each fertilizer-based node was separated into four states according to their nonlinear influences on rice production (described in Appendix).

Pesticides can control the effect of harmful organisms on rice

productivity, e.g. by poisoning, attracting and seducing pests (Heong and Escalada, 2015; Jørgensen et al., 1997). The term “pesticide” in this study covers herbicides, insecticides, and fungicides used by local farmers on their paddy fields. However, the information provided by farmers indicates only whether or not they have applied pesticides on their paddy fields, data about amounts are not available. Thus, the “pesticide” node (No. 26) was classified only into the two options “used” and “not used”. In case pesticides are used incorrectly, negative impacts on the rice productivity may be caused, especially by plant-hopper outbreaks (Heong et al., 2015a; Heong and Schoenly, 1998; Way and Heong, 1994). Heong et al., (2015b) found that insecticide use could raise the vulnerability of plants to hopper outbreaks, instead of securing the rice productivity. Insecticide use in an early state of the rice season can increase the probability of heavy plant hopper attacks. As proposed by Jørgensen et al. (1997), the “spraying period” variable (No. 27) was divided in the BBN into “beginning” and “middle” periods, allowing the assessment of the quality of the pesticides use.

2.3. Network assessment

The final BBN for the rice provisioning ES assessment was verified with two approaches: The first method was the sensitivity evaluation between the “rice provisioning ES supply” (No. 1) with its parent nodes through direct findings. It was processed symmetrically between two nodes. All findings currently being between two nodes will be taken into the BBN to measure the mutual information values (in bits). These values were calculated with the *Netica* software by an expected reduction in entropy of the “rice provisioning ES supply” node due to a change in each relative variable. According to the sensitivity analysis, the most important variables contributing to the variability of the rice provisioning ES supply were identified through the mutual information values (Dlamini, 2010; Nicholson and Korb, 2004) as follows:

$$I = \sum_q \cdot \sum_f \cdot [P(q) / (P(q) \cdot P(f))] \quad (3)$$

where I is the mutual information value, q is a state of the query variable (or the dependent variable) and f is the state of the varying variable (or the independent variable) (Hough et al., 2010). The higher the number of mutual information, the more sensitive will the target variable be interacting with the “rice provisioning ES supply” variable. If this value is equal to zero, the variable “rice provisioning ES supply” is independent from the target variable (Norsys, 2010).

An evaluation of a BBN can be achieved by determining the Kappa value, which calculates the agreement between actually positive cases and negative cases in the test data. As a precise index, the Kappa value is used to quantify the magnitude of true agreements among observations (Viera and Garrett, 2005) as follows:

$$\text{Cohen's Kappa} = (p_0 - p_e) / (1 - p_e) \quad (4)$$

here p_0 is the observed proportional agreement and p_e is the overall probability of random agreement. The final BBN was tested on the subset of 40 cases (20% of total cases) by calculating the Kappa index for cases that were not used to predict the node “rice provisioning service supply” (No.1) in the training process. The observed cases with “medium”, “high” or “very high” capacities of rice provisioning ES supply were grouped into positive conditions. Observed cases with “very low” and “low” capacities were summarized in the group of negative conditions. The validation process counted the number of true/false agreements (of predicted capacities) in two groups, and then calculated the Kappa index. The model can be classified as validated if the Kappa value is higher than 0.75 (Viera and Garrett, 2005).

2.4. Scenario development

The most attracting function of a fully worked-out BBN is to calculate probabilities for the outcome variable – in this case rice yield – in dependence of different expected or assumed input values – derived for

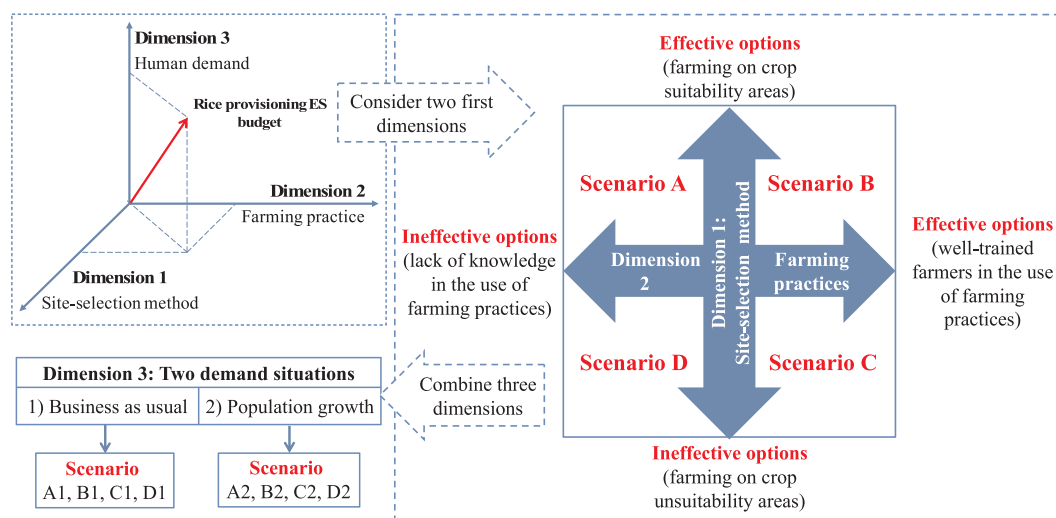


Fig. 3. Structure of eight scenarios based on changes of site selection (dimension 1) and farming practices (dimension 2) in two demand situations (dimension 3).

example within scenarios (Troldborg et al., 2013). The scenarios can be implemented in the BBN once the network structures are completed and verified. By choosing alternative states for the input nodes (for example modified farming practices, hydrological or topographical components), the resulting probabilities of ES nodes (No. 01–03) can be calculated accordingly. In this case, the goal of the scenarios was to formulate alternative land use policies and to estimate resulting impacts on the supply–demand balance in the study area with respect to the rice provisioning ES budget (No. 3). It was hypothesized that optimized farming practices for rice production minimize negative impacts on the supply of other ES. The scenario development can be explained as follows:

Step 1: Scenario design - The principal approach to develop scenarios is depicted in Fig. 3. Based on selected nodes for the dimensions 1, 2 and 3, the developed BBN can calculate the expected probability of the node “rice provisioning service supply” in order to cover the demand for rice in the study area. The dimensions represent:

- Dimension 1: Site selection method – related to changes of abiotic components (Nodes 4 to 21 in Fig. 3),
- Dimension 2: Farming practice – related to changes of anthropogenic factors (Nodes 22 to 29 in Fig. 3) and
- Dimension 3: Human demand – related to changes of population size (Nodes 30 in Fig. 3).

According to this approach, the farmers have two methods to optimize the posterior probability of the node “rice provisioning service supply”: selection of suitable sites and appropriate farming practices. The choices of suitable sites (dimension 1) refer to the use of “natural productivity” or the “site potential” to provide ES, without the need of additional anthropogenic inputs (such as fertilizer and pesticides) into the system. This method would take full advantage of the ecosystem functions at cropping sites which harness natural processes and the self-organizing capacities of ecosystems. Once the rice has been cropped under suitable natural conditions, the farmers can decide about additional farming activities (dimension 2) in order to maximize the efficiency of the farming practices and the capacity of rice provisioning service supply. The efficiency of these methods was assessed in four scenarios (Fig. 3): (A) and (C) scenarios where only one method (site selection or farming practice) does not use the effective options; (D) scenario where two methods apply the ineffective options and (B) the most promising scenario where both methods use the effective options. The details of effective/ineffective options are presented in step 2 (selection of agricultural management options).

In order to account for potential future developments in the study area, two different situations of demand for rice provision (represented in dimension 3) were assumed: (1) *Business as usual*: the population and the respective demand for rice provisioning service in the study area will stay stable at the current level; (2) *Population growth*: The population will grow by 20% due to potential increases in tourism and migration. Based on this setting, the results of eight scenarios could be analyzed, representing two situations for the rice demand (1) and (2) and four management options (A, B, C, D), characterized in the following as A1, B1, C1, D1, A2, B2, C2 and D2.

Step 2: Selection of agricultural management options – this step describes the options that farmers can choose in the developed BBN specified for each of the eight proposed scenarios and how they are classified as “effective” or “ineffective” for dimension 1 (site selection) and dimension 2 (farming practice). As a guideline to agricultural policy towards optimizing the probability of a balanced ecosystem service budget, the effective and ineffective options were identified for the farming and site selection methods as depicted in Table 1. The chosen criterion for the *site selection* method was based on six easy-to-identify nodes in the BBN including temperature (No. 8), solar radiation (No. 7), precipitation (No. 9), altitude (No. 15), slope (No. 16), and soil type (No. 20). The probabilities of other intermediate nodes in the abiotic variables and ecosystem functions were calculated accordingly. For example, surface runoff becomes more rapid on steeper slopes (No. 19) and with high precipitation (No. 6), leading to an increase of erosion (No. 18) and water and nutrient shortages (No. 5 and No. 6) in soils. The efficiency of the *farming practice* was constrained by the varying socio-economic conditions of households and government policies. Furthermore it depends on the farmer’s education, addressing the nodes from No. 24 to No. 29. A site selection or farming practice is assumed to be “effective” when the changes in that method do not limit the rice productivity. Unsuitable choices in site selection or farming practice causing a lower productivity than possible were classified as “ineffective”.

Step 3: Scenarios implementation – In this step, the proposed site selection options shown in Table 1 accessed the conditional probability table of corresponding nodes in the BBN database to calculate the probabilities of the nodes “rice provisioning service supply” (No. 1) and “budget” (No. 3) for the eight scenarios. The probability of success in land use strategies was indicated by the value for the state “unmet demand” of the node “rice provisioning service budget” (No. 3). If the probability of the “unmet demand” state in the node 3 was lower than 50%, the rice production would be high enough to meet the demand of the local population and tourists in the Sapa region. In contrast, if the

Table 1
The most effective and ineffective options of farming and site selection methods focus on easy-to-observe/manage nodes by farmers.

Option	Effective	Ineffective
Site selection	<ul style="list-style-type: none"> – Temperature (No.8): 22–24.5 °C with strong solar radiation – Precipitation (No.9): lower than 1800 mm – Altitude (No.15): lower than 1030 m – Slope (No.16): lower than 13 degree – Soil (No.20): plinthic Acrisols 	<ul style="list-style-type: none"> – Temperature (No.8): less than 21.5 °C with weak solar radiation – Precipitation (No.9): higher than 1930 mm – Altitude (No.15): higher than 1240 m – Slope (No.16): higher than 24 degree – Soil (No.20): humic Acrisols
Farming practice	<ul style="list-style-type: none"> – Investment (No.24) higher than 5.8 Million VND – Using 180 kg/ha per year of compound fertilizer (No.22) and 130 kg/ha per year of straight fertilizer (No.23) – Using Vietnamese hybrid seeds (No.25) – Using pesticides (No.26) at the middle of season (No.27) 	<ul style="list-style-type: none"> – No investment (No.24) (or less than 3.5 Million VND) – Using less than 45 kg/ha per year of compound fertilizer (No.22) and 30 kg/ha per year of straight fertilizer (No.23) – Using Chinese hybrid seeds (No.25) – Using pesticides (No.26) at the beginning of season (No.27) (or do not use pesticide)

probability of this state was *higher than 50%*, households would be unable to get enough rice for food to meet their basic nutritional needs. Consequently, the approaches of site selection and farming practices would need to be modified. Based on these outcomes, the local farmers can make suitable decisions for their rice production scheme.

3. Results

3.1. Statistical analysis of interdependences as basis to parameterize the BBN

The identification of interactions between the selected variables influencing rice productivity and their significance is based on a cluster analysis. Fig. 4 describes the correlations between 18 environmental and societal components related to the site selection and the intensive farming in agricultural management. Some variables in the BBN (such as solar radiation, silicon availability, photosynthesis process) have not been depicted in this figure due to missing statistical data. According to the different relations with the rice provisioning ES (or “Rice PES” variable), four groups (one topographical group (G3), two hydrological groups (G2 and G4) and one additional group (G1)) could be identified. The anthropogenic components (such as fertilizer inputs, investments and farming practice) in group G1 have clustered around the variable “rice provisioning ES”. However, the most powerful positive uphill

linear relationship can be found between the nutrient availability (in group G1) and rice production with a correlation of +0.78. The groups G2 and G4 include the hydrological components. The water availability calculated from precipitation, evapotranspiration, released water, ratio of evapotranspiration to precipitation, and runoffs (through length of flows and distance to upstream forest) were positively correlated with the rice provisioning ES with a correlation of +0.53. Overall, the interactions of the processes grouped in G2 with the “Rice PES” variable are stronger than with those in group G4. The four topographical components (elevation, erosion, height of terraces and slope) grouped in G3 have influence rice productivity via water and nutrient availabilities (No. 05 and No. 06). However, the correlation of the group G3 with the “Rice PES” variable fluctuates from –0.2 down to –0.4 and is weaker than with the other groups. As shown in Fig. 4, “farming practice”, “water availability” and “nutrient availability” are the three main variables linking directly to the “Rice PES” because of their strong correlations and hence justify identifying them as parent nodes to develop the respective BBN.

According to the results depicted in Fig. 4, the parent and child nodes have been identified and support the BBN development. In the groups G1 or G2, strong positive interactions have been found between the components. The interactions within the groups G3 and G4 were less homogeneous than those in the two other groups. In contrast, negative connections were recognized between the groups G1/G2 and

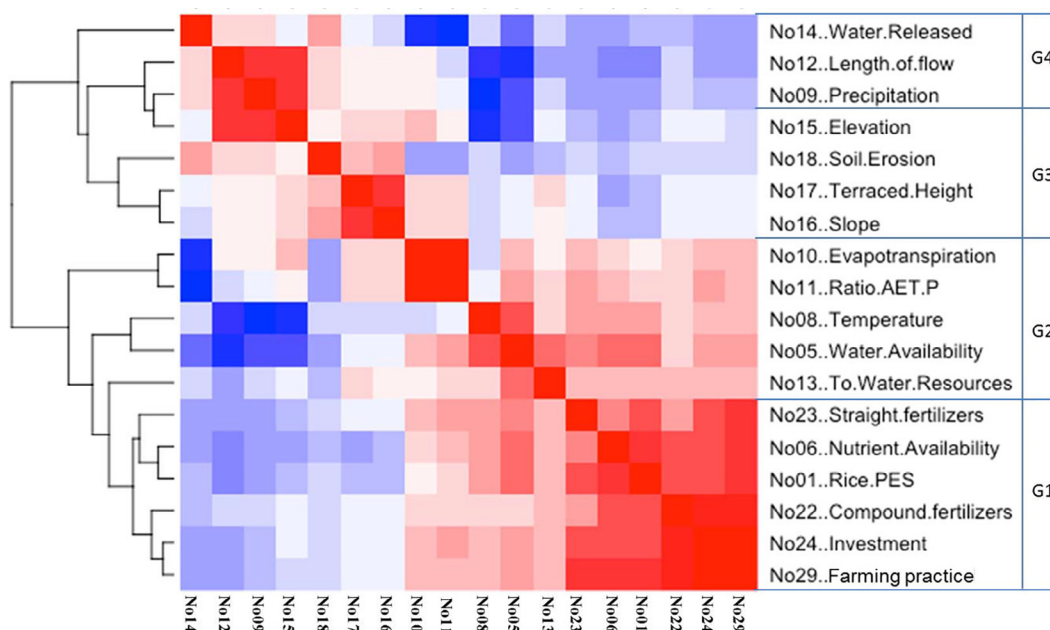


Fig. 4. Interdependences of natural and anthropogenic components and rice provisioning ecosystem services (numbers of these components are linked to Appendix). Darker red color illustrates correlations that are more positive, darker blue color illustrates correlations that are more negative.

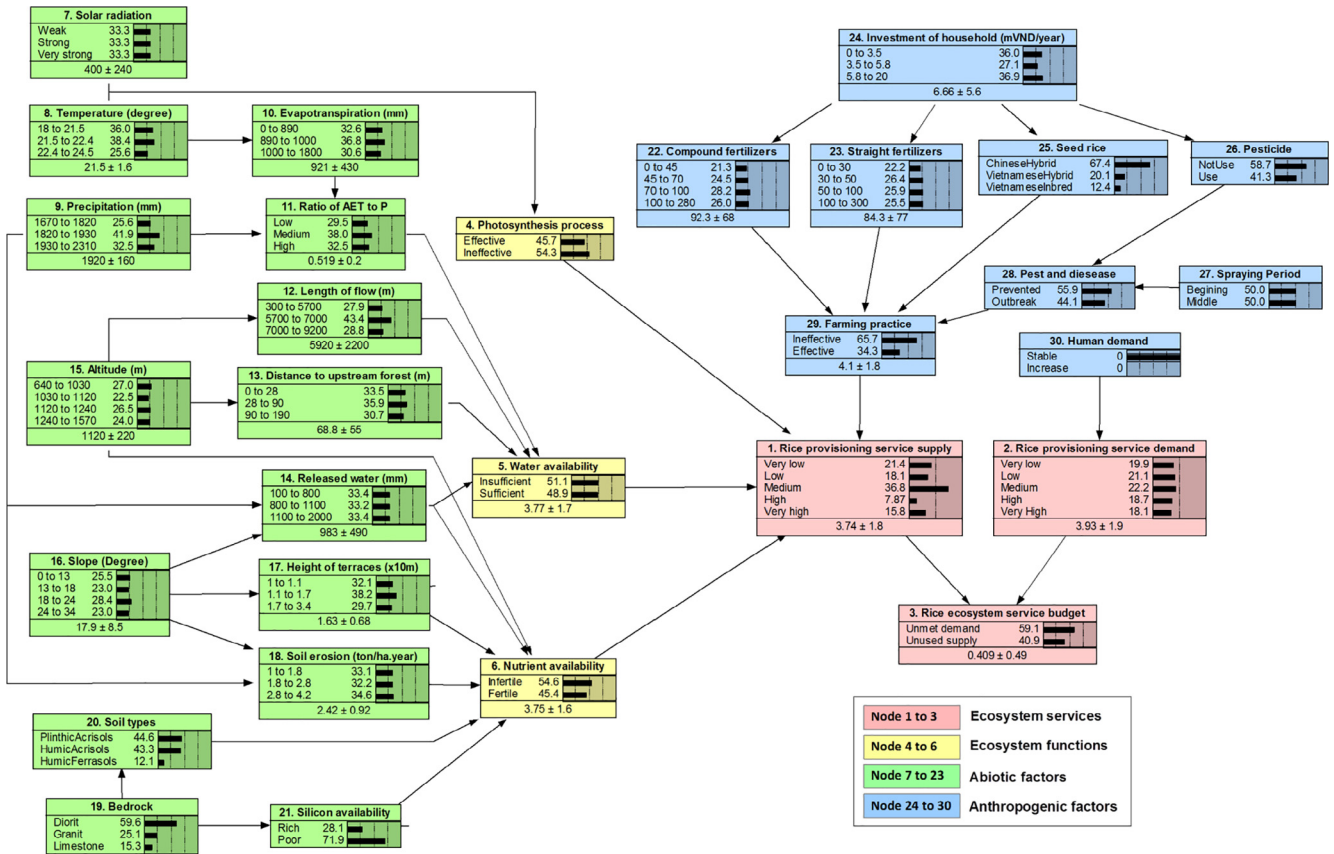


Fig. 5. Bayesian Belief Network of rice provisioning ecosystem service supply and demand (Prior probabilities of states in “Business as usual” situation).

G3/G4. Unfavorable dependencies were identified between the rice provisioning ES with the groups G3 and G4, while favorable dependencies exist with the groups G1 and G2. Statistical meaning and correlations can be found between topographical and hydrological components, such as correlations of -0.51 between the released water (No. 11) and water availability (No. 05); -0.85 between the length of flow (No. 12) and water availability (No. 05) and -0.27 between the slope (No. 16) and the nutrient availability (No. 06).

The cluster analysis clearly illustrates the complex connections between abiotic factors, ecosystem functions and land management in the rice supply network based on the Bayesian framework (Fig. 5). Prior probabilities were identified in each state based on the current situations of paddy fields in the Sapa region. For example, the areal percentages of paddy fields cultivated on the “Plinthic Acrisols”, “Humic Acrisols” and “Humic Ferrasols” soil types in the year 2010 are 44.6%; 43.3% and 12.1% respectively (No. 20 in Fig. 5). Besides, causal relationships were developed between 15 parent nodes “abiotic factors” and three child nodes “ecosystem functions”. The comparably easy-to-identify physical conditions (Nodes from 07 to 21) were significantly influential on the photosynthesis process and the water and nutrient supplies of paddy fields. On the other hand, these parent nodes can indirectly influence the rice provisioning ES supply and budget through three functional nodes. The positive adaptations of the service supply in the different cases of food demands can raise the probabilities of an “unused supply” state in the ES budget (No. 03), in particular if the probabilities of each state in the service supply node are higher than the similar state in the service demand node. In contrast, if the outcome probabilities of each state in the node “service supply” is lower than the similar state in the node “service demand”, the posterior probability of “unmet demand” state in the node ES budget will increase.

3.2. Parameterization of the BBN with classified data

While the probability for the node “Solar radiation” (No. 07) was determined based on expert perspectives, the node “Silicon” (No. 21) refers to local geological properties, especially bedrock features. Though the diorite and granite bedrocks cannot create absolute weathering crusts to fully support the required silicon requirements in the research area, the amount of silicon taken from granite is higher than that from diorite and limestone. Bedrocks attributed to the state “poor silicon availability” cause rice yield reductions of about 3–5% compared to the sites with “Si-rich” bedrocks. Regarding the solar radiation, according to the National Center for Hydro-Meteorological Forecast Service in Vietnam, the mean sunshine hours in the mountainous research area amount to about 1400 h annually and are clearly lower than in flat agricultural regions with 2500 h annually. The state “strong” is attached to the node “Solar radiation” for locations in the research area with regular temperatures from 22 to 25 °C, assuming that the “effective” photosynthesis process is maximized within this temperature range.

The node “farming practice” relates to the additional input nodes 22 up to 28 directly to node 01 “Rice provisioning service supply”. In the research area, the investment of each household is limited to 20 million VND (equal to nearly 800 EUR) per year apportioned to three major purposes (fertilizers, seeds and pesticides). According to the interviews carried out in 2015, the fertilizer use improves the rice provisioning ES supply starting with application rates of about 180 kg/ha per year of compound fertilizer and 130 kg/ha per year of straight fertilizer. However, the rice yields have steadily been increasing in the last decades because the level of “luxury consumption” of rice plants has not yet been reached. Pesticides: about 30% of local households in the research area cannot afford to invest in chemical pest management. Nevertheless, local farmers have shifted to blame pests as explanation

Table 2
Sensitivity analysis results of influences on rice provisioning ES supply based on mutual information and entropy reduction (calculated in percentage).

Node (Variable)	Mutual info/Entropy reduction (%)
Rice provisioning service supply (No.1)	2.49155 (100)
Nutrient availability (No.6)	0.18624 (7.47)
Farming practice (No.29)	0.16995 (6.82)
Photosynthesis process (No.4)	0.08880 (3.56)
Water availability (No.5)	0.03522 (1.41)

for low rice provisioning ES supply, serving as justification for an increased use of pesticides. The suitable period for spraying pesticides is in the middle of the growing season, but many farmers use pesticides at the beginning of the season. More than 40% of the paddy fields have been sprayed with insecticides, but the success rate of pest prevention is just a bit more than 50%. *Seeds*: Chinese hybrid seeds may be chosen preferentially due to their lower costs. However, the productivity of these seeds is lower than that of Vietnamese seed varieties. Thus, the combination of these situations has raised the probabilities of “ineffective” states of the node “farming practice” in the Sapa region.

3.3. Sensitivity analysis of rice yield probabilities in dependence of varying parameters for BBN nodes

The sensitivity analysis of the “rice provisioning ES supply” node is presented in Table 2. The directly connected nodes were ranked according to their influences on changes of the probability of the service supply node. These influences have been calculated by a measure of mutual information value (MIV) and entropy reduction (shown as a percentage). The entropy of the child node “Rice provisioning service supply” was assumed to be 100%, respectively with its MIV of about 2.5. The entropy reduction values of the four parent nodes express a ratio of their MIV to the MIV of the child node. The higher the values of MIV and entropy reduction, the stronger a node affects the node “Rice provisioning service supply”. Nutrient availability is the most significant component with the highest entropy reduction (7.5%). A strong influence was also attributed to the “farming practice” node with approximately 7% of entropy reduction.

According to alternative choices in three ecosystem functions and farming practices (or parent nodes), the posterior probabilities in five states of the node “rice provisioning service supply” (as a child node) was estimated accordingly (Table 3). The four parent nodes in the

Table 3

Conditional probability table (CPT) of the node “rice provisioning service supply”; calculated in current demand as a function of the node “farming practice” (No.29) and three ecosystem functions (No.4, 5 and No.6).

Case	Farming practice (No.29)	Site selection method			Probability that the “Rice provisioning service supply” (No.1) will meet the current demand in study area				
		Photosynthesis process (No.4)	Water availability (No.5)	Nutrient availability (No.6)	Very low	Low	Medium	High	Very high
1a	Effective	Effective	Insufficient	Fertile	1	5	15	9	70
2a	Effective	Effective	Insufficient	Infertile	0	3	70	20	7
3a	Effective	Effective	Sufficient	Fertile	0	4	6	11	79
4a	Effective	Effective	Sufficient	Infertile	0	0	54	10	36
5a	Effective	Ineffective	Insufficient	Fertile	5	10	50	10	25
6a	Effective	Ineffective	Insufficient	Infertile	10	30	40	13	7
7a	Effective	Ineffective	Sufficient	Fertile	0	5	45	20	30
8a	Effective	Ineffective	Sufficient	Infertile	0	20	50	15	15
1b	Ineffective	Effective	Insufficient	Fertile	0	1	66	2	31
2b	Ineffective	Effective	Insufficient	Infertile	50	30	19	1	0
3b	Ineffective	Effective	Sufficient	Fertile	0	0	47	8	45
4b	Ineffective	Effective	Sufficient	Infertile	35	30	26	8	1
5b	Ineffective	Ineffective	Insufficient	Fertile	40	10	50	0	0
6b	Ineffective	Ineffective	Insufficient	Infertile	55	35	10	0	0
7b	Ineffective	Ineffective	Sufficient	Fertile	15	25	45	15	0
8b	Ineffective	Ineffective	Sufficient	Infertile	38	32	25	5	0

conditional probability table (CPT) of the node “rice provisioning service supply” separated farming practices and site selection constraints as three “ecosystem functions”. Thus, the probability of the site selection’s success depends on the nodes “photosynthesis process”, “water availability” and “nutrient availabilities”, while the farming practice is the combination of fertilizer use, pesticide applications and seed choice. In order to unveil the potential and combined effects of different states of these four nodes on the resulting rice provisioning service supply, the likelihood of each option in the parent nodes was set to 100% (such as for “effective” or “ineffective” states in the “farming practice” node (No. 29)). According to Table 3, the combined positive impacts of the farming practices contribute from 20 to 40% to the probabilities that the node “rice provisioning service supply” (No. 01) will be classified as “high” or “very high”, depicted as outcome probabilities for the cases 1a and 1b; 2a and 2b. The absence of solar energy, which can obstruct the rice growth through the photosynthesis process, can increase the probabilities of the “low” and “very low” states of the node “rice provisioning service supply” (No. 1) from 10 to 40% (such as the outcome probabilities in the cases 1a and 5a; 2a and 6a in Table 3).

The results presented in Table 3 disclose that the success ratio of cases cannot reach the absolute value (100%). Moreover, the non-linear effect of farming practices on the resulting probability for the node “rice provisioning ES supply” (No. 01) is the most important outcome on the farmer’s level. Hence, the questions arise how farmers can optimize the site selection and farming practices for particular areas and which maximum probability of the rice supply–demand balance can be achieved. To identify the range of opportunities for the farmers, different scenarios could address these questions.

3.4. Results of scenarios

Fig. 6 presents subsequent probabilities for the eight scenarios of the node “rice provisioning service budget” (No. 03) associated with the eight options for site selection and farming practices defined during the scenario setup. The presented results focus: i) on the rice provisioning service supply determined on farming level by decisions on site selection and farming practices; and ii) on the overall balance between supply and demand of the rice provisioning service on a regional level. In this section, the scenario outcomes refer to the values for the probability of the state “unmet demand” in node 03. Such situations would ask for improvement by decision makers, e.g. farmers (local level) and politicians on the regional level.

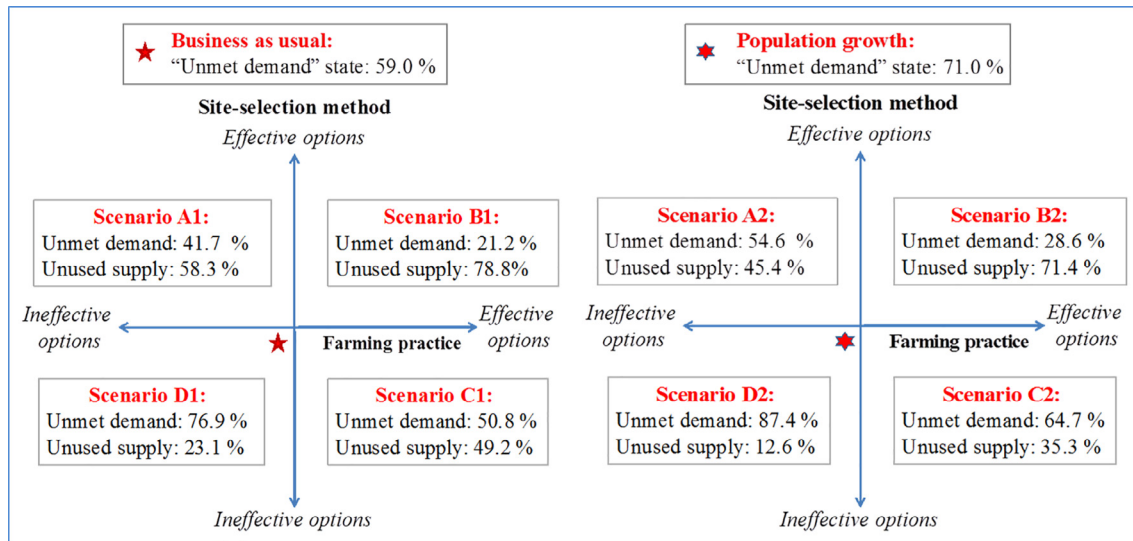


Fig. 6. Probability changes of the rice provisioning ecosystem service budgets in the different scenarios. The percentages of “unmet demand” state explain the probabilities of rice production not enough to meet the local demand for food rice. Scenarios A1, B1, C1, D1 were calculated basing upon the BAU situation. Scenarios A2, B2, C2, D2 were calculated for a population growth situation. The site selection method relating to a predetermined location for crop farming was decided by three ecosystem functions (photosynthesis process, water availability and nutrient availability). The intensive-farming practice relates to additional system inputs.

The probability of an “unmet demand” state in the “business as usual” scenario was chosen as a reference point that mirrors the present (from 2012 to 2015) land use situation in the case study area and was depicted as “star 1” in Fig. 6. In such a situation, the probability of the “unmet demand” state was 59 %, meaning that the probability that a person could suffer from malnutrition in the research area would be nearly 59 %. These findings were validated by records concerning the provision of food in poor villages in the Sapa region. A potential population growth of 20 % will increase this probability up to 71% – indicated by “star 2” in Fig. 6.

If farmers would select the effective options concerning the farming level – according to Table 1 “effective site selection”, the probability to find a suitable site reaches about 80 %. Whereas if the “ineffective options in the site selection” – according to Table 1 – would be chosen, the probability to find a suitable site is reduced to 30 %. The optimal use of seeds, fertilizers, and pesticides – according to Table 1 “effective farming practices” – can increase the probability of success in the node “farming practice” up to 87 %. In contrast, the probability of failure in the farming practices would reach 97 % if the farmers use inappropriate additional inputs – according to Table 1 “ineffective farming practices”.

Regarding the scenario results on the regional level for the ecosystem service budget, three scenario setups (A1, B1 and B2) would improve the situation in the Sapa region. These situations would reduce the probability for the state “unmet demand”, indicating that expected rice yields would meet the local demand for food rice, compared to its probability in the present situation, indicated by “star 1” in Fig. 6. In contrast, the other scenario setups (A2, C1, C2, D1 and D2) would aggravate the situation and potentially increase the risk of unmet demand in the case study area. According to scenario A1, the probability for the state “unmet demand” would decrease by about 17 % compared to those in the “business as usual” situation (star 1, Fig. 6). However, in case of population growth, the improved site selection would only be able to keep the present level for the state “unmet demand” stable, as indicated by the results for scenario A2 in Fig. 6. This would be similar in scenarios C1 and C2, where farmers would solely direct their attention toward the effective farming practice, but keep farming on unfavorable locations. In both scenarios, the reduction of the probability for the state “unmet demand” was limited at 10 % in scenario C1 and 6% in scenario C2.

The most optimal solutions were achieved by the scenario settings B1 and B2, yielding low probabilities for the states “unmet demand” (21

% in scenario B1 and 29 % in scenario B2). Probabilities of “unmet demand” were about 20 % lower than those in the scenarios A1 and A2. Although the optimal options could be tested, the probability of the “unmet demand” state could not be reduced to 0 % due to fluctuations of environmental and human-derived components. The ineffective options depicted in scenarios D1 and D2 were considered to cause crop failures because their probabilities of the “unmet demand” state were higher than 76 %. To sum it up, the optimal options in the scenarios B1 and B2 indicate the solutions to ensure that there will be enough rice for the case study area in a long-term.

4. Discussion

4.1. Comparison with formal networks/frameworks

The study investigated rice provisioning ecosystem service supply through a Bayesian Belief Network that is suitable to integrate environmental and societal knowledge. The network has applied and practiced the conceptual ES supply–demand model developed by Burkhard et al. (2014) with data for rice ecosystems in order to understand interactions between ecosystem functions, land management and their benefits to humans. The BBN that was calibrated for the Sapa region is transferable to other mountainous areas. The target areas of the developed BBN are upland and irrigated rice fields in mountainous areas, which should be distinguished from other types of rice (such as lowlands and flood-prone rice). Compared to other agricultural regions, the paddy fields in mountainous areas are not regularly irrigated. Furthermore, the provision of nutrients is largely dependent on natural sources and hence on different topographical, hydrological, and climatic factors. In order to compensate reductions of ecosystem functions on which rice agriculture depends, additional irrigation or fertilization and/or further complementary farming practices may be required to achieve and to sustain a sufficient rice provision in the Sapa region.

Through the ES approach, the BBN complements previous frameworks in studying rice production, such as the Bayesian network of Cain (2001). Some environmental and human-derived components including water, fertilizer and pesticide application have been inherited from previous networks (Jørgensen et al., 1997; Poppenborg and Koellner, 2014), while other components were added to represent the influences of the social-ecological system on rice ecosystems: the photosynthesis process (No. 04), nutrient availability in soils (No. 06), amounts of

silicon (No. 21) and spraying period of the pesticide use (No. 27). Instead of concentrating on biological aspects based on qualitative methods, the nodes relating to nature and society were quantified by various methods that make the outcome more precise and practical. Especially the scenario development based on three dimensions, which has not been clearly presented in other studies, makes the BBN of rice provisioning ES more applicable with regard to the target to develop sustainable strategies in agriculture. Nevertheless, the BBN of this study could be improved by incorporating additional components, especially those addressing the efficiencies of biophysics and/or solar energy and the applications of agro-chemical products (Gupta and Toole, 1986; IRRRI, 1985). For example, the relationship between rice production and lithology in the network was based on only three typical soil types in Sapa. The details of soil characteristics (such as texture or structure) could be added as intermediate nodes between the node “Soil type” (No. 20) and the node “Nutrient availability” (No. 06) (Baveye et al., 2016), provided the respective data are available in future.

Compared to the previous network developed by Cain (2001), the “pesticide” node in the final network was not meticulously analyzed due to missing data. Besides, the FAO (2011) also has recommended no intensive insecticide use in tropical countries due to its harmfulness to human health and plants. Moreover, Heong and Escalada (2015) claimed that the rice production can be improved by ecological engineering methods and the reduction of pesticide use. Especially the methods to efficiently applying pesticides require a strong investment in equipment and training of local farmers, which is challenging for poor and developing countries. Consequently, a general minimization of pesticide use in paddy fields should be encouraged (Jørgensen et al., 1997). Local farmers can invest more in other technical methods or better seeds, instead of applying farming practices based on the use of chemicals.

4.2. Contributions to sustainable agriculture

The fertilizers need to be used appropriately for the deficient nutrient of rice (de Baar, 1994). As a solution toward sustainable agriculture, a policy to stop local farmers from using more fertilizers (with the limitation at 180 kg/ha per year for compound ones and 130 kg/ha per year for straight ones) needs to be implemented, reducing related external effects such as increasing freshwater pollution. If the fertilization is higher than these thresholds, any additional inputs from fertilizers cannot increase rice yields. On the other hand, the limitation of fertilizers and pesticides can prevent nitrate and other contamination of the groundwater (Gilliom et al., 2006) and uncontrollable growth of invasive alien species (Ongley, 1996). The use of chemical products higher than these thresholds can lead to high amounts of nitrate in groundwater that then becomes un-potable.

With the developed BBN, farmers and other decision makers can easily identify suitable crop fields for sustainable cropping of rice using data describing the initial natural components (such as temperature, precipitation, altitude, slope and bedrock). According to the results presented in Table 3, the site selection method can yield more positive effects than the farming practice. However, the natural availability of nutrients and water supporting paddy fields will decrease with time. This applies especially for easily available nutrients like nitrogen, potassium, phosphate and silicon in the topsoil (Datta, 1981). The amount of nutrients accessible for plants will significantly decrease after few years, leading to increasing fertilizer needs if biomass growth is to be maintained. Nevertheless, optimized site selection methods improve the irrigation efficiency, save water resources and reduce the probability of land degradation and soil erosion (represented by negative correlations between No. 01 and No. 18 in Fig. 4). Furthermore, the impact of extreme climatic events on plant growth eventually leading to poor crops (Tadele, 2017) can be reduced efficiently by choosing suitable rice field sites. Once paddy fields are located at sites with favorable environmental conditions - according to Table 1 “effective” site selection,

farmers would need to invest less money and effort on these fields than required by farming on unfavorable sites. Thus, an optimized site selection would increase the sustainability of the land management.

Within the eight analyzed scenarios, the probabilities of the “unused supply” state (of No. 03) were higher in three scenarios (A1, B1 and B2) than those of the “unmet demand” state. The high probability values of the “unmet demand” state in five other scenarios (C1, D1, A2, C2 and D2) proved the need for a long-term solution for local rice farming, especially in the case of population growth. An integrated land management policy, regarding the combination of effective site selection and farming practices, is considered to be an optimal solution.

The effective and ineffective choices presented in Table 1 can be used as guidelines for farmers, land managers, planners and scientists for optimizing the rice provisioning ecosystem service budgets and minimizing negative effects on other ES. Optimal options for crop suitability are Plinthic Acrisols with slopes lower than 13 degrees, altitudes lower than 1000 meters, precipitation lower than 1800 mm, temperatures from 22 to 24.5 °C and strong solar radiation (see Table 1). The following input parameters could be identified as suitable farming options: application of 150–180 kg/ha per year compound fertilizers and from 130 kg/ha per year straight fertilizer, using Vietnamese hybrid seeds and spraying pesticides in the middle of the growth period. The effective choices in site selection methods help farmers and politicians to explicitly identify crop suitability areas. However, the BBN also provides information for alternative land use options for those sites that were identified as not suitable to crop rice. For example, the probability of sufficient water (No. 05) to irrigate upland rice fields from upstream forests (with altitudes higher than 1100 meters (No. 15) and a length of flow (No. 12) longer than 7000 meters) is higher than for water coming from downstream forests. Therefore, the upstream areas should be afforested if farmers want to crop rice in downstream areas. This identification can avoid uncontrollable rice expansion as could be observed in recent years (Hoang et al., 2014). Also, in order to crop rice on areas with slopes steeper than 24 degrees and precipitation higher than 1240 mm, additional measures (like artificial walls) to avoid erosion are indispensable.

4.3. Uncertainty

Regarding the certainty of the network, the final BBN can clearly reflect the reality of the rice provisioning ES supply. The Kappa index of the BBN reaches about 0.8, which proves the high certainty of the results. Except the “Silicon” and “Solar radiation” components, almost all correlations between the natural elements and rice production were analyzed through multiple linear regression models with high statistical significances ($p < 0.05$).

Regarding uncertainties of the study, some of the following challenges relating to the general approach and the underlying data need to be dealt with. The highly complex network (with 30 different nodes) in this study needs a higher number of samples for training and testing purposes. Another further step to enhance the certainty of the network would be improvements of the quantitative methods to replace or better calibrate the parameters of the expert-based nodes/variables values (such as silicon and pesticide variables) in order to have a more consistent database. The conditional probability tables of these variables were obtained from published results and expert assessments, instead of statistical data, which can introduce further uncertainties to the study and its results. Missing data for qualitative variables has become a big challenge in the BBN development (Dlamini, 2010; Kleemann et al., 2017; Taalab et al., 2015). Besides, it could be more interesting if the BBN could give more feedbacks for agricultural policies or impacts of environmental changes on rice provisioning ES.

5. Conclusions

In order to answer the research questions raised in the introduction

section, the study used a conceptual Bayesian Belief Network to identify the effects of ecological structures and processes, ecosystem functions, additional anthropogenic inputs and population dynamics on rice provisioning ES supply and demand. Following are the answers:

- **Is it feasible and effective to model the interactions between a regional social-ecological system and rice provisioning ES by developing a Bayesian Belief Network?** Yes, because of the probabilistic nature of Bayesian inference, the developed BBN can efficiently analyze interactions between the paddy rice ecosystems and the general social-ecological system they are embedded in. Thereby, the BBN yielded different probabilities for the provision of rice in the Sapa region based on changes in abiotic variables, ecosystem functions, additional anthropogenic inputs and population dynamics. The posterior probabilities calculated by the network are in harmony with the monitored present rice provision in the Sapa region – meaning the occurrence of hunger periods in some of the villages.
- **Which are effective and ineffective choices on the local level for farmers to cultivate rice in a remote mountainous region?** On the local level, preferential/unsuitable sites and appropriate farming practices for a sustainable rice production can be identified. Different options were proposed for the case study (in Table 1), based on the diagnosis functions of the developed BBN. They could become the base for future policies related to agricultural development and spatial planning, whereas the four guidelines for implementing different farming practices need to be explicitly introduced to the farmers. In transitional regions - like the study area - the provision of data mirroring the natural productivity of sites will contribute much more to a sustainable development of the agricultural sector than the uninformed use of chemical farming practices on the farm and field levels. As demonstrated with the scenarios, the efficient combination of both methods site selection and farming practices would substantially contribute to a long-term more sustainable agriculture.
- **Is it possible to equip stakeholders on the regional level with information to foster a sustainable regional development plan by supporting sustainable rice cropping?** Yes, the developed BBN furthermore provides information for decision makers on the present situation of ES supply–demand budgets in mountainous regions. It could furthermore inform about spatial relations between rice ecosystem service providing units and benefiting areas.

Further studies can harness the mapping function of BBNs as a promising tool to provide additional feedbacks related to environmental issues and food supply chains for farmers, scientists and agricultural managers.

Acknowledgements

The study was embedded in the LEGATO (Land-use intensity and Ecological Engineering – Assessment Tools for risks and Opportunities in annual crop based production systems) project, funded by the German Ministry of Research and Education within their funding measure Sustainable Land Management; Funding No. 01LL0917. This study was co-financed by the Vietnamese Government Scholarship (911). Furthermore, we would like to thank all our LEGATO colleagues and especially Associate Professor Isoda Yuzuru from the Graduate School of Science at Tohoku University in Japan and all our colleagues in the Institute for Natural Resource Conservation, Department of Ecosystem Management at Kiel University, Germany. The authors would like to thank Mrs. Angie Faust for language corrections of the manuscript.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.ecolind.2018.04.055>.

References

- Anastácio, P.M., Nielsen, S.N., Marques, J.C., Jørgensen, S.E., 1995. Integrated production of crayfish and rice: a management model. *Ecol. Eng.* 199–210.
- Balbi, S., del Prado, A., Gallejones, P., Geevan, C.P., Pardo, G., Perez-Minana, E., Manrique, R., Hernandez-Santiago, C., Villa, F., 2015. Modeling trade-offs among ecosystem services in agricultural production systems. *Environ. Model. Softw.* 72, 314–326. <http://dx.doi.org/10.1016/j.envsoft.2014.12.017>.
- 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. *Ecol. Econ.* 66, 91–104. <http://dx.doi.org/10.1016/j.ecolecon.2008.02.012>.
- Baveye, P.C., Baveye, J., Gowdy, J., 2016. Soil “Ecosystem” services and natural capital: critical appraisal of research on uncertain ground. *Front. Environ. Sci.* 4, 1–49. <http://dx.doi.org/10.3389/fenvs.2016.00041>.
- Burkhard, B., De Groot, R., Costanza, R., Seppelt, R., Jørgensen, S.E., Potschin, M., 2012a. Solutions for sustaining natural capital and ecosystem services. *Ecol. Indic.* 21, 1–6. <http://dx.doi.org/10.1016/j.ecolind.2012.03.008>.
- Burkhard, B., de Groot, R., Costanza, R., Seppelt, R., Jørgensen, S.E., Potschin, M., 2012b. Challenges of sustaining natural capital and ecosystem services: quantification, modelling & valuation/accounting. *Ecol. Indic.*
- Burkhard, B., Kandziara, M., Hou, Y., Müller, F., 2014. Ecosystem service potentials, flows and demands – concepts for spatial localisation, indication and quantification. *Landscape Online* 32, 1–32. <http://dx.doi.org/10.3097/L.O.201434>.
- Burkhard, B., Kroll, F., Nedkov, S., Müller, F., 2012c. Mapping ecosystem service supply, demand and budgets. *Ecol. Indic.* 21, 17–29. <http://dx.doi.org/10.1016/j.ecolind.2011.06.019>.
- Burkhard, B., Müller, A., Müller, F., Grescho, V., Anh, Q., Arida, G., Bustamante, J.V. (Jappan), Van Chien, H., Heong, K.L., Escalada, M., Marquez, L., Thanh Truong, D., Villareal, S. (Bong), Settele, J., 2015. Land cover-based ecosystem service assessment of irrigated rice cropping systems in southeast Asia—an explorative study. *Ecosyst. Serv.* 14, 76–87. <http://dx.doi.org/10.1016/j.ecoser.2015.05.005>.
- Cain, J., 2001. Planning improvements in natural resources management: guidelines for using Bayesian networks to support the planning and management of development programmes in the water sector and beyond. *Ecology* 44, 132.
- Catling, H.D., Hobbs, P.R., Islam, Z., Alam, B., 1983. Agronomic practices and yield assessments of deepwater rice in Bangladesh. *F. Crop. Res.* 6, 109–132. [http://dx.doi.org/10.1016/0378-4290\(83\)90052-7](http://dx.doi.org/10.1016/0378-4290(83)90052-7).
- Chan, K.M.A., Shaw, M.R., Cameron, D.R., Underwood, E.C., Daily, G.C., 2006. Conservation planning for ecosystem services. *PLoS Biol.* 4, 2138–2152. <http://dx.doi.org/10.1371/journal.pbio.0040379>.
- Charniak, E., 1991. Bayesian networks without tears. *AI Mag.* 12, 50. <http://dx.doi.org/10.1609/aimag.v12i4.918>.
- Datta, S.K. De, 1981. Principles and Practices of Rice Production. A Wiley-Interscience publication doi:10.1007/s13398-014-0173-7-2.
- Dawe, D., 2010. The rice crisis: market, policies and food security, The Rice Crisis: Markets, Policies and Food Security. The Food and Agriculture Organization of the United Nations and Earthscan. doi:10.4324/9781849776684.
- de Baar, H.J.W., 1994. von Liebig's law of the minimum and plankton ecology (1899–1991). *Prog. Oceanogr.* 33, 347–386. [http://dx.doi.org/10.1016/0079-6611\(94\)90022-1](http://dx.doi.org/10.1016/0079-6611(94)90022-1).
- Defra, 2007. An introductory Guide to Valuing Ecosystem Services, Forestry. Department for Environment, Food and Rural Affairs.
- Dlamini, W.M., 2010. A Bayesian belief network analysis of factors influencing wildfire occurrence in Swaziland. *Environ. Model. Softw.* 25, 199–208. <http://dx.doi.org/10.1016/j.envsoft.2009.08.002>.
- Dobermann, A., Fairhurst, T., 2000. Rice: nutrient disorders & nutrient management, Handbook Series.
- Dunbar, M.B., Panagos, P., Montanarella, L., 2013. European perspective of ecosystem services and related policies. *Integr. Environ. Assess. Manage.* 9, 231–236. <http://dx.doi.org/10.1002/ieam.1400>.
- FAO, 2011. Save and Grow, A policymaker's guide to sustainable intensification of smallholder crop production. doi:10.1787/9789264162600-en.
- FAO, 2000. Bridging the Rice Yield Gap in the Asia-Pacific Region. Food and Agriculture Organization, FAO.
- FAO, 1991. Manual on fertilizer statistics. Food and Agriculture Organization of the United Nations, Viale delle Terme di Caracalla, 00100 Rome, Italy.
- Farmani, R., Henriksen, H.J., Savic, D., 2009. An evolutionary Bayesian belief network methodology for optimum management of groundwater contamination. *Environ. Model. Softw.* 24, 303–310. <http://dx.doi.org/10.1016/j.envsoft.2008.08.005>.
- Gilliom, R.J., Barbash, J.E., Crawford, C.G., Hamilton, P.A., Martin, J.D., Nakagaki, N., Nowell, L.H., Scott, J.C., Stackelberg, P.E., Thelin, G.P., Wolock, D.M., 2006. Pesticides in the Nation's Streams and Groundwater, 1992–2001: U.S. Geological Survey, Circular 1291.
- Glickman, M.E., van Dyk, D., a, 2007. Basic Bayesian methods. *Methods Mol. Biol.* 404, 319–338. http://dx.doi.org/10.1007/978-1-59745-530-5_16.
- Guo, H., Hsu, W., 2002. A survey of algorithms for real-time Bayesian network inference. *Jt. Work. Real-Time Decis. Support Diagnosis*.

- Gupta, P.C., Toole, J.C.O., 1986. Upland Rice: A Global Perspective. International rice research institute, Philippines.
- Haines-Young, R., 2011. Exploring ecosystem service issues across diverse knowledge domains using Bayesian Belief Networks. *Prog. Phys. Geogr.* 35, 681–699. <http://dx.doi.org/10.1177/0309133311422977>.
- Haines-Young, R., Potschin, M., 2012. Common International Classification of Ecosystem Services (CICES, Version 4.1) 1–17.
- Heong, K.L., Cheng, J., Escalada, M.M., 2015a. Rice planthoppers: Ecology, management, socio economics and policy. *Rice Planthoppers Ecol. Manag. Socio Econ. Policy* 1–231. doi:10.1007/978-94-017-9535-7.
- Heong, K.L., Escalada, M.M., 2015. Are there productivity gains from insecticide applications in rice production? 181–192. doi:10.1007/978-94-017-9535-7-9
- Heong, K.L., Schoenly, K.G., 1998. Impact of insecticides on herbivore-natural enemy communities in tropical rice ecosystems. *Ecotoxicol. Pestic. Benef. Org.*
- Heong, K.L., Wong, L., Reyes, J.H.D., 2015b. Addressing planthopper threats to Asian rice farming and food security: Fixing insecticide misuse. *Rice Planthoppers Ecol. Manag. Socio Econ. Policy* 65–76. doi:10.1007/978-94-017-9535-7-3
- Hoang, H.T.T., 2014. Multi-scale Analysis of Human-Environment Interactions. A Case-study in the Northern Vietnamese Mountains. Katholieke Universiteit Leuven.
- Hoang, H.T.T., Vanacker, V., Van Rompaey, A., Vu, K.C., Nguyen, A.T., 2014. Changing human-landscape interactions after development of tourism in the northern Vietnamese Highlands. *Anthropocene* 5, 42–51. <http://dx.doi.org/10.1016/j.anucene.2014.08.003>.
- Hou, Y., Burkhard, B., Müller, F., 2013. Uncertainties in landscape analysis and ecosystem service assessment. *J. Environ. Manage.* 127, S117–S131. <http://dx.doi.org/10.1016/j.jenvman.2012.12.002>.
- Hough, R.L., Towers, W., Aalders, I., 2010. The risk of peat erosion from climate change: land management combinations—an assessment with Bayesian belief networks. *Hum. Ecol. Risk Assess. An Int. J.* 16, 962–976. <http://dx.doi.org/10.1080/10807039.2010.511964>.
- Huan, N.H., Thiet, L.V., Chien, H.V., Heong, K.L., 2005. Farmers' participatory evaluation of reducing pesticides, fertilizers and seed rates in rice farming in the Mekong Delta, Vietnam. *Crop Prot.* 24, 457–464. <http://dx.doi.org/10.1016/j.cropro.2004.09.013>.
- IRRI, 2006. The sustainability of rice farming. International Rice Research Institute, CAB International Publishing. International rice research institute, Philippines 10.5860/CHOICE.35-3847.
- IRRI, 1985. Progress in upland rice research, Progress in upland rice research. The International Rice Research Institute, P.O. Box 933, Manila, Philippines.
- IRRI, 1984. Research Priorities in Tidal Swamp Rice, PhD Proposal. The International Rice Research Institute. doi:10.1017/CBO9781107415324.004.
- IRRI, 1982. Rice Research Strategies for the Future. International rice research institute, Philippines.
- Jacobs, S., Wolfstein, K., Vandenbruwaene, W., Vrebos, D., Beauchard, O., Maris, T., Meire, P., 2015. Detecting ecosystem service trade-offs and synergies: a practice-oriented application in four industrialized estuaries. *Ecosyst. Serv.* 16, 378–389. <http://dx.doi.org/10.1016/j.ecoser.2014.10.006>.
- Ji, Q., Marefat, M.M., 1995. Bayesian approach for extracting and identifying features. *Comput. Des.* 27, 435–454. [http://dx.doi.org/10.1016/0010-4485\(95\)00017-L](http://dx.doi.org/10.1016/0010-4485(95)00017-L).
- Jones, L., Norton, L., Austin, Z., Browne, A.L., Donovan, D., Emmett, B.A., Grabowski, Z.J., Howard, D.C., Jones, J.P.G., Kenter, J.O., Manley, W., Morris, C., Robinson, D.A., Short, C., Siriwardena, G.M., Stevens, C.J., Storkey, J., Waters, R.D., Willis, G.F., 2016. Stocks and flows of natural and human-derived capital in ecosystem services. *Land Use Policy* 52, 151–162. <http://dx.doi.org/10.1016/j.landusepol.2015.12.014>.
- Jørgensen, S.E., 2016. Handbook of Ecological Models Used in Ecosystem and Environmental Management. CRC Press.
- Jørgensen, S.E., 2012. Introduction to Systems Ecology. CRC Press.
- Jørgensen, S.E., 2010. Ecosystem services, sustainability and thermodynamic indicators. *Ecol. Complex* 7, 311–313. <http://dx.doi.org/10.1016/j.ecocom.2009.12.003>.
- Jørgensen, S.E., 2009. Ecological Modelling: An Introduction. WIT Press.
- Jørgensen, S.E., 2006a. Application of holistic thermodynamic indicators. *Ecol. Indic.* 6, 24–29. <http://dx.doi.org/10.1016/j.ecolind.2005.08.003>.
- Jørgensen, S.E., 2006b. Eco-exergy as sustainability. *Sustain. World Vol 16* 207 p.
- Jørgensen, S.E., 2002. Integration of Ecosystem Theories – a Pattern. Springer Publishers.
- Jørgensen, S.E., Burkhard, B., Müller, F., 2013. Twenty volumes of ecological indicators—an accounting short review. *Ecol. Indic.* 28, 4–9.
- Jørgensen, S.E., Fath, B., 2011. Fundamentals of Ecological Modelling. Elsevier Publishers.
- Jørgensen, S.E., Fath, B., Bastianoni, S., Marques, J.C., Müller, F., Nielsen, S.N., Patten, B.C., Tiezzi, E., Ulanowicz, R.E., 2011. A new Ecology: Systems Perspective. Elsevier Publishers.
- Jørgensen, S.E., Fath, B.D., Nielsen, S.N., Pulselli, F.M., Fiscus, D.A., Bastianoni, S., 2015a. Flourishing within limits to growth. flourishing within limits to growth follow. *Nature's W* 1–220. <http://dx.doi.org/10.4324/9781315731445>.
- Jørgensen, S.E., Marques, J.C., Anastácio, P.M., 1997. Modelling the fate of surfactants and pesticides in a rice field. *Ecol. Modell.* 104, 205–213. [http://dx.doi.org/10.1016/S0304-3800\(97\)00134-8](http://dx.doi.org/10.1016/S0304-3800(97)00134-8).
- Jørgensen, S.E., Marques, J.C., Nielsen, S.N., 2015b. Integrated Environmental Management. CRC Press.
- Jørgensen, S.E., Nielsen, S.N., 2015. A carbon cycling model developed for the renewable Energy Danish Island. *Samsø. Ecol. Modell.* 306, 106–120.
- Jørgensen, S.E., Nielsen, S.N., 2014. Use of eco-exergy in ecological networks. *Ecol. Modell.* 293, 202–209. <http://dx.doi.org/10.1016/j.ecolmodel.2014.05.007>.
- Jørgensen, S.E., Nielsen, S.N., 2007. Application of exergy as thermodynamic indicator in ecology. *Energy* 32, 673–685. <http://dx.doi.org/10.1016/j.energy.2006.06.011>.
- Jørgensen, S.E., Nielsen, S.N., 1996. Application of ecological engineering principles in agriculture. *Ecol. Eng.* 7, 373–381. [http://dx.doi.org/10.1016/S0925-8574\(96\)00018-3](http://dx.doi.org/10.1016/S0925-8574(96)00018-3).
- Jørgensen, S.E., Svirezhev, Y.M., 2004. Towards a Thermodynamic Theory for Ecological Systems. Elsevier Publishers.
- Jørgensen, S.E., Xu, L., Costanza, R., 2016. Handbook of Ecological Indicators for Assessment of Ecosystem Health. CRC Press.
- Kandziora, M., Burkhard, B., Müller, F., 2013a. Mapping provisioning ecosystem services at the local scale using data of varying spatial and temporal resolution. *Ecosyst. Serv.* 4, 47–59. <http://dx.doi.org/10.1016/j.ecoser.2013.04.001>.
- Kandziora, M., Burkhard, B., Müller, F., 2013b. Interactions of ecosystem properties, ecosystem integrity and ecosystem service indicators—a theoretical matrix exercise. *Ecol. Indic.* 28, 54–78. <http://dx.doi.org/10.1016/j.ecolind.2012.09.006>.
- Kleemann, J., Celio, E., Fürst, C., 2017. Validation approaches of an expert-based Bayesian Belief Network in Northern Ghana, West Africa. *Ecol. Modell.* 365, 10–29. <http://dx.doi.org/10.1016/j.ecolmodel.2017.09.018>.
- Klotzbücher, T., Marxen, A., Jahn, R., Vetterlein, D., 2016. Silicon cycle in rice paddy fields: insights provided by relations between silicon forms in topsoils and plant silicon uptake. *Nutr. Cycl. Agroecosyst.* 157–168. <http://dx.doi.org/10.1007/s10705-016-9782-1>.
- Klotzbücher, T., Marxen, A., Vetterlein, D., Schneiker, J., Turke, M., Van Sinh, N., Manh, N.H., Van Chien, H., Marquez, L., Villareal, S., Bustamante, J.V., Jahn, R., 2014. Plant-available silicon in paddy soils as a key factor for sustainable rice production in Southeast Asia. *Basic Appl. Ecol.* 16, 665–673. <http://dx.doi.org/10.1016/j.baae.2014.08.002>.
- Kragt, M.E., 2009. A beginners guide to Bayesian network modelling for integrated catchment. *Landscape Log.* 22.
- Kruschke, J.K., 2015. Doing Bayesian data analysis, second ed. John K. Kruschke. Elsevier Inc. 10.1002/9781444395105.fmatter.
- Kubo, M., Purevdorj, M., 2004. The future of rice production and consumption. *J. Food Distrib. Res.* 35, 128–142.
- 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. *Environ. Model. Softw.* 46, 1–11. <http://dx.doi.org/10.1016/j.envsoft.2013.03.011>.
- McCann, R.K., Marcot, B.G., Ellis, R., 2006. Bayesian belief networks: Applications in ecology and natural resource management. *Can. J. For. Res.* 36, 3053–3062. <http://dx.doi.org/10.1139/x06-238>.
- McLean, J., Hardy, B., Hettel, G., GRiSP, 2013. *Rice Almanac, fourth ed.* Global Rice Science Partnership. International rice research institute, Los Baños, Philippines 10.1093/aob/mcg189.
- McVittie, A., Norton, L., Martin-Ortega, J., Siameti, I., Glenk, K., Aalders, I., 2015. Operationalizing an ecosystem services-based approach using Bayesian Belief Networks: an application to riparian buffer strips. *Ecol. Econ.* 110, 15–27. <http://dx.doi.org/10.1016/j.ecolecon.2014.12.004>.
- Millennium Ecosystem Assessment, 2005. Ecosystems and human well-being. *Ecosystems.* <http://dx.doi.org/10.1196/annals.1439.003>.
- Müller, F., Burkhard, B., Hou, Y., Kruse, M., Ma, L., Wangai, P., 2016. Indicators for ecosystem services. In: *Handbook on Ecosystem Services*. Routledge handbooks, pp. 157–169.
- Müller, F., de Groot, R., Willemen, L., 2010. Ecosystem services at the landscape scale: the need for integrative approaches. *Landscape Online* 23, 1–11. <http://dx.doi.org/10.3097/LO.201023>.
- Müller, F., Jørgensen, S.E., 2000. Ecological Orientors: A Path to Environmental Applications of Ecosystem Theories. In: Jørgensen, S.E., Müller, F. (Eds.), *Handbook of Ecosystem Theories and Management*. CRC Publishers, New York.
- Nguyen, H., Dang, K.B., Dang, V.B., 2011. Application of N-SPECT model and GIS for soil erosion assessment in Sapa district, Lao Cai province. *J. Earth Sci. Vietnam Natl. Univ. Publ.* 27, 199–207.
- Nicholson, A.E., Korb, K.B., 2004. Bayesian AI tutorial. *Technology* 1, 2009. <http://dx.doi.org/10.1007/s00261-003-0121-z>.
- Norsys, 2010. Netica-J reference manual. Norsys Software Corp.
- Ongley, E.D., 1996. Control of water pollution from agriculture - FAO irrigation and drainage paper 55 5–7.
- Palmeri, L., Barausse, A., Jørgensen, S.E., 2013. *Ecological Processes Handbook*. CRC Press.
- Petter, M., Mooney, S., Maynard, S.M., Davidson, A., Cox, M., Horosak, I., 2013. A methodology to map ecosystem functions to support ecosystem services assessments. *Ecol. Soc.* 18. <http://dx.doi.org/10.5751/ES-05260-180131>.
- Pirmoradian, N., Sepaskhah, A.R., 2006. A very simple model for yield prediction of rice under different water and nitrogen applications. *Biosyst. Eng.* 93, 25–34. <http://dx.doi.org/10.1016/j.biosystemseng.2005.09.004>.
- Poppenborg, P., Koellner, T., 2014. A Bayesian network approach to model farmers' crop choice using socio-psychological measurements of expected benefits of ecosystem services. *Environ. Model. Softw.* 57, 227–234. <http://dx.doi.org/10.1016/j.envsoft.2014.03.006>.
- Potschin, M., Haines-Young, R., Fish, R., Turner, R.K., 2016. *Routledge Handbook of Ecosystem Services*. Routledge.
- Power, A.G., 2010. Ecosystem services and agriculture: tradeoffs and synergies. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.* 365, 2959–2971. <http://dx.doi.org/10.1098/rstb.2010.0143>.
- Barker, Randolph, Herdt, Robert W., Rose, B., 1986. *The Rice Economy of Asia, Resources for the Future*. Resources for the Future and IRRI, US 10.1097/00010694-198612000-00011.
- Schipanski, M.E., Barbercheck, M., Douglas, M.R., Finney, D.M., Haider, K., Kaye, J.P., Kemanian, A.R., Mortensen, D.A., Ryan, M.R., Tooker, J., White, C., 2014. A framework for evaluating ecosystem services provided by cover crops in agroecosystems. *Agric. Syst.* 125, 12–22. <http://dx.doi.org/10.1016/j.agry.2013.11.004>.

- Schulp, C.J.E., Burkhard, B., Maes, J., Van Vliet, J., Verburg, P.H., 2014. Uncertainties in ecosystem service maps: a comparison on the European scale. *PLoS One* 9, e109643. <http://dx.doi.org/10.1371/journal.pone.0109643>.
- Settele, J., Spangenberg, J.H., Heong, K.L., Burkhard, B., Bustamante, J.V., Cabbigat, J., Van Chien, H., Escalada, M., Grescho, V., Hai, L.H., Harpke, A., Horgan, F.G., Hotes, S., Jahn, R., Kühn, I., Marquez, L., Schädler, M., Tekken, V., Vetterlein, D., Villareal, S.B., Westphal, C., Wiemers, M., 2015. Agricultural landscapes and ecosystem services in South-East Asia-The LEGATO-Project. *Basic Appl. Ecol.* 16, 661–664. <http://dx.doi.org/10.1016/j.baae.2015.10.003>.
- Sharp, R., Tallis, H., Ricketts, T., Guerry, A., Wood, S., Chaplin-kramer, R., Nelson, E., Ennaanay, D., Wolny, S., Olwero, N., Vigerstol, K., Pennington, D., Mendoza, G., Aukema, J., Foster, J., Forrest, J., Cameron, D., Arkema, K., Lonsdorf, E., Kennedy, C., Verutes, G., Kim, C., Guannel, G., Papenfus, M., Toft, J., Marsik, M., Bernhardt, J., Griffin, R., Glowinski, K., Chaumont, N., Perelman, A., Lacayo, M., Mandle, L., Griffin, R., Hamel, P., 2016. *INVEST 3.0.1 User's Guide*, The Natural Capital Project, Stanford. The Natural Capital Project.
- Slaets, J.L.F., Schmitter, P., Hilger, T., Vien, T.D., Cadisch, G., 2015. Sediment trap efficiency of paddy fields at the watershed scale in a mountainous catchment in Northwest Vietnam. *Biogeosci. Discuss.* 12, 20437–20473. <http://dx.doi.org/10.5194/bgd-12-20437-2015>.
- Soediono, B., 1989. Land cover based ecosystem service assessment of irrigated rice cropping systems in Southeast Asia – an explorative study of areas with different production intensities Anja. *J. Chem. Inf. Model.* 53, 160. <http://dx.doi.org/10.1017/CBO9781107415324.004>.
- Swinton, S.M., Lupi, F., Robertson, G.P., Hamilton, S.K., 2007. Ecosystem services and agriculture: cultivating agricultural ecosystems for diverse benefits. *Ecol. Econ.* 64, 245–252. <http://dx.doi.org/10.1016/j.ecolecon.2007.09.020>.
- Taalab, K., Corstanje, R., Zawadzka, J., Mayr, T., Whelan, M.J., Hannam, J.A., Creamer, R., 2015. On the application of Bayesian Networks in Digital Soil Mapping. *Geoderma* 259–260, 134–148. <http://dx.doi.org/10.1016/j.geoderma.2015.05.014>.
- Tadele, Z., 2017. Raising crop productivity in Africa through Intensification. *Agronomy* 7, 22. <http://dx.doi.org/10.3390/agronomy7010022>.
- Searchinger, Tim, 2013. *Creating a Sustainable Food Future: A menu of solutions to sustainably feed more than 9 billion people by 2050*, World Resources Report 2013–14. World Resources Institute 10.1016/S0264-8377(03)00047-4.
- Troldborg, M., Aalders, I., Towers, W., Hallett, P.D., McKenzie, B.M., Bengough, A.G., Lilly, A., Ball, B.C., Hough, R.L., 2013. Application of Bayesian belief networks to quantify and map areas at risk to soil threats: using soil compaction as an example. *Soil Tillage Res.* 132, 56–68. <http://dx.doi.org/10.1016/j.still.2013.05.005>.
- Uusitalo, L., 2007. Advantages and challenges of Bayesian networks in environmental modelling. *Ecol. Modell.* 203, 312–318. <http://dx.doi.org/10.1016/j.ecolmodel.2006.11.033>.
- Viera, A.J., Garrett, J.M., 2005. Understanding interobserver agreement: the kappa statistic. *Fam. Med.* 37, 360–363.
- Virmani, S., Siddiq, E., Muralidharan, K., 1996. *Advances in Hybrid Rice Technology*. In: Proceedings of the 3rd International Symposium on Hybrid Rice. IRRI, India. doi:10.1017/S001447970031211X
- Way, M.J., Heong, K.L., 1994. The role of biodiversity in the dynamics and management of insect pests of tropical irrigated rice—a review. *Bull. Entomol. Res.* 84, 567–587. <http://dx.doi.org/10.1017/S000748530003282X>.
- Wu, Y., Chen, J., 2013. Estimating irrigation water demand using an improved method and optimizing reservoir operation for water supply and hydropower generation: A case study of the Xinfengjiang reservoir in southern China. *Agric. Water Manage.* 116, 110–121. <http://dx.doi.org/10.1016/j.agwat.2012.10.016>.
- Xue, J., Gui, D., Lei, J., Sun, H., Zeng, F., Feng, X., 2016. A hybrid Bayesian network approach for trade-offs between environmental flows and agricultural water using dynamic discretization. *Adv. Water Resour.* 1–14. <http://dx.doi.org/10.1016/j.advwatres.2016.10.022>.
- Youshida, S., 1981. *Fundamentals of Rice Crop Science*. International rice research institute, Los Baños, Philippines.

Appendix chapter 4: Data sources and description of the explanatory/independent variables (The states have been classified based on equal intervals of collected data, the numbers of variables are linked to the corresponding nodes in the BBN).

No.	Variable (Node)	Type	Source	State (ranges)
Ecosystem services variables:				
1	Rice provisioning service supply	Discrete	Used rice yield (from interviews) as an indicator	From "No" capacity to "Very high" capacity (6 states)
2	Rice provisioning service demand	Discrete	Derived based on two situations of local population	From "No" capacity to "Very high" capacity (6 states)
3	Rice provisioning service budget	Discrete	Derived from comparison between supply and demand	Unused supply (supply equal as or higher than demand), Unmet demand (supply lower than demand)
Ecosystem functions variables:				
4	Photosynthesis process	Discrete	Referred from IRR1 (2006, 1985)	Effective, Ineffective
5	Water availability	Discrete	Derived from hydrological variables based on multiple linear regression models	Sufficient, Insufficient
6	Nutrient availability	Discrete	Derived from nutrient variables based on multiple linear regression models	Fertile, Infertile
Abiotic variables representing ecological structures and processes:				
7	Solar radiation	Discrete	Referred from IRR1 (2006, 1985)	Weak, strong, very strong
8	Temperature	Continuous	Downloaded from WorldClim ¹⁰ website - Free global climate data (period of 1960-1990)	< 21.5, 21.5 - 22.5; > 22.5 degree Celsius
9	Precipitation	Continuous	Meteorological Services weather stations of the Lao Cai province (period of 1990-2006)	<1820 mm, 1820 - 1930 mm; >1930 mm
10	Evapotranspiration	Continuous	Calculated from "Water yield" model in InVEST tool	<890 mm, 890 - 1000 mm, >1000 mm
11	Ratio of evapotranspiration (AET) to precipitation (P)	Continuous	Calculated from "Water yield" model in InVEST tool	Low (< 0.45), Medium (0.45 - 0.55), High (> 0.55)
12	Length of flow	Continuous	Derived from the DEM (10 m resolution)	< 5700 m, 5700 - 7000 m, > 7000 m

¹⁰ <http://www.worldclim.org/>

13	Distance to upstream forest	Continuous	Derived from the DEM and LULC (10 m resolution)	< 280 m, 280 - 900 m, > 900 m
14	Released water on surface	Continuous	Calculated from "Water yield" model in InVEST tool	< 800 mm, 800 - 1100 m, > 1100 m
15	Elevation	Continuous	Derived from the DEM (10 m resolution)	< 1030 m, 1030 - 1120 m, 1120 - 1240 m, > 1240 m (above sea level)
16	Slope	Continuous	Derived from the DEM (10 m resolution)	< 13 degree, 13 - 18 degree, 18 - 24 degree, > 24 degree
17	Height of terraces	Continuous	Derived from the DEM and LULC (10 m resolution)	< 1.1 m, 1.1 - 1.7 m, > 1.7 m
18	Soil erosion	Continuous	Calculated from "Sediment retention" model in InVEST tool	< 1.8 ton, 1.8 - 2.8 ton, > 2.8 ton (per ha. year)
19	Bedrock	Discrete	Geology map from the Center for Information and Archives of Geology at the General Department of Geology and Minerals of Vietnam	Diorite, Granit, Limestone
20	Soil	Discrete	Soil map from the Department of Geography at the Hanoi University of Science	Plinthic Acrisols, Humic Acrisols, Humic Ferrasols
21	Silicon	Discrete	Referred from Klotzbücher et al., 2016, 2014	Rich, poor
Anthropogenic variables:				
22	Compound fertilizers	Continuous	Interviews in 2010-2011 (Unit: kg/ha per year)	< 45 kg, 45 - 70 kg, 70 - 100 kg, > 100 kg
23	Straight fertilizers	Continuous	Interviews in 2010-2011 (Unit: kg/ha per year)	< 30 kg, 30 - 50 kg, 50 - 100 kg, > 100 kg
24	Investment	Continuous	Interviews in 2010-2011 (Unit: Million VND/ha.year)	< 3.5 mVND, 3.5 - 5.8 mVND, > 5.8 mVND (per year) (mVND: million VND)
25	Seed rice	Discrete	Interviews in 2010-2011	Chinese hybrid, Vietnamese hybrid, Vietnamese inbred
26	Pesticide	Discrete	Interviews in 2015 and Referred Heong et al., 2015	Not used, used
27	Spraying period	Discrete	Referred Heong and Escalada, 2015, 2015; Heong and Schoenly, 1998; Huan et al., 2005; Way et al., 1994	Beginning, Middle (of cropping seasons)
28	Pest and disease	Discrete		Prevented, Outbreak
29	Farming practice	Discrete	Derived from human variables based on multiple linear regression models	Effective, ineffective
30	Human demand	Discrete	Two situation of rice demand: Business as usual (BAU) and population growth	Stable, increase (of population)

Chapter 5.

Potential, supply, flow and demand of rice provisioning ecosystem services - Case study in Sapa district, Vietnam

Kinh Bac Dang, Benjamin Burkhard, Felix Müller,
Wilhelm Windhorst, Van Bao Dang

(Will be submitted to "Landscape Online" journal in May 2018)

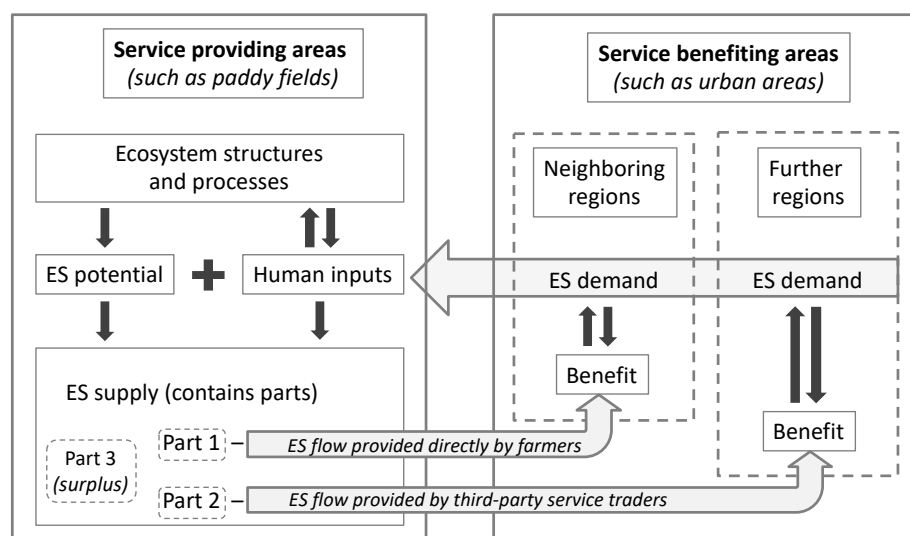


Figure 8 (Graphical abstract). A general framework of the Rice Provisioning Ecosystem service supply chain from service providing areas to service benefiting areas; Grey arrows present the movements of material, energy or information related to rice provision across space; Dark arrows present the one or two ways relations between the components. Part 3 of Ecosystem Service (ES) supply can be stored and supplied for parts 1 and 2 avoiding famine threats, or the exports to the global market.

Abstract:

Although Vietnam has become the third biggest rice exporter in the world, famine is yet challenging managers in many provinces, especially in the Northern mountainous areas of Vietnam. In contrast with financial profits, formal rice supply chains have recently not provided enough food for all people in these provinces. The ecosystem service approach has given chances to better communicate with agricultural managers by raising awareness and improving understanding related to potential, flow and demand of/for rice provision. In this study, probability approaches through a Bayesian Belief Network and statistical approaches through a Hybrid Neural-Fuzzy Inference System were used to quantify and map the potentials of the rice provisioning ecosystem service (RPES) in the Sapa district in the Lao Cai province in northern Vietnam. In addition, various statistical data related to actual rice production, population numbers and rice consumption were collected from 1990 to 2010 to quantify the flows and demands of/for RPES. A conceptual model depicting the relations between RPES potential, supply, flow and demand is proposed, in which the efficiency of site selection for rice cultivation and implemented farming practices play important roles in determining RPES supply. The results indicate an ineffective use of farming practices in the 1990s and show improvements in the new millennium in the case study area. A small surplus of RPES supply was found in the whole Sapa district since the year 2003, which has been used for tourism and export purposes. At the same time, the RPES demand was unmet in six communities. To generate a better rice supply chain and to match supplies with demand, the surplus of RPES should be transported from service providing areas to neighboring poor communities.

Keywords: ecosystem service supply chain, potential, flow, demand, budget, Bayesian Belief Network, hybrid neural-fuzzy inference system

Highlights:

- Relations between rice provisioning ecosystem service potential, flow and demand are assessed.
- Crop productivity can be used as an indicator to assess the potential/flow of rice provisioning ecosystem services at regional scales, demand for this service depends on rice consumption and population dynamics.
- Short and efficient ecosystem service supply chains for rice can prevent famine threats and reduce environmental impacts.
- Bayesian Belief Networks and Hybrid neural-Fuzzy Inference Systems can be used as tools for regional decision making.

1. Introduction

In 2016/2017, the US Department of Agriculture¹¹ recorded Vietnam as the third biggest rice exporter of the world, but this ranking did not demonstrate that there was no hunger in Vietnam. Reports from the General Statistics Office of Vietnam¹² indicate that the national poverty rate in Vietnam has been higher than 7 % and that nearly 270,000 households have been suffering from food shortage, especially in the north-eastern mountainous communities (General Statistics Office of Vietnam, 2016). Due to high interests in financial profits, the surplus of rice products from providing communities has often been exported to more developed regions (Wailes, 2004; FAO, 2000; Minor et al., 2017), instead of being transferred to poorer communities. Therefore, it is necessary to locate rice ecosystem Service Providing Areas (SPA) and Service Benefiting Areas (SBA; Walz et al., 2017) and communities and to assess potentials for rice provision in poorer communities where hunger exists (Demont and Rutsaert, 2017). These areas can be identified by understanding the spatial relations between (potential and actual) food supply and demand at regional and national levels (Bukvareva et al., 2017; Minor et al., 2017).

1.1. Background

Nowadays, Ecosystem Service (ES) assessments have started to positively affect agricultural policies due to their potential to reveal the direct connections of ES, ecosystem functions and anthropogenic contributions in agro-ecosystems (Burkhard et al., 2014a, 2012a; Villamagna et al., 2013). ES are generated based on ecosystem structures and processes which lead to ecological functions and ES which are delivered to human communities along ES supply chains (Lähtinen et al., 2016; Potschin et al., 2016; Tallis et al., 2012; Van Alfen, 2014). ES supply chains related to crop products from agro-ecosystems have been depicted as complex human-environmental systems, leading from the crop production on agricultural fields to final consumers (Burkhard et al., 2014).

In this study, Rice Provisioning Ecosystem Services (RPES) supply chains can be understood as an integrated system of rice production, distribution and consumption. One related management target is yield maximization based on sustainable agriculture and preventing famine threats. A sustainable system need to ensure that the demand for rice is fulfilled, including the poorer households. Moreover, environmental issues such as pollution and soil degradation are to be minimized (ADB, 2012; Barbosa-Póvoa, 2009; Tseng et al., 2018). Such supply-demand chains are commonly managed at different administrative levels, from farming plots to national levels (Galli and Brunori, 2013). The production process transforms natural resources (e.g. nutrients, water and energy from nature) and additional inputs introduced by humans (e.g. fertilizers, seeds, energy and labor) into rice products (Bukeviciute et al., 2009). The farmers' main objectives are to contribute to the quality and quantity

¹¹ <https://www.statista.com/>

¹² <https://www.gso.gov.vn/>

of their end-products. Officers at community levels play an important role in both rice production and distribution, including training farming practices and suggesting areas suitable for rice cultivation. Thereby, they partly also contribute to the quantity and quality of rice. They implement policies from higher levels (e.g. province and national levels) and guide farmers in using agricultural lands in more sustainable ways (Pullman and Wu, 2012). Additionally, officers from the community and regional levels need to find consumer markets for the produced rice. The transportation process from providing areas to consumers are usually implemented through third-party service providers such as food dealers, food companies and retailers (ADB, 2012; Burkhard et al., 2014a; FAO, 2017) under the management of community and regional units. Therefore, analyses at community and regional scales have been chosen as main spatial scales for this study.

Famine threats at community levels and an increase of environmental issues indicate disturbed or inefficient RPES supply chains. Crop failures and increasing food demands due to increasing population and tourist developments are main causes of famine threats (FAO, 2017, 2015). Intensive farm management based on chemical products such as mineral fertilizers, herbicides and pesticides could result in negative effects on the environment including soil degradation, biodiversity loss, eutrophication and the increase of nitrate leaching into the groundwater (Kamoshita, 2007). The overuse of pesticides, especially by plant-hopper outbreaks in the beginning of a rice sowing period, can cause negative impacts on rice production (Heong et al., 2015; Way et al., 1994).

In order to improve the efficiency of RPES supply chains, decision makers at community and regional levels need to identify three key issues, including (1) Service Providing Areas (SPA) and Service Benefiting Areas (SBA) as well as their spatial relations (see Walz et al., 2017), (2) the potential and actual amount of rice provided by SPAs, and (3) the rice demand from SBAs. In such a system, SPAs can be understood as spatially explicit regions providing RPES based on specific environmental conditions and rice farming practices (Egoh et al., 2008; García-Nieto et al., 2013; Syrbe and Walz, 2012). SBAs are spatially explicit regions where humans benefit from RPES that are provided and exported from the SPAs (Syrbe and Grunewald, 2017; Syrbe and Walz, 2012). Depending on the spatial relations between RPES providing areas (representing RPES potential, supply and their actual use/flow) and RPES benefitting areas, the SPA can coincide (being “*in situ*”) with the SBA; or the areas can be spatially *decoupled* from each other (Burkhard et al., 2014; Walz et al., 2017; Fisher et al. 2009). An *in situ* SPA-SBA relation of RPES supply would mean that farmers in an agricultural community would use their rice products for their own families. A decoupled supply takes place in case of food trades from agricultural communities to areas of food demand, such as industrial cities (Serna-Chavez et al., 2014).

Understanding spatial ES supply relations in a particular region does not automatically reduce transportation costs and related environmental effects, but it can raise awareness for alternative direct marketing approaches from suppliers to consumers (Uthes and Matzdorf, 2016). The costs for RPES

in direct marketing systems are usually lower than in import-based systems, because consumers do not need to pay for operational and transport costs in long supply chains (Burkhard et al., 2014a). Long supply chains usually lead to increased prices of rice (and other products) because traders, refinement, selling and transporting entities need to be compensated (ADB, 2012). If managers cannot provide more simple (and logical) supply chains for rice products, local people have to buy rice at more expensive prices, which is a burden especially for poor people.

The overall aim of this research is to indicate the balance between RPES supply and demand (the RPES budget) on different spatial scales with a special focus on the community and the regional scale in order to understand RPES supply chains. At first, the RPES supply chain, including potential supply, flow and demand, will be analyzed. Then, two methods to estimate and map RPES supply through “Bayesian Belief Networks” (BBN) (developed by Dang et al. (2018c)) and a “Hybrid Neural-Fuzzy Inference System” (S-HyFIS) (developed by Dang et al. (2018b, submitted)) will be presented. Subsequently, an example using the proposed methods for the evaluation of RPES potential supply, flow and demand in the Sapa district in northern Vietnam during a 20 years period will be shown. Finally, the RPES budget will be assessed in order to find communities with under-respectively oversupply of rice ES. The following research questions - relevant for studying the budget of rice provisioning ES – were guiding this study:

- How are RPES potential supply, flow and demand related to rice imports and exports?
- Can the agricultural regions in the mountainous provinces of northern Vietnam provide sufficient rice for local people to avoid hungers and reduce poverty?
- How could managers at community/regional levels improve the RPES supply chains?

1.2. Conceptual relations between rice provisioning ecosystem services potential, supply, flow and demand

The potential of RPES can be defined as the hypothetical maximum natural yield provided by rice ecosystems, without the contribution of human inputs and regardless of whether these services will provide direct benefits to humans or not (after Bukvareva et al., 2017; Burkhard et al., 2014). Whereas, RPES supply is defined as the provision of rice in a particular time and region and is impacted by mutual interactions between natural and socio-economic capitals (Burkhard and Maes, 2017; Jones et al., 2016). Because paddy fields have been modified by human over many generations, it is difficult to separate the natural potential from the potential based on human inputs. In rice production, natural capital includes structures, processes and functions of the paddy fields which, in co-production with anthropogenic inputs into the system, deliver benefits to the human society (after Burkhard et al., 2014, 2012b). The environmental characteristics at the rice plots can generally provide typical and appropriate functions for all growing stages of the rice plants. According to IRRI (2006) and Dang et al. (2018c), three main functions from nature including the photosynthesis process

and the availability of sufficient water and nutrients need to be paid attention by the land managers. The natural ecological functions differ from rice paddy to rice paddy and also within each individual field. Hence, if agricultural managers want to optimize the RPES potential based on natural functions, the cropping plot selection has to consider suitable ecological production functions of rice ecosystems (Figure 1).

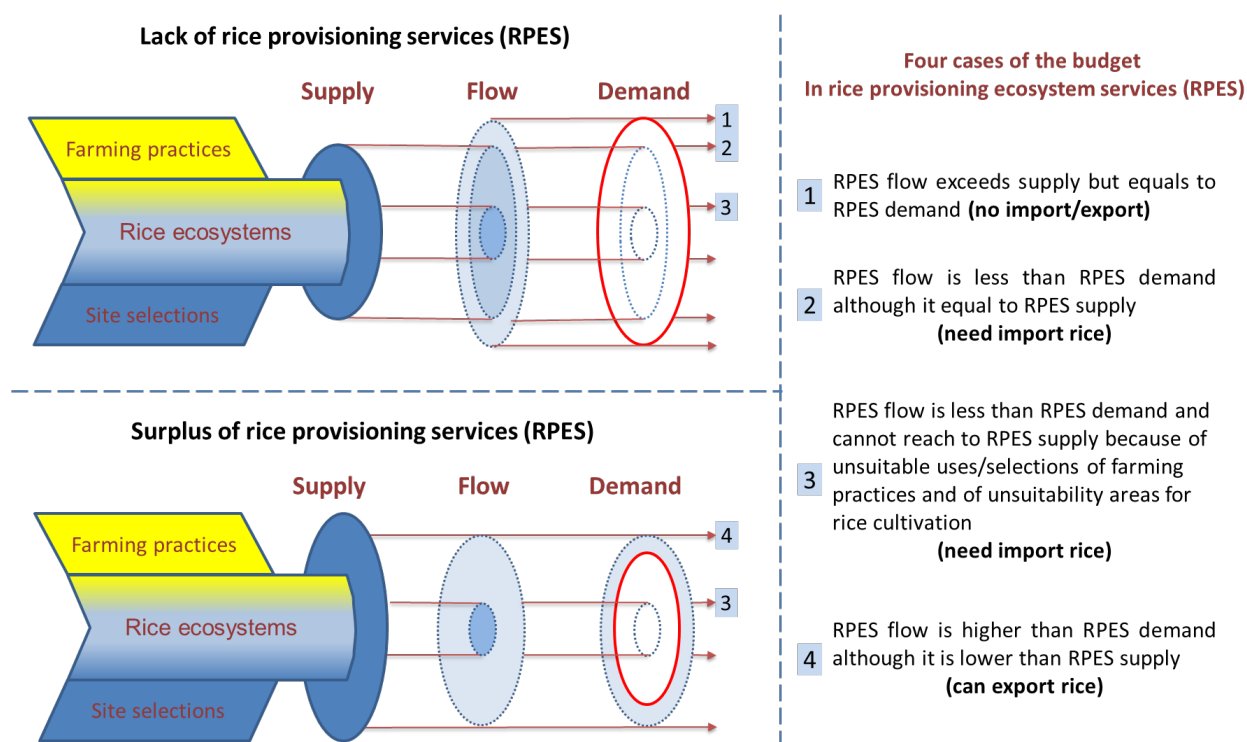


Figure 1. Conceptual model used in the study at various spatial scales, showing the relations between the supply, flow and demand of rice provisioning ecosystem services (RPES).

The socio-economic capital can be understood as additional (anthropogenic) inputs into the system, including rice plants, fertilizers, irrigation water, pesticides, labor and knowledge. Thus, the socio-economic capital in rice ecosystems includes contributions from humans related to produced capital (e.g. fertilizers, pesticides, plants and machineries), human capital (e.g. labor, knowledge, education and skills), social capital (e.g. relationships between groups of people), cultural capital (e.g. human-environmental interactions such as land use) and financial capital (e.g. amount of money invested for cultivation) (after Jones et al., 2016). Produced and financial capitals can be quantified comparably accurately. It is however difficult to quantify or optimize the other forms of capital that are needed for rice production because they include very subjective issues related to the farmers, their lifestyles and traditions. In this study, we use the term “farming practices” to represent the contributions of the socio-economic capital in rice production. Figure 1 shows different scenarios of interactions between

RPES supply, flow and demand. Each scenario has different consequences for the social-ecological system, including needs for rice imports and options to export rice.

The RPES flow is defined as the *de facto* ecosystem services supplied and used by people in a region in a given time period (Burkhard et al., 2012b) or goods and services actually mobilized to societies (Burkhard and Maes, 2017). The RPES flow is commonly distinguished from the demand for services. The demand for RPES has been defined as the amount of rice needed to ensure sufficient food supply for people living in a particular area (after Bukvareva et al., 2017; Burkhard et al., 2014; Kandziora et al., 2013). The demand connects the RPES flow to specific beneficiaries such as farmers, their families or/and regional populations. In other words, the RPES flow is transported from service providing units to service benefiting areas based on the demand for foods. In the connection between service flow and demand, the beneficiaries do not only express a service demand, but could also exchange this demand into an actual service use.

The interrelations of RPES potential, supply, flow and demand vary between different agricultural regions, between different socio-economic systems (Bukvareva et al., 2017) and during different periods of the growing cycle. If farmers select a specific site for rice cultivation and a specific farming practice, the RPES supply as well as the RPES flow are determined (Figure 1). The differentiation between RPES supply, flow and demand help to understand RPES delivery and to identify which region needs import or can actually export rice. RPES supply, flow and demand are compared through three cycles (solid blue, dot blue and red cycles in Figure 1). In regions with high population densities (such as urban areas), the demand for RPES is usually exceeding the RPES supply, leading to insufficient flows and unsatisfied demands. In agricultural regions with lower population numbers, the demand for RPES is usually also lower than the RPES supply. If the RPES budget (the balances between RPES flow and demand) is negative, the RPES flow cannot fulfill the demand of a region, even if the flow is reaching to the supply (case 2 of Figure 1). This means that local people need to import rice from other regions.

1.3. Background of Bayesian Belief Network for rice provisioning ecosystem services

Bayesian Belief Networks (BBN) are a powerful tool to overcome gaps in data, uncertainties and to understand complex causal relations in social-ecological systems (Kleemann et al., 2017). BBNs are based on Bayes's theorem - generated by Bayes (1763) – and are representing posterior probabilities of output nodes in different evidences of related input nodes (Ellison, 2004). The approach of Bayesian Belief Networks (BBN) initiated from artificial intelligence researches has become an increasingly popular method in environmental studies to simulate uncertain and complex issues through a Directed Acyclic Graph (DAG) (Uusitalo, 2007). Recently, BBNs have been used also in ecosystem service studies (Barton et al., 2008; Pascual et al., 2016).

Dang et al. (2018c) developed a BBN running in the Netica software to distinguish ecological variables, ecosystem functions, additional anthropogenic inputs and RPES (generalized in Figure 2). Developed BBNs are commonly applied for plot levels, instead of regional scales, due to the increasing complexity of the networks with increasing system sizes (Burkhard and Maes, 2017; Dang et al., 2018c). The complexity of the social-ecological system was simplified in this study through the inclusion of inter-connections between different nodes. To generate the BBN, rice yields were used as an indicator for RPES supply, whereas the number of beneficiaries using rice as a main food source were chosen as an indicator for demand for the service. 30 nodes in the developed BBN model are corresponding to 30 options of data available in a particular time and a particular region. The network can run even if the users has only data available for one or several nodes. The additional inputs from humans (including fertilizers, seeds and pesticides) were analyzed in the “farming practice” nodes. Three types of natural ecosystem functions were defined, including photosynthesis processes, water availability and nutrient availability. Through the conditions of these three ecosystem functions, site selections for rice cultivation (based on 21 “site” nodes in the BBN) are affecting RPES supply. Probabilities of different supply-demand balances to occur were expressed in the node “RPES budget”. The probabilities were calculated based on environmental characteristics in the paddy plots and the implemented farming practices (Figure 2).

In the developed BBN of RPES, three main components of Bayes’ rule were integrated in the network including the prior probability of input and output nodes, and conditional probability tables (CPTs). For prediction purposes, users need to supply new evidences/probabilities of the “site” and “farming practice” nodes happening on paddy fields. The new evidences of the “site” variables could be calculated as the areal percentages of rice cultivated in different states of the “site” nodes in a given time. As an example in 2010, the areal percentage of paddy fields cultivated on slopes of 0 to 13, 13 to 18, 18 to 24 degrees and higher than 24 degrees respectively are 40 %, 25 %, 25 % and 10 %. Therefore, the ratio between 4 states of the node “slope” is 40:25:25:10. The likelihoods of the “farming practices” nodes can be collected from the literature, statistical data and interviews and then added in the developed BBN. These evidences access the conditional probability tables of the “ecosystem function” and “RPES supply” nodes (Figure 3a), then update all the probabilities in the network. For example, knowing that the condition of cropping sites is appropriate would lead to an increase of the “efficiency” state in the “ecosystem function” node, which again would raise the belief in high rice provision. Figure 3b shows that although rice was cultivated at suitable sites with effective additional anthropogenic inputs, the probability for very low RPES supply is still about 3 % (Dang et al., 2018c).

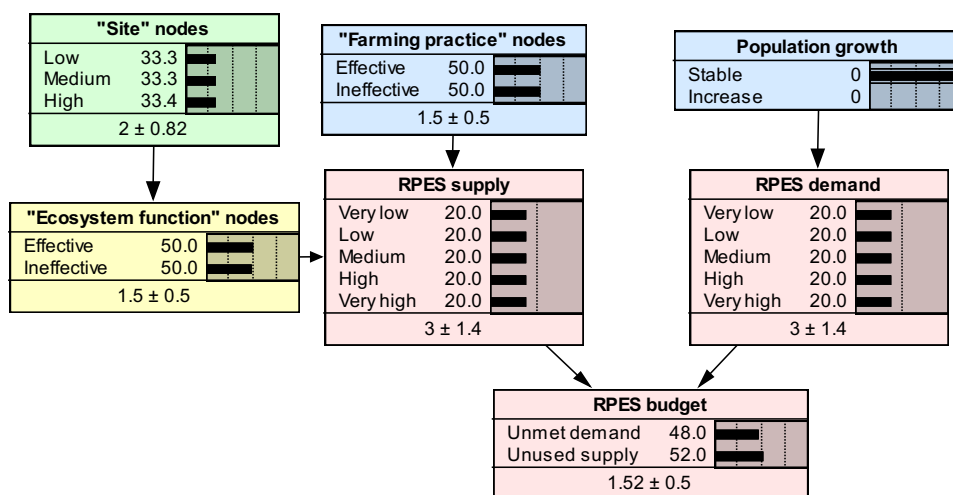


Figure 2. Bayesian Belief Network structure for modelling rice provisioning ecosystem services (RPES) (based on conceptual ES framework from Burkhard et al. (2014); and BBN applications from Dang et al. (2018c) and Haines-Young and Potschin (2010)).

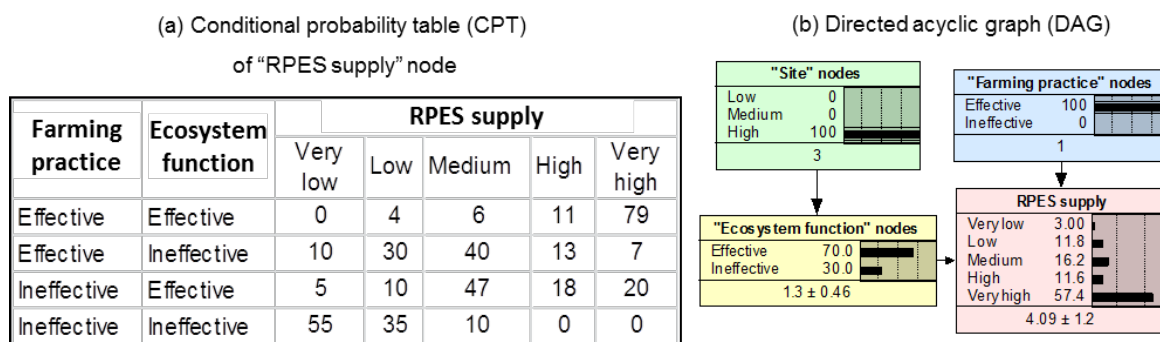


Figure 3. Conditional probability table of the node "rice provisioning ecosystem service supply" (a) and an example to predict the capacity of rice provision in the case of high appropriate sites and effective additional inputs (b).

Dang et al. (2018c) made diagnosis to select crop suitability areas and the most effective farming practices for rice cultivation in the Sapa region. The evidences related to the capacity of RPES supply were inserted to find out the best conditions of the "site" and "additional inputs" nodes. Because of the complexity of the developed BBN, authors focused on six easy-to-observe "site" nodes that include "temperature", "solar radiation", "precipitation", "altitude", "slope" and "soil" nodes in order to find out environmental criterions suitable/unsuitable for rice cultivation. The "additional inputs" nodes were all assessed. The description of those outcomes is shown in Table 1. The above information is very important to assess and map the RPES potential that will be presented in Section 2.2.

Table 1. Criteria to select suitable/unsuitable areas and effective/ineffective farming practices for rice cultivation in the Sapa district (adapted from Dang et al. (2018c)).

Criterion	Effective	Ineffective
Site selection	<ul style="list-style-type: none"> - Temperature: 22 to 24.5 °C with strong solar radiation - Precipitation: lower than 1800 mm - Altitude: lower than 1030 meter - Slope: lower than 13 degree - Soil: plinthic Acrisols 	<ul style="list-style-type: none"> - Temperature: less than 21.5 °C with weak solar radiation - Precipitation: higher than 1930 mm - Altitude: higher than 1240 meter - Slope: higher than 24 degree - Soil: humic Acrisols
Farming practice	<ul style="list-style-type: none"> - Investment: higher than 5.8 Million VND - Using 180 kg/ha per year of compound fertilizer and 130 kg/ha per year of straight fertilizer - Using Vietnamese hybrid seeds - Using pesticides at the middle of season 	<ul style="list-style-type: none"> - No investment (or less than 3.5 mVND) - Using less than 45 kg/ha per year of compound fertilizer and 30 kg/ha per year of straight fertilizer - Using Chinese hybrid seeds - Using pesticides at the beginning of season (or do not use pesticide)

2. Material and methods

2.1. Case study

The Sapa district in the Lao Cai province in northern Vietnam was selected as a case study area to assess relations between RPES potential, supply, flow and demand. “Sapa center” is the main administrative and tourism unit in the Sapa district. The other communities (Figure 4) focus on rice cultivation as the main livelihood, which is especially relevant in communities of ethnic minority people (Hoang et al., 2014). Rice ecosystems have been developed in this area on terraces along the valleys of the two main rivers Ngoi Dum and Ta Van. The altitudes reach more than 2,500 m at the highest mountain known as the Fansipan peak. From there it is easy to observe three types of rice ecosystems, that are typical in the Sapa district: irrigated, rain-fed lowland and upland rice ecosystems (as described by IRRI, 2006).

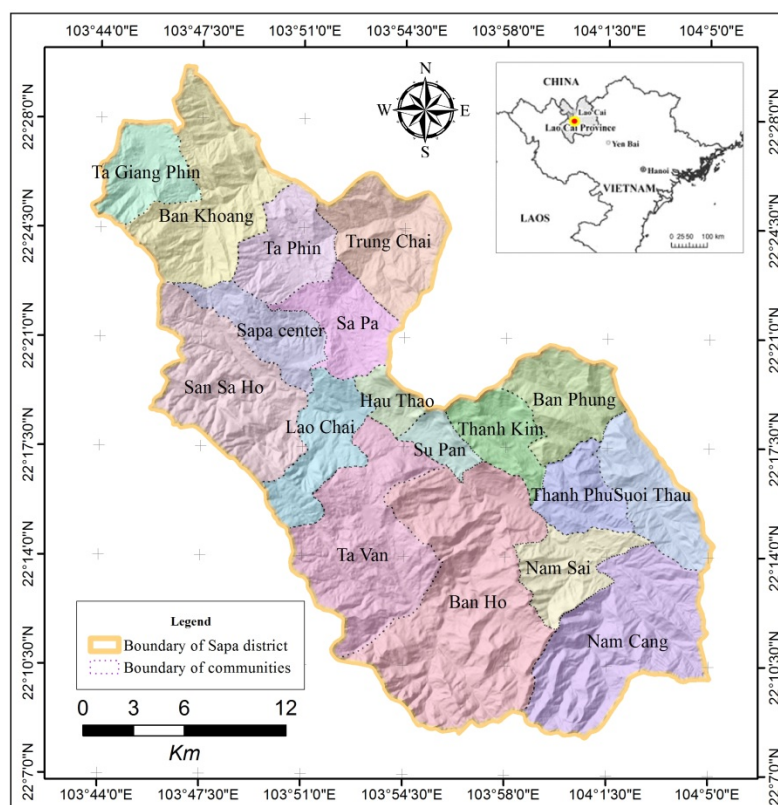


Figure 4. The 18 communities of the Sapa district on a hill-shade background according to the Vietnam Publishing House of Natural Resources, Environment and Cartography ¹³.

According to remote sensing data analyses, a trend of rice cultivation area expansion was recorded in Sapa from 1993 to the 2000s. A newer trend of land abandonment has been recorded since the 2000s (Jadin et al., 2013). In the year 1952, serious deforestation has started in the area and 2 % of forest and 15 % of shrub areas were converted into arable lands. Hoang (2014) indicated a significant expansion of arable lands by 30 % from 1993 to 2006 and by 10 % from 2006 to 2014. The latter development was due to the implementation of forest policies leading to reforestation and tourism development in Sapa. Nevertheless, the area of arable lands has been expanded by 17 % over 21 years.

Regarding the demand for rice products in the case study area, natural population growth, migration and increasing tourism are putting more pressure on local food supply and security. The local population has increased since the 1960s when the new socialist regime started to implement the New Economic Zones Policy (Hoang, 2014), resulting in an increasing demand for rice. This policy has become known as a migration scheme to encourage the Vietnamese Kinh people to move from the lowlands to the highlands of the north-western part of Vietnam for agricultural and economic developments (Hardy, 2005). Consequently, a twofold population growth has been recorded in the

¹³ <http://www.bando.com.vn/>

case study area since the year 1993¹⁴. According to regional statistics, there were 1,846 poor households in the Sapa district in 2015 that do not have enough money to buy enough food. The income of these households has been lower than 700,000 VND/person per month (about 26 EUR/person per month). Particularly the Ta Giang Phin, Hau Thao, Sa Pả, San Sa Ho and Ta Van communities have more than 150 poor households in each community. Bonnin and Turner (2012) indicated that the rice supply has not been sufficient for the local needs for rice, leading to the existence of hunger in the Sapa district.

According to a map of areas suitable for rice cultivation in the Sapa region produced by Dang et al. (2018b), only about 70 % of the paddy fields were indicated to have a high potential for rice provision. Hence, several paddy fields are located in areas that are rather unsuitable for rice cultivation. Alternatively, several areas including meadows, grasslands and bare soils could be used as paddy fields and could replace about 30 % of the unsuitable areas (Dang et al., 2018b). Together with calculations of the potentials and supply-demand budgets of rice provision at regional scales, mapping suitability areas for rice cultivation (as done by Dang et al. (2018b)) could unfold the full natural potential of RPES.

The New Economic Zones policy from the government of Vietnam has encouraged domestic and international tourists to visit the Sa Pa district. This change leads to increasing tourist numbers from 16,100 in 1995 to 610,000 in 2012 (GSO, 2012, 1995). Recently, statistical reports from the Lao Cai province have recorded about one million domestic and international visitors coming to Sapa during the year 2015¹⁵. This development has certainly additionally increased the pressure on food security in this comparably small mountainous district.

Several barriers preventing the application of innovations in rice production could be identified. Firstly, rice in the Sapa region is mainly cultivated in summer because of climatic constraints in winter and water scarcity from upstream forests (Burkhard et al., 2015; Tekken et al., 2017). This makes efforts to increase the rice productivity in the case study area difficult. Secondly, due to the scarcity of cultivation lands and the rapid recent conversion of arable lands into urban lands, local people have moved their paddy fields towards the upstream areas where slopes are much steeper. Meanwhile, permanent agricultural lands in the Sapa district have become less appropriate for cultivation because of poor management practices that have been leading to significant decreases in soil fertility and increasing of erosion through many years (Jadin et al., 2013). Lastly, ineffective rice supply chains in the Sapa district have prevented poor households from approaching enough food. Dang et al. (2018c) indicate a high probability of unmet rice demand in the Sa Pả and Ta Phin communities and in the center of the Sapa district. Shortages in RPES supply have happened due to the selection of unsuitable sites and ineffective farming practices of local farmers. Therefore, gaps

¹⁴ <https://www.gso.gov.vn/>

¹⁵ <sapa.laocai.gov.vn/>

between rice supply and demand need to be clearly understood in order to balance supply-demand budgets and to find suitable solutions for RPES supply in the Sapa district.

2.2. Methods to assess RPES budget

This section explains 6 steps to quantify RPES potential, supply, flow and demand in the Sapa district (see Figure 5). Subsequently, the RPES budget was analyzed in 18 communities. In this study, authors integrate the outcomes of the BBN model and a “hybrid neural-fuzzy inference system” model (so-called HyFIS developed by Dang et al. (2018b)) to map the RPES potential. The outcomes from the Bayesian Belief Network (BBN) are used as the RPES supply. RPES flow and demand were calculated based on actual productivity and rice consumptions, respectively. The indicators of RPES supply, flow and demand are described in Table 2.

2.2.1. Step 1: Collect spatial data related to the boundary of paddy fields

In order to understand the dynamics of the RPES potential, supply, flow and demand throughout the years in the Sapa district, information related to location and area of paddy fields needs to be collected. In this study, the spatial data of paddy fields were derived from five years (1993, 1995, 2005, 2006 and 2010) land use/land cover (LULC) maps. The LULC maps in 1995, 2005 and 2010 were generated by the People’s Committee of Lao Cai province, whereas the LULC maps in 1993 and 2006 were interpreted by Hoang (2014) from Landsat satellite imagines (resolution 30 m²) with accuracies of 80 % and 86 % respectively (Jadin et al., 2013).

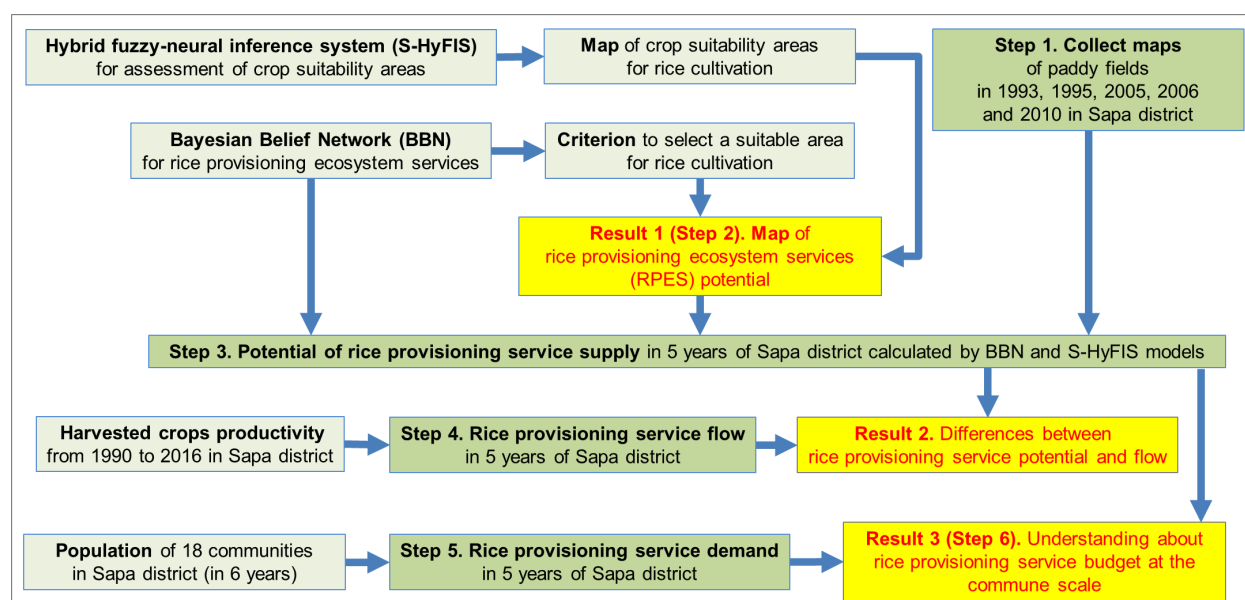


Figure 5. The structure of the ecosystem-service assessment based on the integration of the Bayesian Belief Network (BBN) and the hybrid neural-fuzzy inference system (S-HyFIS).

Rice provisioning ecosystem service	Indicator	Data sources
Supply	Yield and productivity	Calculated from BBN and S-HyFIS models
Flow	Actual rice productivity	Recorded from statistical data of Sapa district
Demand	Population	Recorded from statistical data of Sapa district
	Rice consumption per capita	Adapted from Dey and Hossain (1995); FAO (2000) and Kubo (2013)

Table 2. Description of indicators of RPES supply, flow and demand.

2.2.2. Step 2: Map the RPES potential

In this step, the S-HyFIS model developed by Dang et al. (2018b) was applied to predict and map the suitability of the areas for rice cultivation in the Sapa district. The input of the S-HyFIS model includes eight environmental variables (“elevation”, “slope”, “soil erosion”, “sediment retention”, “length of flow”, “water yield”, “ratio of evapotranspiration to precipitation” and “topological wetness index”) with their spatial data (Appendix Chapter 5). The more accurate the map of crop suitability areas, the more reliable is the productivity prediction. Therefore, the map of crop suitability areas for rice cultivation from the S-HyFIS model was integrated with the effective/ineffective options for cropping site selection from the BBN model (see Section 1.3). The total information was then used as the RPES potential map (Figure 5). Some typical terrains such as areas coinciding with ineffective options from the BBN model will not provide any potential for rice cultivation. Therefore, they need to be reclassified into a separate class. In this study, the ES supply and demand categories (including six classes from “no” to “very high” RPES supply or demand) of the ES matrix approach by Burkhard et al. (2014) were adopted, instead of the four classes from the map proposed by Dang et al. (2018b).

Table 3. The integration between five criteria for cropping site selection and the map of crop suitability areas.

No.	Criterion for cropping site selection (based on BBN network)	Classification in the map of crop suitability areas (based on S-HyFIS model)	New classification for the map of RPES potential
1	Ineffective site selection	Low	No relevant potential
2	<i>Not assessed</i>		Very low relevant potential
3		Medium	Low relevant potential
4		High	Medium relevant potential
5		Very high	High relevant potential
6	Effective site selection		Very high relevant potential

In detail, the location of paddy fields attained five effective/ineffective criteria for rice cultivation from the BBN model were identified. The “low suitability areas” identified by the S-HyFIS model coinciding with the ineffective criteria for rice cultivation were assigned to the class “no relevant potential” for RPES supply. In contrast, the “very high suitability areas” coinciding with the effective criterions for rice cultivation were assigned to the “very high relevant potential” class. Other parts of the “crop suitability areas” map were changed to the new classification listed in Table 3. After the integration process, the map of the RPES potential was generated as a first result with raster format at the resolution of 20 m x 20 m.

2.2.3. Step 3: Quantify the annual RPES supply

In step 3, the RPES supply was quantified through estimations of rice production (tons per ha per year) as a function of the two parameters rice yield and cultivating area size (as shown in formula 1). Several studies have indicated the increase of potential yields in Vietnam since the 1990s (Dey and Hossain, 1995; FAO, 2000; Kubo, 2013). Therefore, the literature that assessed the potential of upland rice yields in the wet seasons of five years was integrated as shown in Table 4. The yield values are different in each RPES class. The higher the capacity of RPES, the higher is the yield.

The cultivating area was calculated from the BBN model and the map of RPES potential. In this step, the results from the map of RPES were only used to validate the outcomes from the BBN model. Regarding the RPES potential map, the ArcGIS 10.4 software was used to cut each class of the map by the boundaries of the paddy fields in five years; then the area of each class was calculated with the “geometry calculation” tool.

Table 4. Corresponding yields for each class of rice provisioning ecosystem services (adapted from Dey and Hossain (1995); FAO (2000) and Kubo (2013)).

No.	Class in the map of RPES potential	States in the node “RPES supply” from BBN model	Potential yields (tons/ha peryear)		
			Years 1993 and 1995	Years 2005 and 2006	Years 2010
1	No capacity	-	0	0	0
2	Very low	Very low	1.2	2.2	2.5
3	Low	Low	2.2	3.2	3.5
4	Medium	Medium	3.1	4.1	4.4
5	High	High	3.8	4.8	5.1
6	Very high	Very high	4.8	5.8	6.1

Regarding the BBN model, the probability of all 15 “site” nodes could not be calculated due to the lack of data. Seven “site” nodes were selected that include “precipitation”, “elevation”, “slope”, “ratio

of evapotranspiration to precipitation”, “length of flow”, “water yield” and “soil erosion”. The description of these data is shown in the Appendix. The spatial data of the parent nodes were overlaid with the boundaries of the paddy fields in different times to calculate the areal percentage (or likelihoods) of rice cultivated in different environmental characteristics. Regarding the “additional inputs” nodes, the effective/ineffective options of farming practices (mentioned in section 1.3) were used to observe the changes of RPES supply, because data related to human impacts in the past years could not be collected. From the changes in seven “site” nodes and “additional inputs” nodes, the posterior probabilities of five states in the node “rice provisioning ecosystem service supply” were calculated in five years in the 18 communities and in the whole Sapa district.

Five states in the node “Rice provisioning ecosystem service supply” including “very low”, “low”, “medium”, “high” and “very high” states can correspond to different average values of yields. The potential of rice yields can be changed throughout years due to influences of climate changes and technological developments. For instance in Figure 6a, the paddy plots in Vietnam in the year 1990s with “medium” state cropping site selection and “medium” state farming practices can provide about 3.1 tons/ha of rice per year in average (FAO, 2000). However, the potential of rice yields reached about 4.4 tons/ha per year in the years 2010s because of the successful implementation of agricultural policies (Tekken et al., 2017).

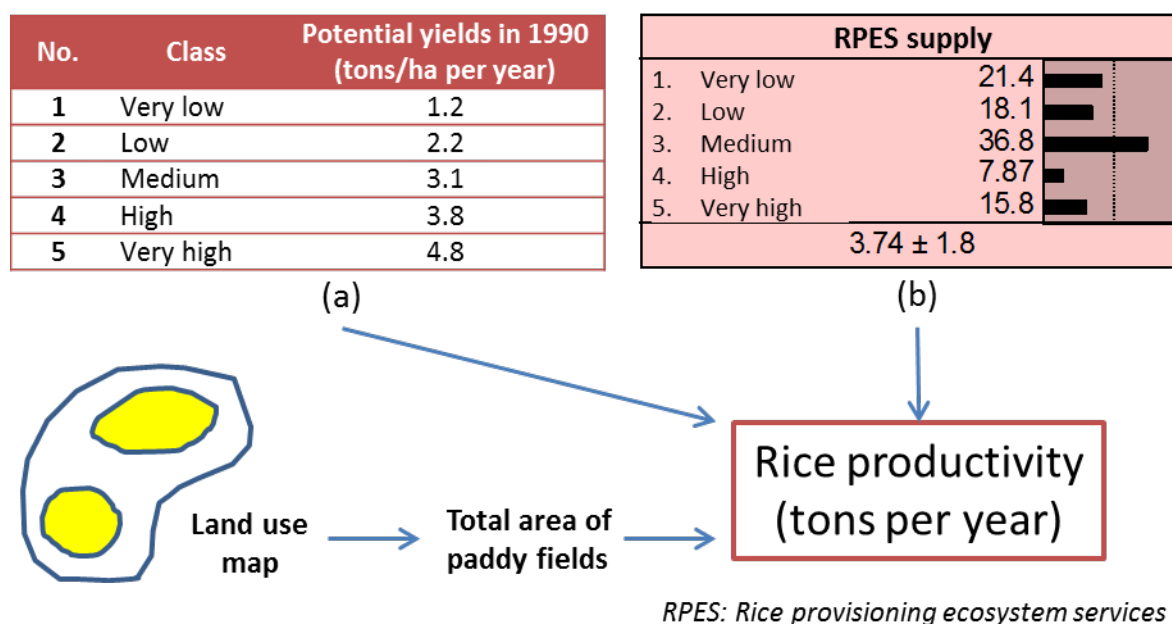


Figure 6. A method to calculate rice productivity in 1990 (as an example) based on a land use map and prior/posterior probabilities from Bayesian Belief Network. (a) Yields corresponding with different states of the node “RPES supply”; (b) Posterior probability of the node “RPES supply” calculated based on given evidences of site selection and the use of farming practices in 1990.

Additionally, the posterior probability calculated in the node “rice provisioning ecosystem service supply” depicts the proportion of states distributed to 100 % (Figure 6b). The distribution of five states can represent the areal percentage of these states in a particular region and indirectly calculates the area of each state. As an example, in 100 ha of agricultural lands farmers can find about 21 % (or 21 ha) of paddy fields at “very low” state (corresponding to about 1.2 tons/ha per year in average) and about 16 % (or 16 ha) of paddy fields at the “very high” state (corresponding to about 4.8 tons/ha per year in average). Hereby, the rice productivity can be calculated easily based on the average yields at the five states of the node “rice provisioning ecosystem service supply” and the posterior probabilities of these states through the following formula:

$$\text{Potential rice productivity (tons/ha per year)} = \sum_{i=1}^5 (Y_i \times P_i \times A) \quad (1)$$

In which, i is the class of “rice provisioning ecosystem service” node, Y is potential yield of class “ i ” in a particular time (see Table 4), P is the posterior probability of class “ i ” in a particular time and A is the total area of paddy fields in a particular time.

2.2.4. Step 4: Quantify the annual RPES flow

According to statistical data from the General Statistics Office of Vietnam (GSO)¹⁶, the numbers of amounts of rice produced during the five years study period were collected for the whole Sapa district. However, the yearly agricultural reports from the Sapa district and the Lao Cai province did not count the actual amount of rice productivity harvested in detail at the community level. Therefore, the comparison between the RPES supply and flow can only assess the efficiency of the site selection for rice cultivation and of the farming practices implemented in whole Sapa district during five years.

2.2.5. Step 5: Quantify the annual RPES demand

Regarding the RPES demand, due to the fact that rice is the main staple food of Vietnamese people (GRiSP, 2013), the population growth and the recent increase of tourism in the case study area have become a big challenge for local food security. Therefore, two types of rice consumers were analyzed in this study including (i) the number of local people and (ii) incoming tourists annually. The data were collected from the GSO (2010, 2004, 1995) in 18 communities of the Sapa district between 1990 to 2010.

In addition, rice consumption (Unit: kg of rice per capita) is varying from year to year, especially in Asian developing countries (FAO, 2014). FAO (2000) indicated that the increase of rice consumption in South-east Asian countries could be faster than the population growth. Furuya et al. (2013) found a linear increase of rice consumption per capita in Vietnam from 190 kg in 1993 and 1995; 200 kg in 2005 and 2006 to 210 kg in 2010. Therefore, the regional RPES demand was calculated for five years by the following function:

$$\text{Demand} = \text{Number of consumers} \times \text{Rice consumption per capita} \quad (\text{Formula 2})$$

¹⁶ <https://www.gso.gov.vn/>

2.2.6. Step 6: Assessment of RPES budget at community scales

In this step, the RPES supply and demand were compared in the communities of the Sapa district to find out which communities have a lack or a surplus of rice provision. If the rice supply in a community is higher than the demand, the community will have surplus of rice (or unused service) that could be used for exports. In contrast, if the rice supply in a community is lower than the demand, the community must import more rice from other regions to support the unmet demand (Jones et al., 2016). Therefore, the map of RPES supply is designed at the community scale through quantifying the potential of rice that could be produced in each community. The map of RPES demand was generated based on the rice consumptions of the 18 communities in the Sapa district. Lastly, the RPES budget of the 18 communities was calculated as the difference between the supply and demand maps.

3. Results

3.1. Map of rice provisioning ecosystem service potential

The map of RPES potential is depicted in Figure 7 based on the integration between the map of crop suitability areas for rice cultivation from the S-HyFIS model and the effective/ineffective criteria for site selection from the BBN model. The plots corresponding to the ineffective criteria from the BBN model were assigned to the “no capacity of RPES” category, whereas the plots corresponding to the effective criteria were assigned to the “very high capacity of RPES” category. Because this result was solely predicted through environmental variables, it can only represent the natural potential of RPES without changes in land management compared to the year 2010. This assumption generates some uncertainties that will be discussed in the next Sections.

According to Figure 7, the plots representing “no capacity of RPES” can be found in the southern parts of the Sapa district, such as Nam Sai and Nam Cang, and the high mountains of the western parts in San Sa Ho, Lao Chai and Ta Van. The plots with the class “high and very high capacities of RPES” are distributed in the lower parts of the Ngoi Dum and Ta Van river valleys. It is easy to observe that the many regions with dense population in the Sapa district (such as Sapa center and San Sa Ho community) have low RPES potentials. In contrast, the scattered communities such as Trung Chai and Thanh Kim contain large areas suitable for rice cultivation. In other words, the unbalance between demand and supply/flow of RPES in these communities is very high.

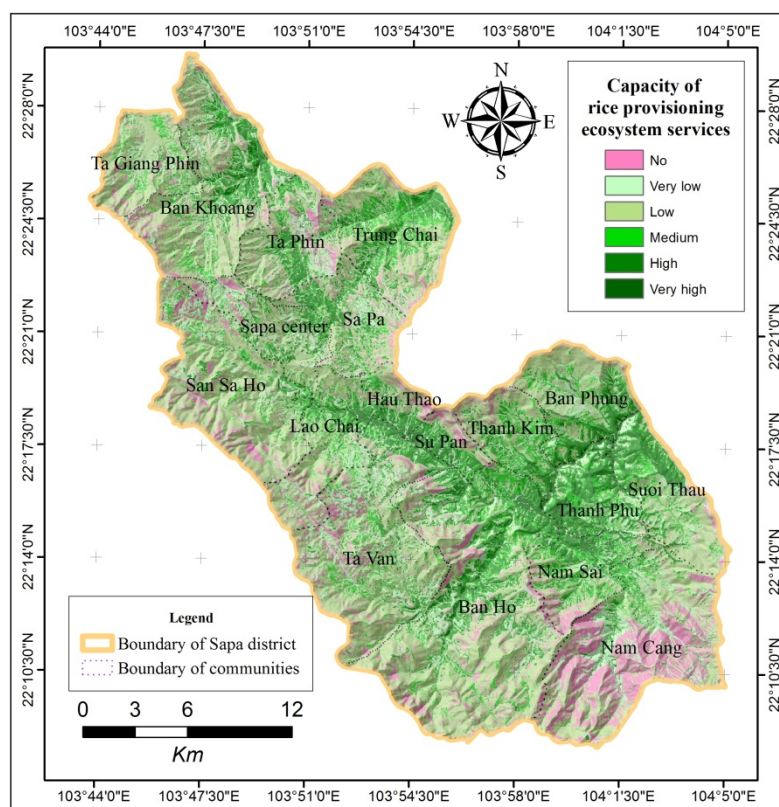


Figure 7. Map of RPES potential in Sapa district.

3.2. Rice provisioning ecosystem services potential, supply, flow and demand at regional scales

Figure 8 describes the changes of RPES supply (predicted from the BBN and integration models), demand (estimated from the number of consumers and rice consumption per capita) and flow (actual rice production) from 1990 to 2010. It is easy to observe the gradual increase of RPES supply, flow and demand during the 20 years. Before 2003, the RPES flow could not support the local demand for services, especially in the years from 1994 to 1999 when the amount of unmet demand reached values higher than 2,500 tons per year. Nevertheless, the difference between the RPES flow and demand had decreased until 2003. After this year, the RPES flow has been higher than the demand of local people. In addition, the food demand of tourists has started to increase since the 2000s. The amount of surplus rice since 2003 could only provide for the food demand from tourist.

According to Figure 8, the predictions of the RPES supply based on the integration of the two models are always close to the “natural potential of RPES” results. In 1993, the prediction from the model integration is lower than the “natural potential of RPES” result from the BBN model and near the point of RPES flow. According to the results of the BBN model shown in Figure 8, the scenario based on effective farming practices could increase the productivity by about 850 tons per year in average, whereas the ineffective farming practices could also decrease the productivity about 800 tons per year in average. Based on the predictions of the BBN model, farmers applied ineffective practices in 1993 and 1995. If the farmers would have applied effective practices in these years, the RPES potential

could not meet the full RPES demand. This corresponds to the case 2 analyzed in Section 1.3. The RPES flow in 1990s was consequently combined with comparably less knowledge in using fertilizers, pesticides and seeds under the prevailing conditions.

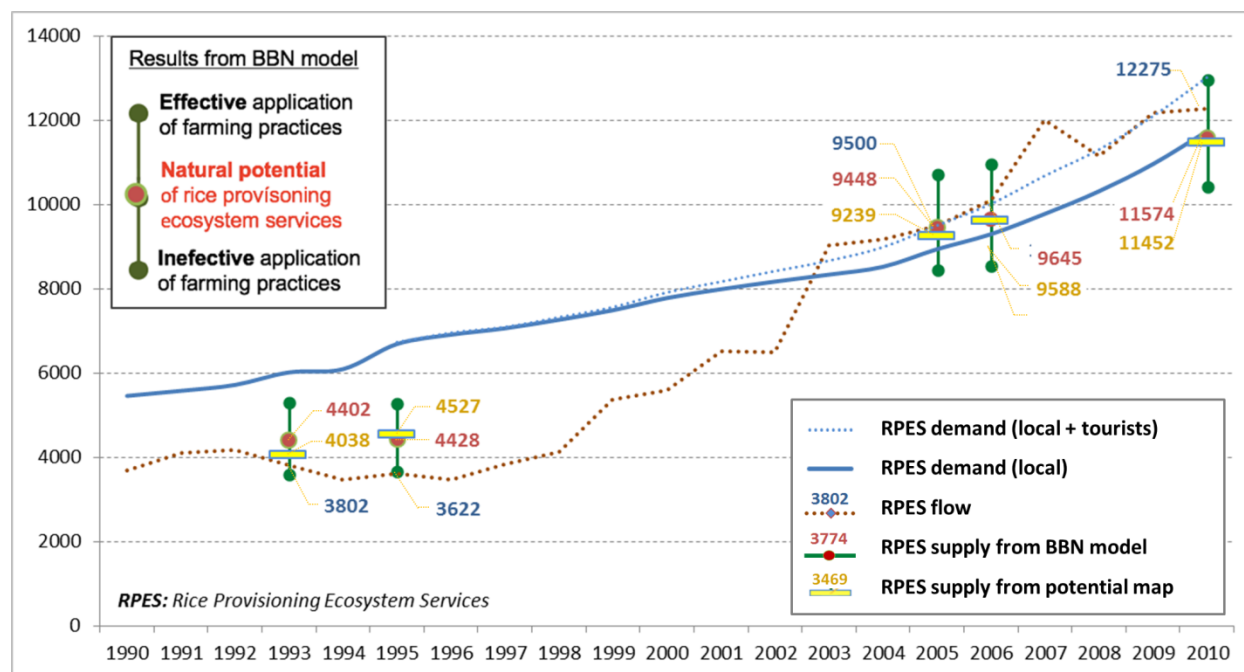


Figure 8. The supply, flow and demand of the rice provisioning ecosystem service (RPES) in the Sapa district in 1993, 1995, 2005, 2006 and 2010 (Unit: tons of rice per year).

The calculation of the natural RPES potential in 2005 showed an effective use of natural resources in rice cultivation. The RPES flow was equal to its potential as assessed by the BBN model and higher than the potential assessed by the integration model. In 2006, the better use of farming practices resulted in an increase of the RPES flow that was clearly higher than the “natural potential of RPES” calculated by the BBN and the integration of the models. A surplus of RPES was also found in the year 2010 when the RPES flow exceeded the “natural potential” by about 1,000 tons. This can be explained by the application of new farming practices. This difference coincided with a raising of food demand due to more incoming tourists. It corresponds to the case 4 analyzed in Section 1.3. Nevertheless, statistical data indicated more than 1,900 poor households in the Sapa district in 2010. In other words, although the above results showed a surplus of RPES in the whole district, a lack of services took place at the community level. The rice supply should first meet the local demand before it can support other purposes such as tourism.

3.3. The budget of rice provisioning ecosystem services at the community scale

The maps of RPES supply, demand and budget in the 18 communities of the Sapa district are shown in Figure 9. Regarding RPES supply, map 9a shows the RPES supply in the service providing areas. Map 9b illustrates the demand for RPES in the service benefiting areas. In general, a high unmet demand of rice is observed in communities near the Sapa center, which is in accordance with real observations. In addition, considering the low RPES supply and demand found in the eastern communities such as Ban Phung, Thanh Phu, Nam Sai and Nam Cang, these communities seem to be neither service providing areas nor service benefiting areas.

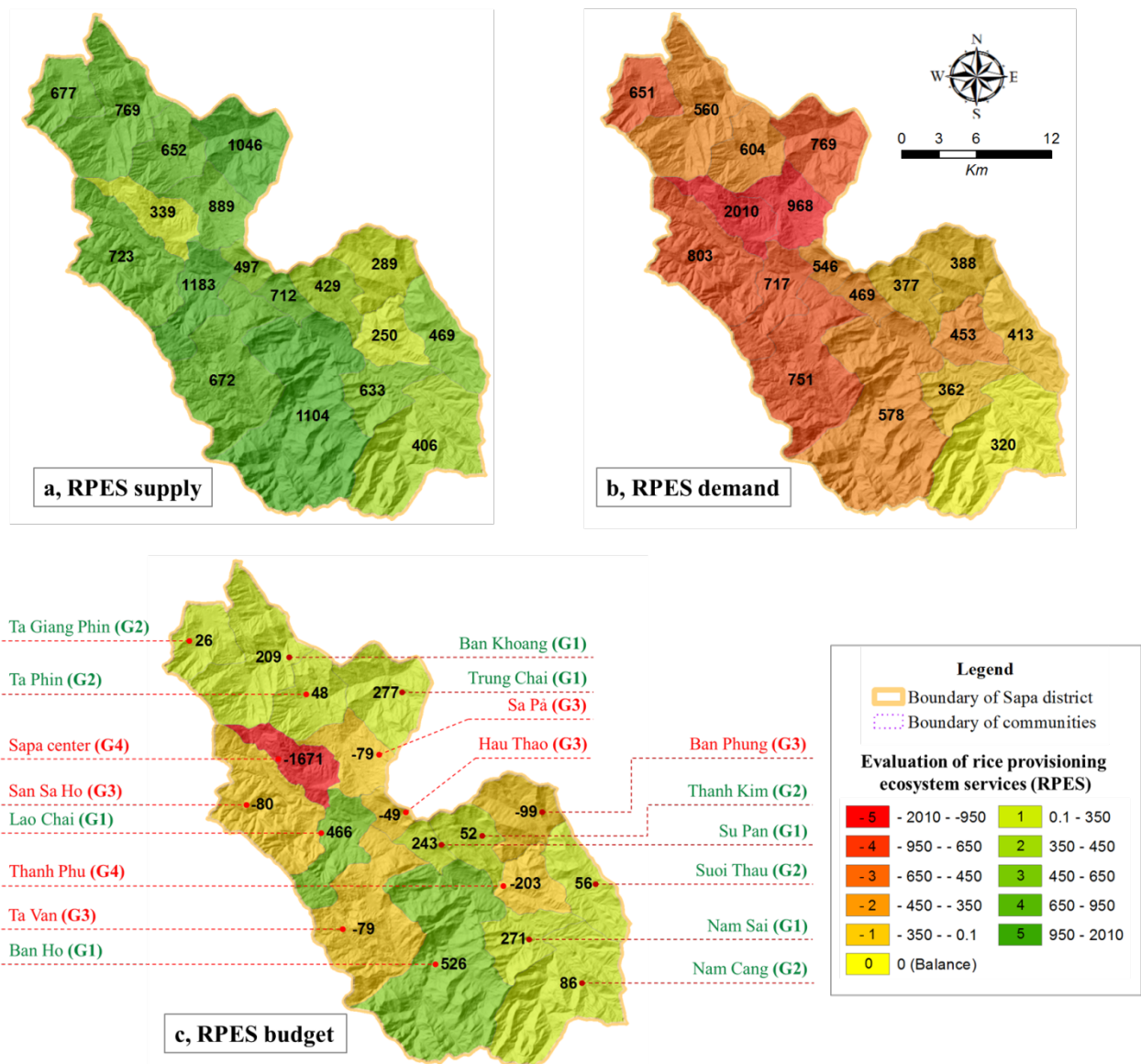


Figure 9. Spatial relations of service providing areas (a) and service benefiting areas (b) between the 18 communities in the Sapa district assessed through the budgets of rice provisioning ecosystem services (c).

According to the balance between RPES supply and demand, the Sapa district can be divided into 4 groups. The amount of rice which is produced from the Ban Khoang, Trung Chai, Lao Chai, Ban Ho, Su Pan and Nam Sai communities (**group 1**) is higher than the amount produced in the other 9 communities. They could be assessed as potential service providing areas with the surplus of rice of more than 200 tons/ha per year. In contrast, the RPES supply in the Sapa center and the Thanh Phu community (**group 4**) were assessed with the lowest values. The difference between rice supply and demand in these two communities was higher than 200 tons per year leading to negative values calculated in the RPES budget. In **group 3**, the Sa Pả, San Sa Ho, Ta Van, Ban Phung and Hau Thao communities were identified as service providing areas with high RPES potentials (with the rice production from 450 to 950 tons per year). Because the demand in these communities is also very high (from 650 to 2010 tons per year), the calculated RPES budgets are negative (about 350 tons per year). **Group 2** includes five high potential service providing areas with positive values of RPES budgets fluctuating from 1 to 2.

4. Discussion

4.1. Rice supply chain in Sapa region

The supply-demand-budget approach was successfully applied in the spatially explicit analysis of ecosystem services based on land use/land cover (following Bukvareva et al. (2017); Burkhard et al. (2014b, 2012b); Nedkov and Burkhard (2012)). This approach has high potential to link the understanding of ecosystem functions, services and food supply chains. The results proved the unbalance between the RPES supply and demand at regional scales. Such unbalance is typical for food-exporting countries, such as Vietnam as mentioned at the beginning of this article. In addition to general indications showing the surplus of rice at national scales and a rice deficit at regional scales (as done by Subramanian et al. (2015); Tsukada (2011)), this study identified the spatial distribution of RPES providing and benefiting areas as shown in Figure 9.

Compared to other agricultural regions, the case study area Sapa is a relatively closed region, which makes the rice use pattern less complex. In fact, most of the rice products are transported to domestic markets. Information related to rice exports from the case study to other districts has not been recorded in statistical data before the year 2010. In interviews carried out in the study region, local people indicated that small amounts of rice produced in the Sapa district was sold in provinces in downstream areas. However, Tsukada (2011) and Nguyen and Lantican (2009) indicated that the high amounts of rice used in Northern Vietnam were imported from agricultural regions in the Red River delta. Since 2003, the amount of rice surplus is estimated at about 1,000 tons per year. This amount is not enough for the food demand of more than one million tourists coming in 2020 that are predicted by local managers (Hoang et al., 2014). Results shown in Figures 8 and 9 demonstrate the existence of

RPES supply-demand mismatches, leading to hunger in the Sapa district, even though a rice surplus has emerged since the year 2010.

Regarding to the spatial relations between service providing and benefiting areas at the community level, the four groups assessed in Section 3.3 could correspond to the four cases mentioned in Figure 1 (see Section 1.2). Firstly, the situation in the six communities of group 1 seem in harmony with case 4, because the RPES supply and flow in these communities are much higher than the RPES demand. This interpretation is supported by statistical data from the communities with high production and large paddy fields (GSO, 2010, 2001, 1995). It can be summarized that the communities in group 1 have high potentials to export rice. Secondly, it is more difficult to explain the cases assessed in group 2. In general, the RPES supply and flow in this group seem to be higher than their demands but the budgets are lower than 90 tons per year. Shortcomings from farming practices or the selections of unsuitability areas for cultivation could reduce RPES flows. At that time, the relations between service providing and benefiting areas in the communities of group 2 could be changed to the case 3 of Figure 1.

Thirdly, in contrast to groups 1 and 2, the RPES supply in groups 3 and 4 is lower than their demand. This situation corresponds to case 2 of Figure 1, especially for three communities in group 4. These communities need to import rice from other communities, for instance those in groups 1 and 2. Except from the Sapa center, the communities assessed in groups 3 and 4 coincide with the poor communities recorded in the statistical data. Nevertheless, the RPES budget in four communities of group 3 fluctuates from 50 to 100 tons per year. If farmers from group 3 can improve farming practices or re-select areas more suitable for rice cultivation, it would have a high potential to change to case 1.

Regarding the policy development, the use of ecosystem-service approaches in agricultural management can assist decision makers to better understand the spatial relations of RPES potential, supply and flows from service providing units and the service demand of benefiting areas. The map of RPES potential provides spatial distributions of areas suitable/unsuitable for rice cultivation - as a key information for policy makers, researchers and private sectors to identify and prioritize relevant climate change adaptation and sustainable agriculture development strategies. The maps of RPES supply, demand and budget generated in this study provide information to allocate rice towards poor communities, resulting in the mitigation of famine threats. Additionally, the integration of the rice production process in the RPES supply chain can help decision makers to better understand the influence of this process on other ecosystem services. For example, the impact of fertilizer and pesticide use on crop production needs to be further studied to reduce effects of these chemical products on fresh water provision and air quality. These can provide more knowledge about natural functionalities for decision makers and can make it easier to modify and adapt agricultural strategies.

4.2. Model development in ecosystem service assessments

The integration of the BBN and S-HyFIS models can be representative for prediction models using formal statistical approaches. The analysis was based on the use of the BBN model based on probability approaches (McVittie et al., 2015). The similarities in productivity predictions from the two models shown in Figure 8 consolidates the accuracy of the RPES potential map shown in Figure 7. Both models used “rice yields” as an indicator for the model development. Further similarities in their application were prediction, modeling and scenario development. Moreover, both models seem to be powerful for the identification of areas suitable/unsuitable for rice cultivation. These results can provide a foundation to quantify the RPES potential from natural sites and to assess the RPES budgets at both plot and regional scales (Dang et al., 2018b, 2018c).

Besides these similarities, each model showed strong and weak points. Firstly, the use of the BBN approach in ecosystem service assessments can visually model: (1) chains of causal relations between environmental and socio-economic components with the RPES; (2) ecosystem functions through biophysical structures of the environment; and the RPES supply based on natural ecosystem functions and additional inputs from humans in one network that cannot be done by the S-HyFIS model. Secondly, although the BBN model used 30 (environmental and anthropogenic) nodes that are higher than the number of variables used in the S-HyFIS model, users do not need to have all data related to these nodes to use it (Dang et al., 2018c). Whereas, the HyFIS model using eight environmental variables as a compulsory data to run. Thirdly, the BBN model can estimate the RPES potential and supply through changes in environmental conditions and anthropogenic factors, whereas the S-HyFIS model focuses on mapping the natural RPES potentials. Fourthly, the BBN model allows to use measured data from fields, farmer interviews and expert data. Therefore, it can be updated from other networks and can be reproduced by new knowledge from other studies such as Bayesian networks developed by Cain (2001); Haines-Young et al. (2013); Kleemann et al. (2017); Xue et al. (2016), whereas, the S-HyFIS model cannot be updated.

The following weak point of the BBN model - compared to the S-HyFIS model - needs to be improved: Although the BBN provides priorities to select suitable/unsuitable cropping areas, this network could – in contrast to the S-HyFIS model - not be used for mapping. In this study, the BBN model was applied for the estimation of RPES supply at the community scale as shown in Figure 9, but it remains a big challenge to interpolate results to the plot scale by the BBN model.

4.2. Uncertainties

This Section presents focal uncertainties that arise from the model development and the scarcity of collected data. Some input variables, such as soil types, evapotranspiration and the use of seeds and pesticides, need to be updated or supplemented due to changes of the environment and farming practices in the case study area. The higher number of nodes used in the BBN model can improve the

accuracy of the outcomes. For example, soil properties are represented as one node in the BBN model. Some specific soil characteristics (such as moisture, structure and texture) have, however, not been quantified, resulting in the reduction of certainties in estimating nutrient and water availabilities in the soil.

The data used in this study are only updated until 2011, especially regarding the use of farming practices. The BBN model only considered three general types of seeds, i.e. Chinese hybrid, Vietnamese hybrid and Vietnamese inbred. Different new hybrid seed types have been used since 2010, leading to an increase of rice yields up to about 4.7 tons/ha per year (Tekken et al., 2017). This fact has not been taken into account in the BBN model. Moreover, after many reports related to the low quality of Chinese seeds in 2010, the Department of Agriculture and Rural Development in the Lao Cai province¹⁷ has encouraged farmers using Vietnamese hybrid seeds. During last five years, this department indicated that these new hybrid seeds have been cultivated in more than 90 % of the paddy fields, which was not considered in this study. Some nodes assessing the knowledge level of local farmers in rice cultivation need to be supplemented. The updated information could reflect the efficiency of training courses related to drought and erosion protection and the sustainable use of pesticides and fertilizers that have been implemented in the Sapa district.

The second source of uncertainties results from the simplification of collected data. In this study, the LULC maps are important data to know the locations and areas of paddy fields. Whereas the LULC maps in 1993 and 2006 were interpreted in a raster format (30 m resolution) from satellite images (source 1), the LULC maps in 1995, 2005 and 2010 were edited in a vector format by the departments of the Lao Cai province (source 2). The area of paddy fields calculated in five years is different from the information given in the statistical data. The area of paddy fields from both sources is commonly higher than the local statistics due to the higher accuracy of the LULC maps, which is about 85 % (Jadin et al., 2013). Additionally, topographical, hydrologic and climatic characteristics can have changed during the last 15 years, but all input data in this study are fixed in the analysis of the time series. The scarcity of data did not allow collecting topographical and hydrological data in 1990, while the continuous climatic data can be downloaded at only 500 m resolution. According to the data collected, the results could be more accurate for calculations since the year 2005. Nevertheless, the methods proposed in this study have the potential to be applied for future studies.

5. Conclusions

In the following, the three questions given in the introduction shall be answered:

- **How are RPES potential supply, flow and demand related to rice imports and exports?**

The balance between RPES supply, flow and demand plays a crucial role in determining the demand

¹⁷ <https://snnptnt.laocai.gov.vn>

for rice imports or the potential for exports of a particular region in a particular time. Four types of the relation between RPES supply, flow and demand were listed in this study. This study demonstrated the practicability of this theoretical relations in a mountainous district of Vietnam. Service providing areas can export rice once the RPES flow is higher than the demand, whereas service benefiting areas need to import rice because local RPES flows are lower than the local RPES demand. The RPES potential determines whether a given region can develop agriculture or not. The difference between the RPES supply and flow represents the efficiency of implemented site selection and farming practices. The success/un-success of an agricultural strategy is determined whether the RPES flow can meet/not meet the demand for the respective services. If the RPES supply is lower than the RPES demand, decision makers need to modify agricultural policies such as rice expansion or developing and applying new farming practices.

- **Can the agricultural regions in the mountainous provinces of northern Vietnam provide sufficient rice for local people to avoid hungers and reduce poverty?** The answer is “yes”. Although unmet demand for RPES was identified for seven communities in the case study area (which is in accordance with the poor communities recorded in the statistical data sets), balance between RPES supply and demand has been found at the regional scale since 2005. Therefore, there is a high potential to provide enough rice for all local people if officers from community levels manage to provide appropriate RPES supply chains.

- **How could managers at community/regional levels improve the RPES supply chains?** Two methods to improve the RPES supply chains are suggested: Firstly, poor households can buy rice products from neighboring service providing areas instead of importing rice from outside regions. Particularly in the case study area, the surplus of RPES from service providing areas can be provided to the closest benefiting areas. Secondly, BBN and S-HyFIS models developed in science are very promising tools to simulate behavior and dynamics of complex social-ecological systems. The outcomes of the models can provide useful, reliable and adaptable information for local decision makers to improve agricultural development. The S-HyFIS model could be used as a first step to find out areas suitable for cropping, where farmers can take full advantage of the RPES potential provided by nature. In the second step, BBN models could be used to estimate probabilities of success of the in application of a particular site selection and farming practice.

A task for the future will be to apply BBN models at national or global levels and to make them more applicable for more complex rice import/export flows and to update new nodes related to farming practices developed. Additionally, these models need to be developed in a really simplified user-interface, to make the models accessible for decision makers.

References

- ADB, 2012. Technical Assistance Consultant's Report; Support for the Association of Southeast Asian Nations Plus Three Integrated Food Security Framework; The Rice Situation in Thailand. Asian Development Bank. doi:TA 7495-REG
- Barbosa-Póvoa, A.P., 2009. Sustainable Supply Chains: Key Challenges, in: de Brito Alves, R.M., do Nascimento, C.A.O., Biscaia, E.C.B.T.-C.A.C.E. (Eds.), 10th International Symposium on Process Systems Engineering: Part A. Elsevier, pp. 127–132. doi:[https://doi.org/10.1016/S1570-7946\(09\)70242-1](https://doi.org/10.1016/S1570-7946(09)70242-1)
- 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. *Ecol. Econ.* 66, 91–104. doi:10.1016/j.ecolecon.2008.02.012
- Bayes, T., 1763. An Essay towards Solving a Problem in the Doctrine of Chances. *Philos. Trans. R. Soc. London* 53, 370–418. doi:10.1098/rstl.1763.0053
- Bonnin, C., Turner, S., 2012. At what price rice? Food security, livelihood vulnerability, and state interventions in upland northern Vietnam. *Geoforum* 43, 95–105. doi:10.1016/j.geoforum.2011.07.006
- Bukeviciute, L., Dierx, a, Ilzkovitz, F., 2009. The functioning of the food supply chain and its effect on food prices in the European Union. doi:10.2765/43477
- Bukvareva, E., Zamolodchikov, D., Kraev, G., Grunewald, K., Narykov, A., 2017. Supplied, demanded and consumed ecosystem services: Prospects for national assessment in Russia. *Ecol. Indic.* 78, 351–360. doi:10.1016/j.ecolind.2017.03.034
- Burkhard, B., De Groot, R., Costanza, R., Seppelt, R., Jørgensen, S.E., Potschin, M., 2012a. Solutions for sustaining natural capital and ecosystem services. *Ecol. Indic.* 21, 1–6. doi:10.1016/j.ecolind.2012.03.008
- Burkhard, B., Kandziora, M., Hou, Y., Müller, F., 2014a. Ecosystem service potentials, flows and demands-concepts for spatial localisation, indication and quantification. *Landsc. Online* 34, 1–32. doi:10.3097/LO.201434
- Burkhard, B., Kandziora, M., Hou, Y., Müller, F., 2014b. Ecosystem service potentials, flows and demands-concepts for spatial localisation, indication and quantification. *Landsc. Online* 34, 1–32. doi:10.3097/LO.201434
- Burkhard, B., Kroll, F., Nedkov, S., Müller, F., 2012b. Mapping ecosystem service supply, demand and budgets. *Ecol. Indic.* 21, 17–29. doi:10.1016/j.ecolind.2011.06.019
- Burkhard, B., Maes, J., 2017. Mapping Ecosystem Services. Pensoft Publishers, Sofia.
- Burkhard, B., Müller, A., Müller, F., Grescho, V., Anh, Q., Arida, G., Bustamante, J.V. (Japan), Van

- Chien, H., Heong, K.L., Escalada, M., Marquez, L., Thanh Truong, D., Villareal, S. (Bong), Settele, J., 2015. Land cover-based ecosystem service assessment of irrigated rice cropping systems in southeast Asia—An explorative study. *Ecosyst. Serv.* 14, 76–87. doi:10.1016/j.ecoser.2015.05.005
- Cain, J., 2001. Planning improvements in natural resources management: Guidelines for using Bayesian networks to support the planning and management of development programmes in the water sector and beyond. *Ecology* 44, 132.
- Dang, K.B., Burkhard, B., Müller, F., Dang, V.B., 2018a. Modelling and Mapping Natural Hazard Regulating Ecosystem Services in Sapa, Lao Cai province, Vietnam. *Paddy Water Environ.* xxx, xxx.
- Dang, K.B., Burkhard, B., Windhorst, W., Müller, F., 2018b. Application of hybrid neural-fuzzy inference system for mapping crop suitability areas and predicting rice yields. *Environ. Model. Softw.* xxx, xxx.
- Dang, K.B., Windhorst, W., Burkhard, B., Müller, F., 2018c. A Bayesian Belief Network - based approach to link ecosystem functions with provisioning ecosystem services. *Ecol. Indic.* xxx, xxx.
- Demont, M., Rutsaert, P., 2017. Restructuring the Vietnamese rice sector: Towards increasing sustainability. *Sustain.* 9, 1–15. doi:10.3390/su9020325
- Dey, M.M., Hossain, M., 1995. Yield potentials of modern rice varieties: an assessment of technological constraints to increase rice production, in: *In Proceedings of the Final Workshop of the Projections and Policy Implications of Medium and Long Term Rice Supply and Demand Project.* Beijing, China, pp. 23–26.
- Egoh, B., Reyers, B., Rouget, M., Richardson, D., Le Maitre, D.C., Van Jaarsveld, A.S., 2008. Mapping and Assessment of Ecosystems and their Services, Agriculture, Ecosystems & Environment. doi:10.2779/12398
- Ellison, A.M., 2004. Bayesian inference in ecology. *Ecol. Lett.* 7, 509–520. doi:10.1111/j.1461-0248.2004.00603.x
- FAO, 2017. The future of food and agriculture: Trends and challenges, FAO. Food and Agriculture Organization of the United Nations, Rome. doi:ISBN 978-92-5-109551-5
- FAO, 2015. The impact of disasters on agriculture and food security. Food and Agriculture Organization of the United Nations. doi:F0134/EN
- FAO, 2014. A Regional Rice Strategy for Sustainable Food Security in Asia and the Pacific, Regional O. ed. FAO, Bangkok.
- FAO, 2000. Bridging the rice yield gap in the Asia-Pacific Region, Food and Agriculture Organization. FAO.

- Fisher, B., Turner, R.K., Morling, P., 2009. Defining and classifying ecosystem services for decision making. *Ecol. Econ.* 68, 643–653. doi:10.1016/j.ecolecon.2008.09.014
- Furuya, J., Kobayashi, S., Yamauchi, K., 2013. Impacts of climate change on rice market and production capacity in the Lower Mekong Basin. *Paddy Water Environ.* 12, 255–274. doi:10.1007/s10333-013-0394-y
- Galli, F., Brunori, G., 2013. Short Food Supply Chains as drivers of sustainable development. Evidence Document, Evidence Document.
- García-Nieto, A.P., García-Llorente, M., Iniesta-Arandia, I., Martín-López, B., 2013. Mapping forest ecosystem services: From providing units to beneficiaries. *Ecosyst. Serv.* 4, 126–138. doi:10.1016/j.ecoser.2013.03.003
- General Statistics Office of Vietnam, 2016. Statistical Yearbook of Viet Nam. Statistical Publishing House, Hanoi.
- GRiSP, 2013. Rice Almanac, 4th edition, Global Rice Science Partnership. International rice research institute, Los Baños, Philippines. doi:10.1093/aob/mcg189
- GSO, 2012. National Vietnamese Census, Year book. The people committee of Lao Cai province. Lao Cai province, Vietnam, Lao Cai province, Vietnam.
- GSO, 2010. Sapa statistical yearbook 2010. The people committee of Sa Pa district, Lao Cai province, Vietnam.
- GSO, 2004. Socio-economic situation in Sapa in period 2000-2005. The people committee of Sa Pa district, Lao Cai province, Vietnam.
- GSO, 2001. National Vietnamese Census, Year book in period 1995-2000. The people committee of Sa Pa district, Lao Cai province, Vietnam.
- GSO, 1995. National Vietnamese Census, Year book. The people committee of Sa Pa district. Lao Cai province, Vietnam, Lao Cai province, Vietnam.
- Haines-Young, R., Nina, D.N.B., Smith, R., Hugin, A.M., 2013. Bayesian Belief Networks , a cross-cutting methodology in OpenNESS: Briefing Note Prepared by 1–8.
- Haines-Young, R., Potschin, M., 2010. Chapter 6: The links between biodiversity, ecosystem services and human well-being, in: Raffaelli, eds. D.G., Frid, C.L.J. (Eds.), *Ecosystem Ecology: A New Synthesis*. Cambridge University Press, pp. 110–139. doi:10.1017/CBO9780511750458.007
- Hardy, A., 2005. Red Hills. Migrants and the State in the Highlands of Vietnam, Institute. ed. NIAS Press, Singapore.
- Heong, K.L., Cheng, J., Escalada, M.M., 2015. Rice planthoppers: Ecology, management, socio economics and policy. *Rice Planthoppers Ecol. Manag. Socio Econ. Policy* 1–231. doi:10.1007/978-94-017-9535-7

- Hoang, H.T.T., 2014. Multi-scale Analysis of Human-Environment Interactions. A Case-study in the Northern Vietnamese Mountains. Katholieke Universiteit Leuven.
- Hoang, H.T.T., Vanacker, V., Van Rompaey, A., Vu, K.C., Nguyen, A.T., 2014. Changing human–landscape interactions after development of tourism in the northern Vietnamese Highlands. *Anthropocene* 5, 42–51. doi:10.1016/j.ancene.2014.08.003
- IRRI, 2006. The sustainability of rice farming, International Rice Research Institute, CAB International Publishing. International rice research institute, Philippines. doi:10.5860/CHOICE.35-3847
- Jadin, I., Vanacker, V., Hoang, H.T.T., 2013. Drivers of forest cover dynamics in smallholder farming systems: The case of northwestern vietnam. *Ambio* 42, 344–356. doi:10.1007/s13280-012-0348-4
- Jones, L., Norton, L., Austin, Z., Browne, A.L., Donovan, D., Emmett, B.A., Grabowski, Z.J., Howard, D.C., Jones, J.P.G., Kenter, J.O., Manley, W., Morris, C., Robinson, D.A., Short, C., Siriwardena, G.M., Stevens, C.J., Storkey, J., Waters, R.D., Willis, G.F., 2016. Stocks and flows of natural and human-derived capital in ecosystem services. *Land use policy* 52, 151–162. doi:10.1016/j.landusepol.2015.12.014
- Kamoshita, A., 2007. Historical Changes in Urban Rice Production Systems in Tokyo, Japan. *Plant Prod. Sci.* 10, 245–269. doi:10.1626/ppp.10.245
- Kandziora, M., Burkhard, B., Müller, F., 2013. Interactions of ecosystem properties, ecosystem integrity and ecosystem service indicators—A theoretical matrix exercise. *Ecol. Indic.* 28, 54–78. doi:10.1016/j.ecolind.2012.09.006
- Kleemann, J., Celio, E., Fürst, C., 2017. Validation approaches of an expert-based Bayesian Belief Network in Northern Ghana, West Africa. *Ecol. Modell.* 365, 10–29. doi:10.1016/j.ecolmodel.2017.09.018
- Kubo, K., 2013. Rice Yield Gap between Myanmar and Vietnam : A Matter of Price Policy or Public Investment in Technology ? *Asian J. Agric. Dev.* 10, 5.
- Lähtinen, K., Guan, Y., Li, N., Toppinen, A., 2016. Biodiversity and ecosystem services in supply chain management in the global forest industry. *Ecosyst. Serv.* 21, 130–140. doi:10.1016/j.ecoser.2016.07.006
- McVittie, A., Norton, L., Martin-Ortega, J., Siameti, I., Glenk, K., Aalders, I., 2015. Operationalizing an ecosystem services-based approach using Bayesian Belief Networks: An application to riparian buffer strips. *Ecol. Econ.* 110, 15–27. doi:10.1016/j.ecolecon.2014.12.004
- Minor, P., Walmsley, T., Strutt, A., 2017. State-owned enterprise reform in Vietnam: A dynamic CGE analysis. *J. Asian Econ.* doi:10.1016/j.asieco.2017.09.002
- Nedkov, S., Burkhard, B., 2012. Flood regulating ecosystem services—Mapping supply and demand,

- in the Etropole municipality, Bulgaria. *Ecol. Indic.* 21, 67–79.
doi:10.1016/j.ecolind.2011.06.022
- Nguyen, T.D.N., Lantican, F.A., 2009. Spatial integration of rice markets in Vietnam. *Asian J. Agric. Dev.* 6, 13–28.
- Pascual, M., Miñana, E.P., Giacomello, E., 2016. Integrating knowledge on biodiversity and ecosystem services: Mind-mapping and Bayesian Network modelling. *Ecosyst. Serv.* 17, 112–122. doi:10.1016/j.ecoser.2015.12.004
- Potschin, M., Haines-Young, R., Fish, R., Turner, R.K., 2016. *Routledge handbook of ecosystem services*. Routledge.
- Pullman, M., Wu, Z., 2012. *Food Supply Chain Management: Economic, Social and Environmental Perspectives*. Taylor & Francis.
- Serna-Chavez, H.M., Schulp, C.J.E., Van Bodegom, P.M., Bouten, W., Verburg, P.H., Davidson, M.D., 2014. A quantitative framework for assessing spatial flows of ecosystem services. *Ecol. Indic.* 39, 24–33. doi:10.1016/j.ecolind.2013.11.024
- Subramanian, S., Nyasani, J., Bukhebi, J., Workshop, S.E., Roth, J., Thomas, R., 2015. *VietNam: Agriculture and Food*. Embassy of Denmark in Vietnam.
- Syrbe, R., Grunewald, K., 2017. Ecosystem service supply and demand – the challenge to balance spatial mismatches. *Int. J. Biodivers. Sci. Ecosyst. Serv. Manag.* 13, 148–161.
doi:10.1080/21513732.2017.1407362
- Syrbe, R.U., Walz, U., 2012. Spatial indicators for the assessment of ecosystem services: Providing, benefiting and connecting areas and landscape metrics. *Ecol. Indic.* 21, 80–88.
doi:10.1016/j.ecolind.2012.02.013
- Tallis, H., Mooney, H., Andelman, S., Balvanera, P., Cramer, W., Karp, D., Polasky, S., Reyers, B., Ricketts, T., Running, S., Thonicke, K., Tietjen, B., Walz, A., 2012. A Global System for Monitoring Ecosystem Service Change. *Bioscience* 62, 977–986. doi:10.1525/bio.2012.62.11.7
- Tekken, V., Spangenberg, J.H., Burkhard, B., Escalada, M., Stoll-Kleemann, S., Truong, D.T., Settele, J., 2017. “Things are different now”: Farmer perceptions of cultural ecosystem services of traditional rice landscapes in Vietnam and the Philippines. *Ecosyst. Serv.* 25, 153–166.
doi:10.1016/j.ecoser.2017.04.010
- Tseng, M.L., Lim, M.K., Wong, W.P., Chen, Y.C., Zhan, Y., 2018. A framework for evaluating the performance of sustainable service supply chain management under uncertainty. *Int. J. Prod. Econ.* 195, 359–372. doi:10.1016/j.ijpe.2016.09.002
- Tsukada, K., 2011. Vietnam: Food security in a rice - exporting country. *world food Cris. Strateg. Asian rice Export.* 32, 53–72.
- Uthes, S., Matzdorf, B., 2016. Budgeting for government-financed PES: Does ecosystem service

- demand equal ecosystem service supply? *Ecosyst. Serv.* 17, 255–264.
doi:10.1016/j.ecoser.2016.01.001
- Uusitalo, L., 2007. Advantages and challenges of Bayesian networks in environmental modelling. *Ecol. Modell.* 203, 312–318. doi:10.1016/j.ecolmodel.2006.11.033
- Van Alfen, N.K., 2014. *Encyclopedia of Agriculture and Food Systems*. Elsevier Science.
- Villamagna, A.M., Angermeier, P.L., Bennett, E.M., 2013. Capacity, pressure, demand, and flow: A conceptual framework for analyzing ecosystem service provision and delivery. *Ecol. Complex.* 15, 114–121. doi:10.1016/j.ecocom.2013.07.004
- Wailes, E.J., n.d. PROTECTIONIST POLICIES , AND THE IMPACT OF TRADE 177–193.
- Walz, U., Syrbe, R.-U., Grunewald, K., 2017. Where to map?, in: Burkhard, B. & J. Maes (Eds.): *Mapping Ecosystem Services*. Pensoft Publishers, Sofia, pp. 159–165.
- Way, M.J., Park, S., Heong, K.L., 1994. The role of biodiversity in the dynamics and management of insect pests of tropical irrigated rice — a review 567–587.
- Xue, J., Gui, D., Lei, J., Sun, H., Zeng, F., Feng, X., 2016. A hybrid Bayesian network approach for trade-offs between environmental flows and agricultural water using dynamic discretization. *Adv. Water Resour.* 1–14. doi:10.1016/j.advwatres.2016.10.022

Appendix chapter 5: Data sources and description of the available environmental variables in Sapa district.

No.	Variable	Source	Available values
1	Elevation	Provided by Ministry of Natural Resources and Environment of Vietnam at scale of 1:25.000	From 500 to 2800 m (above sea level)
2	Temperature	Downloaded from WorldClim ¹⁸ website - Free global climate data (period of 1960-1990)	From 18 to 25 degree Celsius
3	Precipitation	Recorded in eight meteorological Services weather stations of the Lao Cai province (period of 1990-2006)	From 1600 to 2300 mm
4	Slope	Derived from the DEM (10m resolution)	< 13 degrees, 13 - 18 degrees, 18 - 24 degrees, > 24 degrees
5	Length of flow	Derived from the DEM (10m resolution)	< 5700 m, 5700 - 7000 m, > 7000 m
6	Released water on surface (water yield)	Calculated from "Water yield" model in InVEST tool	< 800 mm, 800 - 1100 m, > 1100 m
7	Ratio of evapotranspiration (AET) to precipitation (P)	Calculated from "Water yield" model in InVEST tool	Low (< 0.45), Medium (0.45 - 0.55), High (> 0.55)
8	Soil erosion	Provided by (Dang et al., 2018a)	From 0 to 5 tons/ha per year
9	Sediment retention	Provided by (Dang et al., 2018a)	From 0 to 5 tons/ha per year
10	Topological wetness index	Provided by (Dang et al., 2018b)	From 1 to 18

¹⁸ <http://www.worldclim.org/>

Chapter 6.

Synthesis

6.1. Summarizing answers of the research questions

In this section, the author summarizes the answers concerning the research questions raised in Chapters 2, 3, 4 and 5. The following sub-sections are related to the four above chapters with scientific articles. The sequence of research questions (from “a” to “1”) is arranged with references to Section 1.5 in Chapter 1.

6.1.1. *Natural hazard regulating ecosystem services (RES)*

a) How do different ecosystems affect the supply of erosion and landslide RES?

A conceptual framework that depicts the impacts of environmental components and land management activities on the provision of natural hazard RES by different ecosystems was proposed in Chapter 2. In general, natural ecosystems have higher capacities to supply erosion and landslide RES in mountainous areas than artificial ones. Forest conservation policies in the case study area have created more dense land covers with near-natural land use types (such as forests or natural grasslands) with the aim to mitigate risks from natural hazards. Human-influenced or inhabited land cover types (such as highly sealed areas) constructed on slope surfaces seem to be more vulnerable by soil erosion and landslides. From the seven types of land uses/land covers that were assessed, forest and urban areas are obtaining higher benefits from erosion RES than others, whereas forest and meadow areas are obtaining higher benefits from landslide RES than the other types of land use. The provision of natural hazard RES in paddy fields was assessed to be at a medium level.

b) How can providing units and benefiting areas of soil erosion and landslide RES be identified, related to different types of land use and land cover?

Natural hazard risk and RES supply maps are promising tools for decision makers to identify service providing units (SPUs) and service benefiting areas (SBAs). Three relationships between the place where the service regulation is provided (SPU) and where the benefits are realized (SBA) include (i) *in situ* conditions (SPU and SBA are located in the same places), ii) *omni - directional* relations (SBAs is located surrounding SPU without directional bias), and iii) *directional* interactions (services flow from SPU to SBA through one or several directions). Hence, ecosystems in upstream areas (SPU) can protect others in downstream areas (SBA) through *directional* relationships. For example, residential areas or planning units were identified as service benefiting areas, whereas forest ecosystems were identified as potential service providing units.

c) Can soil erosion and landslide RES effectively be supplied in paddy fields and forest areas?

In general, the erosion and landslide RES are supplied better in forest areas than in paddy fields. About 35 % of the paddy fields and 20 % of the forest areas in the Sapa district are not well-protected from soil erosion and landslides. The recovery of forest ecosystems during the last few years in the case study area is a good signal for the improvement of natural hazard mitigation. The forestation in

upstream areas will create a denser land cover to prevent downstream regions from erosion and landslides. As a suggestion for the local managers, 35 % paddy fields with low natural hazard RES supply could be converted into forest land covers. In the last years, the area of paddy fields has been narrowed and was replaced by urban areas. The reduction of natural land covers on slope lands (or terraces) through urbanization has led to the degradation of the natural hazard RES in the case study area.

6.1.2. Mapping crop suitability areas and predicting rice yields

d) Is it feasible and effective to use natural and anthropogenic factors to explain the dynamics of rice production at regional and plot scales?

The dependencies of rice production on eight selected environmental and three socio-economic variables were explained through a correlation analysis. Negative correlations were found between rice yields and elevation, flow length, water yields, slopes, sediment retention and erosion. Positive correlations were found between rice yields and the ratio of evapotranspiration and precipitation, and the topographical wetness index. According to the availability of spatial data, eight environmental variables could be used to predict the suitability of individual areas for rice cultivation at the regional scale. The additional inputs from humans have contributed positively to rice production at plot scales.

e) How can neural-fuzzy inference system and GIS analysis be integrated to map crop suitability areas on the regional scale and predict the potential of rice yields on the plot scale?

The integration of neural-fuzzy inference systems with GIS analysis (so-called HyFIS model) was developed and shown in Chapter 3. Throughout the HyFIS development, the iterative processes are used to optimize initial parameters, antecedent and consequent rules. The first model (so-called S-HyFIS model) with 86 % accuracy was used for assessing and mapping areas suitable for rice cultivation. The second model (so-called I-HyFIS model) with 90 % accuracy was used to predict rice yields. The goodness-of-fit and prediction-power values of both models were higher than those of traditional models.

f) How strong is the potential of agricultural development in other ecosystems in the Sapa region?

Three types of land use/land cover including paddy fields (in 2010), meadows and bare soils showed environmental conditions that would be suitable for rice agricultural developments. Local managers should consider the conversion from meadows and bare soils to paddy fields. The size of the areas of meadows and bare soils suitable for rice cultivation was shown to be equal to the size of the areas that are unsuitable for crop production but presently used as paddy fields. However, forest ecosystems need to be preserved for providing different regulating ecosystem services. Therefore, the conversion of forest areas and water-bodies to arable lands is not encouraged. The areas of paddy fields that are

unsuitable for agricultural use could be converted into forest areas, if the goal is a support natural water and nutrient supply for downstream paddy fields.

6.1.3. A Bayesian Belief Network for the assessment of rice provisioning ecosystem services

g) Is it feasible and effective to model the interactions between a regional social-ecological system and rice provisioning ecosystem services by developing a Bayesian Belief Network?

A Bayesian Belief Network was developed to explain the complexity and functionality of the regional social-ecological system and its interactions with rice provision. Significant statistics were recorded to characterize the interactions between the social-ecological system components in the network. It was demonstrated that the cause-effect linkages between environmental components as well as between these components and additional inputs in rice production were systematic and non-ignorable. The probability approach of Bayesian inference can effectively analyze the impacts of disturbances from environmental and socio-economic components on ecological structures and processes. This is also possible referring to natural functions of rice ecosystems including photosynthesis, nutrient and water availabilities. The posterior probabilities for rice provision calculated from the network are in harmony with the local statistical reports in the case study.

h) Which are effective and ineffective choices of farmers on the local level to cultivate rice in a remote mountainous region?

According to the diagnosis function of the Bayesian Belief Network, effective and ineffective options to select a suitable area for rice cultivation and an appropriate farming practice were proposed for the case study area. The contribution of nature and additional inputs from humans need to be regarded separately. Optimal options for crop suitability are Plinthic Acrisols with slopes lower than 13 degrees, altitudes lower than 1000 meters, precipitation lower than 1800 mm, temperatures from 22 to 24.5 °C and strong solar radiation. The following input parameters could be identified as suitable farming options: application of 150 - 180 kg/ha per year compound fertilizers and from 130 kg/ha per year straight fertilizer, using Vietnamese hybrid seeds and spraying pesticides in the middle of the growth period. Due to effective site selections, higher benefits can be provided than by intensifying available farming practices in the case study area. The effective choices in site selection methods help farmers and politicians to explicitly identify crop suitability areas.

i) Is it possible to equip stakeholders on the regional level with information to foster a sustainable regional development plan by supporting sustainable rice cropping?

Different stakeholders in the region have an interest to achieve various benefits from a sustainable rice cropping and a sustainable regional development. At first, taking advantage of natural ecosystem potentials by choosing suitable cropping sites will result in less use of chemical farming products such as fertilizers and pesticides through and more effective farming practices. Secondly, unmet demands

for rice products could be met if regional products would be traded within the region by more efficient supply chains. This was shown by the scenarios developed from the Bayesian Belief Network. Both benefits can contribute to a long-term agriculture with increased sustainability.

6.1.4. Ecosystem service supply chain for rice products

j) How are potential, supply and demand of rice provisioning ecosystem services related to rice imports and exports?

The relations between potential, flow and demand of rice provisioning ecosystem services (RPES) were identified in four cases in Chapter 5. In all cases, the demand for rice import and options for export were determined in the study region. If the actual ecosystem service flow in an agricultural region exceeds the natural ES potential, but equals the demand due to intensive farming practices, the farmers in this region still do not need to import rice. If the actual service flow is lower than the demand, although maybe equaling the RPES potential, local people need to import rice. If the ecosystem service flow is lower than the demand and cannot fully harness the natural ES potential because of unsuitable site selections and inefficient farming practices, local people also need to import rice. The case of rice export could be found if the service flow is higher than the demand, even though it may still be lower than the full RPES potential.

k) Can the agricultural regions in the mountainous provinces of northern Vietnam provide sufficient rice for local people to avoid hungers and reduce poverty?

According to the results from Chapter 5, agricultural regions in the mountainous areas of Vietnam could potentially provide enough rice for all local people. Especially, the actual rice productivity (RPES flow) in the case study area has been higher than the food demand (RPES demand) since the year 2012. However, the farmers are often selling their rice products for financial profits, instead of for more sustainable purposes – particularly for the mitigation of famine threats. Therefore, farmers are commonly exporting rice to outside regions, instead of providing it to local people. This is leading to the increase of hunger situations in the case study area. The authorities have to generate financial funding to support farmers and to avoid hunger in the future.

l) How could managers at community/regional levels improve the RPES supply chains?

To optimize the RPES supply chains, different tools were developed in this study. Maps depicting the spatial-temporal relations (and distribution) between ecosystem service providing units and benefiting areas are promising tools for decision makers to identify and predict RPES potentials, supply, flows and demand, and the location of RPES undersupply, resulting in hungers. Two models were developed, including the S-HyFIS model - *to assess the suitability of agricultural land for rice cultivation (as the first step before implementing farming practices)* - and the BBN – *to predict the*

probability to reach a high rice productivity in agricultural lands as proposed by the HyFIS model. Based on these models, the balances between RPES supply and demand were identified.

6.2. Conclusions

In this section, the three main questions of this thesis given in the introduction shall be answered (Section 1.5). The answers of these questions will generalize the outcomes from Chapters 2, 3, 4 and 5.

6.2.1. How are erosion and landslides regulated in terraced rice ecosystems?

Rice cultivation on terraces is not always an appropriate land use activity to mitigate risks of soil erosion and landslides. In the Sapa district, areas with “no capacity” for soil erosion and landslide regulating ecosystem services were estimated to include between 10 % – 20 % of the total area of terraced rice fields. Areas with “very low and low capacity” to supply these ecosystem services were estimated to cover 20 % - 40 % of the area of terraced rice fields. Soil erosion regulating ecosystem service supply in terraced rice fields seems to be slightly higher than in meadow areas, which is the opposite case for landslide regulation. Landslide risks are mitigated in the meadow areas more effectively than in the terraced rice fields. Forest ecosystems showed higher capacities for both regulating services. One idea would be to convert paddy fields located in areas with “no, low and very low capacities” for these services into forest land. Additionally, farmers should choose suitable areas for rice cultivation if they want to expand the terraced rice fields. Regarding permanent paddy fields, farmers should build appropriate constructions to protect from risks from natural hazards and apply innovative farming practices to support natural nutrient and water supply.

6.2.2. How can farmers improve rice production in mountainous areas?

In this study, three types of rice provisioning ecosystem services (RPES) were differentiated, including their potential, flow and demand. In order to improve RPES supply, farmers need to consider three main criterions: (1) take full advantage of the potential of nutrient, water and energy supplies from nature, (2) apply appropriate farming practices for particular cropping areas and (3) identify optimal markets and supply chains to sell the rice products in more sustainable ways. The site selection for rice cultivation is determined by the natural potentials for rice production. In mountainous environments, the areas suitable for rice cultivation have been narrowed by urbanization and reforestation processes. Consequently, farmers have also chosen areas unsuitable for agricultural purposes, resulting in a reduction of rice productivity. If farmers could avoid areas unsuitable for rice cultivation, the potential of rice productivity might be improved. Additionally, an effective site selection could reduce the probability to choose areas with low capacities for erosion and landslide regulating ecosystem services.

Regarding the farming practices, an appropriate and site- and time-specific use of fertilizers, pesticides and seeds is suggested. Fertilizers should be limited to supply nutrients that are deficient from nature. In the case study area, the amount of fertilizer use should be stopped at 180 kg/ha per year for compound fertilizers and at 130 kg/ha per year for straight fertilizers. These amounts could be changed in correspondence with the types of seeds used and according to the individual agricultural lands' needs. The avoidance of intensive pesticide uses and excessive fertilization, leading to an increase of nitrate concentrations in the groundwater and making the water unusable for drinking, should be avoided. The use of pesticides is not encouraged by this study due to its negative effects on local biodiversity, soil quality and the groundwater as well as its harmfulness to human health. Alternatively, farmers can use pesticides only in times when they really are needed, for instance to avoid the increase of heavy plant hopper attacks in the middle of the growing season as it has been the case in the study area. Nevertheless, local farmers should invest more in other biotechnical methods or better hybrid seeds, instead of applying farming practices based on the use of chemicals. Regional and local agricultural and land use policies should consider these facts and develop appropriate support and implementation regulations and measures.

Neighboring regions surrounding agricultural areas with high demands for food are proposed as optimal markets for rice products. It requires better rice supply chains, which could be based on ecosystem services approaches, in which famine and environmental issues (e.g. soil degradation and freshwater pollution) need to be considered. Service providing areas and service benefiting areas and their spatial relations in a particular region are important keys to identify flows between neighboring regions. The approach demands the participation of administrative managers at regional and local levels, agents such as traders and dealers, and farmers. As a result, unmet demands for food in service benefiting areas could be received enough food while environmental issues could be minimized through more effective site selection and better farming practices.

6.2.3. What are the differences in the use of Bayesian Belief Networks in ecosystem service assessments in comparison with other formal models, particularly in neural networks?

Two models for ecosystem service assessments were proposed in this study. The first one is the “hybrid neural-fuzzy inference system” (HyFIS) models, which can be a representative for other prediction models such as the support vector machine, linear regression, traditional neural networks or, decision trees in ecological analysis. The second model was the Bayesian Belief Network (BBN), which uses probability approaches. The HyFIS models can represent the formal statistical approaches in data analysis such as linear regression, support vector machine and neural networks. In this study, an example for model-based assessments of rice provisioning ecosystem services (RPES) was made. The two models used “rice yields” as an indicator to quantify the potential of rice provisioning ecosystem services. Further similarities in their application were prediction, modeling and scenario development (Table 3). Both models seem to be powerful for the identification of suitable/unsuitable

areas for rice cultivation that were shown in the effective/ineffective options for rice cultivation from the BBN model, and in the map of suitable areas resulting from the HyFIS models. These results are a foundation to quantify the potential of rice provisioning ecosystem services from natural sites and to assess service budgets at both plot and regional scales.

Besides these similarities, each model showed strong and weak points. **Firstly**, the use of the BBN approach in ecosystem service assessments can visually model: (1) chains of causal relations amongst environmental and socio-economic components with the RPES; (2) ecosystem functions through biophysical structures of the environment; and the RPES supply based on natural ecosystem functions and additional inputs from humans in one network (see also Burkhard and Maes, 2017) that cannot be done by the HyFIS models. Secondly, although the BBN model used 26 (environmental and anthropogenic) nodes that are higher than the number of variables used in the HyFIS models, users do not need to have all data related to these nodes to use it. The modification in one or several nodes can change the probabilities in the intermediate nodes and then the node “rice provisioning ecosystem service supply” (Figure 3). Whereas, the HyFIS models use eight environmental variables as a compulsory data to run it. Thirdly, the BBN model can estimate the natural RPES potentials and the additional inputs from humans, whereas the HyFIS models only focus on mapping the natural RPES potentials. Fourthly, the BBN model allows to use measured data from fields, data from farmer interviews and expert data from scientists. Therefore, it can be easily updated from other networks and be reproduced by new knowledge from other studies. Whereas, the HyFIS models need digital data that were measured or calculated in particular paddy fields, and it cannot be updated.

Two weak points from the BBN model - compared to the HyFIS models - need to be improved. Firstly, although the BBN provides priorities to select suitable/unsuitable cropping areas, this network could not be used for mapping that can be done by the HyFIS models. In this study, the BBN model was applied for the estimation of RPES potentials in different communities, which were shown on the map; but the potentials in each paddy plot cannot be shown based on the BBN. This is a big disadvantage, because farmers cannot find areas that are suitable for rice cultivation in a larger region. Secondly, because the BBN model was developed on the Netica interface (a commercial software), users (such as farmers) need to pay if they want to use it. This model needs to be developed in a really simplified user-interface, to make the models accessible for decision makers. Whereas, the HyFIS models are developed on R-Studio program – a free software. It would be better both models could be integrated in the future. Table 1 shows a systematic comparison of both models.

Table 2. A comparison between the use of Bayesian Belief Networks (BBN) and the Hybrid Neural-Fuzzy Inference System (HyFIS) for ecosystem service assessments.

No.	Content	Bayesian Belief Network	Hybrid neural-fuzzy inference system
1	Basic knowledge to use	Bayesian theory or probability theory	Fuzzy logic, neural network, statistical analysis and coding
2	Indicator used	Yields	Yields
3	Represent causal relations in social-ecological system	Yes	No
4	Predictable with natural potential	Yes	Yes
5	Predictable with natural and anthropogenic potential	Yes	No
6	Assessments related to RPES demand and budget	Yes	Yes
7	Uncertain in comparison with RPES flow	Low (with different options of farming practices)	High
8	Mapping	No	Yes
9	Research scales	From plot scales to national scales	Better with plots and small regions
10	Inputted data requested	Flexible from 1 to 30 environmental and anthropogenic variables	Fixed with 8 environmental variables
11	Allow to integrate with other network	Yes, easy to update	No, difficult to update
12	Editable by expert experience	Yes (integrated with expert knowledge through CPT's tables)	No
13	Application	Prediction/modeling, diagnosis, scenario development and knowledge exchanges	Prediction/modeling and scenario development
14	Financial investment	High (depending on software)	Free
15	Research question	<p>* How do socio-economic and ecological components link to ecosystem service provision?</p> <p>* How is the probability of success to achieve high capacity of ecosystem services under the changes in policy and climate change?</p>	<p>* Which exact value/capacity of ecosystem services could be obtained?</p>

6.3. Outlook

The interdisciplinary approach applied in this study results from many discussions and conclusions related to different subjects. In some cases, various interlinked research questions could be asked from the breadth of this approach. The complexity of the investigated social-ecological system requires a more detailed exploration, for instance about rice production, related environmental issues and rice supply markets. As a result, three interesting questions remain for further research as following:

Firstly, how can a balance and synergies between rice production/provision and other types of ecosystems services be achieved, toward a sustainable development? In order to answer this question, trade-offs between ecosystem services need to be explored. For example, due to low capacities to mitigate erosion and landslide risks in terraced rice ecosystems, the improvement of rice provisioning ES could lead to the decrease of natural hazard regulating ES. In addition, intensive farming practices in rice production based on chemical products are leading to the reduction of biodiversity and freshwater provision. Although these correlations were proposed in some previous studies, they have not been quantified in detail, especially their dynamics and changes during the course of a year.

Secondly, how is the dynamic of RPES supply chains? In this question, three contents need to be understood, including: (1) the movement of rice products from field and households to regional and national scales (Question: where do the farmers sell their rice products? Are the markets optimal?); (2) the change of rice prices over different intermediate sellers/markets (Question: Why do the farmers not sell to poorer households?); (3) find alternative livelihoods for poor farmers (Question: Which jobs are suitable for them?). These contents do not only link the results from this study with socio-economic approaches, they provide also foundations to generate better policies in agricultural development that are considered as the third outlook. Is it feasible to generate local policies to encourage farmers selling their rice products within the region, including poorer households? If possible, this policy would need to ensure stable incomes for farmers. The interest of farmers to sell their rice to traders needs to equal to the interests from poor people. The aim of this policy is to fulfill unmet demands for foods at both local and national scales. Farmers should *live for their surrounding communities and landscapes, instead of solely living for their own financial profits*. Selling their rice products to the region could lead to reduced farmer's financial profits, but the life quality of life in the surrounding communities would increase once the local famine is solved.

6.4. Highlights of the dissertation

According to the discussion and conclusions provided above, four summarizing messages can be formulated as following:

- Rice production on terraces is **not always and in all places a sustainable way** to regulate erosion and landslides.
- Five important components in rice provisioning ecosystem services assessments include: (1) **ecosystem service potential** or natural potential; (2) **ecosystem service supply**; (3) **ecosystem service flow** or the *de facto* services supplied; (4) **ecosystem service demand** and (5) **spatial relations** between **service providing units and benefiting areas**. Quantitative and directional relations between these components determine needs for rice-provisioning-ecosystem-service imports/exports.
- **Living for communities is a long-term investment**. To do so, farmers should sell their rice products to neighboring communities rather than to export them to outside regions.
- **Machine learning** methodologies (e.g. neural networks, fuzzy logics and Bayesian approaches) are promising tools to assess and map ecosystem services.

REFERENCES

*(Besides the individual references listed in Chapters 2, 3, 4 and 5,
the following references were used in Chapters 1 and 6)*

- ADB, 2010. Country Strategy and Program Viet Nam. Asian Development Bank, Vietnam.
- Aitkenhead, M.J., Coull, M.C., 2016. Mapping soil carbon stocks across Scotland using a neural network model. *Geoderma* 262, 187–198. doi:10.1016/j.geoderma.2015.08.034
- Bagstad, K.J., Semmens, D.J., Waage, S., Winthrop, R., 2013. A comparative assessment of decision-support tools for ecosystem services quantification and valuation. *Ecosyst. Serv.* 5, 27–39. doi:10.1016/j.ecoser.2013.07.004
- Barton, D.N., Benjamin, T., Cerdán, C.R., DeClerck, F., Madsen, A.L., Rusch, G.M., Salazar, Á.G., Sanchez, D., Villanueva, C., 2016. Assessing ecosystem services from multifunctional trees in pastures using Bayesian belief networks. *Ecosyst. Serv.* 18, 165–174. doi:10.1016/j.ecoser.2016.03.002
- Bastian, O., Haase, D., Grunewald, K., 2012. Ecosystem properties, potentials and services - The EPPS conceptual framework and an urban application example. *Ecol. Indic.* 21, 7–16. doi:10.1016/j.ecolind.2011.03.014
- Bauer, Kohavi, 1999. An empirical comparison of voting classification algorithms: bagging, boosting, and variants. *Mach. Learn.* 36, 105–139.
- Bayes, T., 1763. An Essay towards Solving a Problem in the Doctrine of Chances. *Philos. Trans. R. Soc. London* 53, 370–418. doi:10.1098/rstl.1763.0053
- Blaschke, A.P., Derx, J., Zessner, M., Kirnbauer, R., Kavka, G., Strelec, H., Farnleitner, A.H., Pang, L., 2016. Setback distances between small biological wastewater treatment systems and drinking water wells against virus contamination in alluvial aquifers. *Sci. Total Environ.* 573, 278–289. doi:10.1016/j.scitotenv.2016.08.075
- Bonnin, C., Turner, S., 2012. At what price rice? Food security, livelihood vulnerability, and state interventions in upland northern Vietnam. *Geoforum* 43, 95–105. doi:10.1016/j.geoforum.2011.07.006
- Bottrell, D.G., Schoenly, K.G., 2012. Resurrecting the ghost of green revolutions past: The brown planthopper as a recurring threat to high-yielding rice production in tropical Asia. *J. Asia. Pac. Entomol.* 15, 122–140. doi:10.1016/j.aspen.2011.09.004
- Brander, L., 2000. The ASEAN TEEB Scoping Study : Valuing ecosystem services in Southeast Asia.
- Brander, L., Eppink, F., 2012. The Economics of Ecosystems and Biodiversity for Southeast Asia (ASEAN TEEB).
- Bray, F., 1986. The rice economies: Technology and development in Asian societies. Basil Blackwell, Oxford, UK.
- Breiman, 1996. Bagging predictors. *Mach. Learn.* 2, 123–140.
- Bui, T.D., Bui, Q.-T.T., Nguyen, Q.-P.P., Pradhan, B., Nampak, H., Trinh, P.T., 2017. A hybrid artificial intelligence approach using GIS-based neural-fuzzy inference system and particle swarm optimization for forest fire susceptibility modeling at a tropical area. *Agric. For. Meteorol.* 233, 32–44. doi:10.1016/j.agrformet.2016.11.002
- Bui, T.D., Pradhan, B., Lofman, O., Revhaug, I., Tien Bui, D., Pradhan, B., Lofman, O., Revhaug, I., Dick, O.B., 2012. Landslide susceptibility assessment in vietnam using support vector machines, decision tree, and naive bayes models. *Math. Probl. Eng.* 2012, 12–29. doi:10.1155/2012/974638
- Burkhard, B., De Groot, R., Costanza, R., Seppelt, R., Jørgensen, S.E., Potschin, M., Jørgensen, S.E., Potschin, M., 2012a. Solutions for sustaining natural capital and ecosystem services. *Ecol. Indic.* 21, 1–6. doi:10.1016/j.ecolind.2012.03.008

- Burkhard, B., Kandziora, M., Hou, Y., Müller, F., 2014. Ecosystem Service Potentials, Flows and Demands – Concepts for Spatial Localisation, Indication and Quantification. *Landsc. Online* 32, 1–32. doi:10.3097/LO.201434
- Burkhard, B., Kroll, F., Müller, F., 2009. Landscapes' Capacities to Provide Ecosystem Services – a Concept for Land-Cover Based Assessments. *Landsc. Online* 1–22. doi:10.3097/LO.200915
- Burkhard, B., Kroll, F., Nedkov, S., Müller, F., 2012b. Mapping ecosystem service supply, demand and budgets. *Ecol. Indic.* 21, 17–29. doi:10.1016/j.ecolind.2011.06.019
- Burkhard, B., Maes, J., 2017. *Mapping Ecosystem Services*. Pensoft Publishers, Sofia.
- Burkhard, B., Müller, A., Müller, F., Grescho, V., Anh, Q., Arida, G., Bustamante, J.V. (Jappan), Van Chien, H., Heong, K.L., Escalada, M., Marquez, L., Thanh Truong, D., Villareal, S. (Bong), Settele, J., 2015. Land cover-based ecosystem service assessment of irrigated rice cropping systems in southeast Asia—An explorative study. *Ecosyst. Serv.* 14, 76–87. doi:10.1016/j.ecoser.2015.05.005
- Carpenter, S.R., Mooney, H.A., Agard, J., Capistrano, D., DeFries, R.S., Diaz, S., Dietz, T., Duraipah, A.K., Oteng-Yeboah, A., Pereira, H.M., Perrings, C., Reid, W. V., Sarukhan, J., Scholes, R.J., Whyte, A., 2009. Science for managing ecosystem services: Beyond the Millennium Ecosystem Assessment. *Proc. Natl. Acad. Sci.* 106, 1305–1312. doi:10.1073/pnas.0808772106
- Catling, H.D., Hobbs, P.R., Islam, Z., Alam, B., 1983. Agronomic practices and yield assessments of deepwater rice in Bangladesh. *F. Crop. Res.* 6, 109–132. doi:10.1016/0378-4290(83)90052-7
- CGIAR, 2016. *The drought and salinity intrusion in the Mekong River Delta of 55*.
- Chiramba, T., Mogoi, S., Martinez, I., Jones, T., 2011. Payment for Forest Ecosystem Services (PFES): pilot implementation in Lam Dong Province, Vietnam. Chapter 3. *Themat. Conf. Pap. UN-Water Int. Conf. Water Green Econ. Pract. Towar. Rio+20*. Zaragoza, Spain. 3-5 Oct. 2011 122–129.
- Comberti, C., Thornton, T.F., Wylliede Echeverria, V., Patterson, T., 2015. Ecosystem services or services to ecosystems? Valuing cultivation and reciprocal relationships between humans and ecosystems. *Glob. Environ. Chang.* 34, 247–262. doi:10.1016/j.gloenvcha.2015.07.007
- Coomes, D.A., Allen, R.B., 2007. Effects of size, competition and altitude on tree growth. *J. Ecol.* 95, 1084–1097. doi:10.1111/j.1365-2745.2007.01280.x
- Costanza, R., D'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R. V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. The value of the world's ecosystem services and natural capital. *Nature* 387, 253–260. doi:10.1038/387253a0
- Crossman, N.D., Burkhard, B., Nedkov, S., Willemen, L., Petz, K., Palomo, I., Drakou, E.G., Martín-Lopez, B., McPhearson, T., Boyanova, K., Alkemade, R., Egoh, B., Dunbar, M.B., Maes, J., 2013. A blueprint for mapping and modelling ecosystem services. *Ecosyst. Serv.* 4, 4–14. doi:10.1016/j.ecoser.2013.02.001
- Daily, 1997. *Nature's services: Societal dependence on natural ecosystems*. Island Press, United States of America. doi:10.1016/S1066-7938(00)80033-0
- De'ath, G., Fracricius, K.E., 2000. Classification and regression trees: A powerful yet simple technique for ecological data analysis. *Ecology* 81, 3178–3192. doi:10.2307/177409
- 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. *Ecol. Econ.* 41, 393–408. doi:10.1016/S0921-8009(02)00089-7

- Delisle, S., 2014. Hmong and Yao Food Security and Emerging Livelihood Vulnerabilities in the Northern Uplands of Vietnam.
- DeWeber, J.T., Wagner, T., 2014. A regional neural network ensemble for predicting mean daily river water temperature. *J. Hydrol.* 517, 187–200. doi:10.1016/j.jhydrol.2014.05.035
- Eckholm, E., 1978. *Disappearing Species: The Social Challenge*, Volume 45, Number 5. Worldwatch Institute, Washington DC.
- Ehrlich, P., Holdren, J.P., 1973. Human population and the global environment, in: UN Symposium on Population, Resources and Environment. Stockholm, p. Volume 26.
- Elith, J., H. Graham, C., P. Anderson, R., Dudík, M., Ferrier, S., Guisan, A., J. Hijmans, R., Huettmann, F., R. Leathwick, J., Lehmann, A., Li, J., G. Lohmann, L., A. Loiselle, B., Manion, G., Moritz, C., Nakamura, M., Nakazawa, Y., McC. M. Overton, J., Townsend Peterson, A., J. Phillips, S., Richardson, K., Scachetti-Pereira, R., E. Schapire, R., Soberón, J., Williams, S., S. Wisz, M., E. Zimmermann, N., 2006. Novel methods improve prediction of species' distributions from occurrence data. *Ecography (Cop.)*. 29, 129–151. doi:10.1111/j.2006.0906-7590.04596.x
- EPA, 2015. National Ecosystem Services Classification System (NESCO): Framework Design and Policy Application NESCO Four-Group Classification.
- Ericksen, P.J., Ingram, J.S.I., Liverman, D.M., 2009. Food security and global environmental change: emerging challenges. *Environ. Sci. Policy* 12, 373–377. doi:10.1016/j.envsci.2009.04.007
- Estoque, R.C., 2011. GIS-based Multi-Criteria Decision Analysis. *Geogr. Compass* 5, 1–24. doi:10.1111/j.1749-8198.2011.00431.x
- FAO, 2013. *Fao Statistical Yearbook 2013, Crop production statistics*. Food and Agriculture Organization: Rome. doi:10.1017/CBO9781107415324.004
- Fisher, B., Costanza, R., Turner, R.K., Morling, P., 2007. Defining and classifying ecosystem services for decision making. *Work. Pap. - Cent. Soc. Econ. Res. Glob. Environ.* 1–18.
- Fisher, B., Turner, R.K., Morling, P., 2009. Defining and classifying ecosystem services for decision making. *Ecol. Econ.* 68, 643–653. doi:10.1016/j.ecolecon.2008.09.014
- Fred, J., Hauke, R., Broder, B., 2011. *Modelling Complex Ecological Dynamic*. Springer-Verlag Berlin Heidelberg, Berlin, Heidelberg. doi:10.1007/978-3-642-05029-9
- Freeman, M., 2014. US EPA Classification System for Final Ecosystem Goods and Services.
- Fujita, K., 2013. Growth and Stagnation of Agriculture in Eastern India and Bangladesh xx.
- Garrity, D.P., 1984. Rice environmental classifications: a comparative review, in: International Rice Research Institute (Ed.), *Terminology for Rice Growing Environments*. Los Baños, Philippines, pp. 11–26.
- Glavan, M., Pintar, M., Urbanc, J., 2014. Spatial variation of crop rotations and their impacts on provisioning ecosystem services on the river Drava alluvial plain. *Sustain. Water Qual. Ecol.* 5, 31–48. doi:10.1016/j.swaqe.2015.01.004
- Grêt-Regamey, A., Sirén, E., Brunner, S.H., Weibel, B., 2017. Review of decision support tools to operationalize the ecosystem services concept. *Ecosyst. Serv.* 26, 306–315. doi:10.1016/j.ecoser.2016.10.012
- GRiSP, 2013. *Rice Almanac, 4th edition*, Global Rice Science Partnership. International rice research institute, Los Baños, Philippines. doi:10.1093/aob/mcg189
- GSO, 2012. *National Vietnamese Census, Year book*. The people committee of Lao Cai province. Lao Cai province, Vietnam, Lao Cai province, Vietnam.

- GSO, 2010. Sapa statistical yearbook 2010. The people committee of Sa Pa district, Lao Cai province, Vietnam.
- GSO, 2001. National Vietnamese Census, Year book in period 1995-2000. The people committee of Sa Pa district, Lao Cai province, Vietnam.
- GSO, 1995. National Vietnamese Census, Year book. The people committee of Sa Pa district. Lao Cai province, Vietnam, Lao Cai province, Vietnam.
- Gu, J., Yin, G., Huang, P., Guo, J., Chen, L., 2017. An improved back propagation neural network prediction model for subsurface drip irrigation system. *Comput. Electr. Eng.* 0, 1–8. doi:10.1016/j.compeleceng.2017.02.016
- Gupta, P.C., Toole, J.C.O., 1986. Upland Rice: A Global Perspective. International rice research institute, Philippines.
- Haines-Young, R., Potschin, M., 2018. Common International Classification of Ecosystem Services (CICES) V5.1 - Guidance on the Application of the Revised Structure.
- Haines-Young, R., Potschin, M., 2013. Common International Classification of Ecosystem Services (CICES): Consultation on Version 4, August-December 2012, EEA Framework Contract No EEA/IEA/09/003.
- Haines-Young, R., Potschin, M., 2010a. Chapter 6: The links between biodiversity, ecosystem services and human well-being, in: Raffaelli, eds. D.G., Frid, C.L.J. (Eds.), *Ecosystem Ecology: A New Synthesis*. Cambridge University Press, pp. 110–139. doi:10.1017/CBO9780511750458.007
- Haines-Young, R., Potschin, M., 2010b. The links between biodiversity , ecosystem services and human well-being. *Ecosyst. Ecol. A new Synth.* 110–139. doi:10.1017/CBO9780511750458.007
- Haines-Young, R., Potschin, M., 2009. Methodologies for defining and assessing ecosystem services. *Cent. Environ. Manag. Rep.* 1–84. doi:Project Code C08-0170-0062, 69 pp.
- Hardy, A., 2005. Red Hills. Migrants and the State in the Highlands of Vietnam, Institute. ed. NIAS Press, Singapore.
- Hastie, T., Tibshirani, R., Friedman, J., 2001. The Elements of Statistical Learning. *Math. Intell.* 27, 83–85. doi:10.1198/jasa.2004.s339
- Heong, K.L., Escalada, M.M., 2015. Are there productivity gains from insecticide applications in rice production? 181–192. doi:10.1007/978-94-017-9535-7.9
- Herdt, R.W., Capule, C., 1983. Adoption, spread and production impact of modern rice varieties in Asia, IRRI, Los Banos, Philippines.
- Ho Huu, L., Ballatore, T.J., Irvine, K.N., Nguyen, T.H.D., Truong, T.C.T., Yoshihisa, S., 2017. Socio-geographic indicators to evaluate landscape Cultural Ecosystem Services: A case of Mekong Delta, Vietnam. *Ecosyst. Serv.* doi:10.1016/j.ecoser.2017.11.003
- Hoang, H.T.T., 2014. Multi-scale Analysis of Human-Environment Interactions. A Case-study in the Northern Vietnamese Mountains. Katholieke Universiteit Leuven.
- Hoang, H.T.T., Vanacker, V., Van Rompaey, A., Vu, K.C., Nguyen, A.T., 2014a. Changing human-landscape interactions after development of tourism in the northern Vietnamese Highlands. *Anthropocene* 5, 42–51. doi:10.1016/j.ancene.2014.08.003
- Hoang, H.T.T., Vanacker, V., Van Rompaey, A., Vu, K.C., Nguyen, A.T., 2014b. Changing human-landscape interactions after development of tourism in the northern Vietnamese Highlands. *Anthropocene* 5, 42–51. doi:10.1016/j.ancene.2014.08.003
- Hochachka, W.M., Caruana, R., Fink, D., Munson, A., Riedewald, M., Sorokina, D., Kelling, S.,

2007. Data-Mining Discovery of Pattern and Process in Ecological Systems. *J. Wildl. Manage.* 71, 2427. doi:10.2193/2006-503
- Hummel, D., Jahn, T., Schramm, E., 2011. Social-ecological analysis of climate induced changes in biodiversity – outline of a research concept. BiK-F Knowledge. Flow Pap. 11, Frankfurt/Main.
- Huntsinger, L., Oviedo, J.L., 2014. Ecosystem Services are Social – ecological Services in a Traditional Pastoral System : the Case of California ’ s Mediterranean Rangelands. *Ecol. Soc.* 19, 8. doi:10.5751/es-06143-190108
- IRRI, 2006. The sustainability of rice farming, International Rice Research Institute, CAB International Publishing. International rice research institute, Philippines. doi:10.5860/CHOICE.35-3847
- IRRI, 1985. Progress in upland rice research, Progress in upland rice research. The International Rice Research Institute, P.O. Box 933, Manila, Philippines.
- IRRI, 1984. Research Priorities in Tidal Swamp Rice, PhD Proposal. The International Rice Research Institute. doi:10.1017/CBO9781107415324.004
- IRRI, 1982. Rice research strategies for the future. International rice research institute, Philippines.
- IUCN, 1980. World Conservation Strategy, World Cons. ed. World Wide Fund for Nature, Gland.
- Jadin, I., Vanacker, V., Hoang, H.T.T., 2013. Drivers of forest cover dynamics in smallholder farming systems: The case of northwestern vietnam. *Ambio* 42, 344–356. doi:10.1007/s13280-012-0348-4
- Jones, L., Norton, L., Austin, Z., Browne, A.L., Donovan, D., Emmett, B.A., Grabowski, Z.J., Howard, D.C., Jones, J.P.G., Kenter, J.O., Manley, W., Morris, C., Robinson, D.A., Short, C., Siriwardena, G.M., Stevens, C.J., Storkey, J., Waters, R.D., Willis, G.F., 2016. Stocks and flows of natural and human-derived capital in ecosystem services. *Land use policy* 52, 151–162. doi:10.1016/j.landusepol.2015.12.014
- Kandziora, M., Burkhard, B., Müller, F., 2013a. Interactions of ecosystem properties, ecosystem integrity and ecosystem service indicators—A theoretical matrix exercise. *Ecol. Indic.* 28, 54–78. doi:10.1016/j.ecolind.2012.09.006
- Kandziora, M., Burkhard, B., Müller, F., 2013b. Mapping provisioning ecosystem services at the local scale using data of varying spatial and temporal resolution. *Ecosyst. Serv.* 4, 47–59. doi:10.1016/j.ecoser.2013.04.001
- Kassam, A.H., Fischer, G., Antoine, J., Food and Agriculture Organization of the United Nations. Land and Water Development Division., International Institute for Applied Systems Analysis., 1991. Agro-ecological land resources assessment for agricultural development planning : a case study of Kenya : resources data base and land productivity. FAO, United Nations.
- Klotzbücher, T., Marxen, A., Vetterlein, D., Schneiker, J., Turke, M., Van Sinh, N., Manh, N.H., Van Chien, H., Marquez, L., Villareal, S., Bustamante, J.V., Jahn, R., 2014. Plant-available silicon in paddy soils as a key factor for sustainable rice production in Southeast Asia. *Basic Appl. Ecol.* 16, 665–673. doi:10.1016/j.baae.2014.08.002
- Kubiszewski, I., Anderson, S.J., Costanza, R., Sutton, P.C., 2016. The Future of Ecosystem Services in Asia and the Pacific. *Asia Pacific Policy Stud.* 3, 389–404. doi:10.1002/app5.147
- Kubo, M., Purevdorj, M., 2004. The future of rice production and consumption. *J. Food Distrib. Res.* 35, 128–142.
- Kumar, P., Verma, M., Wood, M.D., Negandhi, D., 2010. Guidance Manual for the Valuation of Regulating Services, UNEP. ed. Publishing Services Section, UNON, Nairobi-Kenya, ISO.

- Langerwisch, F., Vaclavik, T., Bloh, W. Von, 2016. Projected provision of ecosystem services , trade-offs and synergies in the LEGATO areas.
- Le, J.A., El-Askary, H.M., Allali, M., Struppa, D.C., 2017. Application of recurrent neural networks for drought projections in California. *Atmos. Res.* 188, 100–106. doi:10.1016/j.atmosres.2017.01.002
- Lek, S., Delacoste, M., Baran, P., Dimopoulos, I., Lauga, J., Aulagnier, S., 1996. Application of neural networks to modelling nonlinear relationships in ecology. *Ecol. Modell.* 90, 39–52. doi:10.1016/0304-3800(95)00142-5
- Levetin, E., McMahon, K., 2008. Chapter 11: Origins of agriculture, *Plants and Society* 5th, *Plants and Society*. The McGraw–Hill Companies.
- Li, S., 2014. Application of the Human Appropriation of Net Primary Production (HANPP) to Rice Agriculture in the Sa Pa Region, Lao Cai , Vietnam Master Thesis In Partial Fulfilment of the Requirements for the Award of the Degree of Erasmus Mundus Master of Science. Christian-Albrechts Universität zu Kiel.
- Liu, Z., Peng, C., Xiang, W., Tian, D., Deng, X., Zhao, M., 2010. Application of artificial neural networks in global climate change and ecological research: An overview. *Chinese Sci. Bull.* 55, 3853–3863. doi:10.1007/s11434-010-4183-3
- Loc, H.H., Diep, N.T.H., Tuan, V.T., Shimizu, Y., 2018. An analytical approach in accounting for social values of ecosystem services in a Ramsar site: A case study in the Mekong Delta, Vietnam. *Ecol. Indic.* 89, 118–129. doi:10.1016/j.ecolind.2017.12.066
- Loft, L., Le, D.N., Pham, T.T., Yang, A.L., Tjajadi, J.S., Wong, G.Y., 2017. Whose Equity Matters? National to Local Equity Perceptions in Vietnam’s Payments for Forest Ecosystem Services Scheme. *Ecol. Econ.* 135, 164–175. doi:10.1016/j.ecolecon.2017.01.016
- Mach, M.E., Martone, R.G., Chan, K.M.A., 2015. Human impacts and ecosystem services: Insufficient research for trade-off evaluation. *Ecosyst. Serv.* 16, 112–120. doi:10.1016/j.ecoser.2015.10.018
- Maniatis, D., 2007. *Ecosystem Services of Southeast Asia: Major Threats and Opportunities Table of Contents*. Global Canopy.
- Manzanilla, D.O., Paris, T.R., Vergara, G. V., Ismail, A.M., Pandey, S., Labios, R. V., Tatlonghari, G.T., Acda, R.D., Chi, T.T.N., Duoangsila, K., Siliphouthone, I., Manikmas, M.O.A., Mackill, D.J., 2011. Submergence risks and farmers’ preferences: Implications for breeding Sub1 rice in Southeast Asia. *Agric. Syst.* 104, 335–347. doi:10.1016/j.agsy.2010.12.005
- Marsh, G.P., 1864. *Man & Nature: or Physical Geography as Modified by Human Action*. Charles Scribner. Charles Scribner, New York.
- Mcclelland, J.L., Rumelhart, D.E., Hayes, P.J., 1988. *Explorations in parallel distributed processing: A Handbook of Models, Programs, and Exercises*. London MIT.
- McDonough, S., Gallardo, W., Berg, H., Trai, N. V., Yen, N.Q., 2014. Wetland ecosystem service values and shrimp aquaculture relationships in Can Gio, Vietnam. *Ecol. Indic.* 46, 201–213. doi:10.1016/j.ecolind.2014.06.012
- MEA, 2003. *Ecosystems and Human Well-being: A Framework for Assessment*. Millenium Ecosystem Assess. 1–25.
- Meylan, L., Merot, A., Gary, C., Rapidel, B., 2013. Combining a typology and a conceptual model of cropping system to explore the diversity of relationships between ecosystem services: The case of erosion control in coffee-based agroforestry systems in Costa Rica. *Agric. Syst.* 118, 52–64. doi:10.1016/j.agsy.2013.02.002

- MFF, 2015. Viet Nam National Strategy and Action Plan (2015 – 2018). IUCN Vietnam.
- MFF, 2012. Viet Nam National Strategy and Action Plan (2011-2013). IUCN Vietnam.
- Michaud, J., Turner, S., 2017. Reaching new heights. State legibility in Sa Pa, a Vietnam hill station. *Ann. Tour. Res.* 66, 37–48. doi:10.1016/j.annals.2017.05.014
- Michaud, J., Turner, S., 2000. The Sa Pa marketplace, Lao Cai Province, Vietnam. *Asia Pac. Viewp.* 41, 85–100. doi:10.1111/1467-8373.00108
- Mihajlović, I., Nikolić, Đ., Štrbac, N., Živković, Ž., 2010. Statistical Modelling in Ecological Management Using the Artificial Neural Networks (ANNs). *Serbian J. Manag.* 5, 39–50.
- Millennium Ecosystem Assessment, 2005. Ecosystems and human well-being, Ecosystems. doi:10.1196/annals.1439.003
- Mukhopadhyay, P., Shyamsundar, P., 2015. Ecosystem Services – An Agenda for Research in South Asia Ecosystem Services in South Asia-Priority Issues for Research. Bengaluru, India.
- Nelson, E., Mendoza, G., Regetz, J., Polasky, S., Tallis, H., Cameron, D.R., Chan, K.M.A., Daily, G.C., Goldstein, J., Kareiva, P.M., Lonsdorf, E., Naidoo, R., Ricketts, T.H., Shaw, M.R., 2009. Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales. *Front. Ecol. Environ.* 7, 4–11. doi:10.1890/080023
- Nguyen, H., Dang, K.B., Dang, V.B., 2011. Application of N-SPECT model and GIS for soil erosion assessment in Sapa district, Lao Cai province. *J. Earth Sci. Vietnam Natl. Univ. Publ.* 27, 199–207.
- Nguyen, T.H.T., Nguyen, T.T., Nguyen, H.D., Do, T. Van, Nguyen, T.D.P., 2009. Situation Analysis Report On Highland Aquatic Resource and Sustainable Development in Northern and Central Vietnam.
- No.1250/QD-TTg, 2012. National Strategy on Biodiversity. he Social. Repub. Vietnam.
- No.20/2008/QH12, 2008. Biodiversity law. Natl. Assem. Social. Repub. Vietnam Legislatur, 30.
- No.45/QD-TTg, 2014. Approving the master plan on biodiversity conservation in the whole country through 2020, with orientations toward 2030. prime Minist. Social. Repub. Vietnam 49–56.
- No.55/2014/QH13, 2014. Law on Environmental Protection. Natl. Assem. Social. Repub. Vietnam 58.
- No.661/QD TTg, 1998. Decision by the prime minister on Objectives, Tasks, Policies and Organization for the Establishment of Five Million Hectares of New Forest (in Vietnamese). prime Minist. Social. Repub. Vietnam.
- No.99/2010/ND-CP, 2010. Decree on the policy on payment for forest environment services. Gov. Social. Repub. Vietnam 11.
- Palomares-Salas, J.C., Agüera-Pérez, A., González De La Rosa, J.J., Moreno-Muñoz, A., 2014. A novel neural network method for wind speed forecasting using exogenous measurements from agriculture stations. *Meas. J. Int. Meas. Confed.* 55, 295–304. doi:10.1016/j.measurement.2014.05.020
- Palomo, I., Martín-López, B., Potschin, M., Haines-Young, R., Montes, C., 2013. National Parks, buffer zones and surrounding lands: Mapping ecosystem service flows. *Ecosyst. Serv.* 4, 104–116. doi:10.1016/j.ecoser.2012.09.001
- Pham, T.T., Loft, L., Bennett, K., Phuong, V.T., Dung, L.N., Brunner, J., 2015. Monitoring and evaluation of Payment for Forest Environmental Services in Vietnam: From myth to reality. *Ecosyst. Serv.* 16, 220–229. doi:10.1016/j.ecoser.2015.10.016
- Phan, T.H.D., Brouwer, R., Davidson, M.D., Hoang, L.P., 2017. A comparative study of transaction

- costs of payments for forest ecosystem services in Vietnam. *For. Policy Econ.* 80, 141–149. doi:10.1016/j.forpol.2017.03.017
- Plieninger, T., Dijks, S., Oteros-Rozas, E., Bieling, C., 2013. Assessing, mapping, and quantifying cultural ecosystem services at community level. *Land use policy* 33, 118–129. doi:10.1016/j.landusepol.2012.12.013
- Potschin, M., Haines-Young, R., 2011. Introduction to the Special Issue: Ecosystem Services. *Prog. Phys. Geogr.* 35, 571–574. doi:10.1177/0309133311422976
- Potschin, M., Haines-Young, R., Fish, R., Turner, R.K., 2016. *Routledge handbook of ecosystem services*. Routledge.
- Prieto, A., Prieto, B., Ortigosa, E.M., Ros, E., Pelayo, F., Ortega, J., Rojas, I., 2016. Neural networks: An overview of early research, current frameworks and new challenges. *Neurocomputing* 214, 242–268. doi:10.1016/j.neucom.2016.06.014
- Quoc Vo, T., Kuenzer, C., Oppelt, N., 2015. How remote sensing supports mangrove ecosystem service valuation: A case study in Ca Mau province, Vietnam. *Ecosyst. Serv.* 14, 67–75. doi:10.1016/j.ecoser.2015.04.007
- Quyen, N.T.K., Berg, H., Gallardo, W., Da, C.T., 2017. Stakeholders' perceptions of ecosystem services and Pangasius catfish farming development along the Hau River in the Mekong Delta, Vietnam. *Ecosyst. Serv.* 25, 2–14. doi:10.1016/j.ecoser.2017.03.007
- Raymond, C.M., Bryan, B.A., MacDonald, D.H., Cast, A., Strathearn, S., Grandgirard, A., Kalivas, T., 2009. Mapping community values for natural capital and ecosystem services. *Ecol. Econ.* 68, 1301–1315. doi:10.1016/j.ecolecon.2008.12.006
- Remme, R.P., Schröter, M., Hein, L., 2014. Developing spatial biophysical accounting for multiple ecosystem services. *Ecosyst. Serv.* 10, 6–18. doi:10.1016/j.ecoser.2014.07.006
- Ren, D., 2015. *Ecosystem of Sloping Terrain, Soil, and Vegetation (Chapter 2), Storm-Triggered Landslides in Warmer Climates*. Springer International Publishing Switzerland. doi:10.1007/978-3-319-08518-0
- Rumelhart, D.E., Hinton, G.E., Williams, R.J., 1986. Learning representations by back-propagating errors. *Nature* 323, 533–536. doi:10.1038/323533a0
- Sanchez-Bayo, F., 2011. Impacts of Agricultural Pesticides on Terrestrial Ecosystems. *Ecol. Impacts Toxic Chem.* 63–87. doi:10.1016/B978-0-12-374849-2.00004-6
- Sattaka, P., Pattaratuma, S., Attawipakpaisan, G., 2017. Agricultural extension services to foster production sustainability for food and cultural security of glutinous rice farmers in Vietnam. *Kasetsart J. Soc. Sci.* 38, 74–80. doi:10.1016/j.kjss.2016.05.003
- SCEP, 1970. *Man's impact on the global environment*, [Study of. ed. MIT Press, Cambridge, Massachusetts.
- Sears, P.B., 1956. The processes of environmental change by man, in: Thomas, W.L. (Ed.), *Man's Role in Changing the Face of the Earth (Volume 2)*. University of Chicago Press, Chicago, p. 1193.
- Settele, J., Spangenberg, J.H., Heong, K.L., Burkhard, B., Bustamante, J.V., Cabbigat, J., Van Chien, H., Escalada, M., Grescho, V., Hai, L.H., Harpke, A., Horgan, F.G., Hotes, S., Jahn, R., K??hn, I., Marquez, L., Sch??dler, M., Tekken, V., Vetterlein, D., Villareal, S.B., Westphal, C., Wiemers, M., 2015. Agricultural landscapes and ecosystem services in South-East Asia-The LEGATO-Project. *Basic Appl. Ecol.* 16, 661–664. doi:10.1016/j.baae.2015.10.003
- Siou, L.K.A., Johannet, A., Borrell, V., Pistre, S., 2011. Complexity selection of a neural network

- model for karst flood forecasting: The case of the Lez Basin (southern France). *J. Hydrol.* 403, 367–380. doi:10.1016/j.jhydrol.2011.04.015
- Spangenberg, J.H., Beaurepaire, A.L., Bergmeier, E., Burkhard, B., Van Chien, H., Cuong, L.Q., Görg, C., Grescho, V., Hai, L.H., Heong, K.L., Horgan, F.G., Hotes, S., Klotzbücher, A., Klotzbücher, T., Kühn, I., Langerwisch, F., Marion, G., Moritz, R.F.A., Nguyen, Q.A., Ott, J., Sann, C., Sattler, C., Schädler, M., Schmidt, A., Tekken, V., Thanh, T.D., Thonicke, K., Türke, M., Václavík, T., Vetterlein, D., Westphal, C., Wiemers, M., Settele, J., 2017. The LEGATO cross-disciplinary integrated ecosystem service research framework: an example of integrating research results from the analysis of global change impacts and the social, cultural and economic system dynamics of irrigated rice production, *Paddy and Water Environment*. Springer Japan. doi:10.1007/s10333-017-0628-5
- Suhardiman, D., Wichelns, D., Lestrelin, G., Hoanh, C.T., 2013. Payments for ecosystem services in Vietnam: Market-based incentives or state control of resources? *Ecosyst. Serv.* 6, 64–71. doi:10.1016/j.ecoser.2013.06.006
- Sun, Z., Müller, D., 2013. A framework for modeling payments for ecosystem services with agent-based models, Bayesian belief networks and opinion dynamics models. *Environ. Model. Softw.* 45, 15–28. doi:10.1016/j.envsoft.2012.06.007
- Syrbe, R.U., Walz, U., 2012. Spatial indicators for the assessment of ecosystem services: Providing, benefiting and connecting areas and landscape metrics. *Ecol. Indic.* 21, 80–88. doi:10.1016/j.ecolind.2012.02.013
- Tran, T.T.H., Zeller, M., Suhardiman, D., 2016. Payments for ecosystem services in Hoa Binh province, Vietnam: An institutional analysis. *Ecosyst. Serv.* 22, 83–93. doi:10.1016/j.ecoser.2016.10.001
- Tran, Nguyen, 1986. Geological Map of Vietnam 1:1500000.
- Tugault-Lafleur, C., 2007. Diversifying Livelihoods: Hmong Use and Trade of Forest Products in Northern Vietnam. (Master thesis).
- United Nations, 1992. Results of the World Conference on Environment and Development: Agenda 21., UNCED. ed. Rio de Janeiro, United Nations, New York.
- Uusitalo, L., 2007. Advantages and challenges of Bayesian networks in environmental modelling. *Ecol. Modell.* 203, 312–318. doi:10.1016/j.ecolmodel.2006.11.033
- Villa, F., Ceroni, M., Bagstad, K., Johnson, G., Krivov, S., 2009. ARIES (ARtificial Intelligence for Ecosystem Services): a new tool for ecosystem services assessment, planning, and valuation. *to Enhanc.* 1–10.
- VNFF, 2014. Payments for forest environmental services (PFES) in Vietnam Findings from three years of implementation.
- Westman, W.E., 1977. How much are nature's services worth? *Science* (80-.). 197, 960–964.
- Windmeijer, P.N., Andriessse, W., 1993. Inland Valleys in West Africa: An Agro-Ecological Characterization of Rice-Growing Environments 160.
- Zacharia, J.T., 2007. Ecological Effects of Pesticides. *Pestic. Mod. World - Risks Benefits* 129–142.

Chapter 7

Curriculum Vitae



KINH BAC DANG

Geographer/Ecologist

Email: kinhbachus@gmail.com

Skype: kinhbackskype

https://www.researchgate.net/Bac_Dang

A. EDUCATION

Educational level	University	Discipline	Year
PhD	Kiel University, Kiel, Germany	Agricultural Science/Ecosystem services	2014 - 2018

Achievements/Tasks

- Analyzed the relations between environmental and anthropogenic impacts on rice provisioning ecosystem services, then using Bayesian Belief Network and hybrid neural-fuzzy inference system for modelling these relations (*presented in two papers*).
- Developed conceptual models to understand relations between potential, flow and demand of crop provisioning ecosystem services; and spatial relations between service providing and benefiting communities (*presented in one papers*).
- Proposed effective indicators and methods to quantify natural hazards/erosion regulating ecosystem services (*presented in one paper*).

Master of Science	Hanoi University of Science, VNU, Hanoi, Vietnam	Cartographic, Remote Sensing and GIS	2010 - 2012
-------------------	--	--------------------------------------	-------------

Achievements/Tasks

- Graduated Master degree with score: 3.44 / 4 or 8.76/10);
- Awarded TOSHIBA Scholarship (Japan) for the excellence of studying and Sciences in 2011 - 2012.
- The score of the thesis entitled: “Apply Remote Sensing and GIS technology to research and re-appear the old-river of Day, Nhue river flows through Hanoi” has achieved 10/10.

Bachelor of Science	Hanoi University of Science, VNU, Hanoi, Vietnam	Geography (Natural Hazard)	2006 - 2010
---------------------	---	-------------------------------	-------------

Achievements/Tasks

- Graduated Bachelor degree in excellent mark (3.39/4 or 8.32/10) and followed the Honor Program of University of Science, Vietnam National University, Hanoi, 2010.
- Awarded Hanoi University of Science Scholarship from 2006 to 2010; and Mrs. Nguyen Thi Thoa's Scholarship (Vietnam) in 2010.
- The third Prize at Scientific Research Student's Award organized by the Minister of Education and Training in 2010.
- The third Prize in Symposium of Scientific Study for Student organized by University of Science, VNU in 2009.

B. PROFESSIONAL EXPERIENCE

Duration	Position	Office	Address
From 8/2017 to present	Researcher	Department of Ecosystem Management, Institute for Natural Resource Conservation, University of Kiel.	Olshausenstr. 75, 24118 Kiel, Germany.

Achievements/Tasks

- Scientific Journal reviewer (Ecological Indicators ¹⁹)
- Programming of a Bayesian Belief Network for the determination of ecosystem services on the german Ostseeküste.
- Application of Bayesian approaches for the assessments of crop provisioning ecosystem services in Schleswig-Holstein state, Germany.
- Voluntary advisor to Master students in facilitating tutorials, Department of Ecosystem Management, Kiel University.

¹⁹ <https://www.journals.elsevier.com/ecological-indicators>

From 8/2010 to 10/2014	Researcher, Assistant lectures	Department of Geomorphology and Marine Geography & Environment, Faculty of Geography, Hanoi University of Science, VNU	334 Nguyen Trai Road, Thanh Xuan District, Hanoi City, Vietnam
---------------------------	--------------------------------------	---	---

Achievements/Tasks

- Taught some subjects: "Basic of Geomorphology", "Application of Remote Sensing and GIS in the study of Geography and Marine Environment", "Climate and environment changes", "Lithology and Weathering crust".
- Researched Karst geo-morphology in Vietnam, supported to firm productions in the caves and to exploring new caves (including Hang-Son-Doong - the largest cave in the world).
- Successfully applied remote sensing and GIS (1) to reappear old-river bed from Landsat satellite imagines and (2) to assess flood hazard in Hanoi city.
- Developed two education and training modules in Geography faculty.
- Hold office as Deputy Secretary of Young Staffs and Students Union of Geography faculty; and achieved the certification of "The typical young face of Hanoi University of Science 2011" in
- the Hanoi University of Science, VNU.

C. CHARACTERISTIC & HOBBIES

- **Fields of interest:** Ecosystem services, rice production, natural hazard, climate change, spatial/non-spatial data analysis and coding (related to data mining and machine learning).
- **Excellent PC skills:** R and Python coding, ArcGIS, InVEST, Netica, ENVI, ILWIS, Global Mapper.
- **Foreign Language:** English (Upper-Intermediate); Vietnamese (Native) and German (Beginner).

D. CERTIFICATIONS		
Name	Organization	Time
Certificate of Outstanding Contribution in Reviewing	Ecological Indicators journal	8/2017
Negotiation Skills	Kiel University	10/2015
Intellectual property protecting and valorizing research	Kiel University	10/2015
Getting started with the doctorate: Setting the compass	Kiel University	4/2015
Writing a scientific publication	Kiel University	3/2015
Slidewriting: Optimize your own academic presentation	Kiel University	1/2015
Environmental Sustainability: Application of Environmental Technology and Approaches Seminar	The University of Queensland	9/2012
Esri Training - ArcGIS Desktop III: GIS Workflows and Analysis	ESRI Vietnam	12/2012

E. SCIENTIFIC PUBLICATIONS

- **Submitted Articles:**

1. **Dang, K.B.**, Burkhard, B., Müller, F., Windhorst, W., Dang, Van Bao, 2018. *Potential, flow and demand of rice provisioning ecosystem services*. Landscape Online. In preparation.
2. **Dang, K.B.**, Burkhard, B., Windhorst, W., Müller, F., 2018. *Application of hybrid neural-fuzzy inference system for mapping crop suitability areas and predicting rice yields*. Ecological Modelling (Submitted)

- **Published Articles:**

3. **Dang, K.B.**, Windhorst, W., Burkhard, B., Müller, F., 2018. *Using a Bayesian Belief Network to assess provisioning ecosystem service patterns in rice agriculture*. Ecological Indicator (In press)
4. **Dang, K.B.**, Burkhard, B., Müller, F., Dang, V.B., 2018. *Modelling and Mapping Natural Hazard Regulating Ecosystem Services in Sapa, Lao Cai Province, Vietnam*. Paddy and Water Environment (In press)
5. **Dang KB**, Dang VB, Burkhard B, Müller F, Giang TL (2017) Cultural Ecosystem Services Assessment Based on Geomorphological Approach – Case Study in Sapa , Lao Cai Province. VNU J. Sci. Earth Environ. Sci. 33, 92–102. doi:10.22144/ctu.jsi.2017.055
6. Limbert, H., Limbert, D., Hieu, N., Phái, V. V, **Bac, D.K.**, Phuong, T.H., Granger, D.,

2016. *The discovery and exploration of Hang Son Doong*. Boletín Geológico y Minero; CODEN BGMIA3; v. 127(1); p. 165-176.
7. Pham, Q.T., Le, D.M., Dang, V.B., Nguyen, D.H., **Dang, K.B.**, Giang, T.L., Tran, T.T., Cao, H.T.M., 2015. Payment for Forest Environmental Services - Solution towards Enhancing the Regional Linkage between Central Highlands and South Central Coast in Environmental Protection and Natural Hazard Prevention. VNU J. Sci. Earth Environ. Sci. 31/1S, pp. 94-104.
 8. **Dang, K.B.**, Thanh, N.T.H., Tuyet, L.T., 2014. *Research on urban changes in a relationship with geographical factors in the western region of Hanoi during the period 2000-2014*. 35th Asian Conf. Remote Sens. 2014 2, 1480–1486.
 9. Limbert, H., Limbert, D., Hieu, N., Phai, V. Van, **Bac, D.K.**, 2013. *Significant discoveries in the cave systems of Phong Nha – Ke Bang National park from 2003 to 2013*. Sci. Technol. Inf. Mag. 3, 65–92.
 10. Nguyen, H., Do, T.H., **Dang, K.B.**, Doan, T.P., 2013. *Assessment of flood hazard risk in Hanoi city*. J. Earth Environ. Sci.
 11. Nguyen, H., **Dang, K.B.**, Dang, V.B., 2011. *Application of N-SPECT model and GIS for soil erosion assessment in Sapa district, Lao Cai province*. J. Earth Sci. Vietnam Natl. Univ. Publ. 27, 199–207.

F. SCIENTIFIC CONFERENCES AND WORKSHOPS SINCE 2014

1. **Dang Kinh Bac**, Benjamin Burkhard, Felix Müller. 2015. Mapping Ecosystem Services supply in Sapa, Lao Cai province, Viet Nam (Example with Landslide Regulating Ecosystem Service). *Rice Ecosystem Services in South-East Asian Landscapes - a LEGATO conference*. Yogyakarta, Indonesia. 19-24 March 2015.
2. **Dang Kinh Bac**, Benjamin Burkhard, Wilhelm Windhorst, Felix Müller. 2018. A Bayesian approach toward sustainable development of rice provisioning ecosystem services. *Landscape 2018 - Frontiers of agricultural landscape research*. Berlin, Germany. 12–16 March 2018.
3. Jakub Zelený, Sabine Bicking, **Dang Kinh Bac**, Felix Müller. 2018. *Combining methods to estimate ecosystem service potentials for crop and fodder production in Schleswig-Holstein, Germany*. The XXIII International Conference of the Society for Human Ecology. Lisbon, Portugal. 7-10 July 2018.

G. RESEARCH PROJECTS

No	Project and Activities performed
1.	<p>LEGATO (<i>Land-use intensity and Ecological EnGineering – Assessment Tools for risks and Opportunities in annual crop based production systems</i>) project (2011 – 2016) - funded by the German Ministry of Research and Education (BMBF) within their funding measure Sustainable Land Management; Funding nos. 01LL0917A-O.</p> <ul style="list-style-type: none"> - The achievements/tasks are the same with PhD studies.
2.	<p>Research and propose the multi-benefit solution for sustainable use lakes and rivers in Hanoi sub-urban areas (in the south and north of Red river) –Project in group A of VNU by Assoc Prof. Dang Van Bao, from 2012 to 2014.</p> <ul style="list-style-type: none"> - Applied Remote Sensing and GIS to reappear old-rivers and lakes systems in Hanoi, Vietnam. - Assessed the vulnerability of constructions built on old-river bed due to erosion and depression. - Contributed in a book “History of rivers in Hanoi” (submitted).
3.	<p>Research and evaluate the flood hazard in Hanoi capital - Project in group B of VNU by Assoc Prof. Nguyen Hieu, from 2011 to 2013.</p> <ul style="list-style-type: none"> - Drawn geomorphological map applied for assessments of flood hazards in Hanoi capital. - Integrated inventories, geomorphological indicators and digital elevation models to identify areas/provinces where are high vulnerable to be inundated in different scenarios.
4.	<p>Discovering and searching caves in the area of Phong Nha – Ke Bang, Quang Binh Province, organized by British Cave Research Association and faculty of geography in Hanoi University of Science, April 2010, May, 2011 and April 2012.</p> <ul style="list-style-type: none"> - Worked as a coordinators and translator for British Cave Research Association (BCRA) in several expeditions around Hang Son Doong cave in Phong Nha – Ke Bang National Park near the border with Laos. - Collected geological samples in Quang Binh and Quang Ninh provinces to analyze the transformation of karst landscapes in Vietnam.