Institute of Agricultural Sciences in the Tropics (Hans-Ruthenberg-Institute)
Field: Management of Crop Water Stress in the Tropics and Subtropics
Prof. Dr. Folkard Asch

Simulating the impact of land use change and climate change on the supply of ecosystem services in a rubber-dominated watershed in Southwestern China

Dissertation
submitted in fulfillment of the regulations to acquire the degree
"Doktor der Agrarwissenschaften"
(Dr.sc.agr. in Agricultural Sciences)
to the
Faculty of Agricultural Sciences

presented by
Kevin Thellmann
born in Bad Friedrichshall, Germany
Stuttgart-Hohenheim, 2020

This thesis was accepted as a doctoral thesis (Dissertation) in fulfillment of the regulations to acquire the doctoral degree "Doktor der Agrarwissenschaften” (Dr.sc.agr. / Ph.D. in Agricultural Sciences) by the Faculty of Agricultural Sciences at University of Hohenheim on August 27, 2020.

Date of the oral examination: October 7, 2020

Examination Committee

Chairperson of the oral examination	Prof. Dr. Andrea Knierim
Supervisor and Reviewer	Prof. Dr. Folkard Asch
Co-Reviewer	Prof. Dr. Christine Fürst
Additional examiner	Prof. Dr. Georg Cadisch

Affidavit

pursuant to Sec. 8(2) of the University of Hohenheim’s doctoral degree regulations for Dr.sc.agr.

1. I hereby declare that I independently completed the doctoral thesis submitted on the topic

“Simulating the impact of land use change and climate change on the supply of ecosystem services in a rubber-dominated watershed in Southwestern China”

2. I only used the sources and aids documented and only made use of permissible assistance by third parties. In particular, I properly documented any contents which I used - either by directly quoting or paraphrasing - from other works.

3. I did not accept any assistance from a commercial doctoral agency or consulting firm.

4. I am aware of the meaning of this affidavit and the criminal penalties of an incorrect or incomplete affidavit.

I hereby confirm the correctness of the above declaration. I hereby affirm in lieu of oath that I have, to the best of my knowledge, declared nothing but the truth and have not omitted any information.

Stuttgart, 2020

Kevin Thellmann

Acknowledgements

My time as a PhD student included some of the most exciting and adventurous moments of my life. It also included some of the most frustrating and exhausting times I ever had to push through. I am thankful for both the good and the bad times. I am even more thankful to the people that made the good moments possible and enjoyable, and to the people who helped and accompanied me through the bad ones.

First and foremost, I would like to thank my team of supervisors Prof. Dr. Folkard Asch, Prof. Dr. Georg Cadisch and Dr. Marc Cotter, who accepted me as a PhD student and made this thesis possible. Not only do I want to thank them for the guidance, encouragement, supervision, personal as well as scientific advice and feedback, but also for the welcoming atmosphere you create at the Hans-Ruthenberg-Institute. I cannot thank Dr. Marc Cotter enough for guiding me through my BSc, MSc and finally this PhD thesis. Thank you to Prof. Dr. Christine Fürst for completing the examination committee.

A big thank you goes to all the members of SURUMER and SOS Uplands. Without their help, organization, field work and collaboration, data sharing and discussions, this thesis would not have been possible. Special thanks go again to Dr. Marc Cotter and to Dr. Inga Häuser, for kicking off my scientific career before I even finished my MSc Degree by offering me to be a co-author on one of Inga's papers, and for laying the foundation of this PhD thesis. Thanks to Dr. Hongxi Liu, Dr. Xueqing Yang, Dr. Reza Golbon, Sabine Baumgartner, Dr. Franziska Harich, Dr. Jue Wang, Moritz Laub, Dr. Thomas Aenis, Dr. Sergey Blagodatsky, Manuel Krauss, Dr. Sabine Stürz, Dr. Christian Brandt, Dr. Konrad Martin, Dr. Anna Treydte, Dr. Carsten Marohn, and the people I forgot to mention by name. Thanks to Dr. Wanwisa Pansak, Dr. Natta Takrattanasaran, Thanachanok Khamkajorn and Mr. Nuntapon, without whom I would have been completely lost in Thailand.

Thanks to my lovely peers at 490g for making daily routine not feel like routine at all. Thanks to Sarah Glatzle, Benjamin Warth, Dr. Alejandro Pieters, Hoang Vu Duy, Hong Van Nguyen, Tanja Weinand, Shimul Mondal, Pia Schneider, Marc Schmierer, Julia Hartmann, Gabriele Schmid and Gabriele Kircher. Special thanks to Jessica Lloyd and Kristian Johnson for their advice on how to use proper English.

Thank you to the Anton-&-Petra-Ehrmann Foundation for funding most of this research and to Marc Giese and Alexandra Schappert for all their help and organization. It was a pleasure to be part of the Water – People – Agriculture Graduate School.

Finally I would like to thank all my friends and relatives, that I could not name here individually, but who kept on lifting my spirit and provided me with endless support. Thank you to my parents Hans and Edith Thellmann for their love, encouragement, financial support and freedom they gave me throughout my life. Last but not least, I want to thank Leni Kraft for always being there for me, no matter what time and distance, and for making me strive to be a better person one day at a time.

Contents

Chapter 1: General Introduction

1.1. Background

The work presented in this thesis was funded by the Anton-&-Petra-Ehrmann Foundation as a part of the Water – People – Agriculture Graduate School and supported by the German Federal Ministry of Education and Research (BMBF) through the research project "SURUMER – Sustainable Rubber Cultivation in the Mekong Region" (Grant number FKZ 01LL091). The objective of the SURUMER project was the development of an integrative, applicable and stakeholder-validated concept for sustainable rubber cultivation in Yunnan Province in the People's Republic of China. The project consisted of an international and multidisciplinary consortium of research partners structured in nine disciplinary sub-projects, ranging from economics and social sciences, soils, plants and carbon dynamics to water management and human-wildlife conflicts. Parts of this thesis were conducted as a part of the "Integrated Ecosystem Service Assessment Group" which aimed to integrate a combination of disciplinary models from the biophysical and socio-economic subprojects of SURUMER in order to develop an interdisciplinary assessment method for the impacts of rubber cultivation in the study region.

Furthermore, parts of this thesis (Chapter 3) are an outcome of the initial phase of the SOS Uplands project, also funded by BMBF (Grant number FKZ 01LC1709). The objective of SOS Uplands was to develop integrated assessment tools for the identification and management of safe operating spaces (SOS) to strike a balance between the conservation of structural and functional biodiversity and land use intensification with the aim of safeguarding livelihood and ecosystem functions in mountainous agricultural landscapes in the tropics.

1.2. Global Change Processes and their Impact in Montane Mainland Southeast Asia

1.2.1. Terminology

Land cover is defined as the biophysical condition of the land, which include both artificial structures as well as the kind and condition of its natural features such as soil, water, vegetation or other biota [1]. Land use is defined as the human employment of the land, meaning the way it is utilized to ensure that human resource demands are met [1]. Meyer and Turner [1] list three ways in which land cover can be changed: (1) Conversion of one land cover into another (quantitative change), (2) modification of the land cover without full conversion (qualitative change), and (3) maintaining the condition of the land cover against drivers of natural change (e.g. pest control). For the sake of simplicity, the term "land use" is referring to both land use and land cover for the remainder of this thesis.

Land use patterns can be observed with remote sensing techniques. For example, groups of pixels in multispectral satellite observations can be assorted into land use categories based on their spectral similarities and differences to other groups of pixels [2]. Simple differentiations, e.g., between vegetated and non-vegetated land, are relatively straightforward as plants feature a distinct peak in the near infrared spectrum of reflected light and absorb solar radiation in the photo-synthetically active radiation spectral region [3]. However, distinguishing between different kinds of crops is more complex and requires advanced classification techniques which rely on extensive ground truth campaigns for training the classification algorithm with geo-referenced (multi-temporal) photo-sequences taken in the field [3].

Land use change can then be detected by comparing sequential land use maps of the same area taken at different points in time using geographic information systems (GIS). Land use change models can be powerful tools to estimate potential future land use changes or support policy, decision-making and planning processes [4]. Land use planners have to ensure that the composition of elements in a landscape is ideally planned in terms of ecological soundness and economic profitability, while taking into account environmental and administrative restrictions such as land tenure rights. In other words, agricultural crops should be grown where they grow best while forests and habitats should be protected where they are most worthy of protection. Available tools to regulate these processes include spatial planning with GIS such as agricultural zoning, the establishment of restrictive areas such as nature reserves, and providing extension services to farmers in order give advice on suitable plantation choices or appropriate crop rotations.

1.2.2. Land Use Change Dynamics in Montane Mainland Southeast Asia

Montane Mainland Southeast Asia (MMSEA) represents a large, ecologically vital region, which spans roughly half of the land area of Cambodia, Laos, Myanmar, Thailand, Vietnam and China's Yunnan Province (Figure 1.1) [5]. Situated within the Indo-Burma Biodiversity Hotspot, the region is one of the most biologically diverse regions on the planet [6].

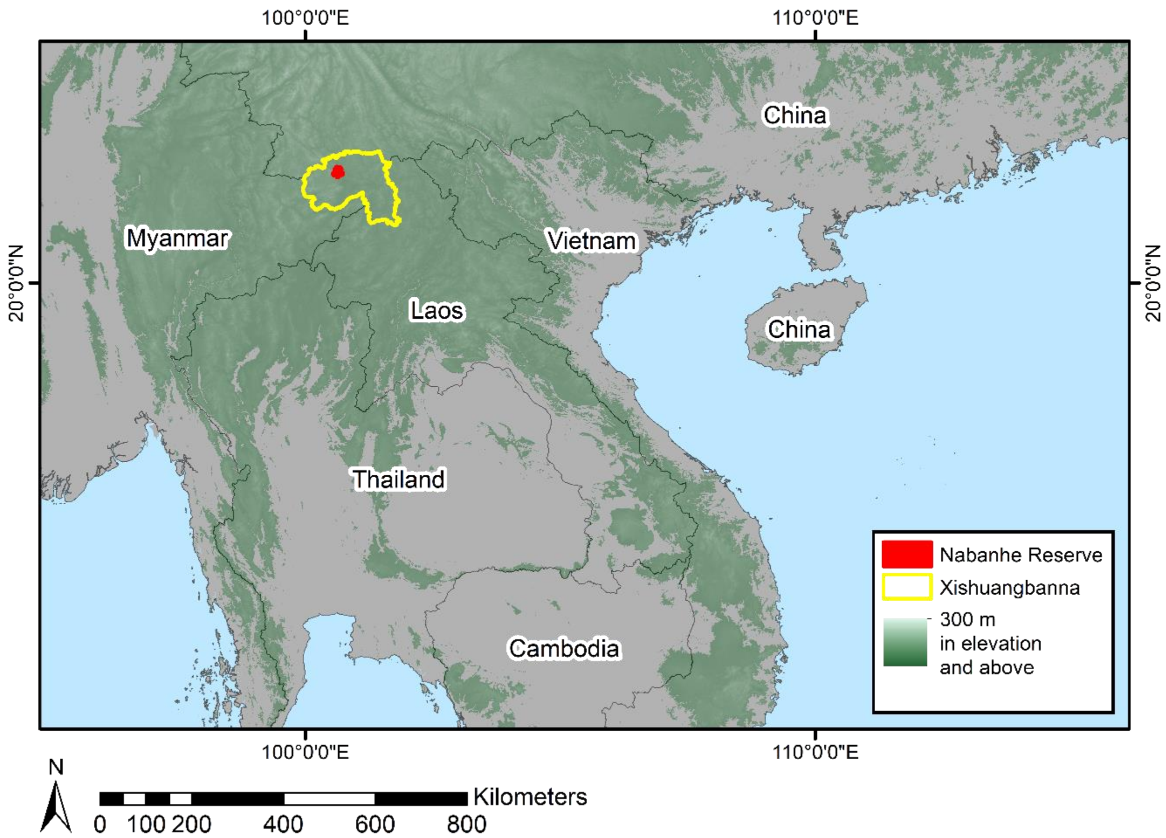


Figure 1.1. Map depicting continental Southeast Asia and the location of the study area, the Nabanhe Reserve (depicted in red). Nabanhe Reserve is located in Xishuangbanna Prefecture (outlined in yellow), in Southwestern China. Areas above 300 meters in elevation are depicted in a green shade (based on CGIAR-CSI SRTM Version 4 [7]). Administrative borders were obtained from the DIVA-GIS free spatial database [8].

The past decades saw an extensive shift in land use patterns in MMSEA. Increasingly more land has been converted to cash crop farming systems such as oil palm or rubber plantations [9,10]. So far, the expansion of cash crops in upland areas has occurred mostly at the cost of traditional (long-fallow) shifting cultivation systems (also referred to as swidden or slash-and-burn cultivation) [9,10]. This transition from shifting cultivation to intensified cropping has resulted in several outcomes in Southeast Asia's (SEA) uplands: increases in overall income for more households, but with the costs of reductions of traditional cultivation methods, socio-economic wellbeing, staple crop yields and livelihood options [10].

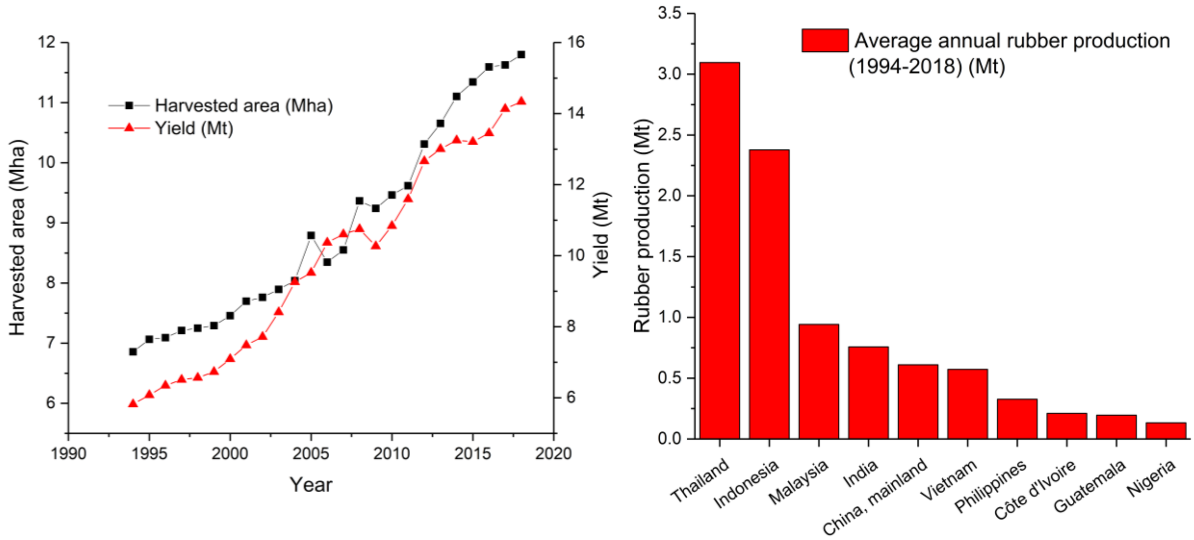
Whereas hydrological and geomorphological effects of traditional shifting cultivation systems have been largely inconsequential in MMSEA, the introduction of permanent cash crops and monocultures has led to numerous negative effects: (1) changes in streamflow response, (2) increased surface erosion, (3) higher probability of landslides, and (4) declines in stream water quality [11]. Furthermore, the transition to permanent cropping systems have negatively affected soil properties, such as soil organic carbon, cation-exchange capacity, and above-ground carbon content [10]. Reasons for the negative impacts include the following: (1) the simultaneous cultivation of large portions of upland catchments, which leads to accelerated hydraulic and tillage erosion as no more fallowing is practiced to allow for the recovery of key soil properties (e.g. infiltration), (2) concentrated overland flow and erosion sources which are connected to the stream network, (3) reduced root strength on permanently cultivated slopes, (4) the use of pesticides, herbicides and irrigation [11]. In addition, shifting from low to high input agriculture reduces both functional and species diversity as well as the availability of suitable habitats for species originating from natural forests [12].

In summary, the underlying drivers pushing land use transitions from traditional shifting cultivation to intensified perennial and annual cash cropping has led to declines in ecosystem services (ESS) and the livelihood security they previously supported [10]. Deforestation, transformation, intensification and degradation not only have extensive impacts on the supply of ESS, but also impact the distribution of habitats and threaten biodiversity [13]. Dressler et al. [10] conclude that the most sensible approach for sustainable upland agriculture and climate change mitigation would be to implement broader landscape-scale policies that keep farmers on their land and cultivation systems that enhance rather than deplete livelihood security and ESS. The expansion of rubber in Xishuangbanna Prefecture serves as a suitable case study to assess past impacts and develop new landscape-scale approaches for sustainable upland agriculture.

1.2.3. Rubber Boom in Xishuangbanna

By the year 2012, more than one million hectares of non-traditional rubber-growing areas had been converted to rubber plantations throughout Thailand, Laos, Vietnam, Cambodia, Myanmar, and China [14]. Fox et al. [5] predict a fourfold increase of area under rubber plantations by the year 2050, mostly at the loss of areas previously under shifting cultivation and secondary forests. New rubber plantations are increasingly established in sub-optimal, marginal environments, where reduced yields are likely due to environmental stresses, such as increased susceptibility to diseases [13,15]. Already in 2010, nearly three fourths of rubber areas in SEA were located on marginal land [13]. Furthermore, 57% of rubber areas in SEA are susceptible to erosion, frost, wind damage and insufficient water availability [13]. In addition, the effects of climate change are expected to mostly lead to an exacerbation of environmental marginality for rubber cultivation in SEA: (1) accelerated erosion rates due to increased precipitation for high altitude plantations, (2) increased risk of drought and ensuing dry stress, (3) increased risk of storm damage, whereas (4) frost risk is expected to decrease in the future [13].

Today, natural rubber of the Pará-rubber tree (*Hevea brasiliensis* Müll. Arg.) is among the world's most important renewable resources, as it is a key industrial commodity in manufacturing a wide range of latex products, and is classified as a strategic resource [16–18]. The tree is native to the tropical rain forests of the Great Amazonian basin in Brazil, where latex collection was traditionally a labour-intensive process, due to the low densities of rubber trees in old growth forests [16,19]. As a result, latex extraction was more comparable to mining of natural resources rather than to a managed agricultural system [16]. Nowadays, more than 90% of all natural rubber is produced in Asia, with Thailand, Indonesia and Malaysia representing the top three rubber producing countries (Figure 1.2) [20]. Large-scale production in South America is hampered by the fungus *Pseudocerospora ulei*, formerly known as *Microcyclus ulei* (South American leaf blight), which has not yet spread to Asia [21,22]. As Asian rubber plantations are susceptible to the fungus, an outbreak might lead to catastrophic consequences for both rubber farmers as well as industries dependent on natural rubber for manufacturing their products (e.g. medical products or the transportation sector) [21]. In such a scenario, the vehicle industry, which uses about three quarters of the total world production of natural rubber, would take the largest hit [23].



(**a**) (**b**)

Figure 1.2. Annual natural rubber yields and annual harvested rubber area from 1994-2018 (**a**), and annual average rubber production by the top ten rubber producing countries (1994-2018) (**b**). Data for both (**a**) and (**b**) is taken from FAOSTAT [20].

The study region, Xishuangbanna Prefecture in Yunnan Province of the People's Republic of China, is located at the northernmost edge of tropical Asia (Figure 1.1) [24]. Tropical seasonal rainforest, tropical montane rainforest, monsoon forest on limestone and on riverbanks, as well as south-subtropical evergreen broad-leaved forest represent the main primary forest types in Xishuangbanna [24]. The environmental impacts of traditional shifting cultivation were relatively inconsequential until after the Second World War, when poppy cultivation for opium was introduced, population density in mountainous areas increased, cropping periods lengthened and fallow periods became shorter [25]. In the early 1950s, rubber was introduced to Xishuangbanna, driven by economic and ideological policies to modernize "primitive" shifting cultivation practices, and ensure the availability of rubber for national defence and construction [26]. Since the 1960s, the most drastic drivers of deforestation observed in Xishuangbanna have been the introduction of rubber trees, as well as logging for commercial and fuel use, while previous shifting cultivation triggered the development of large scale areas of secondary vegetation, such as deciduous monsoon forests, grasslands and savannah woodlands [24]. As the planting of rubber trees was seen as a favourable alternative to traditional shifting cultivation, the expansion of rubber plantations was encouraged through policies such as the "Sloping Land Conversion Program", which made the establishment of new rubber plantations officially count as reforestation [25].

Prices for natural rubber saw an incredible increase from around 0.5 US$/kg at the turn of the century to a peak of more than 6 US$/kg in 2011 until it steadily declined to less than 2 US$/kg in 2018 [27]. The steady increase in prices for natural rubber in the early 2000s was reflected in the land use conversion rates in SEA. In Xishuangbanna, forest cover declined from 71% to 52% of the land area, whereas rubber increased from 11% to 21% in the same time period (2002-2018) [27]. Unprotected forest areas are disproportionately located on steep slopes at high altitudes, whereas only smaller forest patches remain in the biologically more diverse valleys at low altitudes [27]. Forest patch numbers increased and forest patch sizes decreased 8-fold and 10-fold, respectively (2001-2014), which creates challenges for conservation planning, as valuable links between habitats are lost [27].

With the environmental consequences of rubber expansions becoming more apparent in recent years, there is an urgent need to assess the impact of potential future rubber expansions in MMSEA. The concept of ESS provides a fitting framework for this analysis.

1.3. Ecosystem Services

1.3.1. General Concepts

ESS are defined as the benefits that ecosystems provide to people [28]. ESS can be considered among the most important building blocks of human society and include the provisioning of food, fibre, medicines, clean water; protection from extreme weather events, flooding or pests; as well as spiritual and cultural well-being [29]. The terms "nature's services" and "ecosystem services" first appeared in academic literature in the 1970s and 1980s, but it was not until 1997 when two seminal publications (an edited book by Gretchen Daily [30] and an article in the journal "Nature" by Costanza et al. [31]) started an explosive increase of research, policies and applications on the concept of ESS [32]. The rapidly growing field of research aimed to address questions on how to assess, value and account for ESS in regional and global economies and decision-making processes [29]. Publications such as the Millennium Ecosystem Assessment (MEA) [28], The Economics of Ecosystems and Biodiversity (TEEB) [33], and the formation of IPBES (the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) in 2012 [34] further reshaped environmental management and policy making.

There is an important distinction between the terms ESS and ecosystem processes and functions. Ecosystem processes and functions do contribute to ESS, but are not synonymous with ESS [32]. Ecosystem processes and functions are biophysical relationships that exist whether humans benefit from them or not, whereas ESS are functions and processes that benefit people, directly or indirectly, consciously or un-consciously [32]. This arguably anthropocentric view of nature has been criticized for conveying the idea that nature only exists to service humans (e.g. [35,36]). The counterarguments of ESS proponents are: (1) that ESS imply the recognition that humans represent an integral part of the biosphere; (2) their well-being, but also the mere survival of *Homo sapiens* as a species is very much dependent on "the rest of nature"; (3) that, as any other species, humans use their environment and resources to survive and thrive; and (4) that with this recognition of our interdependence with the rest of nature, the ESS concept makes it clear that not only humans matter, but that the whole system is of importance [32].

Ecosystems that supply ESS are also referred to as "natural capital" (a stock that yields a flow of services over time), which provides the link between ecology and economics [32]. Natural capital does not require human activity to be built or maintained, but requires the interaction with other forms of capital and human agency in order to generate benefits [32]. The other types of capital include: (1) built or manufactured capital, (2) human capital, and (3) social (or cultural) capital [32]. Figure 1.3 depicts the interaction of the four types of capital, which highlights the need for transdisciplinary approaches in order to measure, model, understand and manage ESS [32].

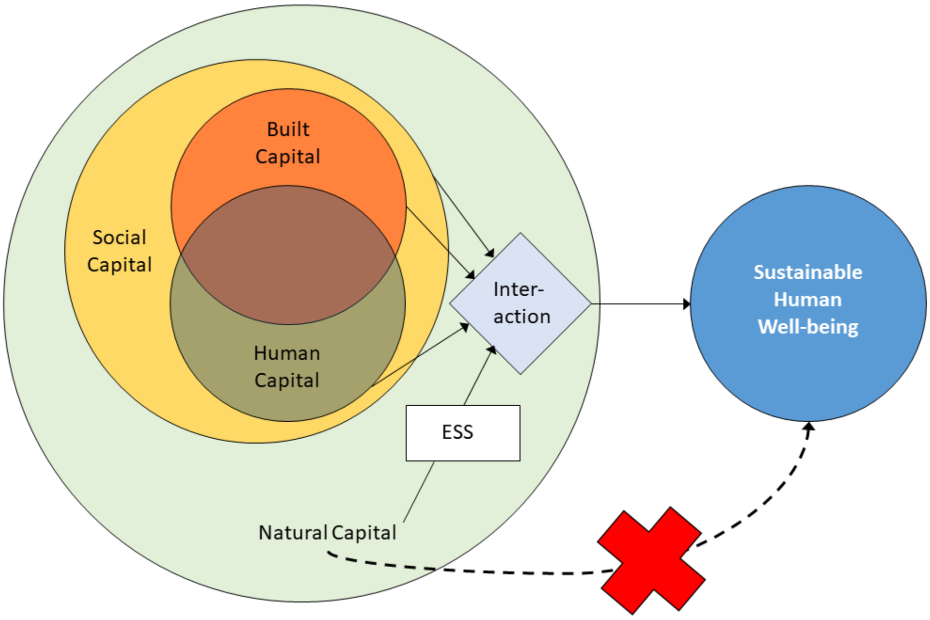


Figure 1.3. The interaction between four types of capital affecting human well-being: built, human, social and natural capital, adapted from Costanza et al. [37]. Ecosystem Services (ESS) are the relative contribution of natural capital to human well-being, as natural capital does not flow directly, but requires interaction in order to contribute to human well-being [32].

Several classification systems for ESS have been proposed in the last decades (e.g. [28,31,33]). They differ in some details, but mostly agree on a general categorization of the following types of services [32]:

(I) **Provisioning services** require the combination with built, human and social capital in order to provide food, timber, fibre or other raw material;

(II) **Regulating service** combine with the other three capitals to generate flood control, storm protection, water and air quality regulation, pollination, control of diseases, pest and the climate. They are often un-regarded by individuals;

(III) **Cultural services** provide recreation, aesthetic, scientific, and cultural identity, sense of place and other cultural benefits in combination with built, human and social capital;

(IV) **Supporting services** include ecosystem processes such as primary productivity, soil formation, biochemistry, nutrient cycling and the provisioning of habitat. They contribute indirectly to human well-being by maintaining ecosystem processes and functions in order to safeguard the other three ESS categories. Supporting services (or biodiversity, primary production, habitat/refugia services) are sometimes used as proxy measures, as ecosystem functions underpin all other ESS.

One of the main reasons for comprehensive classification systems for ESS is to prevent double-counting in ESS accounting, so as to avert an overestimation of ESS supply. As outlined in Section 1.2., ecosystems and the ESS they supply are under increasing pressure from human activities [38,39]. The main reason for overexploitation of ESS is mono-functional use (maximization of one ESS) and the consequences of the corresponding landscape management, as opposed to a less frequently favoured multifunctional use concept [40]. This enables a maximum of economic gains, but reduces the opportunities for current and future generations to sustain the same level of well-being, as the costs and benefits of unsustainable resource use are not evenly spread across time and space [41]. This circumstance can favour economically rational decisions of certain stakeholder groups to pursue the unsustainable use of resources, as it is unlikely for them to experience the negative consequences of their decisions [42]. Since it is impossible to maximize all ESS simultaneously, environmental management should be aimed at the optimal balance of services in accordance with stakeholder's needs [41]. One means to achieve this balance is through the quantification and valuation of ESS (using ESS modeling tools), which is generally referred to as ecosystem service assessments (ESAs).

1.3.2. Ecosystem Service Assessment Approaches

The past years saw the development of several software approaches for modeling and evaluating ESS. Tools for replicable and quantifiable ESS analyses include InVEST (Integrated Assessment of Ecosystem Services and Trade-Offs) [43,44], ARIES (Artificial Intelligence for Ecosystem Services) [45], and MIMES (Multiscale Integrated Model of Ecosystem Services) [46]. These models can be categorized as independently applicable and generalizable landscape-scale models [47].

After an extensive review of the available software solutions for modeling and assessing ESS, InVEST became the model of choice for this thesis. This decision was made according to the following criteria: InVEST features (1) spatially explicit applicability from watershed to landscape scale, (2) estimation of uncertainty through varying inputs, (3) biophysical values as model output with optional monetization, (4) an open source framework, (5) a modular design of independently applicable modules, (6) the capability of batch-processing with Python 2.7, (7) extensive documentation and an online support forum, and (8) is ready-to-use, as opposed to many other approaches, which were still in development at the beginning of this study.

As opposed to many other modeling frameworks used in environmental science (process-based models, cellular automata, agent-based models, system dynamics) most of the InVEST modules rely on deterministic production functions. This approach reduces model complexity and the level of detail in the ecosystem processes InVEST modules are able to represent, but makes it possible to apply them on larger scales, increases generalizability and the amount of integrated services. Another advantage of spatially explicit computer models such as InVEST is the ability to include both perceived and non-perceived benefits, allowing for the evaluation of a range of different policy scenarios [32].

1.4. Justification

In Xishuangbanna Prefecture, the extensive expansion of rubber plantations has fundamentally impacted environmental and socio-economic conditions on many levels. It has changed the local hydrology, water quality and quantity, erosion and river sedimentation, reduced suitable habitats and decreased habitat quality for a number of plant and animal species, and reduced the capacity of the landscape to serve as a long-term carbon sink and provide other essential ESS. While it has brought a new and tempting source of income to the rural population, in many cases alleviating poverty, it has also lead to higher livelihood vulnerability due to less diversification in income sources and a higher dependency on global market prices. There is an urgent need to assess the environmental impact of future land use changes in regard to rubber expansion in order to offer decision support for environmental management, land use planning, and policy design, especially under the altered environmental conditions a changing climate is likely to introduce to the region.

Until now, not much research has been conducted on multidisciplinary ESS assessments for rubber-producing landscapes. Studies on ESS in rubber plantations have only focused on one or a few ESS. The strength of the ESS concept lies in its holistic approach, in the assessment of multiple ESS, in the identification of trade-offs between them, and in the integration of feedback and experience of stakeholders in an iterative process.

With these gaps in knowledge, the presented thesis is scientifically relevant, as it not only includes the first spatially explicit ESS assessment for rubber producing landscapes under multiple drivers of change (land use change and climate change), but also introduces multiple methods for evaluating and further utilizing modeling results (evaluation based on stakeholder preferences (Chapter 2), tipping point analysis (Chapter 3), and integrating the uncertainty of climate change (Chapter 4)). Further, the thesis shows the need for ESS assessments to evolve beyond their existing concepts in order to provide more utility and be more relevant for both science and for different groups of stakeholders.

1.4.1. Hypotheses

There are several hypotheses which serve as a guiding thread through this thesis:

(I) A continuation of the past trend of rubber expansions in the study area will lead to declines in water availability, increased erosion and river sedimentation as well as reductions in habitat quality and carbon storage potential on a watershed scale. The reductions in hydrological ESS will be further amplified by the impact of climate change.

(II) The incorporation of stakeholder preferences into the evaluation of different land use change trajectories in regard to ESS supply will provide additional aspects of assessing the suitability of land use plans to preserve ESS in comparison to relying only on bio-physical modeling results.

(III) The identification of tipping points in the supply of ESS at different spatial scales will provide a tool that can be used in environmental management for early interventions within land use change trajectories.

(IV) Land use plans incorporating water protection measures, such as riparian buffer zones and reforestation on steep slopes, are able to buffer against the negative effects of climate change in the study area watershed. In addition, these measures will increase the capacity of the landscape to serve as a carbon sink and provide more suitable habitats in comparison to the current land use situation.

1.4.2. Objectives

The aim of the presented thesis is to assess the potential impacts of future rubber expansions on the supply of ESS and biodiversity in Nabanhe Reserve. In particular, the three case studies examined:

(I) if the InVEST (Integrated Assessment of Ecosystem Services and Trade-Offs) modeling framework could be used to provide a holistic quantification of ESS supply in a data-scarce environment, and if stakeholder preferences could be used to evaluate these spatio-temporal model results in order to generate new insights on the suitability of several land use change trajectories for the future of the study area.

(II) if a simple tool for regional policy making and land use planning could be produced by combining time series results derived from InVEST with a data-driven algorithm in order to reduce the risk of traversing future tipping points in the supply of ESS at multiple spatial scales.

(III) if InVEST could be used to analyse land use scenarios in combination with multiple climate change scenarios in order to assess hydrological ESS in Nabanhe Reserve while capturing the uncertainty in climate projections.

1.4.3. Outline

The work presented in this cumulative PhD thesis is divided into five chapters. The first chapter serves as a general introduction to the study region, research concepts and introduces the overarching research questions, hypotheses and objectives. It provides the background for the research on ecosystem services, current approaches on how they can be assessed, as well as an overview of the global change processes which compromise their provisioning, such as the recent land use change dynamics in MMSEA. Chapter 2 introduces the multidisciplinary modeling approach for ESS and biodiversity in rubber-dominated landscapes using the InVEST modeling framework. Chapter 3 builds on the methodological framework introduced in the previous chapter and expands on it by integrating the concept of tipping points into the spatial and temporal analysis of ESS. Chapter 4 focusses on the supply of hydrological ESS and discusses how they are altered under the pressure of both land use change and climate change. Chapter 5 provides a general discussion of the previous chapters and touches upon the shortcomings, strengths and uncertainties as well as future research potentials. The appendix contains a complete list of the literature referenced in this thesis, summaries in English and German language as well as a curriculum vitae of the author.

Chapter 2: Assessing ecosystem services in rubber dominated landscapes in South-East Asia – a challenge for biophysical modeling and transdisciplinary valuation

Kevin Thellmann [1], Sergey Blagodatsky [1], Inga Häuser [2], Hongxi Liu [1], Jue Wang [3], Folkard Asch [1], Georg Cadisch [1] and Marc Cotter [1]

[1] Institute of Agricultural Sciences in the Tropics and Subtropics (Hans-Ruthenberg-Institute), University of Hohenheim, 70593 Stuttgart, Germany

[2] Naturschutzjugend Baden-Württemberg, 70178 Stuttgart, Germany

[3] Extension and Communication Group, Humboldt-Universität zu Berlin, 10099 Berlin, Germany

Abstract: The concept of ecosystem services (ESS) has been increasingly recognized for its potential in decision making processes concerning environmental policy. Multidisciplinary projects on rubber (*Hevea brasiliensis*) cultivation, integrating research on a variety of ESS, have been few and far between. More than three years of iterative workshops with regional stakeholders resulted in the development of future land use scenarios for our study area in Xishuangbanna, PR China. We used the InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) modeling framework to analyze their impact on sediment retention, water yield, habitat quality, and carbon sequestration and developed a model for assessing rubber yields. We investigated the percentage deviations of integrated ESS indices in each scenario, as compared to the initial state of 2015 and as a novelty used different statistical weighting methods to include rankings for the preference of ESS from three contrasting stakeholder groups. The business-as-usual scenario (BAU, continuous rubber expansions) revealed an increase in rubber yields trading off against all other ESS analyzed. Compared to BAU, the measures introduced in the balanced-trade-offs scenario (reforestation, reduced herbicide application, riverine buffer zones, etc.) reduced the total amount of rubber yield but enhanced habitat quality and regulating ESS. The results show that the integrated indices for the provisioning of ESS would be overestimated without the inclusion of the stakeholder groups. We conclude that policy regulations, if properly assessed with spatial models and integrated stakeholder feedback, have the potential to buffer the typical trade-off between agricultural intensification and environmental protection.

Keywords: South-East Asia, ecosystem services, rubber, land use planning, biodiversity, scenario modeling, InVEST

A version of this chapter was published as [48]:

Thellmann, K.; Blagodatsky, S.; Häuser, I.; Liu, H.; Wang, J.; Asch, F.; Cadisch, G.; Cotter, M. Assessing Ecosystem Services in Rubber Dominated Landscapes in South-East Asia—A Challenge for Biophysical Modeling and Transdisciplinary Valuation. Forests 2017, 8, 505 (https://doi.org/10.3390/f8120505).

The original publication is available at: https://www.mdpi.com/1999-4907/8/12/505

2.1. Introduction

Ecosystem services (ESS) are defined as the benefits people obtain from ecosystems [28]. In recent years, the ESS concept has increasingly gained importance and its potential for shaping decision making processes with regard to environmental policy formulation and sustainability issues has been widely recognized [49]. Sustainably maintaining ESS and ecosystem functions (ESF) is crucial considering the increasing pressure on ecosystems caused by climate change and land use change due to e.g., deforestation, agricultural expansion, and intensification [50,51]. Spatially explicit analyses and the mapping of ESS, as well as ESF, are essential for developing management strategies for ecosystems adaptation to climate change, the maximization of socio-ecological resilience, and to ensure sustainable ESS and ESF for mankind [52].

In Montane Mainland South-East Asia (MMSEA), extensive land use changes during the last decades have resulted in the disappearance of traditional swidden farming systems and an intensification of cash crop cultivation [11]. For example, suitable environmental conditions and the absence of South American leaf blight (*Pseudocercospora ulei*, a major pest in rubber production systems in South America) have resulted in the expansion of rubber tree plantations in South-East Asia (SEA), today producing the majority of the world's natural latex supply [53]. As a consequence, rubber plantations in SEA have spread mostly into former forest areas at increasingly higher altitudes and steeper slopes, which are sub-optimally suited for the growth and productivity of rubber trees [15]. In Xishuangbanna, located in Yunnan Province of P.R. China, this development was mainly driven by the expected high income possibilities from rubber cultivation [54], which is a prime example for this trade-off between economic development and environmental conservation.

Over the last ten years, numerous changes in biophysical ESF related to the large-scale implementation of rubber plantations have been reported. Forest to rubber conversions have been shown to have negative effects on soil quality [55], to increase soil erosion and surface run-off [56,57], and to reduce carbon stocks [58,59]. Hydrological effects include increased water loss through evapotranspiration during the dry season, decreasing water storage in subsurface soil and, thus, basin discharge [60]. The expansion of rubber plantations in MMSEA has led to serious losses of highly diverse rain forest areas [61], resulting in decreased floral and faunal species abundance [12] and altered species composition, mostly in disfavour of forest specialists [62]. On the other hand, rubber plantations maintain a higher number of plant species (with a lower proportion of exotic and invasive species) compared to tea plantations or irrigated crops cultivated in the area [63].

A recent review on ESS in rubber plantations has shown that the majority of publications on the subject focused on only a few ESS, thus providing incomplete and therefore insufficient information for sustainable land use planning or long-term investment decisions [64]. There is an urgent need for multidisciplinary approaches integrating research on a wide variety of ESS for ecosystem service assessments (ESA) related to rubber cultivation, as shown by Häuser et al. [64].

Several approaches for valuing ESS in rubber cultivation systems have been pursued in recent years: ESS valuation via stakeholder perceptions or expert judgements [65,66], benefit transfer methods [67], and bio-physical approaches lacking any valuation procedures [68]. Hu et al. [67] used benefit transfers based on Costanza et al. [31] to assess the monetary loss of ESS in Xishuangbanna from 1988 to 2006. Benefit transfer methods are only reasonable when provisioning changes are given across comparable goods and contexts [69], which Hu et al. [67] attempted to account for by using coefficients of sensitivity. A point of criticism for this method would be the comparison between gross domestic product and ecosystem service value, as the former is based on market prices while the latter is largely based on willingness to pay (WTP), therefore representing only limited comparative validity. Koschke et al. [70] provided a comparison between benefit transfers and valuation approaches based on expert opinions and found considerable differences for their impact on the outcome of the evaluation. The difficulty of attributing a value for biodiversity was pointed out by Atkinson et al. [71]. Concordantly, no value is given for “Habitat/refugia” as an ESS in Hu et al. [67]. Areas of high plant diversity values generally overlap with areas of high aesthetic value and high regulatory ESS [72]. To our knowledge, no study has yet been conducted to assess the effects of future trajectories of rubber-related land use changes on multiple ESS and biodiversity and subject these results to a valuation based on stakeholder perceptions.

After reviewing the currently available software solutions to model multiple ESS and biodiversity, we chose the InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) modeling framework. InVEST is a suite of free and open source software models to map and value ESS [44]. It allows independent modeling of different sets of ESS, enabling the user to ensure the biophysical realism of each sub-model with respect to input data and model results. Furthermore, InVEST is able to offer flexible customizability and generalizability options, not only in terms of scaling and input data, but also for stakeholder integration and trade-off evaluation. These points represent the essential parts to be included in any ESA [73], in addition to off-site effects, which we are only able to assess in a qualitative manner for this study. Additionally, InVEST provides a sophisticated basis for reporting the modeling results in terms of transparency and comparability [41], since it has been repeatedly applied to investigate the provisioning of ESS all around the globe [74].

Thompson et al. [75] highlighted the importance of comparing contrasting scenarios to better understand the complex dynamics and relationships in socio-ecological systems. Seppelt et al. [76] further developed this idea by suggesting the combination of scenario analysis with optimization algorithms, while also stressing that optimized plans might not always be reachable for the current land system and political instruments.

The aim of this study is to attempt an assessment of ESS for a landscape significantly influenced by the expansion of rubber plantations by combining biophysical aspects of ESS modeling with the feedback of stakeholders on rules of decision making. We place an emphasis on repeatedly integrating stakeholder feedback into the scenario design and evaluation process to ensure their feasibility in regard to land use planning and policies, expert recommendations, and management practices. Thus, we aim at quantifying and evaluating the ESS provided by the land use systems and subject them to scenario analyses assessing the effect of several possible land use change trajectories for the future.

2.2. Material & Methods

2.2.1. Study area

The research area was the Naban River Watershed National Nature Reserve (henceforth referred to as Nabanhe Reserve), located at the south-western border of the Peoples Republic of China, in the Xishuangbanna Prefecture of Yunnan Province (22°08′ N 100°41′ E). It spans an area of about 271 km^2. The region is characterized by an exceptional species richness, being situated within the Indo-Burma biodiversity hotspot [6]. Annual average precipitation varies between 1100 and 1600 mm and the mean annual temperature is 18–22 °C [57]. The climate of Xishuangbanna is subtropical and mostly dominated by monsoon cycles, where up to 87% of the annual precipitation occurs during the wet season from May to October [77]. With altitudes ranging from about 500 to 2300 m.a.s.l., the Nabanhe Reserve features a variety of natural vegetation types, as well as several agricultural land use systems. The nature reserve is inhabited by people from different ethnical backgrounds [78], formerly engaged in shifting cultivation and increasingly adapting the cultivation of cash crops such as rubber, sugarcane, and tea in the recent past [26]. In this region, rubber has been grown for decades in lowland valley bottoms. Over the past 15 years, rubber cultivation has spread into the hillsides, being planted on terraced slopes (at planting distances of approximately 2 m within the row and 5 m between rows), often replacing traditional orchards, vegetable cultivation or, most commonly, semi-natural or natural tropical mountainous rainforest [58]. Due to the presence of cold-spells during the dry season in spring, rubber plantations have so far been restricted to altitudes below 1000–1200 m.a.s.l. Rubber plantations are relatively prone to erosion during strong rain events before canopy closure is reached at about five years after the establishment of the plantation, with tapping (harvest of raw latex) starting two years later.

2.2.2. Scenario development

Three key stakeholder groups were identified in our study area. These are local village heads and innovative farmers, prefecture administration, and politicians at a provincial level [79,80]. In a series of workshops held between January 2013 and October 2016, environmental problems, as well as management challenges related to rubber cultivation systems, were discussed by our consortium of researches and key stakeholders. The structure of the workshops was based on presentations of our consortium of researchers with a focus on thematic clusters (e.g., soil erosion, water availability, or biodiversity) followed by interactive discussion rounds. Based on the discussions and results from these workshops, we developed three future land use scenarios for the Nabanhe Reserve. Stakeholders additionally participated in the scenario development process by confirming the viability of the land use changes introduced in the scenarios regarding their spatial extent (e.g., land ownership, land use restriction), as well as their feasibility in regard to management practices. Land cover patterns derived from Rapid Eye satellite images of 2015 served as the spatially explicit starting point for the scenarios. The percentages of each land cover category in the study area at the initial state of 2015 are listed in Table 2.1.

Table 2.1. Proportions of land cover categories in the Nabanhe Reserve (271 km^2) as of 2015.

Land Cover Category	Coverage in 2015 (%)
Upland forest [1]	45.9
Lowland forest [1]	15.4
Bamboo	5.8
Rubber	9.4
Rice	4.1
Perennial crops	1.1
Bushland/tea [2]	8.8
Annual crops	5.8
Water	1.3
Urban	0.4

[1] Upland forest and lowland forest are based on the altitude of their respective location (above/below 1000 m.a.s.l.). [2] Bushland areas and tea plantations were put into one category since the similarity of the spectral signature did not allow for a reliable distinction between them.

The scenarios were set out to simulate land use and land management changes over the course of 25 years, ending in the year 2040. Several land use restrictions were active in the Nabanhe Reserve, as it is subdivided in different zones according to the Man and Biosphere Programme [81]. In the core zone, all access is prohibited and, therefore, no changes were set to occur in any of the simulations. Limited access was imposed in the buffer zone, whereas the experimental zone does not comprise any land use restrictions. The zones are shown in Figure 2.1.

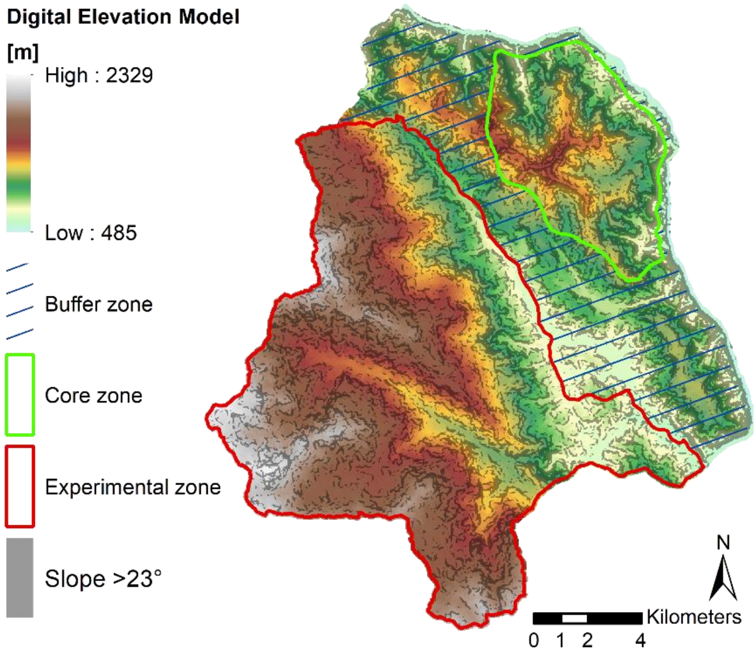


Figure 2.1. Map of Nabanhe Reserve featuring functional zones from the Man and Biosphere Programme and a digital elevation model in a 30 × 30 m resolution (ASTER Digital Elevation Model ("astergtm2_n22e100_dem" (ASTER GDEM is a product of METI and NASA))). Steep slopes (>23°) were derived from the ASTER DEM using the "Slope" tool of ArcGIS (Version 10.3.1) and are depicted in a grey shade.

For the first scenario, called Business-as-usual (BAU), we assumed a further extension of rubber, based on past rubber expansion rates in Xishuangbanna [82] and in Nabanhe Reserve [59]. This extension was set to 2% per year in relation to the area occupied by rubber in the previous year, resulting in an encroachment of rubber plantations into higher altitudes and also steeper slopes, where they replace secondary forest areas. This scenario represents the continuation of a trend observed in many other parts of MMSEA [13,15]. According to this trend, we expected this scenario to result in increased dry rubber yields trading off against the supply of other ESS.

The second scenario, called the 5-years-plan scenario (5YP), is based on the policy plan of the Xishuangbanna Prefecture Government concerning the development of rubber in Xishuangbanna for the 12th five-year plan from 2011 to 2015 [83]. Rubber plantations on sub-marginal plots are planned to be restored into near natural forest. The scenario features an annual gain of 1% of existing forest areas targeted at bushland/tea areas and rubber plantations with the following conditions: (1) Rubber sites located above 900 m.a.s.l.; and (2) rubber sites located on slopes with an inclination of more than 23°, as these areas feature a high erosion risk. With these parameters, all rubber areas eligible for reforestation will be occupied by forest before the end of the scenario run. Additionally, no further expansion of rubber plantations is allowed on locations with the aforementioned spatial properties. With the aim of evaluating the measures enforced by this governmental plan, this scenario is expected to keep rubber plantations at locations of high productivity and restore ESFs at sub-marginal areas for rubber cultivation.

The balanced-trade-offs scenario (BTO) represents the third scenario, which also incorporates all rules specified in the 5YP scenario. Additional measures include the establishment of buffer strips along the main streams in the nature reserve (Mandian and Naban). These strips were 30 m wide and consisted of secondary forest vegetation. Water conservation priority zones were to be established around the locations used by the nature reserves' inhabitants as sources for drinking water. As a land use management measure, a reduced frequency of herbicide application for rubber plantations was introduced, starting in the first year of the simulation period, to maintain a higher amount of undergrowth in order to reduce soil erosion [57]. This scenario was expected to significantly enhance the supply of ESS without trading-off most of the financial benefits gained by rubber cultivation.

For all scenarios, the corresponding land use changes were implemented using the Land Use Change Generator module of LUCIA (Land Use Change Impact Assessment) [84]. The Land Use Change Generator does not include spatial optimization algorithms (see [85–87] for examples), but represents a rule-based tool allowing for spatially explicit expansion rates, target land use categories, and restricted zoning. The scenarios are not intended to accurately predict future land use patterns in the Nabanhe Reserve, but rather to assess and evaluate possible consequences of land use planning and land use management decisions as a basis for discussion with the stakeholders. The simulated land cover maps have been presented at stakeholder workshops in order to confirm their validity in terms of consistency and feasibility (Figure S2.1).

2.2.3. Selection of ESS, Model Description and Data Integration

The selection of relevant ESS is based on the results of early stakeholder workshops. Problems addressed in these workshops include the turbidity and limited availability of water in the dry season and high amounts of soil erosion, especially in the rainy season. Because of the decrease in forest areas in Nabanhe Reserve, villagers increasingly rely on buying imported vegetables, as opposed to their past lifestyle of collecting wild plants and hunting game in the forest. The concept of carbon storage and sequestration as a climate regulation service was introduced in the workshops by government officials and was previously largely unknown to the other stakeholders. While rubber yield serves as the most important proxy for private goods, all other ESS can be seen as public goods to a certain degree.

The ESA includes four sub-models of InVEST (Version 3.3.3, The Natural Capital Project: Standford, CA, USA) related to the ESS of carbon storage and sequestration, habitat quality, sediment retention, and water yield, as well as a self-developed model approximating rubber yields. Details on the biophysical relationships realized in the InVEST sub-models are given in the InVEST user guide [44]. Input parameters, spatial data, and their sources are given in the supplementary material for each sub-model (Tables S2.1 to S2.8). InVEST's coastal ecosystem service modules were not considered, as they were not relevant for the study area. The same applies to pollination services, as there are hardly any crops dependent on insects as pollinators in the Nabanhe Reserve. Although identified as a relevant topic during workshops with the stakeholders, nutrient retention or water quality in general could not be assessed due to insufficient data.

The carbon storage and the water yield models were implemented without any further modifications following the methodology of previous InVEST implementations [88–90]. For habitat quality, model parameterization and implementation was largely identical to Cotter et al. [12], updated and adapted only to reflect changes in land cover categories, using overall habitat scores as described in the supplementary material (Table S2.6). These habitat scores were derived from both field and literature data sets involving plant and animal species, and were normalized according to their abundance values for comparison. The habitat quality sub-model estimates habitat scores based on land use categories and considers threats to habitat sensitivity such as roads, settlements, and agricultural activities (e.g., chemical pest control). The sediment retention sub-model of InVEST is based on the widely used USLE (Universal Soil Loss Equation) and assigns a crop management factor (C-factor) and a support practice factor (P-factor) to every land use category [91]. By reclassifying each land use cell based on the slope of its location, we were able to implement the P-factor in a spatially explicit manner [92], allowing for better capture of the complex topographic conditions in the study area. As the crop production sub-model of InVEST was still being developed at the time of the study, we developed our own model to assess potential dry rubber yields. This model is not based on biophysical functions, but uses regional survey data of average yields corresponding to altitude, as well as the age of each respective plantation [93]. How rubber yields respond to changes in the aforementioned variables is shown by Nguyen [94], and the average yields we derived from surveys show a comparable range in relation to altitude and plantation age. Starting with plantation age values based on Beckschäfer [95], who assessed the age of rubber plantations in Xishuangbanna using remote sensing, the model dynamically simulates the economic lifespan of rubber plantations. Lowland rubber trees (<800 m.a.s.l.) are ready to be tapped after an establishment phase of seven years and remain economically viable for 25 years, while upland rubber is tapped at the age of nine (800–1000 m.a.s.l.) to 10 (>1000 m.a.s.l.) and reaches the end of its economic lifespan at the same age as lowland rubber plantations [59]. Input parameters for this procedure are given in the supplementary material (Table S2.8) and the model was implemented using ArcGIS (Version 10.3.1). Climatic variables as the input for relevant models, such as precipitation amounts, were based on 30 year averages (1960–1990) and kept constant throughout the simulation period in order not to obfuscate the influence of land use change on the ESS results [96].

2.2.4. Ecosystem Service Evaluation

Similar to the normalization methods applied in other ESAs [97,98], all biophysical sub-model results were normalized to a scale ranging from 0 to 1 according to the lowest and highest values, respectively. The normalization procedure is used to transform the bio-physical results of each sub-model into comparable indices and gives five spatially explicit ESS maps for every year of every scenario, where every pixel has a value between 0 and 1. These maps serve as the basis for the weighting procedure described in the following paragraphs.

For the evaluation, we used survey data of three stakeholder groups considering their preference for each of the five modeled ESS. These groups were (1) prefecture administration (PA), (2) tourists in Xishuangbanna (T), and (3) off-site citizens surveyed in Shanghai (S) [99]. Group PA serves as the most representative group for the evaluation, being most familiar with the history and environmental consequences of rubber cultivation in Xishuangbanna. Group T was considered to be important as tourism is another source of economic income for Xishuangbanna and we assumed a considerable difference in the preference of ESS between both groups. Group S represents a neutral group as many group members had no connection to Xishuangbanna.

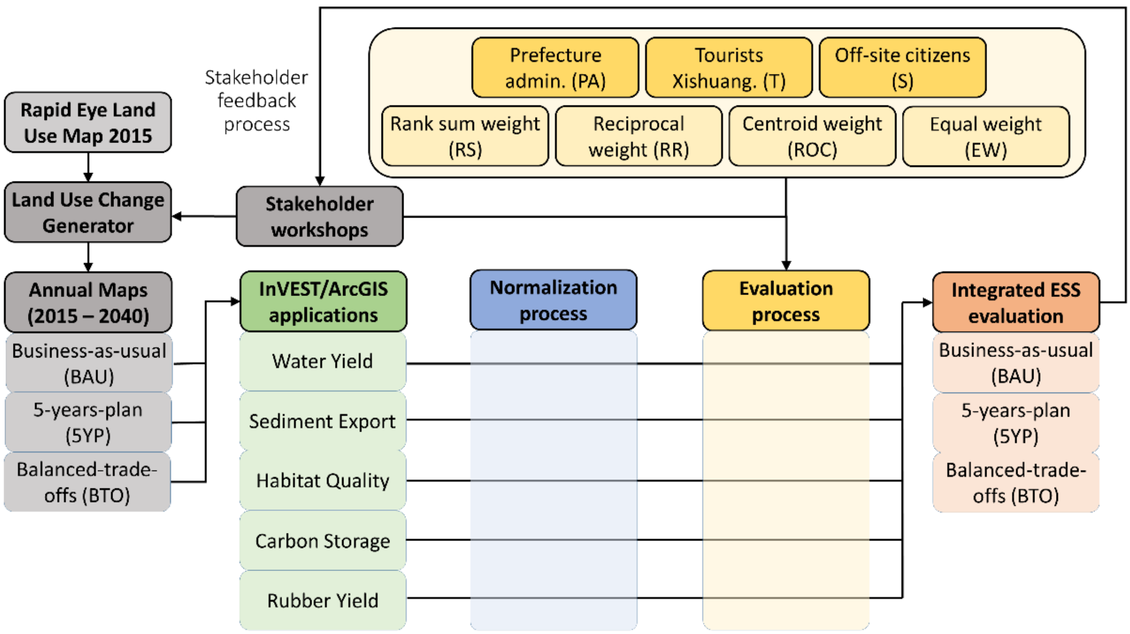
The five ESS investigated were ranked according to their importance in descending order by each stakeholder group. Based on these ranks, different weighting factors were applied to the normalized sub-model results. Table 2.2 shows the ranks of each ESS and their corresponding weighting factors, based on three statistical rank weighting methods: The rank sum method (RS), inverse (or reciprocal) weights (RR), and the rank-order centroid weight method (ROC) [100]. The RS method distributes weights more homogeneously among items, whereas the RR and ROC methods apply larger weights to the top ranking items. The main difference between RR and ROC is how steep the weights decay towards the lower ranking items. We chose to employ all three methods in order to compare their effect on the end results. We also used equal weights (EW) as a neutral option, eliminating the influence of the stakeholder groups to serve as a basis for comparison. This procedure results in maps of integrated ESS indices for every year of every scenario, which feature ESS indices ranging from 0 to 1 for every pixel. These maps are the basis for spatial comparisons of changes in integrated ESS supply between the scenarios.

Table 2.2. Ranking of each ecosystem service based on feedback of three stakeholder groups concerning their importance in descending order and their corresponding weight factors used for the ecosystem service evaluation.

Rank	ESS and Stakeholder Groups			Weighting Method			
	PA	T	S	RS	RR	ROC	EW
1	Water	Soil	Biodiversity	0.33	0.44	0.45	0.2
2	Soil	Biodiversity	Water	0.27	0.22	0.26	0.2
3	Biodiversity	Water	Rubber	0.21	0.14	0.16	0.2
4	Rubber	Rubber	Soil	0.12	0.11	0.09	0.2
5	Carbon	Carbon	Carbon	0.07	0.09	0.04	0.2

Note: The terms for ecosystem services were abbreviated as follows: "Water" for water yield, "Soil" for sediment retention, "Biodiversity" for habitat quality, "Rubber" for rubber yield, and "Carbon" for carbon storage. The full descriptions for the stakeholder groups and weighting methods are: Prefecture administration (PA), Xishuangbanna tourists (T), Off-site citizens (S), Rank sum weight (RS), Reciprocal weight (RR), Centroid weight (ROC), and Equal weight (EW).

To allow a temporal comparison, the integrated ESS indices for every year of every scenario were summed up for the whole Nabanhe Reserve. The percentage deviations in the sums of the integrated ESS indices, resulting from the land use changes introduced in the scenarios, were compared to the initial state in 2015, which was set to 100%. This approach allowed evaluating the quantitative model results in a qualitative manner with respect to the ESS prioritized by the stakeholder groups. Scheme 2.1 depicts a comprehensive overview of the applied methodology.



Scheme 2.1. Comprehensive scheme of the applied methodological framework.

2.3. Results

2.3.1. Simulated Land Use Change and Biophysical Model Results

The proportions of land cover categories in the Nabenhe Reserve at the end of each scenario are shown in Table 2.3. In the BAU scenario, rubber areas increased from 9.4 to 15.2% of the study area. This resulted in the loss of 5.8% of the total forest areas in the nature reserve. In comparison to their extent in 2015, bushland/tea areas increased by 23.3%. The reforestation measures in the 5YP scenario lead to an increase of 20.5% of upland forest areas in comparison to their coverage in 2015. Lowland forest areas decreased by 12.3%, while rubber plantations gained 11.5% in comparison to 2015. The reforestation measures resulted in bushland/tea areas decreasing to a quarter of their size of 2015 in the 5YP scenario and to a fifth in BTO. In BTO, rubber areas increased by 12.6% while upland forest areas increased by 21.6% of their former shares of the nature reserve in 2015.

Table 2.3. Proportions of land cover categories in the Nabanhe Reserve (271 km^2) for the final year of each scenario.

Land Cover Category	Coverage in 2040 (%)		
	Business as Usual (BAU)	**5-Years-Plan (5YP)**	**Balanced-Trade-Offs (BTO)**
Upland forest [1]	43.7	55.3	55.7
Lowland forest [1]	12.6	13.5	13.4
Bamboo	5.0	5.8	5.8
Rubber	15.2	10.4	10.5
Rice	4.1	4.1	4.1
Perennial crops	1.1	1.1	1.1
Bushland/tea [2]	10.9	2.3	1.9
Annual crops	5.8	5.8	5.8
Water	1.3	1.3	1.3
Urban	0.4	0.4	0.4

[1] Upland forest and lowland forest are based on the altitude of their respective location (above/below 1000 m.a.s.l.) [2] Bushland and tea plantations were put into one category since the similarity of the spectral signature did not allow for a reliable distinction between them.

These simulated land use changes had varying effects on the supply of ESS. Summed results for the whole Nabanhe Reserve of each sub-model of InVEST are shown in Table 2.4 for the initial time step (2015) and the final year of each scenario (2040). In BAU, sediment export rates increased by 13.8% throughout the simulation period. Carbon storage, habitat quality, and water yield decreased by 4.5%, 3.1%, and 3.7%, respectively. In comparison to the BAU scenario, the 5YP and BTO scenarios lead to a higher potential for carbon storage, provision of high quality habitats, and increasing sediment retention. Compared to the initial state of 2015, all three scenarios resulted in an increase of predicted rubber yields for 2040: 61.2% for BAU, 36.4% for 5YP, and 57.8% for BTO. There is a discrepancy in the relatively low rates of rubber-related land use changes and the large differences in rubber yields when comparing the initial and the final states of the scenarios. The explanation for this is that about 50% of the areas classified as rubber in the land use map of 2015 are rubber plantations, which are too young to be tapped and only reach their productive age throughout the course of the simulation period.

In addition to a depiction of land cover in the Nabanhe Reserve, spatial representations for every ESS are shown in Figure 2.2. The results are depicted for the initial condition (2015) and the results for the final year of each scenario are given in the supplementary material (Figures S2.2 to S2.4).

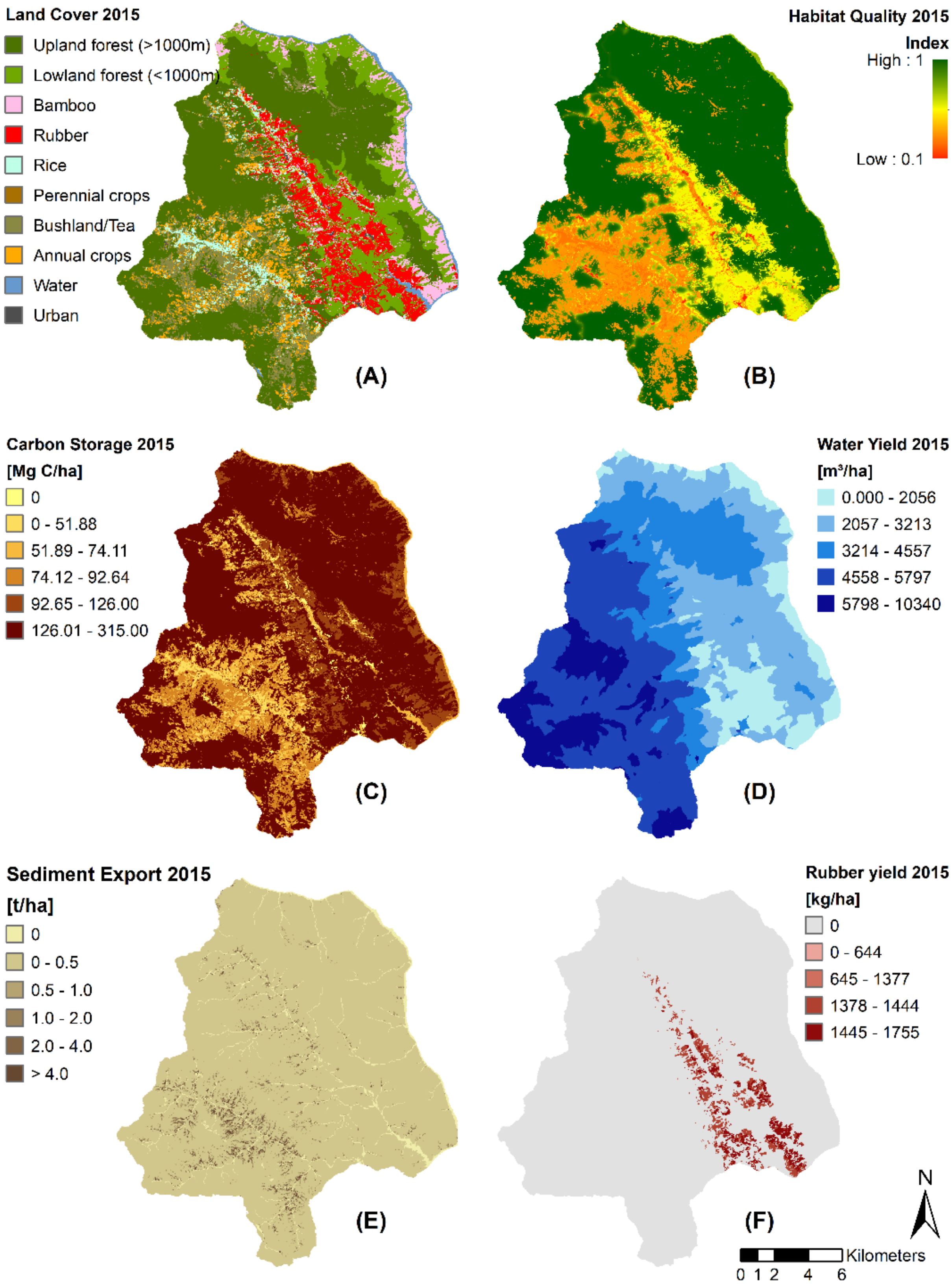


Figure 2.2. (**A**) depicts land cover in the Nabanhe Reserve in the baseline year 2015, derived from Rapid Eye scenes. (**B**–**F**) show the corresponding ESS maps for habitat quality, carbon storage, water yield, sediment export, and rubber yield, respectively. All maps feature a resolution of 30 × 30 m.

Table 2.4. Ecosystem service provision determined by InVEST at the initial state of 2015, as well as the final year (2040) of each scenario for the Nabanhe Reserve (271 km^2).

Scenario	Water Yield (km³)	Sediment Export (10^6 kg)	Habitat Quality (10^3 HQ Index)	Dry Rubber Yield (10^6 kg)	Carbon Storage (10^6 kg)
Initial state (2015)	102	53	232	1.85	5337
Business-as-usual (2040) [1]	99	61	225	2.98	5095
5-years-plan (2040) [2]	102	24	248	2.52	5693
Balanced-trade-offs (2040) [3]	102	19	249	2.92	5693

[1] Business-as-usual: Further rubber expansion based on past expansion rates in South-East Asia. [2] 5-years-plan: Restricted rubber expansion and reforestation of high altitude and steep slope plantations and bushland areas. [3] Balanced-trade-offs: Includes all measures introduced in the 5-years-plan-scenario, as well as reduced herbicide application for rubber plantations, riverine buffer zones, and water source protection areas.

2.3.2. Scenario Comparison of Integrated Spatial ESS Supply

Figure 2.3 depicts a map of integrated ESS supply for the initial state of 2015 (A). We chose to limit the mapped results of ESS indices to rankings by the PA group using the ROC weighting method. Results based on the other stakeholder groups and weighting methods feature a similar spatial representation and are shown in the next sub-section of the results chapter using a temporal representation. In the integrated ESS supply map, dark green areas (high ESS index) mainly represent secondary forest areas in the uplands. Lower values are found in urban, as well as in agriculturally dominated areas. (B–D) depict changes in the integrated ESS values compared to (A) at the end of the BAU, 5YP, and BTO scenario, respectively. Integrated ESS supply maps for the final year of each scenario are given in the supplementary material (Figure S2.5). In BAU, we mainly observe the negative impact of rubber expansion on the integrated ESS index. New rubber plantations on locations in the lowlands with potentially high yields show positive changes. None of the land use changes introduced in the scenarios change the integrated ESS index by more than 20% per pixel in comparison to the initial state. In (C,D), we observe the positive changes introduced by the reforestation efforts in the uplands, as well as the weed management changes in rubber plantations (D), as they increase the integrated ESS index for rubber areas with reduced erosion amounts. The negative changes are mainly due to shifting rubber yields in the lifespan of rubber plantations, as many areas that were productive in 2015 go through a re-establishment phase and are not yet ready to be tapped in 2040.

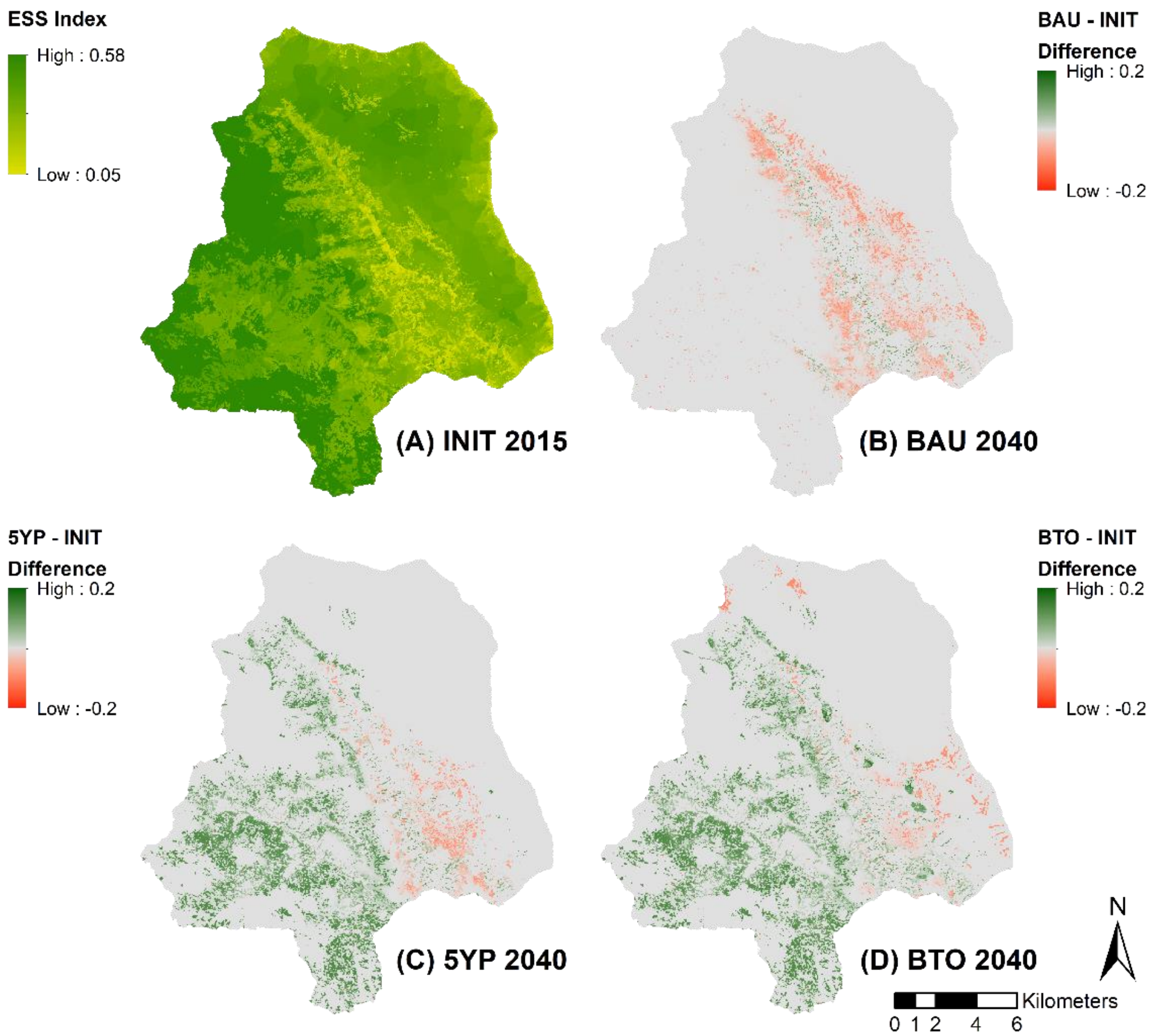


Figure 2.3. (**A**) shows the ecosystem service index integrating the five ecosystem services weighted by Xishuangbanna prefecture administration using the ROC (centroid weight) method for the year 2015. (**B**–**D**) show differences in the ESS index between the BAU (Business-as-usual), the 5YP (5-years-plan), and the BTO (Balanced-trade-offs) scenarios and the initial state of 2015, respectively.

2.3.3. Scenario Comparisons of Temporal Integrated ESS Supply

Figure 2.4 shows the changes in the summed integrated ESS indices for the Nabanhe Reserve throughout the simulation period for each scenario according to each stakeholder groups' ranks and weighting method. With rankings of the PA group, the curves for the weighted integrated ESS indices are generally lower in comparison to the curve of equal weights. The weighted curves for the BAU scenario ranked by the T group depict a similar relationship to the curve of equal weights in comparison to PA. In contrast, the trajectories using the T group ranks for the 5YP and BTO scenario result in higher ESS indices as compared to equal weights by the end of the scenario. These exceptions aside, comparing the scenario trajectories with respect to weighting methods, we find the same trends throughout the scenarios and stakeholder rankings, with ROC and RR leading to similar results and RS resulting in slightly higher values in comparison to ROC and RR.

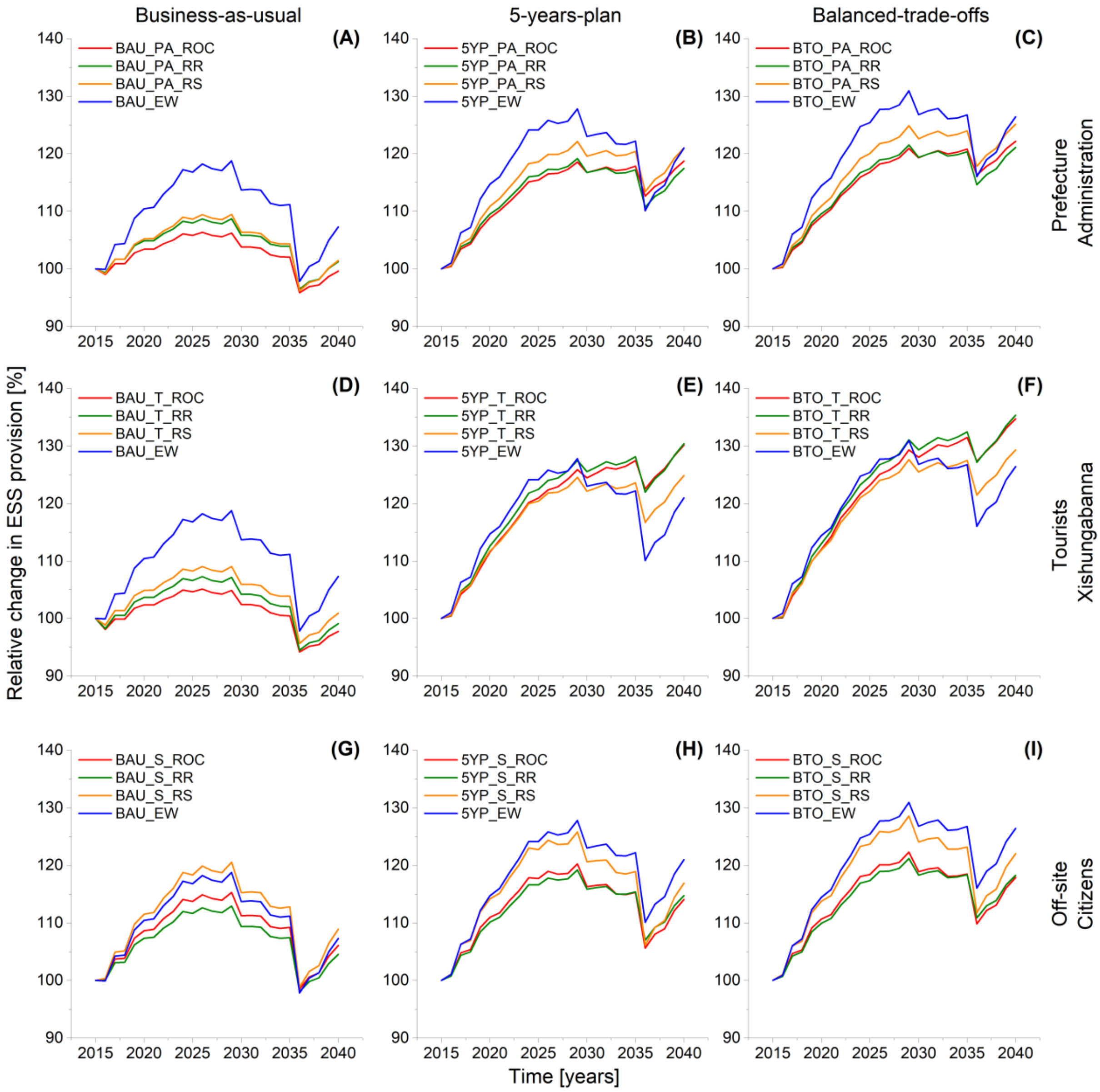


Figure 2.4. Changes in integrated ESS provision relative to the initial state of 2015. Each graph contains time series corresponding to the scenario (BAU: Business-as-usual (**A**), (**D**), (**G**); 5YP: 5-years-plan (**B**), (**E**), (**H**); BTO: Balanced-trade-offs (**C**), (**F**), (**I**)) and stakeholder group ranking (Prefecture Administration (**A**), (**B**), (**C**), Tourists Xishuangbanna (**D**), (**E**), (**F**), Off-site Citizens (**G**), (**H**), (**I**)), as well as the statistical weighting method (ROC: centroid weights, RR: inverse weights, RS: rank sum; EW: equal weights).

To give an indicator of the performance of the scenarios in relation to the initial condition of 2015 (set to 100%) with respect to the ranks of the stakeholder groups and weighting methods, we list the integrated ESS indices at the end of the simulation period (2040) in Table 2.5. We generally find the lowest values in the BAU scenario, higher values for 5YP, and the highest values for BTO, regardless of which weighting method or stakeholder groups' preferences were used. Differences between the ranks of the stakeholder groups are most pronounced in group T, as the lowest ESS indices result from the BAU scenario and the highest ESS indices from the BTO scenario.

Table 2.5. Integrated ESS indices at the final year of the simulation (2040) for all stakeholder groups and weighting methods in comparison to the initial condition of 2015, which is set to 100%.

Stakeholder Group and Weighting Method	Business-As-Usual (BAU) (%)	5-Years-Plan (5YP) (%)	Balanced-Trade-Offs (BTO) (%)
PA_ROC	99.60	118.71	122.16
PA_RR	101.25	117.45	121.08
PA_RS	101.47	121.01	125.15
T_ROC	97.76	130.15	134.71
T_RR	99.10	130.40	135.35
T_RS	100.91	124.85	129.33
S_ROC	106.07	114.07	117.89
S_RR	104.54	114.75	118.27
S_RS	108.91	116.90	122.01
EW	107.29	120.99	126.42

Note: The full descriptions for the stakeholder groups and weighting methods are: Prefecture administration (PA), Xishuangbanna tourists (T), Off-site citizens (S), Centroid weight (ROC), Reciprocal weight (RR), Rank sum weight (RS), and Equal weight (EW).

2.4. Discussion

2.4.1. Weighting Methods and ESS Evaluation

While reviewing tools for the spatial modeling of ESS, Ochoa & Urbina-Cardona [101] found that of all reviewed publications, only 21.6% analysed three or more ESS categories, with the majority focusing on only one ESS category (60%). With this study, we contribute to the small number of papers quantitatively assessing multiple ESS including regulation services (water yield, sediment retention, and carbon storage), biodiversity (habitat quality for multiple species), and a very crucial provisioning service for the study area (rubber yield).

The time series of integrated ESS indices for all three scenarios generally showed the results we expected during the scenario design phase. The biophysical results assessed by InVEST depict a decreasing trend for all ESS in the BAU scenario, while rubber yields are increasing. When compared to the other scenarios, the equally weighted integrated ESS trajectories showed the lowest values in BAU as the expansion of rubber plantations lowers the provision of all ESS aside from rubber yields. Nevertheless, the increase in rubber yields is high enough to trade off against the loss in other ESS, when focusing on equally weighted indices only. Rubber yields are increasing throughout the greater part of the simulation period until the year 2036. At that point in time, many plantations which were planted before 2011, when market prices for rubber were at a peak, reach the end of their economic lifespan in the simulation. At this point, the negative trend in the other ESS becomes apparent and leads to the first negative changes of the integrated ESS indices in relation to the initial state of 2015. As roughly half of all rubber plantations in Nabanhe Reserve reach their productive stage during the first years of the simulation, a high increase in rubber yields is present in all scenarios, regardless of the differing rubber expansion rates. For the provisioning of ESS, our results show that the 5YP scenario is a clear improvement in comparison to the BAU scenario, confirming that the current regional policy, if properly implemented, could improve the provision of ESS. Additionally, we were able to further develop the 5YP scenarios' positive impacts on the supply of ESS with the BTO scenario by means of a reduced herbicide application in rubber plantations, as well as upland and riverine buffer zone reforestation measures.

In a review on the social evaluation of ESS, Felipe-Lucia et al. [102] found that 22.9% of the reviewed studies focused on preference rankings for ESS, while only 7.2% provided a comparison between the present and future provision of ESS. This study adds to the lacking numbers of ESAs for future scenarios and is the first to do so for rubber production systems. Improvements in regard to the ESS evaluation could be made by using more sophisticated techniques such as Likert Scales [103] or the Analytical Hierarchy Process [104].

2.4.2. Transdisciplinarity and Ranking of Multiple ESS

We deem the rankings of the PA group to be the most representative for the ESA, as this group has the longest and most direct relationship with environmental changes in the study area. The beneficial effects of the measures introduced in the 5YP and BTO scenario are not only present for the equally weighted ESS indices, but also for the ESS indices as weighted by the PA group, albeit with lower total values. The ESS indices as weighted by the T group lead to the lowest values for BAU and the highest values for 5YP and BTO. This suggests that the governmental land use plan might also be beneficial for the tourism sector. We assume that this result would have been even more pronounced if cultural services had been included in the ESA. The ESS indices as weighted by the S group show the highest ESS indices for BAU and the lowest values for 5YP and BTO in comparison to the other stakeholder groups. Many measures introduced in 5YP and BTO were specifically targeted to enhance sediment retention. Group S ranked sediment retention as second to last in terms of importance (as compared to rank 1 for Group T and rank 2 for Group PA). Therefore, the improvements in the landscapes potential to retain sediments in the 5YP and BTO scenario have a lower impact on the integrated ESS indices as ranked by Group S in comparison to the ranks of Group T or Group PA.

The results suggest that the integrated indices for the provisioning of ESS in all scenarios would be overestimated without the inclusion of the stakeholder groups, as the integrated ESS indices based on equal weights generally lead to higher values in comparison to the rank-weighted ESS indices. The difference between the weighted and unweighted integrated ESS trajectories was most pronounced in the BAU scenario when using the rankings of the PA and T groups.

We refrained from using benefit transfer methods for the ESA, as the assignment of monetary values to ESS is highly dependent on the beneficiaries and the case-specific context, and may vary highly in terms of spatial and temporal scales [105]. Roughly half of all publications on ESS in China focus on monetary valuation, with about 32% adopting the benefit transfer framework proposed by Costanza et al. [31,106]. Only 31% of ESS studies relied on quantitative assessments and only 2% used a perspective-based valuation approach [106], which represent the approaches we combined in this study. The spatial heterogeneity of the study area precluded the use of direct benefit transfers. Different ESS evaluation methods, ranging from monetary to expert-opinion-based evaluation, can drastically alter the outcome of the assessment [70]. This holds true for the preference-based evaluation method used in this study as well. The importance of each ESS is dependent on whom the question is posed to, who the actual beneficiaries are, and which method is used to weigh the options against one another.

As shown in this study, future land use scenarios in combination with stakeholder preferences on ESS is an advantageous pathway to pursue for assessing the effect of policy plans on the supply of ESS. Using a dedicated and well-documented software application such as InVEST provides a basis for comparisons with future ESAs of rubber cultivation systems, as it has become the most frequently applied tool to model ESS in recent years [101]. Improvements to the design of the scenarios would be possible by utilizing land use optimization algorithms, which were shown to successfully optimize the provision of ESS [86,87], as well as an active integration of multifunction and uncertainty effects [107]. We do not claim that BTO is the best possible solution for our study area, but we want to emphasize that the close interaction with stakeholders not only confirmed the viability of our suggested management measures, but also widened their understanding of the consequences of future land use conversions they are accountable for. As put forward by Seppelt et al. [76], optimized landscapes might not be reachable given the current political environment and land use system. Our method of involving stakeholders from the very start of the scenario design allowed us to circumvent this problem.

The evaluation of ESS presented in this study is based on stakeholder preferences, but critical decisions concerning land use change and management still lie in the hands of the farmers. Water availability and erosion have been identified as being of critical importance to the local stakeholders (PA), but it is hard to imagine the conservation of environmental services without economic incentives or policy regulations. Smajgl et al. [108] concluded that incentive mechanisms such as PES (payments for ecosystem services) should be implemented with great caution, as they can lead to unexpected results such as a further increase of rubber areas. On the other hand, PES schemes might lead to higher adoption rates of rubber agroforests, as shown in a case study from Sumatra by Villamor et al. [109], although the majority of (simulated) farmers there persisted in cultivating monoculture rubber. Although beneficial, our work with stakeholders still only accounted for a very limited reach, leaving a majority of the potential beneficiaries of our work out of the picture. Our results revealed promising land use plans for the future in Xishuangbanna, but their implementation might still pose a considerable challenge.

2.4.3. Model Uncertainties

Model calibration and validation represent crucial factors for uncertainty evaluation in ESAs, but are often omitted due to the scale, scope, and multidisciplinary character of the respective assessments [88,98,110]. These factors also increase the difficulty to appropriately monitor variables such as sediment export or water yield over a long term, especially in remote areas of subtropical mountainous SEA.

Several studies conclude that the expansion of rubber plantations has negative effects on the water cycle in Xishuangbanna and other parts of SEA [60,111,112]. Liu et al. [68] found that the expansion of plantations (also including tea and sugarcane) decreased the water yield by 32% (and carbon storage by 45%) in a period between 1976 and 2012. In comparison, our study revealed relatively minor changes for water yield (a decrease of 4.5% in BAU), even though forest and rubber areas undergo the highest transformation rates throughout all scenarios. Reasons for this are the shorter simulation period and the large share of forest areas in the Nabanhe Reserve. Averaged on an annual basis, there is only a 10% difference between the evapotranspiration coefficients (K_c) for rubber and the forest categories, which largely explains the small changes in total water yield predicted by the InVEST water yield model. The model is likely to yield different results when seasonal variations of K_c coefficients are implemented into the model, reflecting the strong seasonality in precipitation and leaf area dynamics in the region.

The initial run of the sediment retention model identified high altitude bushland areas as most prone to erosion. The expansion of rubber plantations in the BAU scenario accounted for the additional sediment exports (an increase of 13.5%). In 5YP and BTO, the encroachment of rubber into the few remaining areas with suitable environmental conditions in the Nabanhe Reserve successfully avoided additional patches with a high erosion probability. On the landscape scale, however, the high reduction of sediment exports in 5YP and BTO was mainly due to reforestation efforts in the uplands, replacing the bushlands with trees. Additional reductions found in BTO were due to changes in ground cover management practices in rubber plantations. The large difference in sediment export compared to the minor differences in water yield seem to be contradictive, but comparable relationships have been confirmed in earlier studies on rubber plantation management changes [113]. However, the water yield sub-model of InVEST did not allow us to adequately capture the effect of management changes introduced in the BTO scenario when compared to field measurements of surface runoff in rubber plantations in the study area [57].

For this study, sediment export and water yield model runs were calibrated with annual sediment export and run-off measurements in a sub-watershed of the study area in 2014, a year with below average precipitation amounts in Nabanhe Reserve [57]. Therefore, a certain discrepancy with the long term annual averages used as the precipitation input is to be expected and we assume the water yield results to be slightly underestimated by InVEST. The same holds true for the sediment export model. Since we evaluated percentage changes compared to the initial situation in 2015, the uncertainties in the quantitative amounts of erosion and run-off are of minor importance to the trajectories of integrated ESS provision within the timeframe of the scenario simulations (Figure 2.4).

Sensitivity analyses of InVEST water yield applications [114] have shown the model to respond most sensitively to the amount of annual average precipitation, followed by potential evapotranspiration and the plant evapotranspiration coefficients K_c. We performed sensitivity analyses for both the water yield and sediment export models. Detailed results for both are given in the supplementary material (Figures S2.6 and S2.7).

2.5. Conclusion

This study estimates the effects of potential future land use change scenarios on the provisioning of multiple ESS in a mountainous watershed. It is the first of its kind to combine spatially explicit modeling of five relevant ESS for scenarios initiated and validated by stakeholders for rubber cultivation systems. Furthermore, we subjected the modeled results to a preference-based evaluation by multiple stakeholder groups. Our analyses show detrimental consequences induced by rubber expansions for all assessed ESS, with the exception of raw material provision (rubber yields). Based on a comprehensive assessment of ESS, we find that further continuing the trend of rubber expansions in the study area is not the best option in terms of integrated ESS supply on a landscape scale. Land use planning alternatives, such as rubber expansions restricted to suitable areas only, in combination with reforestation efforts at less suitable locations, might be used to keep crucial environmental functions intact. Management options such as reduced herbicide application in rubber plantations and the establishment of riverine buffer zones reduce the amount of exported sediments. Additionally, the landscape’s potential to sequester carbon and provide suitable habitats for a variety of plant and animal species is enhanced by these measures. The cycle of repeatedly integrating stakeholder feedback into scenario development and model adaptions not only confirmed the practicability of our suggested rubber management options, but also gave stakeholders a wider view on the consequences of future land use conversions they are accountable for. The inclusion of stakeholder preferences in the evaluation of ESS was crucial, as the integrated ESS indices were generally overestimated when using equally weighted ESS results in the ESA. We conclude that policy regulations at the local level, if properly assessed with spatial models and integrated stakeholder feedback, have the potential to buffer the typical trade-off between agricultural intensification and environmental protection for rubber cultivation systems in South-East Asia. Implementing these regulations at the local level might still pose a considerable challenge.

Supplementary Materials: The following are available online at www.mdpi.com/1999-4907/8/12/505/s1, Figure S2.1: Land cover maps of the Nabanhe Reserve of the initial state of 2015 (**A**) and the final year (2040) of each scenario: Business-as-usual (**B**), 5-years-plan (**C**) and Balanced-trade-offs (**D**), Figure S2.2: Ecosystem service results at the last year (2040) of the BAU scenario (**A**) including habitat quality (**B**), carbon storage (**C**), water yield (**D**), sediment export (**E**) and rubber yield (**F**), Figure S2.3: Ecosystem service results at the last year (2040) of the 5YP scenario (**A**) including habitat quality (**B**), carbon storage (**C**), water yield (**D**), sediment export (**E**) and rubber yield (**F**), Figure S2.4: Ecosystem service results at the last year (2040) of the BTO scenario (**A**) including habitat quality (**B**), carbon storage (**C**), water yield (**D**), sediment export (**E**) and rubber yield (**F**), Figure S2.5: Ecosystem service index integrating the five ecosystem services weighted by Xishuangbanna prefecture administration using the ROC (centroid weight) method for the initial year of 2015 (**A**) as well as additional results for the final year of each scenario (Business-as-usual (**B**), 5-years-plan (**C**) and Balanced-trade-offs (**D**)), Figure S2.6: Sensitivity analysis of the InVEST sediment export model, Figure S2.7: Sensitivity analysis of the InVEST water yield model, Table S2.1: Input values for the InVEST sediment retention model for the C- and P-factors of the USLE equation for every land cover category, Table S2.2: Additional parameterization (spatial data and calibration parameters) for the InVEST sediment retention model, Table S2.3: Kc coefficients and rooting depth of every land cover category for the InVEST water yield model listed with their sources, Table S2.4: Additional input parameters for the InVEST water yield model, Table S2.5: Input values for the carbon storage model for each carbon pool and every land use category in Nabanhe Reserve, Table S2.6: Habitat quality threats for the BAU, the 5YP and the BTO scenario in parenthesis (where applicable), Table S2.7: Overall habitat scores (vertebrates, invertebrates, flora) and the sensitivity of each land cover category to each threat, Table S2.8: Rubber yield estimations based on survey data in Xishuangbanna.

Acknowledgments: This study was supported by the German-Chinese joint research project SURUMER (Sustainable Rubber Cultivation in the Mekong Region), funded by the German Federal Ministry of Education and Research (BMBF) (Grant number FKZ 01LL0919), who also provided the funding for open access publication. Many thanks go to all SURUMER members, especially Xueqing Yang, Reza Golbon, Manuel Krauss, Lydia Seitz, Franziska Harich, Sabine Baumgartner, Sabine Stürz, Konrad Martin, Michael Ahlheim, Hermann Waibel, Shi Min, Thomas Aenis, Gerhard Langenberger, and Carsten Marohn. Thanks to EFTAS Remote Sensing Transfer of Technology GmbH group for creating the initial land use map. The financial support of the "Water–People–Agriculture" Research Training Group funded by the Anton & Petra Ehrmann-Stiftung is gratefully acknowledged. We would like to thank two anonymous reviewers for their comments and suggestions, which strengthened the quality of the paper substantially.

Author Contributions: All authors contributed to the ideas and experimental design of the project. S.B. created the land use maps of the scenarios. K.T. and I.H. performed the model parameterization. K.T. modeled the results. K.T., I.H., and M.C. analyzed the results. J.W. facilitated stakeholder interactions. H.L. provided field data for model parameterization and calibration. K.T. wrote the paper. All authors provided editorial advice to the structure and content of the paper.

Conflicts of Interest: The authors declare no conflict of interest.

2.6. Supplementary Material

2.6.1. Land use change scenarios

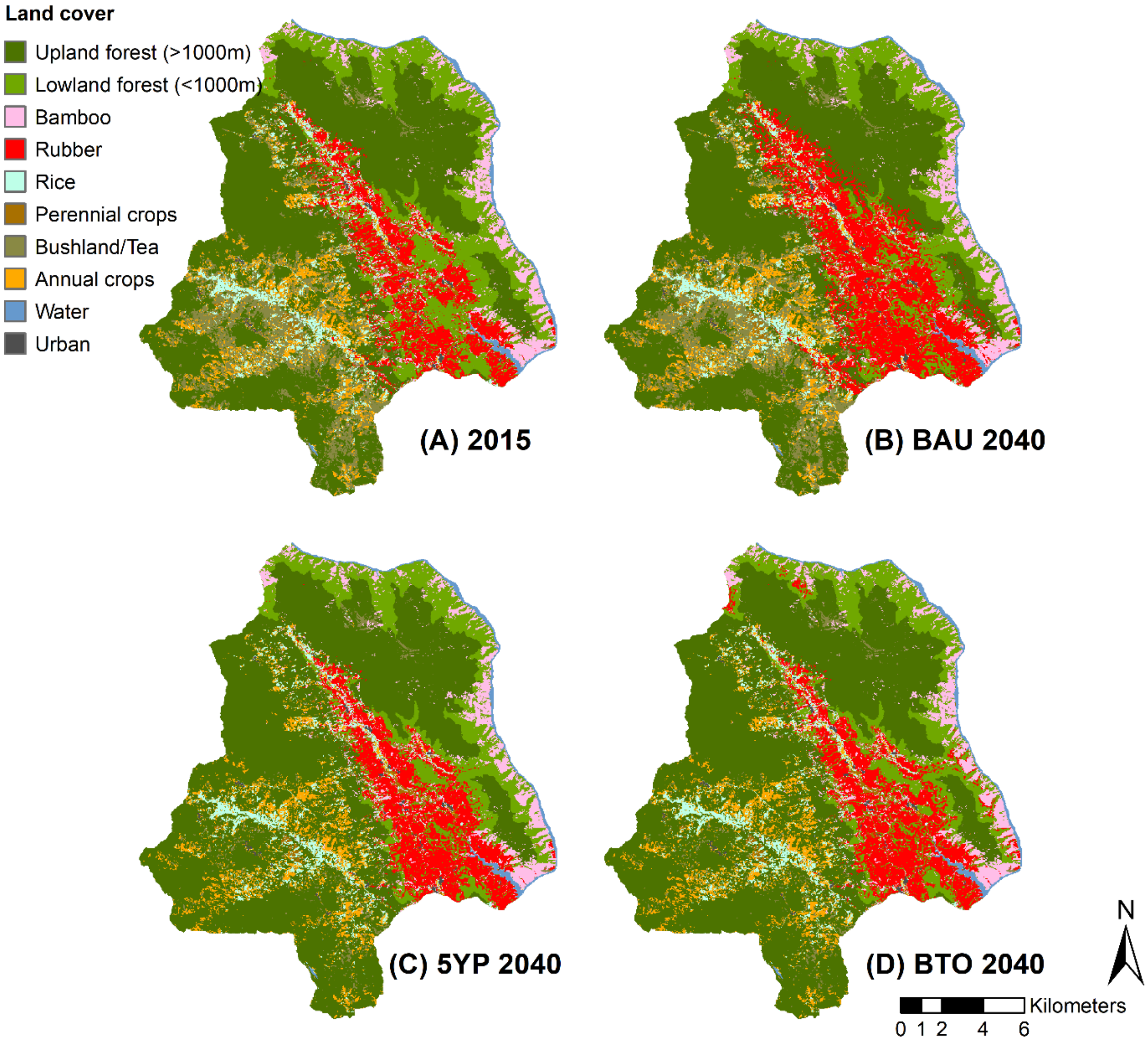


Figure S2.1. Land cover maps of the NRWNNR (Naban River Watershed National Nature Reserve) of the initial state of 2015 (**A**) and the final year (2040) of each scenario: Business-as-usual (**B**), 5-years-plan (**C**) and Balanced-trade-offs (**D**).

2.6.2. Model parameterization

For detailed descriptions on the manner of functioning for each of the four InVEST model applications used in this study, the reader is referred to the InVEST user guide: (http://data.naturalcapitalproject.org/nightly-build/invest-users-guide/html/). The following chapters provide a list of input parameters and spatial data we used to run the models.

2.6.2.1. InVEST Sediment Retention Model

Table S2.1. Input values for the InVEST sediment retention model for the C- and P-factors of the USLE equation for every land cover category. On the basis of [92] (Sheikh, Palria et al. 2011), values for P are assigned in relation to the slope of the landscape and management measure (no measures, terracing, contouring, strip cropping) on a pixel basis. Elevation data for calculating the slope with ArcGIS (Version 10.3.1) is derived from ASTER Digital Elevation Model Data ("astergtm2_n22e100_dem" (ASTER GDEM is a product of METI and NASA)).

Land use	USLE C	Source C	USLE P measures
Upland forest	0.001	[115]	no measures
Lowland forest	0.001	[115]	no measures
Bamboo	0.04	[116]	no measures
Rubber	0.029 (C*P)	[57], 2 herbicide applications per year	terracing
Rice	0.18	[117]	terracing
Perennial crops	0.13	[118]	strip cropping
Bushland/Tea	0.18	From [119] (Primary sources: [120,121])	contouring
Annual crops	0.31	From [119] (Primary sources: [120,121])	strip cropping
Water	0	From [119] (Primary sources: [120,121])	no measures
Urban	0.2	From [119] (Primary sources: [120,121])	no measures

Table S2.2. Additional parameterization (spatial data and calibration parameters) for the InVEST sediment retention model.

Input	Range	Source of input data	Source of calculation procedure
Rainfall Erosivity R	2911 – 4492 [MJ*mm*(ha*hr)$^{-1}$]	Annual average precipitation (see below)	[122]
Annual average precipitation	1233 – 1631 [mm]	[96] (Resolution ~900*900m)	
Soil Erodability K	0 – 0.035 [t*ha*hr*(MJ*ha*mm)$^{-1}$]	[123] (Resolution ~900*900m)	[57,124]
LS Factor	0.02 – 4579	InVEST internal calculation based on ASTER DEM (mean LS factor=40.7, some few values are extreme outliers), which are capped at 333 according to the InVEST user manual. (Resolution = 30*30m)	[125]
Borselli k	1.096	Calibration parameter	[126]
SDR max	0.8	InVEST default setting	[127]
IC0	0.5	InVEST default setting	[127]
Threshold Flow Accumulation	500	Calibrated to fit the hydrological network in NRWNNR	

2.6.2.2. InVEST Water Yield Model

Table S2.3. K_c coefficients and rooting depth of every land cover category for the InVEST water yield model listed with their sources.

Land use	Kc coefficient	Kc source	Rooting depth [mm]	Rooting depth source
Upland forest (>1000m)	1	[43]	7000	[43]
Lowland forest (<1000m)t	1	[43]	7000	[43]
Bamboo	1.1	[128]	4000	[129]
Rubber	1.1	Own measurements	5000	Own measurements
Rice	1.2	Own measurements	300	Own measurements
Perennial crops	1.2	[130]	400	[131]
Bushland/Tea	1	[130]	3500	[88]
Annual crops	0.65	Own measurements	2100	[132]
Water	1.05	[130]	0	Not applicable
Urban	0.3	[43]	200	[43]

Table S2.4. Additional input parameters for the InVEST water yield model.

Input	Range	Source of input data	Source of calculation procedure
Annual average precipitation	1233 – 1631 [mm]	[96] (Resolution ~900*900m)	[96]
Annual potential evapotranspiration	1209 – 1610 [mm]	[133] (Resolution ~900*900m)	Direct implementation
Plant available water content (PAWC)	0.115 – 0.138	[123] (Resolution ~900*900m)	Direct implementation
Root restricting layer depth	920.2 – 1130 [mm]	[123] (Resolution ~900*900m)	Direct implementation
Zhang constant Z	23		[134]

2.6.2.3. InVEST Carbon Storage Model

Table S2.5. Input values for the carbon storage model for each carbon pool and every land use category in Nabanhe Reserve.

Land use	Above ground C [Mg C/ha]	Below ground C [Mg C/ha]	Soil organic C [Mg C/ha]	Dead matter C [Mg C/ha]	Source
Upland forest (<800m)	145	29	82	5	[59]
Lowland forest (>800m)	189	41	79	6	[59]
Bamboo	42	4	72	4	[59]
Highland rubber (<800m)	24	5	62	1.76	[59]
Lowland rubber (>800m)	58	10	56	2.11	[59]
Rice	5	1	39	1	[59]
Perennial crops	15	3	56	1	[59]
Bushland/Tea	6	10	73	0.5	[59]
Annual crops	6	1.67	50	0.5	[59]
Urban	2	1	50	0	[43]
Water	0	0	0	0	[43]

2.6.2.4.InVEST Habitat Quality Model

Table S2.6. Habitat quality threats for the BAU, the 5YP and the BTO scenario in parenthesis (where applicable). All values are based on Cotter et al. [12]. Threats are assigned weights concerning their severity in relation to the strongest threat (Urban areas with a value of 1). The weight of all threats decays in an exponential manner until the maximum distance is reached.

Threat	Maximum distance [km]	Weight	Decay
Rubber	0.1	0.27 (0.135)	exponential
Agriculture	0.1	0.3	exponential
Urban	1	1	exponential
Roads	0.1	0.5	exponential

Table S2.7. Overall habitat scores (vertebrates, invertebrates, flora) and the sensitivity of each land cover category to each threat. All values are based on Cotter et al. [12].

Land use	Habitat score	Rubber	Agriculture	Urban	Roads
Upland forest (>1000m)	1	0.7	0.6	1	0.8
Lowland forest (<1000m)	1	0.7	0.6	1	0.8
Bamboo	1	0.7	0.6	1	0.8
Rubber	0.57	0	0.1	0.87	0.63
Rice	0.26	0	0.07	0.47	0.33
Perennial crops	0.32	0.13	0.07	0.2	0.2
Bushland/Tea	0.33	0.12	0.17	0.39	0.29
Annual crops	0.33	0.1	0	0.5	0.33
Water	0.73	0.82	0.82	0.97	0.75
Urban	0.1	0	0	0	0

2.6.2.5.ArcGIS Rubber Yield Model

Table S2.8. Rubber yield estimations based on survey data in Xishuangbanna [93]. Spatially explicit land use data is derived from Beckschäfer [95] concerning plantation age. Altitude data is derived from ASTER Digital Elevation Model Data ("astergtm2_n22e100_dem" (ASTER GDEM is a product of METI and NASA)). Yields are listed from the first year of plantations being tapped, since plantations have different lengths of establishment phases, depending on elevation. Pixel size is 30x30 m.

	Potential rubber yield [kg/(year*pixel)]		
Elevation	**1-5 years**	**6-10 years**	**> 10 years**
< 800m	124.12	158.20	158.20
800-1000m	124.12	129.55	151.30
> 1000m	58.50	58.50	58.50

2.6.3. Additional Results

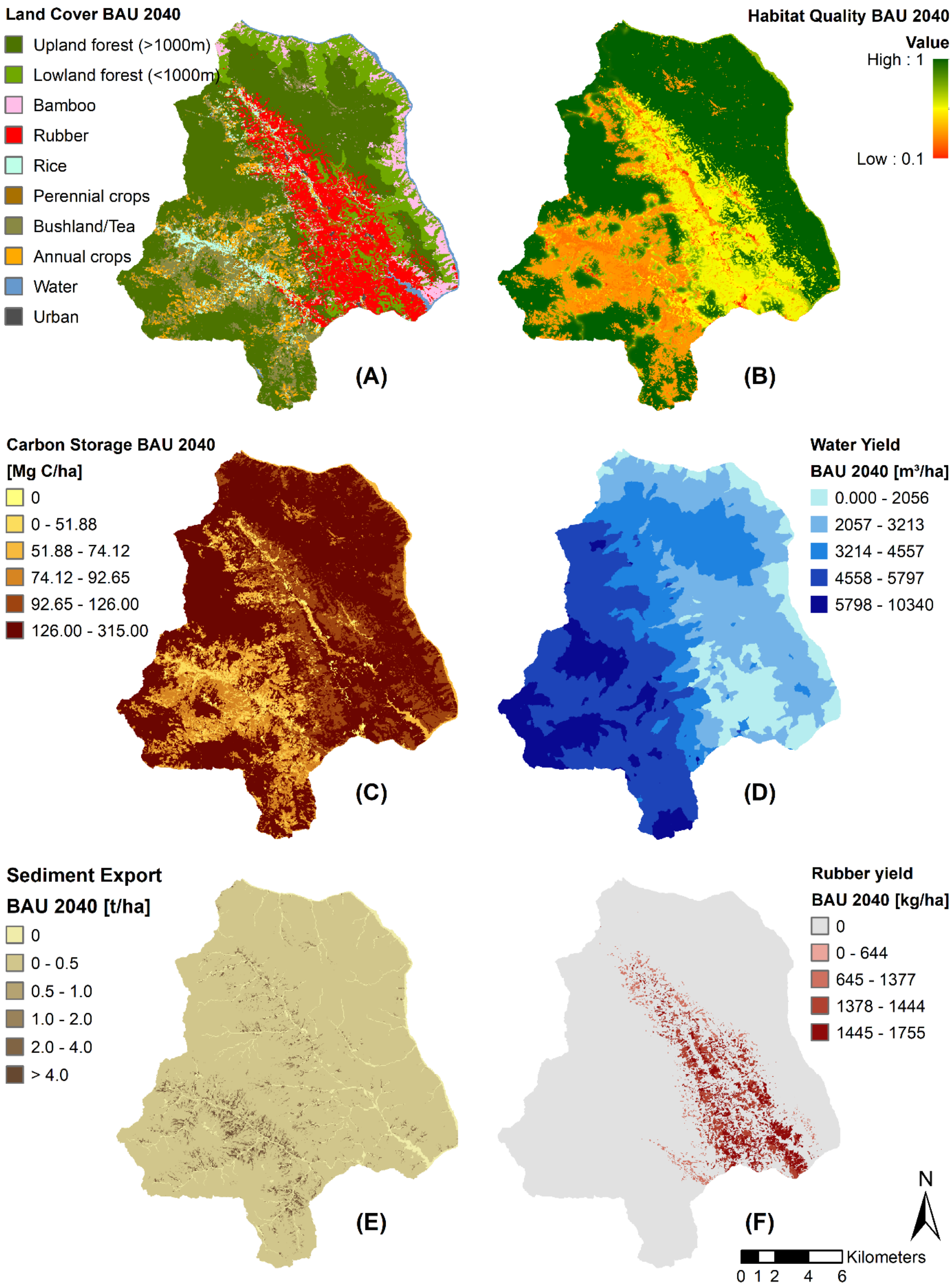


Figure S2.2. Ecosystem service results at the last year (2040) of the BAU scenario (**A**) including habitat quality (**B**), carbon storage (**C**), water yield (**D**), sediment export (**E**) and rubber yield (**F**).

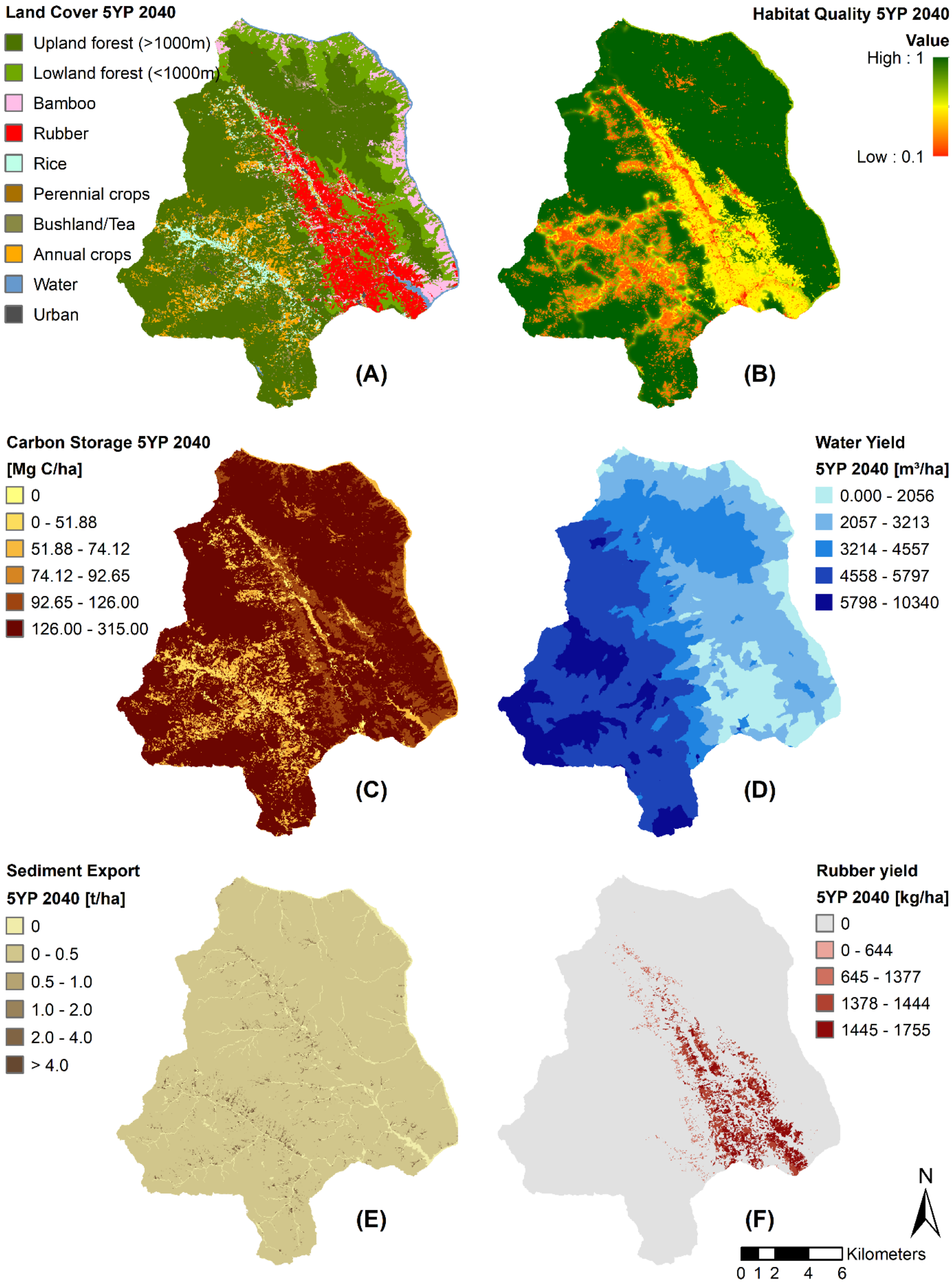


Figure S2.3. Ecosystem service results at the last year (2040) of the 5YP scenario (**A**) including habitat quality (**B**), carbon storage (**C**), water yield (**D**), sediment export (**E**) and rubber yield (**F**).

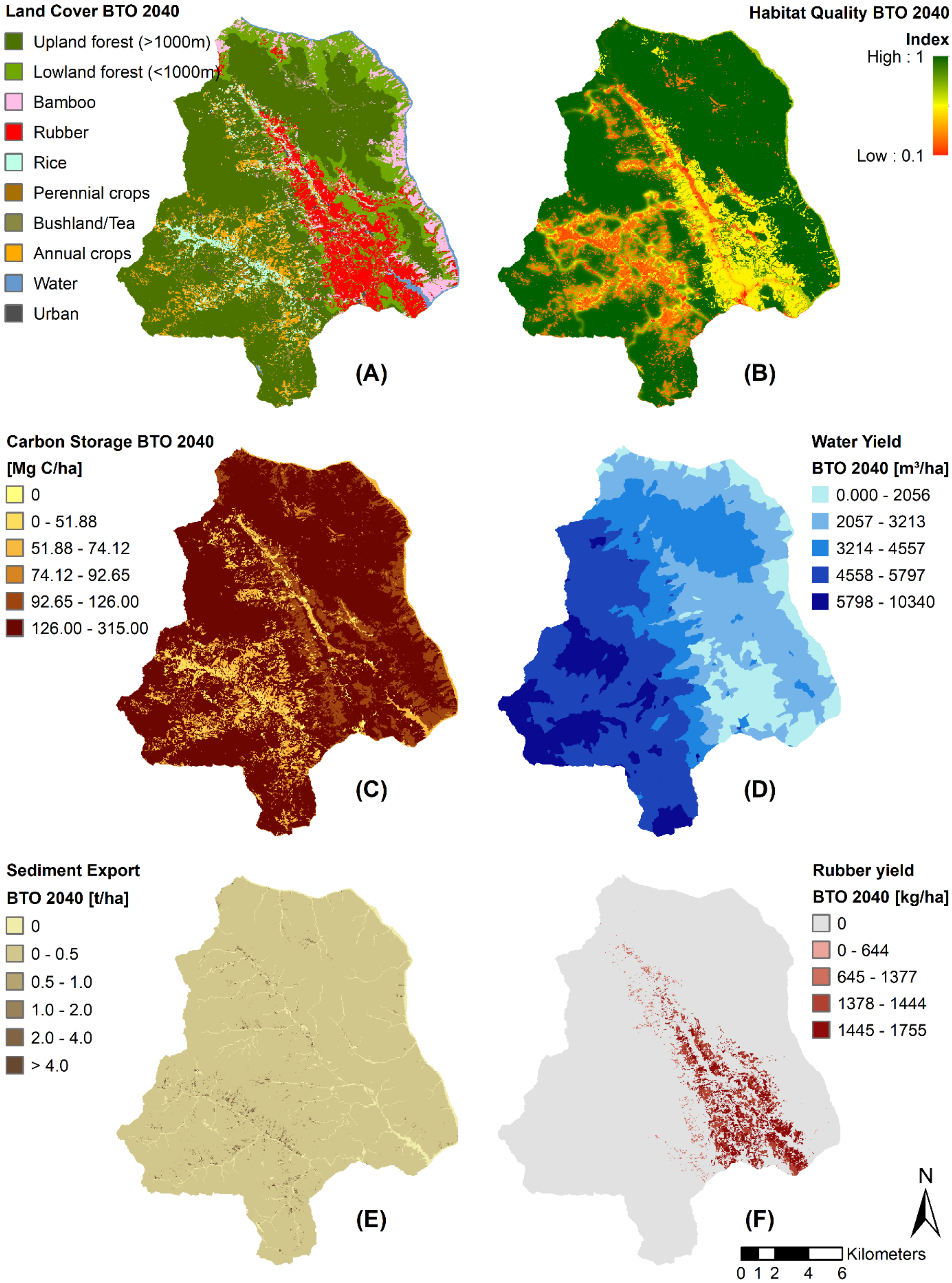


Figure S2.4. Ecosystem service results at the last year (2040) of the BTO scenario (**A**) including habitat quality (**B**), carbon storage (**C**), water yield (**D**), sediment export (**E**) and rubber yield (**F**).

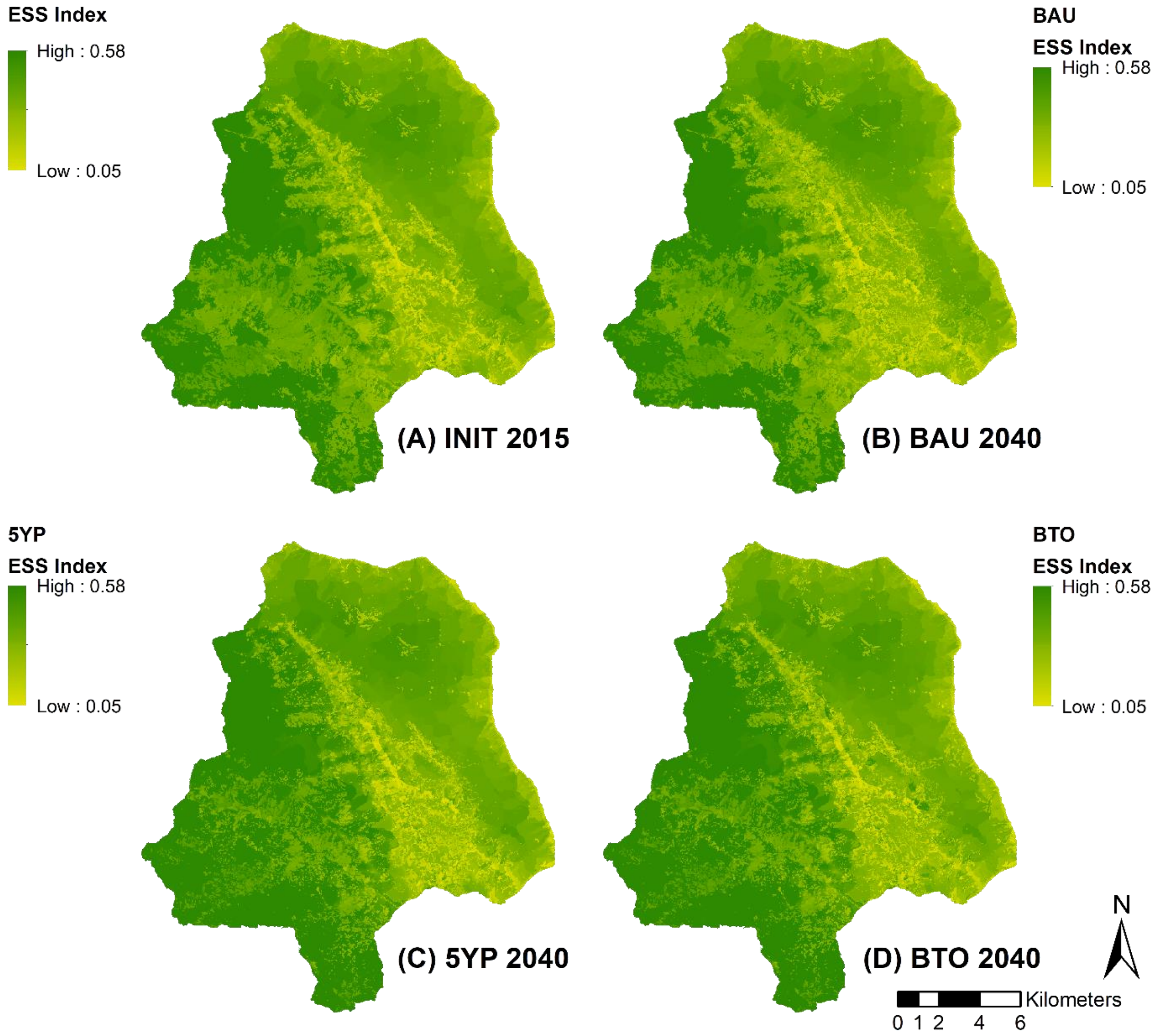


Figure S2.5. Ecosystem service index integrating the five ecosystem services weighted by Xishuangbanna prefecture administration using the ROC (centroid weight) method for the initial year of 2015 (**A**) as well as additional results for the final year of each scenario (Business-as-usual (**B**), 5-years-plan (**C**) and Balanced-trade-offs (**D**)).

2.6.4. Sensitivity Analysis of Hydrological Models

The sensitivity analysis for the sediment export model showed the expected behaviour of a model based on the USLE. Linear relationships between sediment export amounts and changes in the K, R and P factor were found. Sediment exports were more sensitive to changes in the C factor, as it also influences downslope sediment retention in addition to potential soil erosion. The highest sensitivity was identified in respect to changes in the Borselli k parameter, explicitly implemented for calibration purposes.

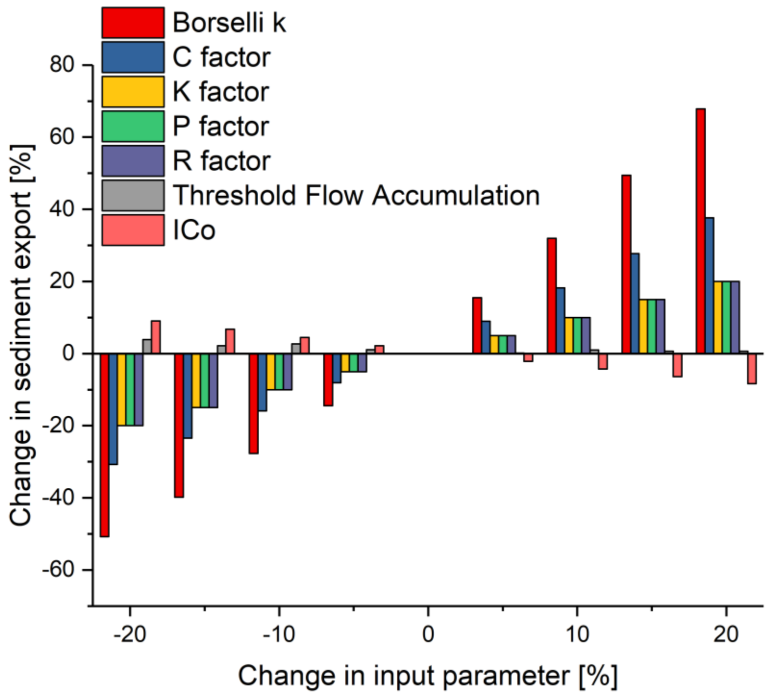


Figure S2.6. Sensitivity analysis of the InVEST sediment export model.

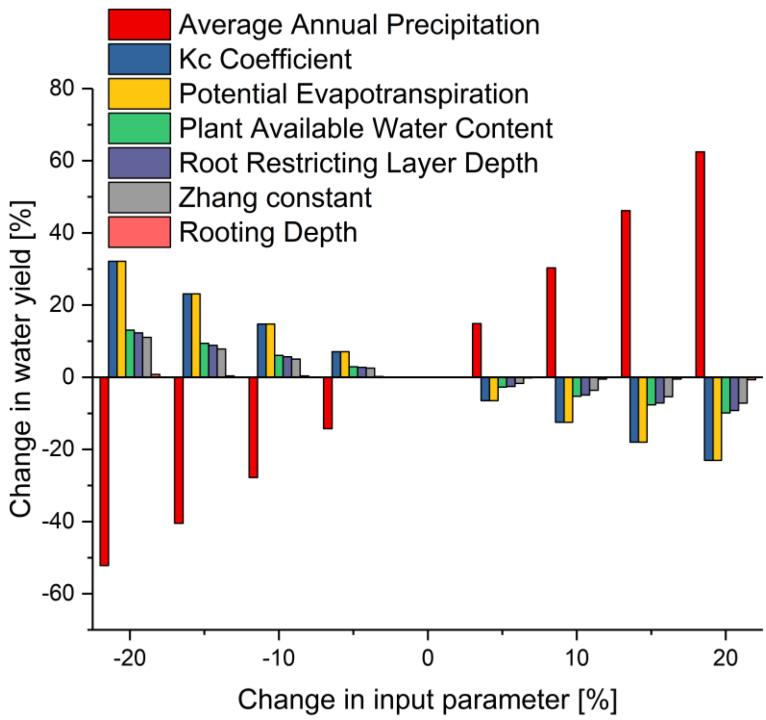


Figure S2.7. Sensitivity analysis of the InVEST water yield model.

Chapter 3: Tipping Points in the Supply of Ecosystem Services of a Mountainous Watershed in Southeast Asia

Kevin Thellmann [1,], Marc Cotter [1], Sabine Baumgartner [1], Anna Treydte [1,2], Georg Cadisch [1] and Folkard Asch [1]

[1] Institute of Agricultural Sciences in the Tropics and Subtropics (Hans-Ruthenberg-Institute), University of Hohenheim, 70593 Stuttgart, Germany

[2] Nelson-Mandela African Institution of Science and Technology, P.O. Box 447, Arusha, Tanzania

Abstract: Rubber plantations have expanded at an unprecedented rate in Southeast Asia in recent decades. This has led to a substantial decline in the supply of ecosystem services (ESS) and has reduced livelihood options and socioeconomic well-being in rural areas. We assessed the impact of two land use scenarios on the supply of ESS in a mountainous watershed in Xishuangbanna Prefecture, People's Republic of China. We combined time-series data derived from spatially explicit ESS models (InVEST) with a sequential, data-driven algorithm (R-method) to identify potential tipping points (TPs) in the supply of ESS under two rubber plantation expansion scenarios. TPs were defined as any situation in which the state of a system is changed through positive feedback as a result of accelerating changes. The TP analysis included hydrological, agronomical, and climate-regulation ESS, as well as multiple facets of biodiversity (habitat quality for vertebrate, invertebrate, and plant species). We identified regime shifts indicating potential tipping points, which were linked to abrupt changes in rubber yields, in both scenarios at varying spatial scales. With this study, we provide an easily applicable method for regional policy making and land use planning in data-scarce environments to reduce the risk of traversing future TPs in ESS supply for rubber producing land use systems.

Keywords: Southeast Asia; ecosystem services; rubber; regime shift; tipping point; scenario modeling; InVEST

A version of this chapter was published as [135]:

Thellmann, K.; Cotter, M.; Baumgartner, S.; Treydte, A.; Cadisch, G.; Asch, F. Tipping Points in the Supply of Ecosystem Services of a Mountainous Watershed in Southeast Asia. Sustainability **2018**, 10, 2418 (https://doi.org/10.3390/su10072418).

The original publication is available at: https://www.mdpi.com/2071-1050/10/7/2418

3.1. Introduction

Ecosystem services (ESS) are defined as the goods and benefits people obtain from ecosystems [28]. The capacity of ecosystems to sustainably deliver ESS can change and is often threatened by increasing anthropogenic pressure. This pressure includes increased climatic variability, land use change, and the overexploitation of resources [67,136,137]. The intensity of external pressure that a system can absorb without changing its characteristic structure and functions is defined as resilience [138,139]. The faster the system returns to its former equilibrium state after disturbance, the more stable it is considered to be [138]. Socioecological systems are characterized by complex interactions between ecosystem properties and social dynamics. Their resilience is defined as the ability of the socioecological system to sustain a set of ESS under changing environmental and management conditions [140]. This ability to generate ESS may shift from desired to less desired states as a result of increasing external pressures, which often act synergistically [141]. Resilience may then be compromised and the system reaches a tipping point (TP). Shifts from one system state to another may not be desirable, costly to revise, or irreversible [139,142].

Using the concept of TPs to analyze socioecological systems has gained considerable momentum in academia in recent years [143]. Milkoreit et al. [143] deduced the concepts most frequently used for defining TPs across scientific disciplines (natural science, social science, and socioecological systems). In their review, the majority of literature on land use change and socioecological systems involve the concepts of “Multiple Stable States” and “Abruptness”. Concepts involving “Feedbacks” are frequently used in socioecological system research, whereas land use change research often involves the concept of “Irreversibility”. The term “Tipping Point” is increasingly used in research on socioecological systems to describe phenomena comparable to the better known term “Regime Shift” in ecological systems [143]. We refer to a general definition for TPs from van Nes et al. [144]: “Any situation where accelerating change caused a positive feedback [that] drives the system to a new state”. To date, only few studies have looked at TPs in ESS supply.

Zhang et al. [145] analyzed time series of 55 social, economic, and ecological indicators, ranging from soil stability, air quality, and water quality to livestock and various crop yields, in order to assess the sustainability of ESS in Eastern China. They found that the analyzed regional socioecological system already passed a TP in the 1970s, coinciding with China’s shift from a planned economy to a market economy. After China’s accession to the World Trade Organization in 2001, the system is now heading towards a new steady state. Such TPs are of concern, as passing critical thresholds and the associated changes can affect the ability of a system to provide ESS and lead to disastrous consequences for human and ecological societies that depend on them [146].

The concept of a “safe operating space for humanity” was proposed by Rockström et al. [39,147]. They interlinked nine critical boundaries of biophysical processes at a planetary scale that frame the safe operating space. Within this space, the risk for unpredictable or catastrophic changes is low. Raworth [148] extended the planetary boundary concept and integrated human well-being into the framework, which has become known as the Oxfam Doughnut. In the Oxfam Doughnut, the borders of the safe operating space are defined by the social foundation and the environmental ceiling. Falling below the social foundation or breaching the environmental ceiling reduces human well-being [148]. On a planetary scale, three of the environmental boundaries have already been transgressed (climate change, rate of biodiversity loss, and the nitrogen cycle) and millions of people’s living standards fall below the social foundation (e.g., food, energy, income) [148].

In contrast to the planetary scale of these approaches, management of resources and decision making mainly takes place at a regional or local scale. Dearing et al. [149] propose a method to transfer the

Doughnut concept into a framework of regional boundaries. They describe four types of time-series analyses to define the boundaries of a safe operating space at a regional scale: (1) linear trends with environmental limits set by scientific, public, or political instances (e.g., urban air quality regulation); (2) the envelope of variability defined by long-term, normal fluctuations of a system (e.g., climate system of planet earth); (3) analysis of systems that crossed a critical threshold in the past (e.g., eutrophication of a lake); and (4) the identification and analysis of early warning signals (e.g., "critical slowing down"). At regional levels, processes of deforestation and agricultural expansion are among the most important drivers for regime shifts that impact the supply of ESS in rural areas [150]. These processes and their impact on ESS can be simulated and assessed with spatially explicit models [52]. Modeling results can then be used to delineate the boundaries of local safe operating spaces in order to predict and reduce the risk of traversing TPs in the future. This is of particular importance in areas where people's current and future livelihoods are directly linked to a sustainable supply of ESS, such as rural agricultural areas.

In Montane Mainland Southeast Asia (MMSEA), the recent intensification in the cultivation of cash crops has led to the demise of traditional swidden farming systems [23]. Major reductions in livelihood options, socioeconomic well-being, and the supply of ESS have been the result of such large-scale land use conversions [10,11,151]. A prime example of these conversions is the introduction and extensive expansion of rubber tree (*Hevea brasiliensis*) plantations in many parts of MMSEA. The Prefecture of Xishuangbanna, located in Southwestern China, has seen increases in area covered by rubber plantations, from 4.5% in 1988 to 22.2% in 2010 [15]. The rapid expansion of rubber plantations has been linked to increased soil erosion, loss of biodiversity, changes in carbon dynamics, and changes in the hydrological cycle [12,55–57,59,61]. However, rural areas in MMSEA often lack the amount of long-term and high-quality data needed to advance the scope of multidisciplinary modeling. To date, no research has been done on deriving potential TPs in ESS in rubber-dominated land use systems.

As rubber expansion has proceeded at an unprecedented rate in MMSEA in recent decades, there is an urgent need for methods to assess the future supply of ESS from rubber-producing land use systems, even in data-scarce environments. We propose a method for identifying TPs in the supply of ESS. For this, we use results from spatially explicit ESS models such as InVEST (Integrated Valuation of Ecosystem Services and Trade-Offs) in combination with a data-driven, sequential algorithm, originally developed to detect regime shifts in climate variations. The analysis includes hydrological, agronomical, and climate-regulation ESS, as well as multiple facets of biodiversity (habitat quality for vertebrate, invertebrate, and plant species) for two rubber-related land use scenarios, simulated at the watershed scale over a 25-year period. We aim at providing a simple tool for regional policy making and land use planning to reduce the risk of traversing future TPs in ESS for rubber producing land use systems. This method can also be transferred to other comparable land use systems outside of MMSEA.

3.2. Material & Methods

3.2.1. Research Area

The research area is the Naban River Watershed National Nature Reserve (hereafter referred to as Nabanhe Reserve). It spans an area of roughly 271 km² and is located in Xishuangbanna Prefecture, Yunnan Province, Southern China (22°08′N 100°41′E). Xishuangbanna is characterized by a subtropical climate, strongly influenced by monsoon cycles and a distinct wet season from May to October [77]. The mean annual temperature lies between 18 and 22 °C and annual average precipitation amounts to 1100–1600 mm [57]. The elevation ranges from 500 to 2300 m.a.s.l., with rubber plantations being located in lowland valley bottoms and, more recently, expanding into higher altitudes [58]. The Nabanhe Reserve is part of the Indo-Burma biodiversity hotspot [6] and is not only rich in floral and faunal species diversity but also in terms of the multiple ethnicities living in the area [63,78]. The largest share of area in the Nabanhe Reserve is covered by natural or seminatural tropical mountainous rainforest (~60%). Other land uses include tea plantations and bushland (~11%), rubber plantations (~9%), bamboo forests (~6%), annual crops such as maize and sugar cane (~6%), paddy rice (~4%), and small patches of perennial crops (~1%) (Figure 3.1a).

3.2.2. Scenario Definition

The scenarios used for this study were developed as part of the Chinese–German project SURUMER (Sustainable Rubber Cultivation in the Mekong Region) [152]. The project had the objective to develop sustainable land use strategies for rubber cultivation through a close interaction of science and practice [153]. A team of relevant stakeholders in collaboration with a multidisciplinary team of scientists developed several future land use scenarios [80]. We used two of these scenarios to assess potential TPs in the supply of ESS in the research area: (1) The Business-As-Usual scenario (BAU) and (2) the Balanced-Trade-Offs scenario (BTO). In BAU, past rubber expansion in Xishuangbanna [82] and the Nabanhe Reserve [59] was linearly continued at an annual rate of 2%, independent of the suitability of the land. In BTO, rubber expansion was restricted to areas suitable for rubber cultivation. These were defined as below 900 m.a.s.l. and with slopes below 23°. These restrictions were chosen based on reduced rubber yields at high altitudes [94] and the aim to reduce soil erosion on sloping areas [57]. BTO additionally included the establishment of riverine buffer zones around the main rivers in Nabanhe Reserve. These consist of secondary forest vegetation and are 30 m wide. Similar reforestation measures were introduced in the initial years of BTO as water protection zones around water sources for domestic use. The land use map of 2015 (Figure 3.1a) served as the initial condition for both scenarios. The scenarios have been described in more detail in Thellmann et al. [48]. Land use changes were simulated for 25 years, from 2015 to 2040. The focus in Thellmann et al. [48] was on deriving realistic land use change scenarios and information on ESS preferences and evaluation through a close interaction with stakeholders. Here, we refrained from social or economic valuation for ESS and focused on analyzing the biophysical changes in ESS supply for two contrasting land use scenarios across varying spatial scales and initial land use conditions. Figure 3.1c–f shows the spatial extent of land use changes introduced in both scenarios for the final year of the simulation (2040).

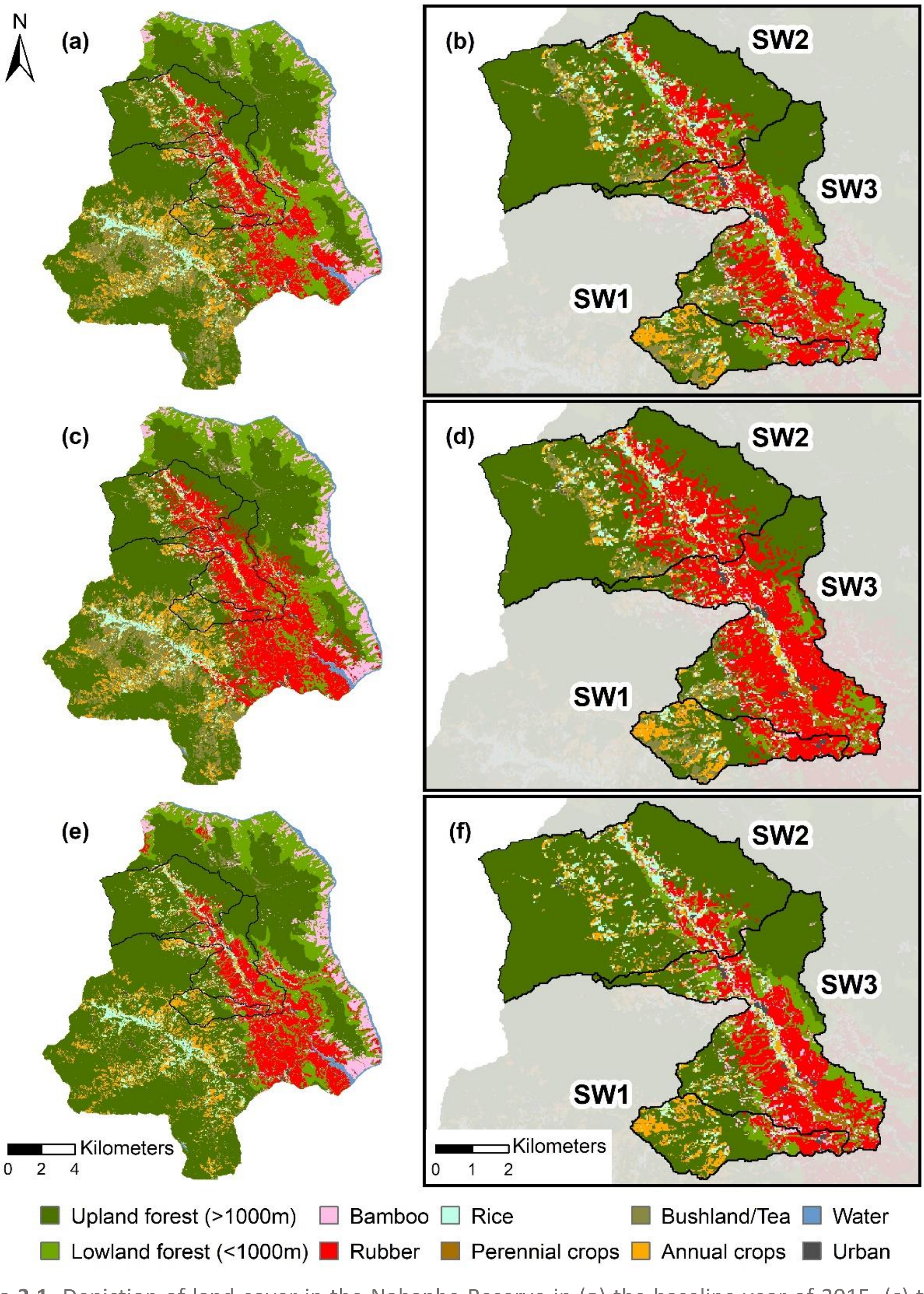


Figure 3.1. Depiction of land cover in the Nabanhe Reserve in (**a**) the baseline year of 2015, (**c**) the final year (2040) of the Business-As-Usual scenario, and (**e**) the final year (2040) of the Balanced-Trade-Offs scenario. The 2015 land cover map features a resolution of 30 × 30 m and was derived from Rapid Eye satellite data. Three subwatersheds (SW1, SW2, SW3) are delineated as focal points for further analysis. Detailed excerpts of the three subwatersheds are depicted in (**b**) for the initial condition of 2015, (**d**) for the final year (2040) of the Business-As-Usual scenario, and (**f**) for the final year (2040) of the Balanced-Trade-Offs scenario.

3.2.3. Ecosystem Service Assessment

Ostrom proposed a framework for analyzing the sustainability of a socioecological system [42]. We used this framework as a basic guideline to identify relevant variables: (1) resource systems—the Nabanhe Reserve; (2) resource units—quantification of ESS supply from spatial models; (3) governance system—future land use plans based on past land use change and governmental land use plans; and (4) users—feedback from local stakeholders to identify locally relevant ESS.

We assessed a set of four ESS using InVEST (Integrated Valuation of Ecosystem Services and Trade-Offs, Version 3.3.3., The Natural Capital Project: Stanford, CA, USA) [44] and used a self-developed model for assessing rubber yields, as rubber is the most important provisioning service in Nabanhe Reserve. These ESS were chosen based on several discussions with stakeholders, including village heads, farmers, prefecture administration, and politicians at the provincial level [48,79,80]. The InVEST submodels we used were: (1) habitat quality (as a proxy for biodiversity), (2) carbon storage and sequestration, (3) water yield, and (4) sediment retention (as proxies for regulating ESS). The code of InVEST was modified to iterate model runs in 25 steps for the 25 years of land use changes outlined in the scenario description. Otherwise, we implemented InVEST according to the developers' user manual [44] and published literature [12,88–90] and used a substantial pool of field studies for model parameterization [48]. Environmental input variables such as long-term mean annual precipitation and soil properties were kept constant throughout the simulation period [123,133]. This was done in order not to bias the effect of land use changes on the model results with changes in other parameters. Note that we considered a decrease in sediment export as beneficial. On the other hand, due to water scarcity in the dry season, decreases in annual water yield were considered to be unfavorable. The rubber yield model was based on local survey data considering average rubber yields with regard to plantation altitude and plantation age [93,95] and was performed with ArcGIS (Version 10.3.1).

We normalized the biophysical model results so that the values of each ESS are set to 1 in the initial year of the simulation. ESS values for the following years in the simulation were then calculated in relation to the initial year. We calculated the arithmetic mean of the five normalized ESS values for every year. This we refer to as the ESS z-score. The time series of the ESS z-score was then used as an input for the TP identification algorithm described in Section 2.4. A detailed description of the conceptualization, parameterization, and results of the InVEST submodels and the rubber yield model can be found in Thellmann et al. [48] for the entire Nabanhe Reserve. Here, we focused on three subwatersheds in the Nabanhe Reserve in more detail: SW1, SW2, and SW3 (Figure 3.1). We selected these subwatersheds as (a) data was available for calibrating the submodels for water yield and sediment export (in SW1) [57], and (b) they feature varied conditions regarding their spatial extent, initial land use conditions, and land use change trajectories in the simulated scenarios. Therefore, they allowed us to analyze the provisioning of ESS in relation to different rubber expansion rates as well as different initial land use conditions. The initial land use conditions are listed in Table 3.1. SW1 is the smallest subwatershed, at 6.92 km² in area. SW2 spans 27.97 km² and SW3 has an extent of 21.34 km².

Table 3.1. Proportions of land cover categories in the Nabanhe Reserve and the analyzed subwatersheds for the initial year of the simulation (2015).

Land Cover Category	Coverage in 2015 (%)			
	NR [1]	SW1 [2]	SW2 [3]	SW3 [4]
Upland forest [5]	45.9	35.8	70.4	29.0
Lowland forest [5]	15.6	7.7	2.6	17.0
Bamboo	5.6	3.7	1.7	5.3
Rubber	9.2	11.8	7.6	30.6
Rice	4.1	5.4	5.8	5.3
Perennial crops	1.1	2.4	1.5	4.0
Bushland/tea [6]	11.1	15.2	6.2	5.0
Annual crops	5.7	17.2	4.1	3.0
Water	1.3	0.0	0.0	0.0
Urban	0.4	0.9	0.2	0.9

[1] NR: Nabanhe Reserve. [2] SW1: Subwatershed 1. [3] SW2: Subwatershed 2. [4] SW3: Subwatershed 3. [5] The distinction between upland forest and lowland forest is solely based on the altitude of their respective location (above/below 1000 m.a.s.l.) [6] Due to the similarity of the spectral signature of bushland and tea plantation areas in the satellite images, no distinction was possible between them. Therefore, these land use categories were merged into one category. The percentage values might not add up to 100% due to rounding.

3.2.4. Identification of Tipping Points

In order to identify potential TPs in the time series of the ESS z-score in our scenarios, we adapted the method of Zhang et al. [145], who used long-term time series of economic and environmental data to analyze the past supply of multiple ESS in eastern China. The algorithm we used to statistically identify TPs was developed to detect regime shifts in time series of climate variations by Rodionov [154]. We chose the Rodionov algorithm (henceforth referred to as the R-method) as it is capable of identifying TPs even in the presence of a background trend and outliers in the data. The R-method does not require prior knowledge of the timing of a potential TP as it is an exploratory data-driven analysis. We refer to the periods separated by TPs as regimes. The input for the R-method was the annual time series of the ESS z-score for both scenarios in the simulation period between 2015 and 2040. Years with potential TPs are indicated by the regime shift index (RSI). A positive RSI signifies a shift to a new regime, where the mean ESS z-score for the entire regime is greater than the mean of the previous regime. The opposite is true for a negative RSI. The higher the absolute value for RSI, the more distinct is the subsequent regime from the previous one. To prevent the misidentification of very short regimes, the R-method was set to a moving average window of half the length of the simulation period (cutoff = 12.5), with significance of $p = 0.01$ and Huber's weight parameter $w = 2$. Huber's weight parameter defines to which extent outliers are taken into account in the algorithm of the R-method.

3.3. Results

3.3.1 Biophysical Model Results of InVEST and Rubber Yield

Table 3.2 shows the results of the InVEST submodels and the rubber yield model for the initial condition (2015) and the final years (2040) of BAU and BTO for the entire Nabanhe Reserve as well as each subwatershed. In both scenarios, the simulated land use changes show the same general trend in affecting the supply of ESS, regardless of the spatial scale of the analysis. These trends are: (1) a decrease of the regulating ESS and habitat quality in BAU and (2) increases of habitat quality and the regulating ESS in BTO in the Nabanhe Reserve and the subwatersheds.

Table 3.2. Annual output of the Integrated Valuation of Ecosystem Services and Trade-Offs (InVEST) submodels and the rubber yield model for the initial state of 2015 and the final year of each land use scenario (2040) for the whole Nabanhe Reserve (NR) [48] and each subwatershed (SW1, SW2, and SW3).

Scenario/Subwatershed	Habitat Quality (10^3 HQ Index) [4]	Rubber Yield (10^6 kg)	Sediment Export (10^3 kg)	Water Yield (km^3)	Carbon Storage (10^6 kg) [5]
Initial state (2015)					
NR [1]	232	1.85	53,441	102	5337
SW1	5	0.06	1005	3	111
SW2	25	0.04	3185	12	589
SW3	16	0.42	2555	5	367
BAU [2] (2040)					
NR	225	2.98	60,814	99	5095
SW1	4	0.10	1128	3	106
SW2	24	0.15	3981	11	556
SW3	15	0.67	3769	4	321
BTO [3] (2040)					
NR	249	2.92	19,040	102	5693
SW1	5	0.09	519	3	129
SW2	27	0.07	1417	12	630
SW3	17	0.62	829	5	380

[1] NR: Nabanhe Reserve. [2] BAU: Business-As-Usual. [3] BTO: Balanced-Trade-Offs. [4] The Habitat Quality submodel of InVEST assigns a value between 0 and 1 to every pixel in the land use map, according to land use, management, and surrounding threats such as roads. The HQ (Habitat Quality) Index for each subwatershed and the Nabanhe Reserve as a whole is the sum of each pixel's habitat quality value. [5] Includes carbon storage estimates for above and below ground biomass, soil (0–30 cm depth), and dead organic matter.

Rubber yields increase in both scenarios but are highly variable throughout the simulation period as plantations shift in and out of their economic life cycle in different parts of the Nabanhe Reserve. The final year of BAU shows an increase of 1.13×10^6 kg rubber yield compared to the initial condition. A slightly lower increase can be seen in BTO (1.07×10^6 kg). Even though there is a decrease of exported sediments in BTO, there are only minor changes in water yield. The land use changes introduced in both scenarios have only minor effects on water yield (±1%, which is masked by rounded numbers in Table 3.1).

3.3.2 Land Use Change and Tipping Points in ESS Supply

Figure 3.2 shows the temporal changes in the normalized supply of ESS as well as rubber- and forest-related land use changes for both scenarios. Additionally, the ESS z-score, the arithmetic mean of the five normalized ESS values (light blue line in Figure 3.2) calculated on an annual basis, is shown. Years with potential TPs are depicted as purple columns in Figure 3.2 (RSI: regime shift index). In both scenarios, we identified potential TPs in all case study subwatersheds, all of which are significant with $p > 0.01$.

In the BAU scenario, for each subwatershed, as well as the entire Nabanhe Reserve, habitat quality and the three regulating ESS decrease in response to the rubber expansion and the loss of forest areas. Rubber yields are increasing in the initial years of the simulation, then remain relatively constant until 2036, and see a steep decline at the end of the simulation.

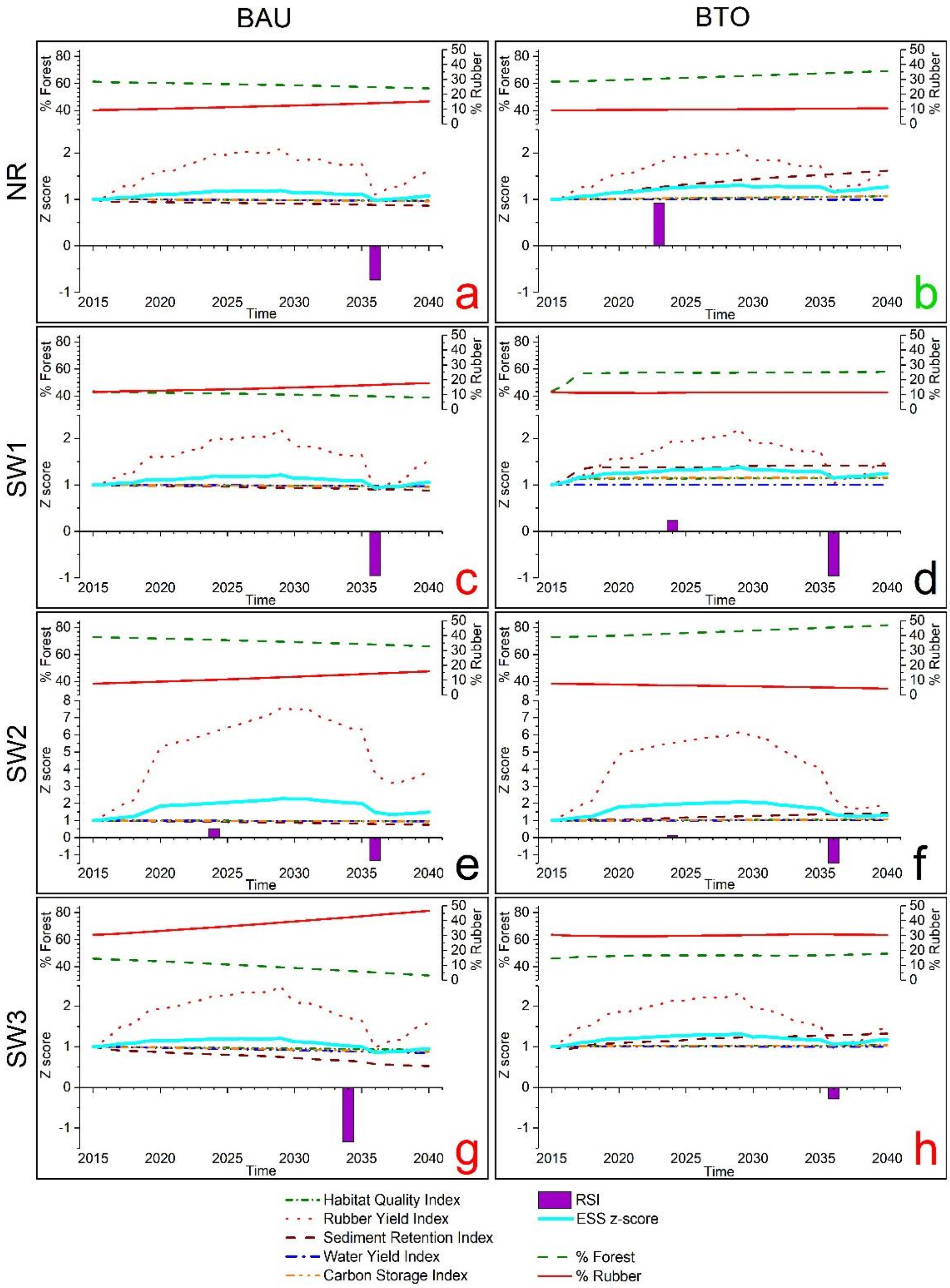


Figure 3.2. Depiction of the modeled and normalized ecosystem services (ESS) indices for Habitat Quality, Rubber Yield, Sediment Retention, Water Yield, and Carbon Storage, as well as their annual arithmetic mean value (z-score) for the Business-As-Usual (BAU) scenario (left column; (**a**,**c**,**e**,**g**)) and the Balanced-Trade-Offs (BTO) scenario (right column; (**b**,**d**,**f**,**h**)) in relation to rubber-related land cover changes throughout the simulation period between 2015 and 2040. The rows of graphs relate to the whole Nabanhe Reserve (**a**,**b**), SW1 (**c**,**d**), SW2 (**e**,**f**), and SW3 (**g**) and (**h**). The land use changes are given in percent of the extent of the Nabanhe Reserve or respective subwatershed for each graph. Years with potential regime shifts are indicated by purple columns (RSI: regime shift index). Note the different scaling on the y-axis for the z-score of the different subwatersheds and the differences in scaling on the axes for rubber and forest coverage. The coloring of the letters (**a**–**h**) indicates if the regime of ESS supply at the end of the scenario is comparatively better (green), worse (red), or approximately the same (black) as the initial condition.

The year of a potential TP in total ESS supply is 2036 for NR, SW1, and SW2. For SW3, a potential TP is found in 2034. The trajectory for sediment retention in SW3 shows a more pronounced decline in comparison to the sediment retention trajectory in the other subwatersheds. SW2 has the smallest share of rubber areas in the initial year of the simulation (7.6%), and with that, also the lowest total annual rubber yield in comparison to the other subwatersheds. As the rubber yield trajectories are all relative to the initial condition (set to 1), a lower initial rubber yield results in a steeper increase of the trajectory, as can be seen for the rubber yield in SW2 (Figure 3.2e). SW2 is the only subwatershed in the BAU scenario where a positive TP can be observed (2024).

In the BTO scenario, the reforestation measures and restricted expansion of rubber plantations led to increases in the regulating ESS and habitat quality. Rubber yields follow trajectories that are comparable to those seen in the BAU scenario, although with lower total values. In the BTO scenario, a positive RSI indicates a potential TP for the entire Nabanhe Reserve in the year 2023. In contrast to the BAU scenario, no further TPs occurred in the remaining years of the simulation for the Nabanhe Reserve. In both SW1 and SW2, positive RSIs indicate TPs in the year 2024, although less distinct than for the entire Nabanhe Reserve. No positive TPs are observed for SW3. Similar to the BAU scenario, negative RSI values in the year 2036 indicate TPs for SW1, SW2, and SW3. In SW1, the steep gain in forest areas in the initial years of BTO are a direct result of the establishment of water protection zones around water sources. In SW3, from 2018 onwards, the changes in the forest categories were only about ±1%. Changes in the rubber category were even less pronounced, ranging between 11.1% and 11.7% of areal coverage of SW3 throughout the simulation period.

3.4. Discussion

3.4.1 Tipping Points in the Supply of ESS

The land use changes introduced in the BTO scenario generally improved regulating ESS and habitat quality. We observed the opposite in the BAU scenario over the 25-year simulation. These results confirmed the expectations developed in the scenario design process with local stakeholders [48]. Similar results have also been reported in other ESS scenario simulations. Bai et al. [155] applied InVEST in Northern China to assess agriculture, forestry, and urban expansion scenarios and found the establishment of riparian buffer zones to be the optimal land management strategy, as it balanced agricultural production and hydrological ESS supply. In contrast to the distinct differences of regulating ESS and biodiversity between BAU and BTO, the time series of total rubber yields in the Nabanhe Reserve and the analyzed subwatersheds follow comparable trajectories for both scenarios but vary in the magnitude of rubber gains and losses. The time series of rubber yields turned out to be a decisive factor in dictating whether a TP has been reached or not. This can be seen in Figure 3.2a,c–f,h, as the models all agree on a negative TP for the year 2036, which coincides with the steepest declines in rubber yields.

As perennial systems, rubber plantations have an economic lifespan of about 30 years [21]. The amount of latex which can be tapped during this period is highly variable. Productivity is low when tapping begins, peaks during the middle years of a plantation's lifespan, and declines again when the plantation approaches the end of its economic lifespan [94]. In the study area, a broad range of plantation ages is present at the start of the simulation [95], which results in high variations of total rubber yield throughout the simulation period as existing plantations shift in and out of their economic lifespan in addition to the variations introduced by newly established plantations. The drop in total rubber yield leading to the TPs in 2034/2036 is a result of multiple plantations in the Nabanhe Reserve reaching the end of their economic lifespan simultaneously and having to be renewed. Rubber plantations are not the only source of income for the population in the Nabanhe Reserve [156]. Paddy rice, maize, and fruit plantations are also relevant [156], but we assumed no changes of those categories in our scenarios. Since our analysis focused on deviations from initial conditions, we argue that the additional provisioning services provided by these land use categories can be neglected within the aims of this study. In addition, we argue that the strong dependency on rubber for the inhabitants of the Nabanhe Reserve justifies rubber yield as the defining provisioning service (like agricultural GDP in Hossain et al. [157]).

The analysis of subwatersheds, varying in their initial land use conditions and land use change trajectories, proved to be a crucial point for the interpretation of the results. For the entire Nabanhe Reserve in BTO, the land use changes led to a positive TP in 2023 (Figure 3.2b). This means that at a large scale, the increases in the regulating ESS and habitat quality are able to buffer against the decline in rubber yield in the later years of the simulation. We expected to find similar results for the three analyzed subwatersheds. These expectations have only partly been met, as we identified positive as well as negative TPs for smaller spatial extents (SW1, SW2, SW3) in BTO. For SW1, SW2, and SW3 in BTO, the results agree on negative TPs in 2036, comparable to the negative TPs identified in the BAU scenario. However, for SW1 and SW2, positive TPs indicate that the system shifted to a comparatively more beneficial state of ESS supply in 2024. This means that the negative TP found for SW1 and SW2 in 2036 in BTO represents a shift back to a comparable system state as that of the initial regime (2015–2023). In SW3 in BTO, this is not the case, as only a negative TP was identified in 2036. This indicates that the increases in other ESS are not sufficient to buffer against the steep drop in rubber yields in 2036 for SW3 in the BTO scenario.

In the BAU scenario, on the other hand, as linear growth of rubber areas and linear decrease of forest areas are set to occur with constant annual rates, the ESS z-scores in the Nabanhe Reserve and analyzed subwatersheds show very similar trajectories, regardless of the differing scales. The exception to this is SW2 in BAU. The high gain in rubber yields shifts the system to a comparatively more beneficial state of ESS supply in 2024. This is very similar to what was observed in SW1 and SW2 in the BTO scenario, the difference being that we observed increased habitat quality and regulatory ESS in BTO, as opposed to increased rubber yields alone in the BAU scenario.

The strengths of our method include the focus on smaller subwatersheds, since this revealed results, which would have gone unnoticed due to aggregation, if the focus had been on the Nabanhe Reserve as a whole. Furthermore, ESS research often focusses on comparing present land use conditions with altered land use “snapshots” of one specific target year in the future, lacking any analyses of the timeframe in between the initial condition and the final year of a scenario (see [12,88,98] as examples). As rubber is a perennial crop and the expected yield can vary substantially with plantation age and location, the annual resolution of our method is more robust in comparison to snapshot approaches. In addition, our method can be transferred to other regions of comparable land use change situations, as a both the InVEST models and the R-method are freely available through online platforms [44,154].

As suggested by Rodionov [154], the applicability of the R-method should be tailored to the topic of study at hand. In Rodionov [154], the R-method was exemplified using the January PDO (Pacific decadal oscillation), which is well known to experience regime shifts. In our case study, no prior knowledge existed for potential future or past shifts in regimes of ESS supply. Analyzing past shifts is very data demanding, as exemplified in Zhang et al. [145]. They analyzed time series (1900–2006) of 55 social, economic, and ecological indicators to assess the sustainability of ESS supply in Eastern China. In Zhang et al. [145], normalized trajectories of regulating services and provisioning services were grouped and depicted as separate time series. This revealed a clear trade-off between the two

ESS categories, with declining regulating services and increasing provisioning services. In both scenarios analyzed in this study, the relationship of regulating services (and habitat quality) with rubber yields (the only provisioning service in our case study) is not as clear because of the variable amount of rubber yield throughout the simulation period.

Depending on the focus of research, definitions for TPs in socioecological systems and land use change can, but do not necessarily have to, include different concepts [143]. Here, we did not focus on specific concepts to define TPs. Instead, we describe TPs as deviations from normal fluctuations in the presence of underlying trends [149]. Nevertheless, we address some of the concepts (indicated by quotation marks in the following paragraph) commonly used in research on socioecological systems and land use change according to Milkoreit et al. [143].

In our results, "Multiple Stable States" can be seen as the regimes between TPs in time series of the ESS z-score. With the chosen models and their structure, we were not able to cover the concept of "Irreversibility". For some submodels we used (e.g., sediment retention and water yield), a reversal of land use change rates in BAU would simply result in an approximately linear increase for these ESS, as opposed to the approximately linear decrease shown in Figure 3.2a,c,e,g. The same can be said for the ESS trajectories of habitat quality and carbon storage. Improvements for both submodels could be made by including an analysis of forest patch connectivity or forest edge effects [68,158]. The habitat quality submodel of InVEST does include edge effects at agricultural areas, as well as for roads and villages, but does not include any landscape connectivity indicators. We were able to include "Feedbacks" in a qualitative manner through the rules and outlines of the scenarios, which were co-designed by stakeholders. However, quantitative feedback is not included in any of modeling structures of InVEST or the rubber yield model. This means that changes in one ESS do not affect other ESS in the simulation. Therefore, the only dynamically changing input parameter throughout the simulation period is land use. The concept of "Abruptness" is crucial, as a majority of identified TPs are related to abruptly declining rubber yields in the case study areas. Hughes et al. [159] highlighted how slow regime shifts provide additional time for taking management actions in order to prevent a change in system states. Our analysis revealed habitat quality and the three regulating ESS to be variables that slowly react to changes in land use at the scale of the entire Nabanhe Reserve. Depicted as the ESS z-score, the decrease in habitat quality and the regulating ESS is masked by increases in rubber yield. This can be seen in the first regime in BAU until the years 2036 (Figure 3.2a,c,e) and 2034 (Figure 3.2g). With an abrupt decrease in rubber yield, the algorithm of the R-method revealed significant differences between the mean ESS z-score of the new regime (2036–2040) in comparison to the previous regime (2015–2035).

3.4.2 Methodological Limits and Future Research

The trajectories of habitat quality and most of the regulating ESS depicted in Figure 3.2 can be approximated by linear functions. These would qualify as type 1 of time-series categories described in Dearing et al. [149]—linear trends with environmental limits set by scientific, public, or political instances. We refrained from an analysis based on environmental limits, as no known thresholds for, e.g., habitat quality, exist for our study area. At the moment, without the quantification of environmental limits, our method can only provide the general direction in which the state of the socioecological system is moving, towards or away from the boundaries of the safe operating space. This, in turn, raises the question of if the system had already been in a state of unsustainable management before the start of the simulation, as all further analysis is related to the initial system state. The next step in improving our method would be to integrate environmental limits for the supply of the analyzed ESS. Our results revealed further weaknesses of using the R-method for the purpose of identifying TPs in modeled time series of ESS supply. For the BTO scenario in SW1, we expected the rapid gain of forest areas to result in a positive TP after the initial two years (Figure 3.2d). However, no TP was identified. This was due to the following reason: The R-method allows for the reduction of influence of outliers on the regime mean in the time series. The ESS z-score of the initial two years of BTO in SW1 are counted as outliers and, therefore, these values enter the calculation of the mean of the respective regime with reduced weights. Furthermore, the methodology of this study does not take any stakeholder preferences for specific ESS into account, as all ESS enter the calculation of the arithmetic mean (ESS z-score) with equal weights. With the inclusion of stakeholder preferences for ESS, the identified years of potential TPs may be subject to change [48]. The potential impacts of stakeholder preferences and weighing methods have been discussed, e.g., in Thellmann et al. [48]. Other points of improving the methodology would be to include natural disturbances (e.g., extreme weather events or pests) in addition to the human drivers we analyzed in this study.

In parts, our results are an example of the modifiable areal unit problem, meaning that results may change depending on where the boundaries are set [160]. To circumvent this problem in future research, agent-based models of ESS provision might be used, which add explicit ESS "use regions" as a link between ESS "source" and "sink regions" [161]. Recent advancements in simulating socioecological systems have shown promising results with the use of system dynamics models for the delineation of regional safe operating spaces [162]. This approach of system dynamics is well suited to capture potential feedbacks for longer simulation periods but is also more dependent on past empirical studies in comparison to the approach we used here. In our case, a simulation period of 25 years was chosen as a realistic timeframe to predict potential future land use changes for rubber cultivation in the Nabanhe Reserve [48]. Future research with the method proposed here could be conducted with longer simulation periods in combination with an earlier year for the initial conditions to: (1) improve validation of model runs, (2) capture long term effects of rubber plantation turnover times, and (3) reveal the impact of past rubber expansion on ESS in the Nabanhe Reserve.

3.5. Conclusion

In an era of global change, decisions may have to be made without full knowledge of potential consequences while making the best possible use of what is known at the time [163]. Within this background, we developed a method of combining spatially explicit modeling with a data-driven, sequential algorithm, both of which are freely available, as an easy-to-adapt concept for land use planning in data-scarce environments. We used this method to identify potential TPs in ESS for rubber expansion scenarios in MMSEA, but the method can be adapted to other areas facing comparable land use change situations, such as deforestation driven by timber or palm oil production in other parts of Southeast Asia. In the study area, we discovered unexpected differences in the results of the TP analysis related to questions of spatial scale. The application of the same TP identification methodology for the same scenario (BTO) resulted in positive TPs for the entire Nabanhe Reserve (large scale), whereas for the analyzed subwatersheds (small scale), conditions remained unchanged or were comparatively worse at the end of the scenario when compared to the initial state. From this, we conclude that sophisticated land use planning is able to provide benefits in the supply of ESS at watershed scale, but that potential trade-offs at subwatershed scales should not be neglected. Even if land use plans aim at a more sustainable manner of production, specific local conditions may prevent them from being adapted. Developing management plans for socioecological systems on multiple spatial scales without exceeding the limits of regional safe operating spaces is a critical challenge that remains for future research.

Author Contributions: K.T. and M.C. conceived and designed the modeling approach. K.T. parameterized and ran the models and analyzed the results. S.B. and K.T. reviewed and compiled relevant literature for the introduction and discussion and wrote these sections of the paper. K.T. wrote materials & methods, results and the conclusions. G.C. facilitated access to calibration and validation data of ESS in SURUMER and supported their interpretation and manuscript structure. M.C., F.A., and A.T. contributed to the interpretation of the results and substantively revised the manuscript.

Funding: This work was supported by the German-Chinese joint research project SURUMER (Sustainable Rubber in the Mekong Region). SURUMER was funded by the German Federal Ministry of Education and Research (BMBF) (Grant number FKZ 01LL0919). BMBF also provided funding for this open access publication. Furthermore, this work was an outcome of the initial phase of the SOS Uplands project, funded by BMBF (Grant number FKZ 01LC1709).

Acknowledgments: Thank you to the teams of SURUMER and SOS Uplands for their support and collaboration. We greatly acknowledge the financial support of the "Water-People-Agriculture" Research Training Group funded by the Anton & Petra-Ehrmann-Stiftung.

Conflicts of Interest: The authors declare no conflict of interest.

Chapter 4: Assessing Hydrological Ecosystem Services in a Rubber-Dominated Watershed under Scenarios of Land Use and Climate Change

Kevin Thellmann [1], Reza Golbon [1], Marc Cotter [1], Georg Cadisch [1] and Folkard Asch [1]

[1] Institute of Agricultural Sciences in the Tropics and Subtropics (Hans-Ruthenberg-Institute), University of Hohenheim, 70593 Stuttgart, Germany

Abstract: Land use and climate change exert pressure on ecosystems and threaten the sustainable supply of ecosystem services (ESS). In Southeast-Asia, the shift from swidden farming to permanent cash crop systems has led to a wide range of impacts on ESS. Our study area, the Nabanhe Reserve in Yunnan province (PR China), saw the loss of extensive forest areas and the expansion of rubber (*Hevea brasiliensis* Müll. Arg.) plantations. In this study, we model water yield and sediment export for a rubber-dominated watershed under multiple scenarios of land use and climate change in order to assess how both drivers influence the supply of these ESS. For this we use three stakeholder-validated land use scenarios, varying in their degree of rubber expansion and land management rules. As projected climate change varies remarkably between different climate models, we combined the land use scenarios with datasets of temperature and precipitation changes, derived from nine General Circulation Models (GCMs) of the Fifth Assessment Report of the IPCC (Intergovernmental Panel on Climate Change) in order to model water yield and sediment export with InVEST (Integrated Valuation of Ecosystem Services and Trade-offs). Simulation results show that the effect of land use and land management decisions on water yield in Nabanhe Reserve are relatively minor (4% difference in water yield between land use scenarios), when compared to the effects that future climate change will exert on water yield (up to 15% increase or 13% decrease in water yield compared to the baseline climate). Changes in sediment export were more sensitive to land use change (15% increase or 64% decrease) in comparison to the effects of climate change (up to 10% increase). We conclude that in the future, particularly dry years may have a more pronounced effect on the water balance as the higher potential evapotranspiration increases the probability for periods of water scarcity, especially in the dry season. The method we applied can easily be transferred to regions facing comparable land use situations, as InVEST and the IPCC data are freely available.

Keywords: Ecosystem services; climate change; land use change; rubber plantation; InVEST

A version of this chapter was published as [164]:

Thellmann, K.; Golbon, R.; Cotter, M.; Cadisch, G.; Asch, F. Assessing Hydrological Ecosystem Services in a Rubber-Dominated Watershed under Scenarios of Land Use and Climate Change. Forests 2019, 10(2), 176 (https://doi.org/10.3390/f10020176).

The original publication is available at: https://www.mdpi.com/1999-4907/10/2/176

4.1. Introduction

Ecosystem services (ESS) are defined as the goods and benefits humans gain from healthy and functional ecosystems [28]. Global change processes such as large-scale land use change and climate change increase pressure on ecosystem functions and threaten the sustainable supply of ESS [38,51,137,165]. In the last decades, the ESS concept has been increasingly used in environmental policy formulation and decision-making processes [49]. High impact publications such as the MEA (Millennium Ecosystem Assessment) [28] and TEEB (The Economics of Ecosystems and Biodiversity) [33] paved the way for the establishment of IPBES (Intergovernmental Platform on Biodiversity and Ecosystem Services) [166], who recently reported extensive land degradation and declining trends for many ESS and biodiversity all over the globe [167]. Several pathways exist for safeguarding the sustainability of future ESS supply. Modeling and mapping ESS for future scenarios of global change is one way to project the impact of land use or climate change on ESS in a spatially explicit manner [52]. Several tools are available to model ESS and how their future provision might be altered under scenarios of climate or land use change. Two of the most-used models are SWAT (Soil and Water Assessment Tool) [168] and InVEST (Integrated Valuation of Ecosystem Services and Trade-Offs) [44], which are most prominently used in the field of water-, soil- and climate-related ESS research [101]. Output of such modeling efforts can assist land use planners and policy makers and serve as a basis for the development of mitigation and adaptation strategies.

Global surface temperature and the variability of precipitation patterns in both time and space are highly likely to change over the course of the next century [169–171]. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC5) [172] provided multiple future trajectories of Representative Concentration Pathways (RCPs), in which the atmospheric concentration of gases relevant for Earth’s climate changes as a result of global-scale socio-economic decisions over the course of the next century. In general, global mean temperature is expected to increase in all RCPs, as the climate system responds with some delay to past changes in atmospheric greenhouse gas concentrations. Regional differences in temperature and precipitation vary in the amount (and direction) of projected changes as a result of the differences in the assumptions, resolutions, and parameterizations of General Circulation Models (GCMs). For this reason, mean results of ensemble model projections are often considered as the best estimate for future conditions in the field of climate research.

In montane mainland Southeast-Asia, the recent shift from traditional swidden farming to permanent cash crop systems has led to a wide range of impacts on ESS [10,11]. In Yunnan Province in Southwest China in particular, large areas of forest have been replaced by rubber (*Hevea brasiliensis* Müll. Arg.) plantations due to increasing rubber-based product demands [15,61,108]. Such extensive changes of land use can strongly affect multiple ESS [135,173]. Effects on hydrological ESS are of major concern, as land use changes influence many hydrological factors such as the interception of precipitation, run-off, sediment transport, and evapotranspiration. Hydrological effects of the expansion of rubber plantations range from increases in surface run-off and soil erosion [56,57], to increases in water loss via evapotranspiration in the dry season, and a reduction of water storage in the subsurface soil [60].

Other authors have estimated potential hydrological effects of climate change in montane mainland Southeast-Asia. Eastham et al. [174] showed potential increases in both mean annual temperature and precipitation in Yunnan Province and the rest of the Mekong basin. Studies on hydrology in the Mekong Region have shown potential impacts of climate change on streamflow, soil erosion rates, and sediment fluxes [175]. Zhu et al. [176] estimated increases in sediment fluxes in a catchment of the Upper Yangtze River as a response of changes in precipitation and temperature. Similar increases in both mean annual streamflow and sediment export have been estimated by Phan et al. [177] for the Song Cau watershed in Northern Vietnam.

However, only few studies included both land use change and climate change scenarios in their estimates for future ESS supply [97]. Trisurat et al. [178] used InVEST in combination with input data of (1) 10-year average precipitation (2000–2010), (2) precipitation predictions of one GCM for 2020, and (3) extreme precipitation (wet year of 2000) in combination with three land use scenarios. They found the highest water yield and sediment export for intensified land use with extreme precipitation conditions. Hoyer & Chang [97] applied InVEST using three GCMs for precipitation and temperature input data in order to represent a low, medium, and high range of potential climate paths. As the projected climate change varies substantially between different climate models, this uncertainty needs to be taken into account for watershed management and climate change adaptation [175].

In this study, we model two indicators for ESS—water yield and sediment export—for a rubber-dominated watershed under multiple scenarios of land use and climate change in order to assess how both drivers influence the supply of these ESS. For this purpose, we use spatially explicit data derived from nine General Circulation Models (temperature and precipitation) in combination with stakeholder-validated land use scenarios as input for a well-tested ESS modeling framework (InVEST). This study represents the first ESS assessment combining land use scenarios and multiple climate scenarios for rubber cultivation systems.

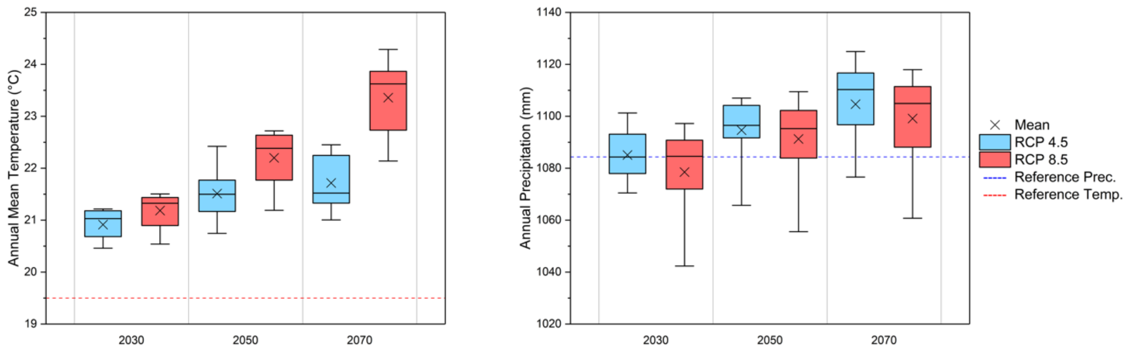
4.2. Material & Methods

4.2.1 Study Area

The study area was the Naban River Watershed National Nature Reserve, which is referred to as the Nabanhe Reserve henceforth. It is located in Yunnan Province, Xishuangbanna Prefecture in the Peoples Republic of China (22°08′ N 100°41′ E). It covers an area of roughly 271 km² and its topography is characterized by sloping hills, with altitudes ranging from about 500 to 2300 meters above sea level (m.a.s.l.). Depending on elevation, mean annual temperature is 18–22 °C and annual average precipitation varies between 1100 and 1600 mm [57]. The region is characterized by a subtropical climate and is influenced by monsoon cycles. The wet season lasts from May to October and about 87% of the annual precipitation occurs within these months [77]. The region is located within the Indo-Burma biodiversity hotspot and features an exceptional species richness [6]. As the study area is located on the northernmost border of tropical Asia, it features a mixture of tropical and temperate florae, which are diversified in their distribution by the mountainous topography [24]. Natural or semi-natural tropical mountainous rainforests represent the largest part of Nabanhe Reserve and cover about 60% of its area. Agricultural land use systems present in the Reserve include paddy rice fields and other annual crops (e.g., maize), as well as perennial systems such as tea, banana, and rubber plantations. More details on land cover in Nabanhe Reserve are listed in Table 4.1. We chose Nabanhe Reserve because it encompasses a watershed with rubber plantations as the dominant land use, but also features extensive protected areas, as it is part of the UNESCO (United Nations Educational, Scientific and Cultural Organization) Man and the Biosphere Programme [179]. Rubber cultivation had been present in the region's valley bottoms for decades, but has increasingly spread into the hillsides, where the rubber trees most commonly replace natural or semi-natural tropical mountainous rainforest [58]. The economic lifespan of rubber plantations in this area is around 20–25 years. Trees are commonly planted in monoculture on terraces in rows with about 3–4 m distance, whereas the distance between two adjacent terraces is about 5–7 m. Tree density ranges between 450 and 600 trees per hectare. Ground cover is kept low by the farmers, usually with two herbicide applications per year.

4.2.2 Climate Change Scenarios

InVEST was designed to be used with long-term average annual precipitation input data. We used the WorldClim dataset (Version 1.4) as baseline data, as it represents average annual precipitation derived from long-term measurements, which were interpolated to local topographical conditions [96,180]. We used precipitation and temperature data of nine GCMs and two RCPs (RCP 4.5 and RCP 8.5) as input for InVEST. RCP 4.5 is a moderate climate scenario which features a stabilization of greenhouse gas concentration by the year 2070 [181]. RCP 8.5 is a high emission scenario leading to an increase of 4 °C in global mean temperature by the end of the century in comparison to the pre-industrial era [182]. The GCMs were chosen based on their regional performance [17] according to the selection criteria of McSweeney et al. [183]. The output of the following GCMs was used: ACCESS1.0 [184,185], BCC_CSM1.1 [186], CCSM4 [187], GFDL CM3 [188], HadGEM2-ES [189], IPSL-CM5A-LR [190], MRI-CGCM3 [191], MPI-ESM-LR [192], and NorESM1-M [193]. Both temperature and precipitation datasets were obtained online at the "Climate Change Agriculture and Food Security-GCM Downscaled Data Portal" [194]. The geo-datasets were downloaded in ASCII-format and feature a horizontal resolution of roughly 900x900 m at the latitude of Xishuangbanna. We used ArcGIS (Version 10.3.1, [195]) to clip the geo-datasets to the extent of our study area, convert them to TIFF-format and project the data from "GCS_WGS_1984" to "WGS_1984_UTM_zone_47N" in order to match the grid of the rest of our spatial input data. The data is structured in three time slices centered around 2030 (2020–2040), 2050 (2040–2060) and 2070 (2060–2080) and includes annual average precipitation as well as monthly minimum, mean, and maximum temperature. Figure 4.1 depicts annual mean temperature (a) and annual precipitation (b) averaged over Nabanhe Reserve from the nine GCMs as well as baseline temperature and precipitation (WorldClim v1.4).



(**a**) (**b**)

Figure 4.1. Annual mean temperature (**a**) and annual precipitation (**b**) in Nabanhe Reserve for two Representative Concentration Pathways (RCP 4.5 and RCP 8.5 of IPCC5) derived from 9 General Circulation Models (GCMs) for the time slices of 2030 (20-year average from 2020–2040), 2050 (20-year average from 2040–2060) and 2070 (20-year average from 2060–2080). Boxes and whiskers show the 25/75 and 10/90 percentiles respectively. Lines in boxes show the ensemble median, whereas crosses show the ensemble mean. The dotted lines show long term annual average precipitation and long term annual mean temperature used as a baseline (WorldClim v1.4. [96,180]).

In addition to annual precipitation, InVEST requires annual potential evapotranspiration (PET_a) as a spatially explicit input layer. In order to calculate PET_a (mm/year) for each time slice of the climate change scenarios we used the output of the GCMs for monthly mean temperature (T_{mean} in °C) and daily temperature range (TD in °C, maximum temperature − minimum temperature). Extraterrestrial radiation (RA, radiation at the top of the atmosphere in mm/month as equivalent of evaporation) was obtained online from the "CGIAR-CSI Global Aridity and PET Database" [133,196,197]. We did not assume changes in RA during the course of the climate scenarios, so the geo-dataset of RA remained constant for each time slice. We used Hargreaves method [198] to calculate PET_m (mm/month):

$$PET_m = 0.0023 \times RA \times (T_{mean} + 17.8) \times TD^{0.5}. \quad (1)$$

We calculated PET_a by summing each cell of the monthly PET layers:

$$PET_a = \sum_{m=1}^{12} PET_m. \quad (2)$$

Hargreaves method [198] was chosen in order to keep consistency with previous InVEST applications in Nabanhe Reserve [48,135], where the InVEST water yield model was fitted to baseline PET_a data derived with the same methodology [133].

4.2.3 Land Use Change Scenarios

The implemented land use scenarios have been developed in the 5-year project SURUMER (Sustainable Rubber Cultivation in the Mekong Region) [152]. The aim of SURUMER was to develop stakeholder-validated land use and land management strategies to improve the sustainability of rubber production systems in Yunnan province. Stakeholders participating in the scenario development process included village heads and innovative farmers, prefecture administration, and local politicians [79,80]. Stakeholder workshops were held between January 2013 and October 2016 and were generally structured around presentations by SURUMER researchers, followed by interactive discussions. Scenario storylines were developed based on past land use changes and their perceived effects on the environment, local policy plans, and at a later stage, best practice recommendations based on preliminary results of field campaigns. Detailed information on the scenario development process can be found in Thellmann et al. [48] and Aenis & Wang [80]. Here, we focus on the implemented land use and land management rules leading to the land use maps we used as input for the modeling procedure with InVEST. The scenario outlines and maps were presented during the stakeholder workshops in order to confirm the viability of the introduced land use changes (e.g., spatial extent, property rights, land use restrictions) and the feasibility of management practices (e.g., weed management). The initial land use map of Nabanhe Reserve (2015) and the scenario maps resulting from the stakeholder participation process are depicted in Figure 4.2.

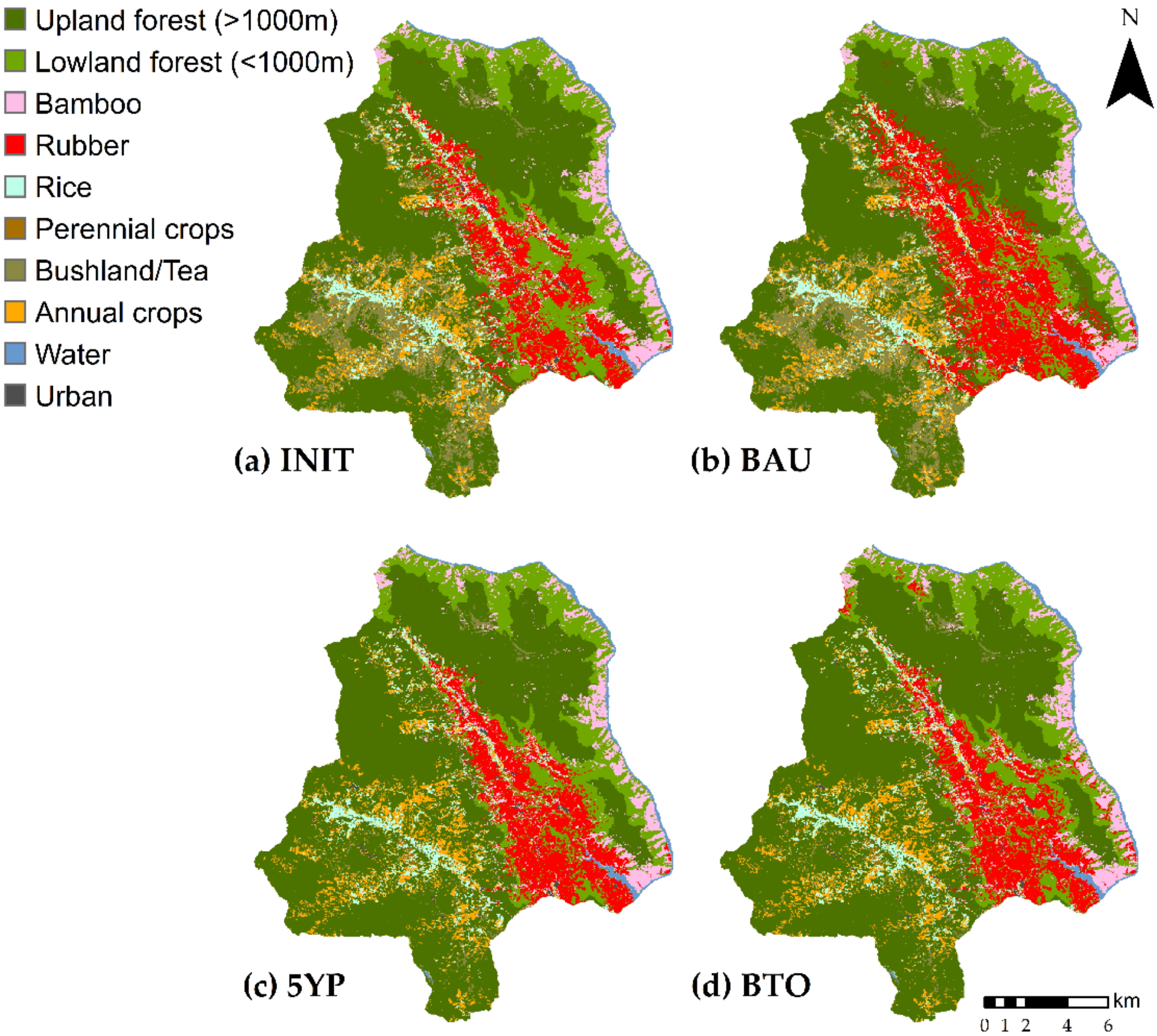


Figure 4.2. Land use maps of Nabanhe Reserve; the initial condition in 2015 (**a**), the Business-As-Usual scenario in 2040 (**b**), based on linear extrapolation of past rubber expansion rates, the 5-Years-Plan scenario in 2040 (**c**), based on province-level policy land use guidelines, and the Balanced-Trade-Offs scenario in 2040 (**d**), based on the 5-Years-Plan and additional measures such as water protection zones and riparian buffer zones. Maps are taken from Thellmann et al. [48].

Land use as of 2015 was derived from Rapid Eye satellite imagery and serves as the initial condition for the InVEST models, as well as the baseline for three land use scenarios developed in the SURUMER project: (1) The Business-As-Usual (BAU) scenario features the unrestricted expansion of rubber plantations based on past expansion rates in the region [59,82]. This translates to an extension of 2% per year in relation to the area occupied by rubber in the previous year, which is targeted at lowland forest areas, and during the course of the scenario, upland forest areas. (2) The 5-Years-Plan (5YP) scenario is based on a local government plan [83]. It includes measures to reduce erosion and keep rubber plantations at suitable production locations only. These measures include the reforestation of bushland areas in the uplands and no further establishment of rubber plantations above 900 m.a.s.l. or on steep slopes (>23°). (3) The Balanced-Trade-Offs (BTO) scenario includes all measures featured in the 5YP scenario, but expands them based on the recommended land use and land management options developed by SURUMER. These recommendations include water protection zones around water sources and buffer strips along the two main streams (Mandian and Naban River) in Nabanhe Reserve. Both measures include the reforestation of degraded areas into secondary forest areas to trap sediments, nutrients, and pesticides in order to improve water quality. The land use scenarios have been set to end in 2040, as we think that any further land use change would be unreasonable to predict by a rule-based mechanism. Table 4.1 shows the percent coverage of land use categories for the initial condition of 2015 and the three land use scenarios.

Table 4.1. Percent coverage of land use categories in Nabanhe Reserve (271 km^2) for each scenario derived from Thellmann et al. [48].

Land Use Category	Coverage (%)			
	Initial Condition 2015 (INIT)	Business-as-Usual 2040 (BAU)	5-Years-Plan 2040 (5YP)	Balanced-Trade-Offs 2040 (BTO)
Upland forest [1]	45.9	43.7	55.3	55.7
Lowland forest [1]	15.4	12.6	13.5	13.4
Bamboo	5.8	5.0	5.8	5.8
Rubber	9.4	15.2	10.4	10.5
Rice	4.1	4.1	4.1	4.1
Perennial crops	1.1	1.1	1.1	1.1
Bushland/tea [2]	8.8	10.9	2.3	1.9
Annual crops	5.8	5.8	5.8	5.8
Water	1.3	1.3	1.3	1.3
Urban	0.4	0.4	0.4	0.4

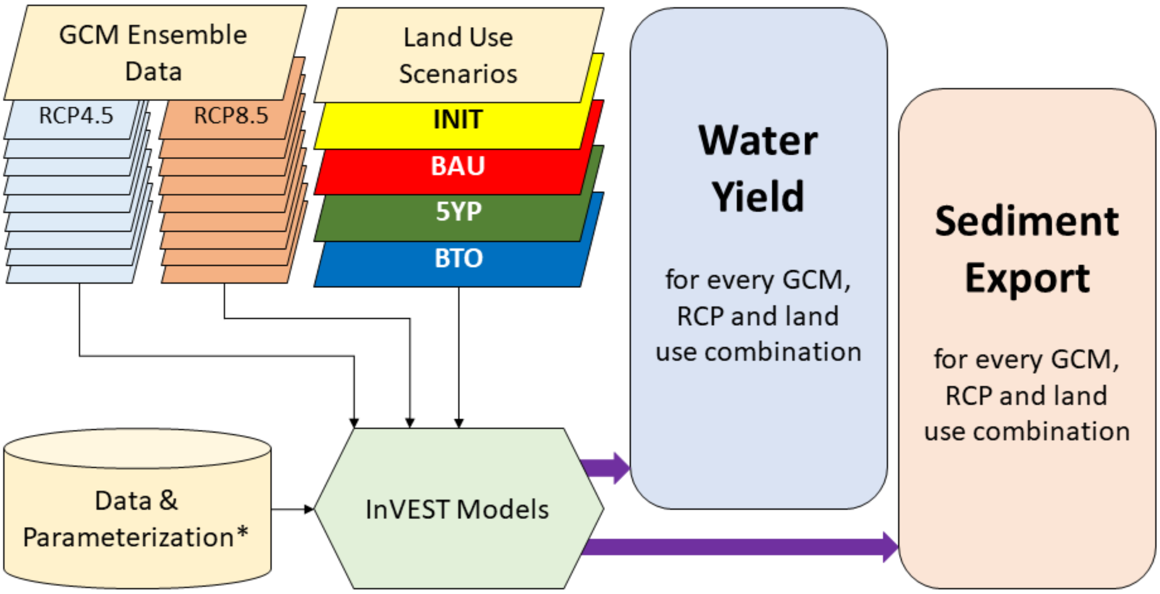
[1] The categories "Lowland forest" and "Upland forest" were split according to their altitudinal location in the landscape (below/above 1000 m.a.s.l.). [2] The categories "Bushland" and "Tea plantations" were merged into one category as their spectral signatures were too similar to distinguish between the two in the land cover mapping process. Coverage values might not add up to 100% due to rounding.

4.2.4 Modeling Framework

Erosion and water quantity were among the most relevant topics for the stakeholders in the SURUMER project [153]. We used InVEST (Version 3.3.3, The Natural Capital Project, Stanford University, USA, [44]) to model water yield and sediment export under the land use and climate change scenarios outlined in the previous sections. InVEST is a well-established modeling framework, which has been applied all around the globe [48,90,97,134,135,178,199]. The water yield model is based on the Budyko curve [200] and estimates annual water yield based on spatially explicit input data of annual average precipitation, annual potential evapotranspiration, root restricting layer depth, plant available water content, as well as rooting depths and evapotranspiration coefficients for each land use category. The sediment export model is based on the widely used USLE (Universal Soil Loss Equation) [91] and uses spatially explicit inputs such as a digital elevation model, annual rainfall erosivity, soil erodibility, as well as cover-management and support practice factors for every land use category. We refer to the InVEST user's guide [44] for detailed descriptions of the biophysical relationships realized in the water yield and sediment export models. Details on model parameterization, application, and sensitivity analysis are given in Thellmann et al. [48]. Both the water yield and sediment export model were fitted to run-off and erosion field measurements in a sub-watershed in Nabanhe Reserve and then extrapolated to watershed scale [48,201].

Instead of using the stand-alone version of InVEST, we made use of InVEST in Python 2.7 in order to facilitate input data management and calculations using batch processing. Model outputs (TIFF-files) were exported to R Studio (Version 1.0.136, R Foundation for Statistical Computing, Vienna, Austria, [202]). We used the R library 'raster' to calculate spatial statistics. We applied two-tailed, paired Student's *t*-tests in order to test if there are significant differences in the water yield, evapotranspiration, or sediment export results between (1) the land use scenarios, (2) the time slices of the climate scenarios, and (3) the two RCPs. We used ArcGIS (Version 10.3.1, Environmental

Systems Research Institute, Redlands, CA, USA, [195]) and the R library 'rasterVis' to visualize spatially explicit results and OriginPro 2017 (Version b9.4.1.354, OriginLab Corporation, Northampton, MA, USA, [203]) to create plots of ensemble results. Scheme 1 provides a comprehensive overview of the modeling methodology.



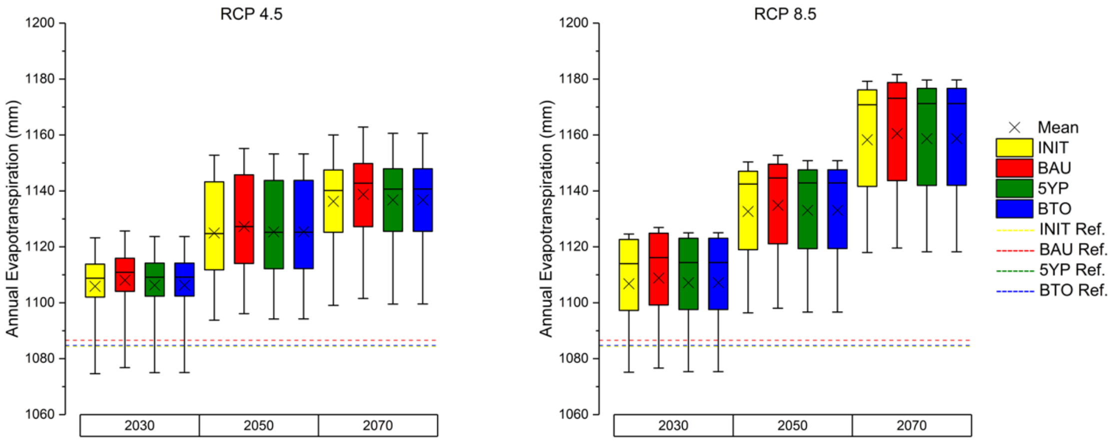
Scheme 4.1. Comprehensive scheme of the modeling methodology used in this study. Model inputs are depicted as black arrows. Model outputs are depicted as purple arrows. * Data & parameterization is based on Thellmann et al. [48].

4.3. Results

The following sections focus on InVEST results for water yield (3.1) and sediment export (3.2) averaged across all cells of the entire Nabanhe Reserve. Due to the large amount of data, spatial statistics and comparisons between the scenarios and baseline conditions are given in the supplementary material (Figures S4.1–S4.18). Total water yield and total sediment export results in Nabanhe Reserve for every climate and land use scenario as well as percentage comparisons to baseline climate and land use conditions are listed in Table S4.1.

4.3.1 Evapotranspiration and Water Yield

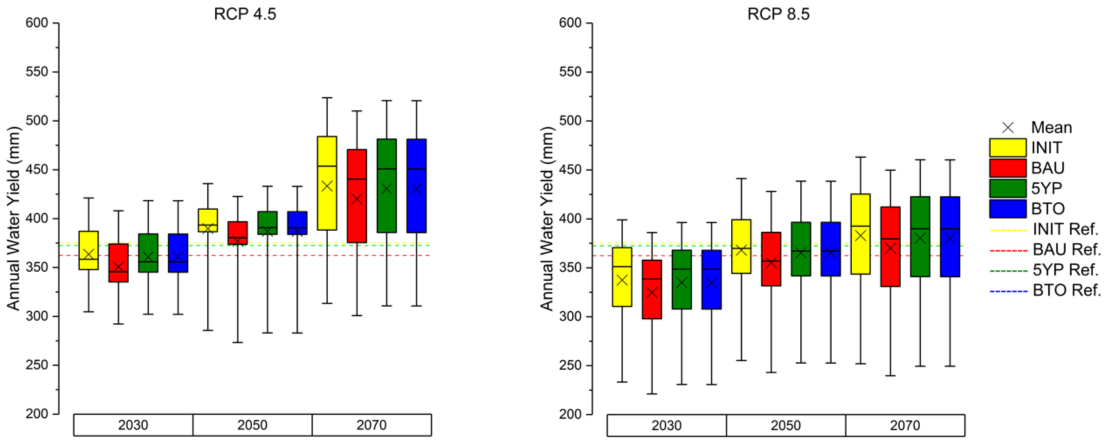
In Figure 4.3, evapotranspiration simulation results are shown as an average across all cells in the study area to make comparisons between the scenarios easier. We observed an increasing trend in evapotranspiration during the course of both RCP scenarios, with higher evapotranspiration values in RCP 8.5. However, only the evapotranspiration results in 2070 were significantly different when comparing RCP 4.5 and RCP 8.5 (Table S4.4). Evapotranspiration in RCP 8.5 was skewed towards the higher values, with differences between median, 75 and 90 percentile ensemble values being in the range of tens of millimeters. For all time slices and RCP scenarios, evapotranspiration values for the BAU scenario were higher than in the other land use scenarios. Generally, the differences between the land use scenarios were minor in comparison to the large differences between the time slices (all with $p < 0.5$).



(a) (b)

Figure 4.3. Annual average evapotranspiration in Nabanhe Reserve calculated with InVEST and ensemble data (9 GCMs) of two Representative Concentration Pathways (RCP 4.5 (**a**) and RCP 8.5 (**b**) of the Fifth Assessment Report of the IPCC) for the time slices of 2030 (20-year average from 2020–2040), 2050 (20-year average from 2040–2060) and 2070 (20-year average from 2060–2080). Boxes and whiskers show the 25/75 and 10/90 percentiles respectively. Lines in boxes show the ensemble median, whereas crosses show the ensemble mean. Colors represent land use conditions: Initial case of 2015 (INIT, yellow), Business-As-Usual scenario (BAU, red), 5-years-plan scenario (5YP, green), Balanced-Trade-Offs scenario (BTO, blue). The dotted lines show annual average evapotranspiration calculated with long-term annual average climate data as a baseline (WorldClim v1.4. [96,180]).

Water yield results were averaged across all cells in the study area in Figure 4.4. The simulated water yield for the baseline climate data and the initial land use was about 375 mm in Nabanhe Reserve. Differences between the initial land use and both 5YP and BTO were only ±1% at watershed scale for each climate condition ($p < 0.5$). On the other hand, the model results indicate a lower water yield ranging from −3.3% to −4.1% (depending on the climate condition) in BAU, when compared to the simulated water yield for the initial land use condition ($p < 0.5$). Both the median and the mean ensemble results of water yield for time slice 2030 in RCP 4.5 were lower in comparison to the baseline climate. This was due to increasing temperatures, which lead to higher potential evapotranspiration (Figure 4.3). As the mean and median precipitation values in the ensemble input data remained at the same level as the baseline climate data (Figure 4.1), the higher evapotranspiration leads to a reduction in simulated water yield in 2030 for both RCP 4.5 and RCP 8.5. An increasing trend for precipitation in 2050 and 2070 increased projected water yield also in RCP 4.5. Baseline evapotranspiration values (Figure 4.3) were in the same range as precipitation input (Figure 4.2). A two-tailed, paired Student’s *t*-test revealed no significant differences ($p > 0.5$) in water yield when comparing RCP 4.5 and RCP 8.5 (Table S4.2). Upland areas, which received the highest amount of precipitation and had lower potential evapotranspiration, contributed the largest share to the annual water yield in Nabanhe Reserve (Figure S4.1).

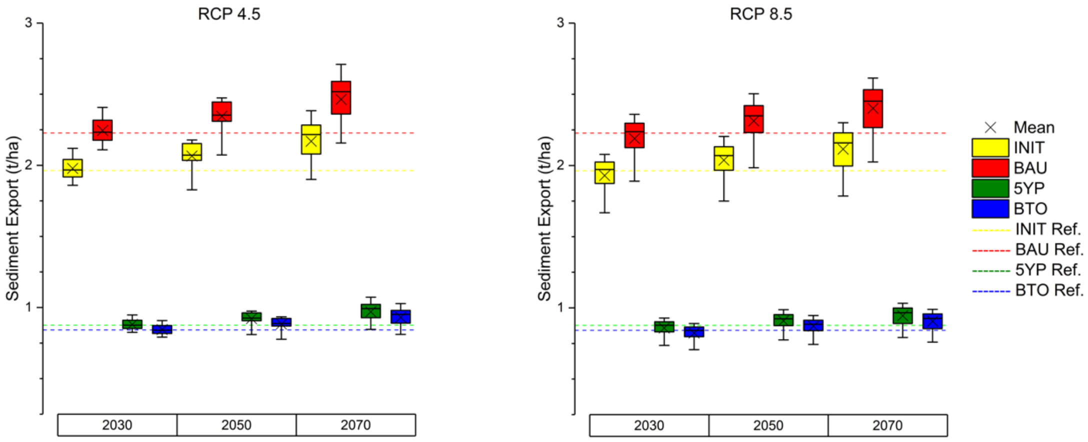


(**a**) (**b**)

Figure 4.4. Annual average water yield in Nabanhe Reserve calculated with InVEST using ensemble data (9 GCMs) of two Representative Concentration Pathways (RCP 4.5 (**a**) and RCP 8.5 (**b**) of the Fifth Assessment Report of the IPCC) for the time slices of 2030 (20-year average from 2020–2040), 2050 (20-year average from 2040–2060) and 2070 (20-year average from 2060–2080). Boxes and whiskers show the 25/75 and 10/90 percentiles respectively. Lines in boxes show the ensemble median, whereas crosses show the ensemble mean. Colors represent land use conditions: Initial case of 2015 (INIT, yellow), Business-As-Usual scenario (BAU, red), 5-years-plan scenario (5YP, green), Balanced-Trade-Offs scenario (BTO, blue). The dotted lines show annual average water yield calculated with long term annual average climate data as a baseline (WorldClim v1.4. [96,180]).

4.3.2. Sediment Export

Simulated sediment export for the baseline climate and land use was about 2 tons per hectare and year in Nabanhe Reserve. Sediment export averaged across all rubber plantation cells accounted for 1.38 t/ha for the initial land use and baseline climate (Figure S4.19). Land use categories with the highest amount of mean sediment export were annual agriculture (10.7 t/ha), bushland and tea plantations (8.5 t/ha), rice (3.6 t/ha), and perennial crops (3.2 t/ha) (Figure S4.19). In general, the simulation results indicate increases in sediment export from 2030 to 2070 for all land use scenarios in both RCPs (Figure 4.5). This is due to the increased amounts of precipitation in both RCP 4.5 and RCP 8.5. However, in RCP 4.5, only comparisons between 2030 and 2070 yield significantly different results (Table S4.6). For every land use scenario, sediment export results in RCP 4.5 were about 2.5% (2030), 0.9% (2050), and 1.6% (2070) higher in comparison to RCP 8.5. However, these differences were not statistically significant ($p > 0.5$) (Table S4.6). Unlike the results for water yield and evapotranspiration, the differences between the land use scenarios for sediment export were more pronounced as compared to the differences between the RCPs and time slices. In comparison to the initial condition of 2015, the model results indicate increased sediment export in BAU (up to 0.48 t/ha) and reductions for both 5YP and BTO (more than 1 t/ha) ($p < 0.5$). The results indicate that the reforestation measures and water protection zoning in the 5YP and BTO scenario slightly increased the sediment retention capacity of the landscape, as sediment from agricultural land use categories is more likely to be trapped by patches of natural vegetation in the down-slope sediment retention path in these scenarios (Figure S4.10 and Figure S4.19). On the other hand, increased sediment export in BAU was mainly due to the expansion of rubber plantations at higher altitudes and steeper slopes (Figure S4.10 and Figure S4.19).



(**a**) (**b**)

Figure 4.5. Annual average sediment export in Nabanhe Reserve calculated with InVEST using ensemble precipitation data (9 GCMs) of two Representative Concentration Pathways (RCP 4.5 (**a**) and RCP 8.5 (**b**) of IPCC5) for the time slices of 2030 (20-year average from 2020–2040), 2050 (20-year average from 2040–2060) and 2070 (20-year average from 2060–2080). Boxes and whiskers show the 25/75 and 10/90 percentiles respectively. Lines in boxes show the ensemble median, whereas crosses show the ensemble mean. Colors represent land use conditions: Initial case of 2015 (INIT, yellow), Business-As-Usual scenario (BAU, red), 5-years-plan scenario (5YP, green), Balanced-Trade-Offs scenario (BTO, blue). The dotted lines shows annual average sediment export calculated with long-term precipitation data as a baseline (WorldClim v1.4. [96,180]).

4.4. Discussion

4.4.1 Climate Change Impacts

If one considers the climate change scenarios alone (using the initial land use data (INIT)), the model results indicate that both annual water yield and annual sediment export in Nabanhe Reserve are likely to increase with climate change by 2070 ($p < 0.5$). These results are in accordance with similar studies in Asia [178,204,205], which showed comparable increases in simulated water yield and sediment export under climate change scenarios. We expected to see significant differences between RCP 4.5 and RCP 8.5, however, with the exception of evapotranspiration results for the 2070 time slice, this was not the case. We conclude that the large difference in annual mean temperature in Nabanhe Reserve in the 2070 time slice (Figure 4.1a) is the main reason why only the evapotranspiration results for this time slice show a significant difference. Based on Figure 4.1b we conclude that the differences in annual precipitation between RCP 4.5 and RCP 8.5 are not large enough to lead to significant differences in both water yield and sediment export.

Our results for Nabanhe Reserve revealed higher percentage increases in water yield in the lowlands as a result of climate change as compared to more complex changes in the uplands (Figures S4.2–S4.9). Simulated water yield in the uplands was reduced (2030), relatively equal (2050), and slightly higher (2070) as compared to the baseline climate. This trend held true for both RCP 4.5 and RCP 8.5, albeit with smaller increases of water yield in the lowlands and larger decreases in the uplands for RCP 8.5. Hoyer & Chang [97] found that water yield estimates are especially sensitive to climate change in the lowlands, while sediment export is projected to increase under the higher erosivity from increased rainfall amounts. Bajracharya et al. [204] found that increases in temperature and precipitation show synergistic effects under climate change and increased water yield by over 50% at the outlet of the Kaligandaki basin of Nepal. We found the highest increase (~15%) in water yield in RCP 4.5 for the initial land use in Nabanhe Reserve. In Bajracharya et al. [204], glacier melt played an additional role in the local hydrology. As there are no glaciers in Nabanhe Reserve, effects of temperature increases throughout the next century will not be as severe as in other mountainous watersheds, e.g., the Kaligandaki basin in Nepal. In a watershed in southern Thailand, which is comparable in land use to Nabanhe Reserve, Trisurat et al. [178] showed that changes in rainfall (extreme value scenarios) exerted a stronger influence on water yield, but also on erosion and sediment export as compared to the effects of land use changes. However, the range of annual precipitation used as input for InVEST in Trisurat et al. [178] was also significantly larger (1980–3838 mm/year) than in this study.

Many studies on the impacts of climate change on water yield consider only changes in precipitation, but do not include changes in potential evapotranspiration (e.g., [97,178]). Our results also show significant increases in potential evapotranspiration as we approach the end of the century. As precipitation also increases, annual water yield in Nabanhe Reserve will be higher as compared to the baseline conditions at the end of the simulation. However, in both RCP 4.5 and RCP 8.5, the increases in temperature and evapotranspiration lead to a reduction of water yield in 2030. This reduction was most severe in RCP 8.5, with a reduction of annual water yield of more than 10% for every land use scenario. We can extrapolate that particularly dry years may have a more pronounced effect on the water balance in the future as the higher potential evapotranspiration increases the probability for periods of water scarcity, especially in the dry seasons.

4.4.2 Land Use Change and Management Implications

The land use scenarios we have analyzed are based on an intensive stakeholder dialogue and represent a transdisciplinary work effort by rubber farmers, policy-makers and scientists alike. During the workshops, stakeholders expressed that the current situation of rubber cultivation is difficult to change for the following reasons: (1) In comparison to other cash crops, there is still a relatively high price to be gained for rubber; (2) No more land is available for the cultivation of other crops; (3) Farmers have invested in their plantations and are hesitant to replace them before the end of the economic life cycle; (4) Farmers know how to manage rubber plantations and lack experience with other crops; (5) Farmers want to continue growing rubber, even under less than optimal market and environmental conditions [201].

Most of the areas in Nabanhe Reserve featuring optimal growth conditions for rubber were already occupied with rubber plantations at the initial year of the simulations (2015). Therefore, the extension of rubber plantations (from 9.2% to 15.2% of Nabanhe Reserve) in the BAU scenario is mostly targeted at locations above 900 m.a.s.l., of which a large part is also characterized by steep slopes (>23°). For the BAU scenario, our results revealed the highest water yield reductions and also the highest sediment export for all simulated climate conditions. Rubber expansions on high altitudes and steep slopes should, therefore, be prevented. During the workshops, stakeholders critically commented further rubber expansions as they saw them as rather unlikely, due to the aforementioned reasons [201]. Nevertheless, the trend of rubber expansions into higher altitudes and steep slopes has been observed all over Xishuangbanna [15]. As in other watersheds [136,206], upland areas have the highest water regulation capacity. Therefore, these should be targeted for protection [206]. Reforesting and protecting these areas were the main aims of both the 5YP and BTO scenario. The BTO scenario featured the highest sediment retention capacity with the implementation of riverine buffer strips, water protection zones and reduced herbicide application in rubber plantations. However, in comparison to the 5YP scenario, the additional benefits of these measures were very small (roughly 0.03 t/ha), as upland reforestation alone significantly reduced exported sediments (roughly 1 t/ha).

Further research should be aimed at cost-benefit analysis and at assessing the effect of these measures on water quality (e.g., fertilizer and pesticide residues). Additional benefits of the BTO scenario in comparison to the 5YP such as improved habitat quality and rubber yields have been shown in other studies [12,48], albeit without the integration of climate change impacts. The land management measures of the BTO scenario have been met with higher approval rates by the stakeholders in comparison to the other two scenarios [201]. Water protection was expressed to be of utmost importance by the stakeholders, as they already experienced the reduction of available drinking water resources [201].

Rubber cultivation provides on average over 40% of smallholder incomes in Xishuangbanna, so household incomes are at risk due to reduced diversification and the dependence on market prices [156]. The reforestation measures as described in BTO (and 5YP to a lesser degree) are unlikely to be adopted by farmers without any economic incentives. Although stakeholders were generally positive about the assumptions in both 5YP and BTO, they were also doubtful about their implementation [201]. Suggestions to completely dispense with weed control measures have been met with disapproval by the farmers, as it reduces tree accessibility for tapping and increases the probability to encounter poisonous caterpillars [207]. Intercropping (with e.g., maize or tea), as a measure to reduce erosion, was discussed controversially during the stakeholder workshops [201]. So far, intercropping methods for rubber plantations have only shown low adoption rates by local farmers, even though these methods are encouraged by the government and have the potential to improve sediment retention and diversify household income sources [208].

4.4.3 Uncertainties and Limitations of the Study

InVEST has been developed as a policy support tool to enable researchers and practitioners to assess the impact of land use planning decisions on ESS. Compared to other, more specialized hydrological models (e.g., SWAT), InVEST represents bio-physical processes in a simplified manner. The choice of this model may not seem ideal for assessing the impact of climate change on hydrological ESS. However, more sophisticated models are much more demanding with regard to the temporal resolution of input data (e.g., daily resolution for SWAT), which makes them less compatible with freely available GCM data. As InVEST was designed to work with long-term average input data, we argue that it is a suitable choice for comparing the impacts of long-term changes in climatic variables on ESS.

Many hydrological ESS modeling studies rely on one or few precipitation and temperature datasets as input, particularly in tropical regions where hydro-meteorological data are often scarce. This makes conclusions about the absolute amount of available water highly dependent on the selected input data [209]. In cases of data scarcity, van Soesbergen & Mulligan [209] suggest percentage comparisons to baseline conditions as an alternative to assess future adaptation options. Shrestha et al. [175] emphasized the need for multi-climate model evaluations of future hydrological conditions for climate change adaptation and sediment management. We included an ensemble of climate datasets derived from nine GCMs in order to define an uncertainty envelope for the hydrological ESS model results (Figure 4.3–4.5) and provided percentage comparisons to baseline conditions (Table S4.1). For the selection of climate data, McSweeney et al. [183] recommended to retain a subset of 8–10 GCMs in order to ensure plausible dispersion while avoiding the least realistic model predictions for a particular study region. As expected, large uncertainties exist in all of the hydrological variables due to the differences in the climate model projections. The spread in the results of water yield (and precipitation input) is generally larger at higher altitudes in Nabanhe Reserve. These areas are also the source of the largest quantities of run-off (Figures S4.1–S4.9). These results are not particular for Nabanhe

Reserve, but have also been assessed in other basins spanning steep gradients in elevation [114,210]. Uncertainties in the results for sediment export are highest in the down-slope sediment retention pathways (Figures S4.11–S4.18). Uncertainties stem from the different assumptions and parameterizations of the GCMs, but also from downscaling temperature and precipitation datasets to a finer resolution.

As the InVEST water yield model works on an annual basis, it is not able to capture intra-annual variability of temperature, precipitation, and evapotranspiration patterns. This is most likely the greatest limitation of our approach, as annual evapotranspiration from rubber trees has been linked with high late dry season water use from rapid refoliation after leaf flush as well as very high wet season evapotranspiration [112]. The same limitation also applies to the sediment export model, as the timing and the amount of daily precipitation intensity also have a large influence on potential erosion [205]. Furthermore, the InVEST water yield model is limited in its representation of plant physiology. An increased intra-annual resolution would open up the possibility to include more phenological variables (e.g., vapor pressure deficit, leaf area or photoperiod) in order to improve how the transpiration of plants is represented in the water yield model. Combined with the available monthly GCM data, this would allow for predictions of water availability in regard to seasonal highs and lows, which in turn would be more beneficial for watershed management than our current approach. Similar benefits would apply to weed management in rubber plantations, as the timing and frequency of herbicide application in rubber plantations has been shown to be highly influential in rubber plantations [207]. Future modeling efforts including improved plant physiology, intra-annual or seasonal variability and extreme wet/dry climate conditions are needed to shed more light on temporal patterns of water provisioning and sedimentation in Nabanhe Reserve.

4.5 Conclusions

Should the expansion of rubber plantations in Nabanhe Reserve continue, the increases in sediment export will be amplified further under the wetter and warmer climate. In addition, we conclude that the effects of land use and land management decisions on water yield in Nabanhe Reserve are relatively minor when compared to the effects that future climate change will exert on water yield. Our results can contribute to an effective management of erosion and sedimentation in Nabanhe Reserve and provide useful insights for future water availability and sediment export under the effects of climate change in the watershed. The method we applied can easily be transferred to other regions facing comparable land use situations, as InVEST and the IPCC5 data are freely available. Furthermore, up-scaling our methodology to larger areas could be beneficial for hydro-power planning in the area [211,212], as it includes information about annual water and sediment volumes under the effect of climate change.

Supplementary Materials: The following are available online at http://www.mdpi.com/1999-4907/10/2/176/s1, Figure S4.1: Water yield results for every land use scenario and the baseline climate data. INIT: Initial land use in 2015, BAU: Business-As-Usual, 5YP: 5-Years-Plan, BTO: Balanced-Trade-Offs, Figure S4.2: Water yield and standard deviation results in Nabanhe Reserve for the initial land use in 2015 (INIT) under RCP 4.5 climate data, Figure S4.3: Water yield and standard deviation results in Nabanhe Reserve for the initial land use in 2015 (INIT) under RCP 8.5 climate data, Figure S4.4: Water yield and standard deviation results in Nabanhe Reserve for the Business-As-Usual scenario (BAU) under RCP 4.5 climate data, Figure S4.5: Water yield and standard deviation results in Nabanhe Reserve for the Business-As-Usual scenario (BAU) under RCP 8.5 climate data, Figure S4.6: Water yield and standard deviation results in Nabanhe Reserve for the 5-Years-Plan scenario (5YP) under RCP 4.5 climate data, Figure S4.7: Water yield and standard deviation results in Nabanhe Reserve for the 5-Years-Plan scenario (5YP) under RCP 8.5 climate data, Figure S4.8: Water yield and standard deviation results in Nabanhe Reserve for the Balanced-Trade-Offs scenario (BTO) under RCP 4.5 climate data, Figure S4.9: Water yield and standard deviation results in Nabanhe Reserve for the Balanced-Trade-Offs scenario (BTO) under RCP 8.5 climate data, Figure S4.10: Sediment export results for every land use scenario and the baseline climate data. INIT: Initial land use in 2015, BAU: Business-As-Usual, 5YP: 5-Years-Plan, BTO: Balanced-Trade-Offs, Figure S4.11: Sediment export and standard deviation results in Nabanhe Reserve for the initial land use (INIT) under RCP 4.5 climate data, Figure S4.12: Sediment export and standard deviation results in Nabanhe Reserve for the initial land use (INIT) under RCP 8.5 climate data, Figure S4.13: Sediment export and standard deviation results in Nabanhe Reserve for the Business-As-Usual scenario (BAU) under RCP 4.5 climate data, Figure S4.14: Sediment export and standard deviation results in Nabanhe Reserve for the Business-As-Usual scenario (BAU) under RCP 8.5 climate data, Figure S4.15: Sediment export and standard deviation results in Nabanhe Reserve for the 5-Years-Plan scenario (5YP) under RCP 4.5 climate data, Figure S4.16: Sediment export and standard deviation results in Nabanhe Reserve for the 5-Years-Plan scenario (5YP) under RCP 8.5 climate data, Figure S4.17: Sediment export and standard deviation results in Nabanhe Reserve for the Balanced-Trade-Offs scenario (BTO) under RCP 4.5 climate data, Figure S4.18: Sediment export and standard deviation results in Nabanhe Reserve for the Balanced-Trade-Offs scenario (BTO) under RCP 8.5 climate data, Figure S4.19: Sediment export averaged over every land use category in Nabanhe Reserve for the initial land use (INIT) and baseline climate. We calculated these values by summing the sediment export amounts from each land use category and divided them by the areal extent of the respective land use category in Nabanhe Reserve, Table S4.1: Total water yield and total sediment export in Nabanhe Reserve estimated by InVEST for all climate and land use scenarios as well as percentage comparisons to the baseline climate and land use conditions. Table S4.2: Simulation results of the InVEST water yield model for the land use scenarios and each General Circulation Model (GCM) in Nabanhe Reserve, Table S4.3: Results of a two-tailed, paired Student's *t*-test to determine significant differences between water yield model results. Green values indicate significant differences ($p < 0.05$), red values indicate no significant difference ($p > 0.05$), Table S4.4: Simulation results for evapotranspiration for the land use scenarios and each GCM in Nabanhe Reserve, Table S4.5: Results of a two-tailed, paired Student's t-test to determine significant differences between evapotranspiration model results. Green values indicate significant differences ($p < 0.05$), red values indicate no significant difference ($p > 0.05$), Table S4.6: Simulation results for sediment export for the land use scenarios and each GCM in Nabanhe Reserve, Table S4.7: Results of a two-tailed, paired Student's t-test to determine significant differences between sediment export model results. Green values indicate significant differences ($p < 0.05$), red values indicate no significant difference ($p > 0.05$).

Author Contributions: Conceptualization, K.T. and M.C.; methodology, K.T., R.G., and M.C.; software, K.T.; validation, K.T.; formal analysis, K.T.; investigation, K.T.; resources, G.C. and F.A.; data curation, K.T. and R.G.; writing-original draft preparation, K.T.; writing-review and editing, K.T., M.C., G.C., F.A.; visualization, K.T.; supervision, M.C., G.C. and F.A.; project administration, M.C., G.C. and F.A.; funding acquisition, K.T., M.C., G.C. and F.A.

Funding: This research was funded by the German Federal Ministry of Education and Research (BMBF), grant number FKZ 01LL0919, FKZ 16PGF0105 and by Deutsche Forschungsgemeinschaft CO 1864/2-1. We greatly acknowledge the financial support of the “Water-People-Agriculture” Research Training Group funded by the Anton & Petra-Ehrmann-Stiftung.

Acknowledgments: Thank you to the SURUMER team for their support and collaboration. We would also like to thank the two anonymous reviewers for their comments and suggestions, which strengthened the quality of the paper substantially.

Conflicts of Interest: The authors declare no conflict of interest.

4.6. Supplementary Material

4.6.1 Total Water Yield and Total Sediment Export at Watershed Scale

Table S4.1. Total water yield and total sediment export in Nabanhe Reserve estimated by InVEST for all climate and land use scenarios as well as percentage comparisons to the baseline climate and land use conditions.

Climate	Land Use	Water Yield (km³)	Standard Deviation	Difference to Baseline (%)	Sediment Export (10^6 kg)	Standard Deviation	Difference to Baseline (%)
Baseline	INIT[1]	101.42	-	-	53.31	-	-
RCP 4.5 2030	INIT[1]	98.26	9.01	-3.12	53.72	2.08	0.76
	BAU[2]	94.45	8.97	-6.87	60.92	2.39	14.26
	5YP[3]	97.47	9.00	-3.89	23.91	0.98	-55.15
	BTO[4]	97.45	9.00	-3.92	22.93	0.94	-56.98
RCP 4.5 2050	INIT[1]	105.37	11.19	3.89	55.80	2.70	4.66
	BAU[2]	101.53	11.14	0.11	63.35	3.10	18.82
	5YP[3]	104.57	11.18	3.11	24.91	1.27	-53.28
	BTO[4]	104.55	11.18	3.08	23.88	1.22	-55.20
RCP 4.5 2070	INIT[1]	117.20	19.61	15.56	58.35	4.42	9.45
	BAU[2]	113.32	19.53	11.73	66.26	5.06	24.28
	5YP[3]	116.39	19.59	14.76	26.10	2.07	-51.04
	BTO[4]	116.36	19.59	14.73	25.03	1.98	-53.06
RCP 8.5 2030	INIT[1]	91.17	13.45	-10.11	52.39	3.43	-1.73
	BAU[2]	87.40	13.38	-13.82	59.44	3.92	11.50
	5YP[3]	90.39	13.44	-10.87	23.31	1.61	-56.29
	BTO[4]	90.37	13.43	-10.90	22.35	1.53	-58.07
RCP 8.5 2050	INIT[1]	99.47	13.95	-1.92	55.34	3.60	3.79
	BAU[2]	95.66	13.88	-5.68	62.81	4.12	17.82
	5YP[3]	98.68	13.93	-2.70	24.68	1.68	-53.70
	BTO[4]	98.66	13.93	-2.73	23.67	1.61	-55.61
RCP 8.5 2070	INIT[1]	103.51	17.02	2.06	57.44	4.33	7.73
	BAU[2]	99.68	16.94	-1.71	65.22	4.96	22.33
	5YP[3]	102.72	16.99	1.28	25.67	2.03	-51.85
	BTO[4]	102.69	16.99	1.25	24.61	1.94	-53.84

[1] INIT: Initial land use in the year 2015. [2] BAU: Business-As-Usual, further rubber expansion based on past expansion rates in the study area. [3] 5YP: 5-Years-Plan, restricted rubber expansion combined with reforestation of bushland areas, high altitude/steep-slope rubber plantations. [4] BTO: Balanced-Trade-Offs, includes all measures of 5YP and reduced herbicide application for rubber plantations, water source protection areas and riverine buffer zones.

When considering climate change impacts in isolation (INIT land use), the model outputs indicate increases in water yield and sediment export by 2070 for both RCPs (Table S4.1). Differences in water yield between the land use scenarios are small, whereas the differences in sediment export between land use scenarios are large. The model output indicates increased sediment export in BAU and decreased sediment export in 5YP and BTO. Uncertainties increase from 2030 to 2070. Uncertainties for sediment export were lower (3.8 – 7.9%) as compared to the uncertainties in the results for water yield (9.1 – 17.2%). Because of lower precipitation in RCP 8.5, the model suggests lower values for both water yield and sediment export in RCP 8.5 compared to RCP 4.5. Differences between the land use scenarios within each time slice all revealed significant differences (p<0.5). Detailed results of water yield, evapotranspiration, and sediment export for each GCM are provided in Table S4.1, Table S4.3 and Table S4.5.

4.6.2 Water Yield and Evapotranspiration

Table S4.2. Simulation results of the InVEST water yield model for the land use scenarios and each General Circulation Model (GCM) in Nabanhe Reserve.

	Water Yield (mm)											
	2030				2050				2070			
	INIT	BAU	5YP	BTO	INIT	BAU	5YP	BTO	INIT	BAU	5YP	BTO
ac 4.5	351	338	348	348	379	366	376	376	388	375	386	386
bc 4.5	348	335	345	345	395	382	393	393	484	471	481	481
cc 4.5	387	374	384	384	391	378	389	388	329	316	326	326
gf 4.5	305	292	302	302	410	397	407	407	518	504	515	515
he 4.5	401	388	398	398	436	423	433	433	454	440	451	451
ip 4.5	336	323	333	333	286	273	283	283	313	301	311	311
mg 4.5	366	353	363	363	387	374	384	384	468	454	465	465
mp 4.5	358	346	356	356	393	380	391	391	423	410	420	420
no 4.5	421	408	418	418	432	418	429	429	524	510	521	521
ac 8.5	310	298	308	308	370	357	367	367	360	347	357	357
bc 8.5	351	339	349	349	441	428	439	438	463	450	460	460
cc 8.5	399	386	396	396	388	375	385	385	425	412	423	422
gf 8.5	355	342	352	352	360	347	357	357	393	380	390	390
he8.5	317	305	315	315	344	332	342	342	340	327	337	337
ip 8.5	233	221	231	231	255	243	253	253	252	240	250	249
mg 8.5	304	291	301	301	336	323	333	333	344	331	341	341
mp 8.5	371	358	368	368	399	386	397	396	421	408	418	418
no 8.5	397	384	394	394	419	406	417	416	450	436	447	447

GCM abbreviations are as follows: ACCESS1.0 (ac), BCC_CSM1.1 (bc), CCSM4 (cc), GFDL CM3 (gf), HadGEM2-ES (he), IPSL-CM5A-LR (ip), MRI-CGCM3 (mg), MPI-ESM-LR (mp), NorESM1-M (no).

Table S4.3. Results of a two-tailed, paired Student's t-test to determine significant differences between water yield model results. Green values indicate significant differences (p<0.05), red values indicate no significant difference (p>0.05).

p-values, Scenario comparison			
RCP 4.5, 2030	BAU	5YP	BTO
INIT	0.000	0.000	0.000
BAU		0.000	0.000
5YP			0.000
RCP 4.5, 2050	BAU	5YP	BTO
INIT	0.000	0.000	0.000
BAU		0.000	0.000
5YP			0.000
RCP 4.5, 2070	BAU	5YP	BTO
INIT	0.000	0.000	0.000
BAU		0.000	0.000
5YP			0.000
RCP 8.5, 2030	BAU	5YP	BTO
INIT	0.000	0.000	0.000
BAU		0.000	0.000
5YP			0.000
RCP 8.5, 2050	BAU	5YP	BTO
INIT	0.000	0.000	0.000
BAU		0.000	0.000
5YP			0.000
RCP 8.5, 2070	BAU	5YP	BTO
INIT	0.000	0.000	0.000
BAU		0.000	0.000
5YP			0.000

p-values, Time slice comparison		
INIT 4.5	2050	2070
2030	0.091	0.033
2050		0.042
BAU 4.5	2050	2070
2030	0.091	0.033
2050		0.042
5YP 4.5	2050	2070
2030	0.091	0.033
2050		0.042
BTO 4.5	2050	2070
2030	0.091	0.033
2050		0.042
INIT 8.5	2050	2070
2030	0.014	0.001
2050		0.038
BAU 8.5	2050	2070
2030	0.014	0.001
2050		0.037
5YP 8.5	2050	2070
2030	0.014	0.001
2050		0.038
BTO 8.5	2050	2070
2030	0.014	0.001
2050		0.038

p-values, RCP comparison	
INIT 2030	0.158
INIT 2050	0.139
INIT 2070	0.068
BAU 2030	0.158
BAU 2050	0.139
BAU 2070	0.068
5YP 2030	0.158
5YP 2050	0.139
5YP 2070	0.068
BTO 2030	0.158
BTO 2050	0.139
BTO 2070	0.068

Table S4.4. Simulation results for evapotranspiration for the land use scenarios and each GCM in Nabanhe Reserve.

	Evapotranspiration (mm)											
	2030				2050				2070			
	INIT	BAU	5YP	BTO	INIT	BAU	5YP	BTO	INIT	BAU	5YP	BTO
ac 4.5	1,114	1,116	1,114	1,114	1,144	1,147	1,145	1,145	1,147	1,150	1,148	1,148
bc 4.5	1,109	1,111	1,109	1,109	1,124	1,127	1,125	1,125	1,146	1,149	1,147	1,147
cc 4.5	1,117	1,119	1,117	1,117	1,125	1,127	1,126	1,126	1,125	1,127	1,126	1,126
gf 4.5	1,103	1,104	1,103	1,103	1,153	1,155	1,153	1,153	1,156	1,159	1,157	1,157
he 4.5	1,110	1,113	1,111	1,111	1,125	1,127	1,125	1,125	1,140	1,143	1,141	1,141
ip 4.5	1,102	1,104	1,102	1,102	1,104	1,106	1,105	1,105	1,117	1,119	1,117	1,117
mg 4.5	1,101	1,103	1,101	1,101	1,112	1,114	1,112	1,112	1,135	1,138	1,136	1,136
mp 4.5	1,075	1,077	1,075	1,075	1,094	1,096	1,094	1,094	1,099	1,102	1,100	1,100
no 4.5	1,123	1,126	1,124	1,124	1,143	1,146	1,144	1,144	1,160	1,163	1,161	1,161
ac 8.5	1,104	1,106	1,105	1,105	1,146	1,148	1,146	1,146	1,165	1,167	1,165	1,165
bc 8.5	1,115	1,117	1,115	1,115	1,147	1,150	1,148	1,148	1,176	1,179	1,177	1,177
cc 8.5	1,125	1,127	1,125	1,125	1,142	1,144	1,143	1,143	1,173	1,176	1,174	1,174
gf 8.5	1,114	1,116	1,114	1,114	1,142	1,145	1,143	1,143	1,171	1,173	1,171	1,171
he8.5	1,097	1,099	1,098	1,098	1,119	1,121	1,119	1,119	1,142	1,144	1,142	1,142
ip 8.5	1,075	1,077	1,075	1,075	1,096	1,098	1,097	1,097	1,118	1,120	1,118	1,118
mg 8.5	1,084	1,086	1,084	1,084	1,103	1,105	1,103	1,103	1,124	1,126	1,125	1,125
mp 8.5	1,123	1,125	1,123	1,123	1,150	1,153	1,151	1,151	1,179	1,182	1,180	1,180
no 8.5	1,124	1,127	1,125	1,125	1,148	1,150	1,148	1,148	1,176	1,179	1,177	1,177

GCM abbreviations are as follows: ACCESS1.0 (ac), BCC_CSM1.1 (bc), CCSM4 (cc), GFDL CM3 (gf), HadGEM2-ES (he), IPSL-CM5A-LR (ip), MRI-CGCM3 (mg), MPI-ESM-LR (mp), NorESM1-M (no).

Table S4.5. Results of a two-tailed, paired Student's t-test to determine significant differences between evapotranspiration model results. Green values indicate significant differences (p<0.05), red values indicate no significant difference (p>0.05).

p-values, Scenario comparison

RCP 4.5, 2030	BAU	5YP	BTO
INIT	0.000	0.000	0.000
BAU		0.000	0.000
5YP			0.000

RCP 4.5, 2050	BAU	5YP	BTO
INIT	0.000	0.000	0.000
BAU		0.000	0.000
5YP			0.000

RCP 4.5, 2070	BAU	5YP	BTO
INIT	0.000	0.000	0.000
BAU		0.000	0.000
5YP			0.000

RCP 8.5, 2030	BAU	5YP	BTO
INIT	0.000	0.000	0.000
BAU		0.000	0.000
5YP			0.000

RCP 8.5, 2050	BAU	5YP	BTO
INIT	0.000	0.000	0.000
BAU		0.000	0.000
5YP			0.000

RCP 8.5, 2070	BAU	5YP	BTO
INIT	0.000	0.000	0.000
BAU		0.000	0.000
5YP			0.000

p-values, Time slice comparison

INIT 4.5	2050	2070
2030	0.004	0.000
2050		0.004

BAU 4.5	2050	2070
2030	0.004	0.000
2050		0.004

5YP 4.5	2050	2070
2030	0.004	0.000
2050		0.004

BTO 4.5	2050	2070
2030	0.004	0.000
2050		0.004

INIT 8.5	2050	2070
2030	0.000	0.000
2050		0.000

BAU 8.5	2050	2070
2030	0.000	0.000
2050		0.000

5YP 8.5	2050	2070
2030	0.000	0.000
2050		0.000

BTO 8.5	2050	2070
2030	0.000	0.000
2050		0.000

p-values, RCP comparison

INIT 2030	0.902
INIT 2050	0.317
INIT 2070	0.045
BAU 2030	0.917
BAU 2050	0.326
BAU 2070	0.048
5YP 2030	0.906
5YP 2050	0.320
5YP 2070	0.046
BTO 2030	0.906
BTO 2050	0.320
BTO 2070	0.046

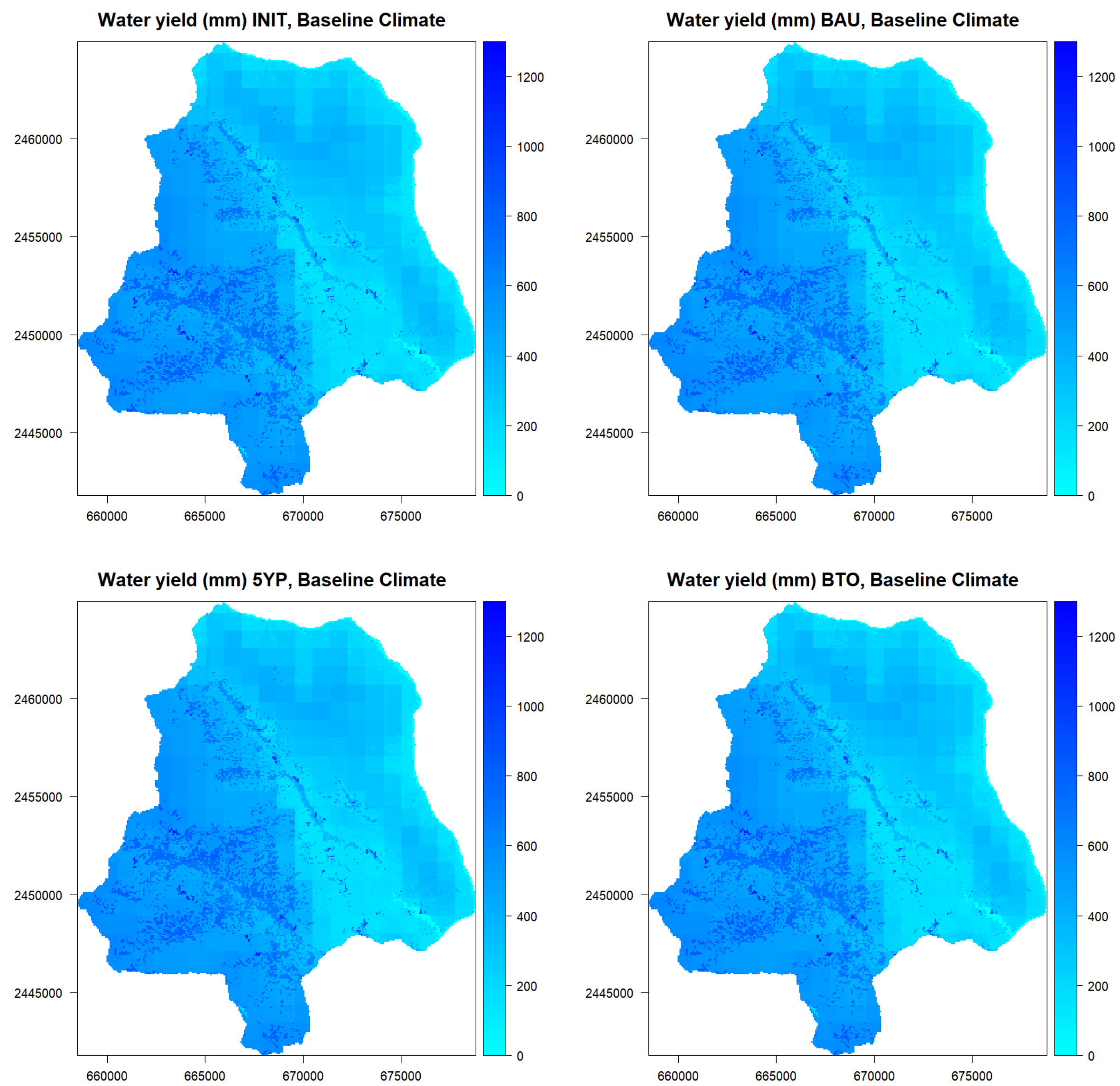


Figure S4.1. Water yield results for every land use scenario and the baseline climate data. INIT: Initial land use in 2015, BAU: Business-As-Usual, 5YP: 5-Years-Plan, BTO: Balanced-Trade-Offs.

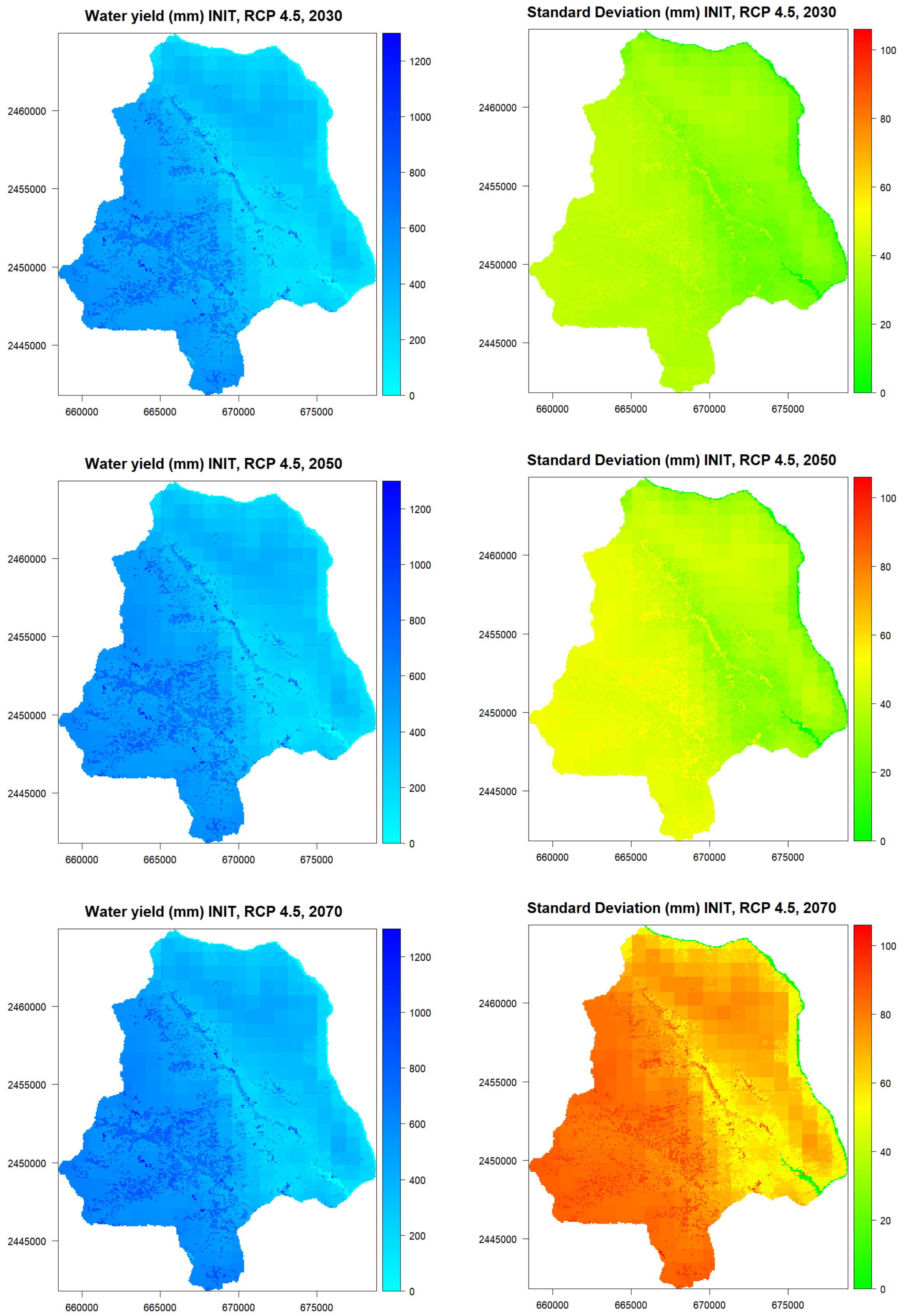


Figure S4.2. Water yield and standard deviation results in Nabanhe Reserve for the initial land use in 2015 (INIT) under RCP 4.5 climate data.

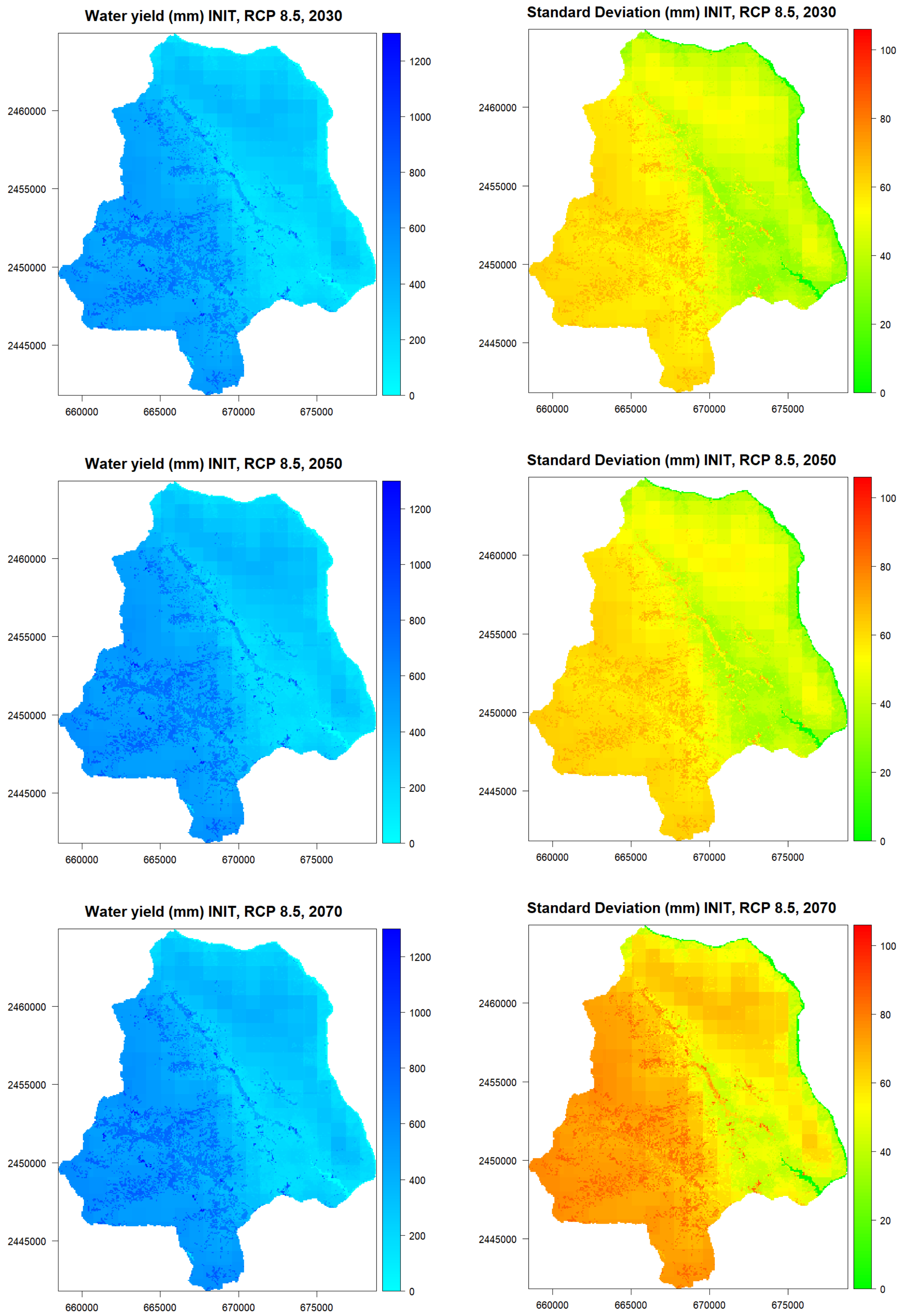


Figure S4.3. Water yield and standard deviation results in Nabanhe Reserve for the initial land use in 2015 (INIT) under RCP 8.5 climate data.

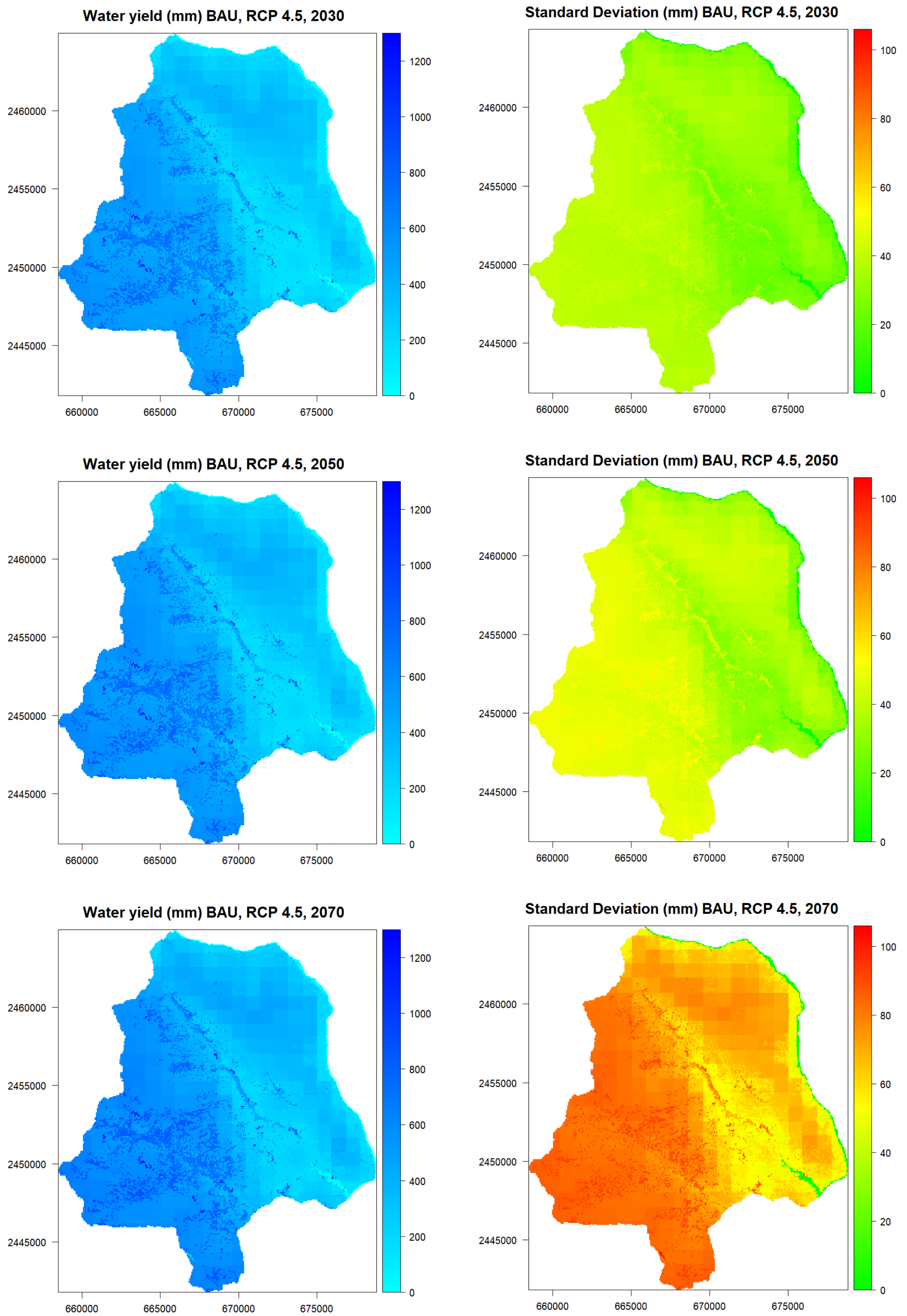


Figure S4.4. Water yield and standard deviation results in Nabanhe Reserve for the Business-As-Usual scenario (BAU) under RCP 4.5 climate data.

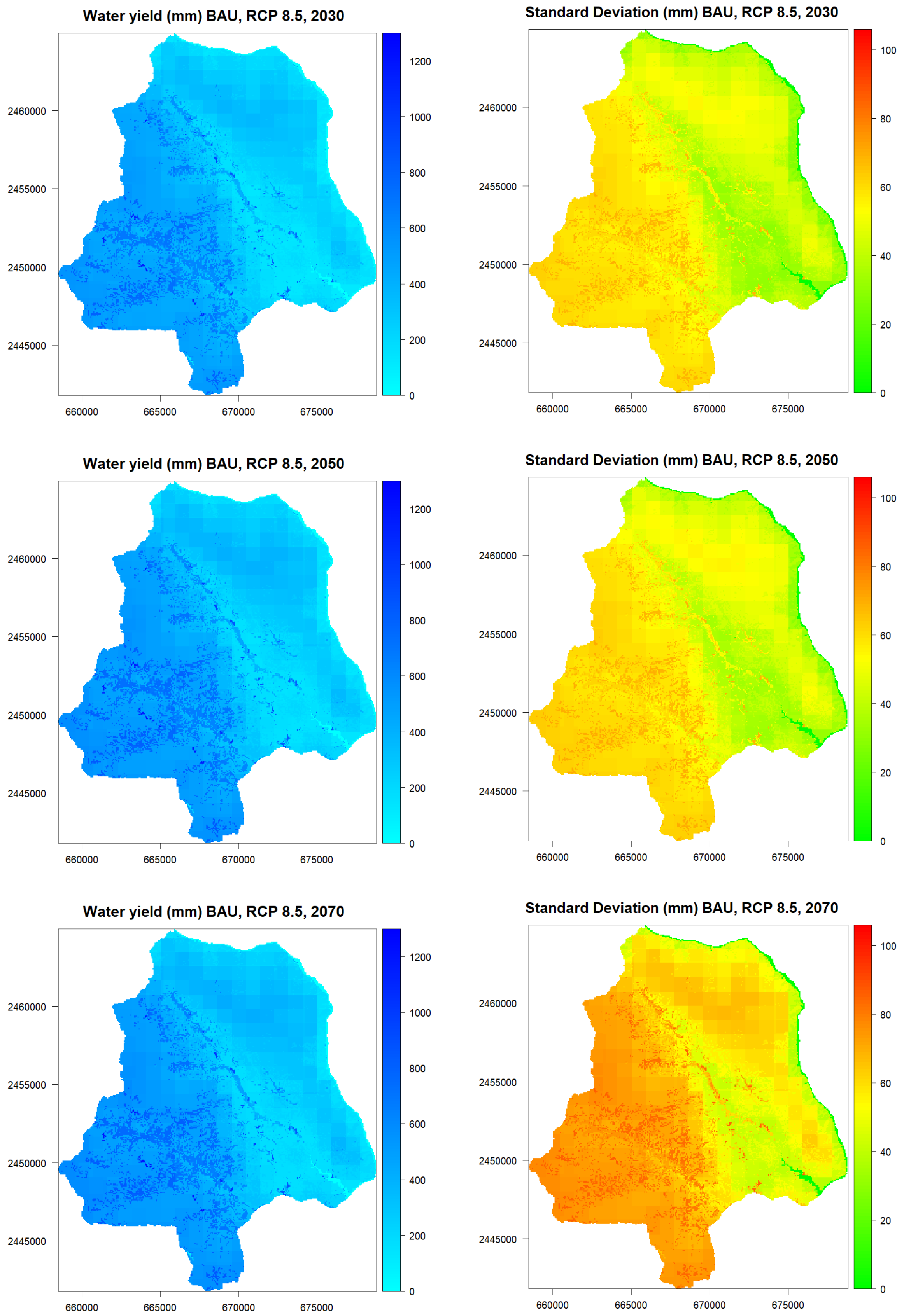


Figure S4.5. Water yield and standard deviation results in Nabanhe Reserve for the Business-As-Usual scenario (BAU) under RCP 8.5 climate data.

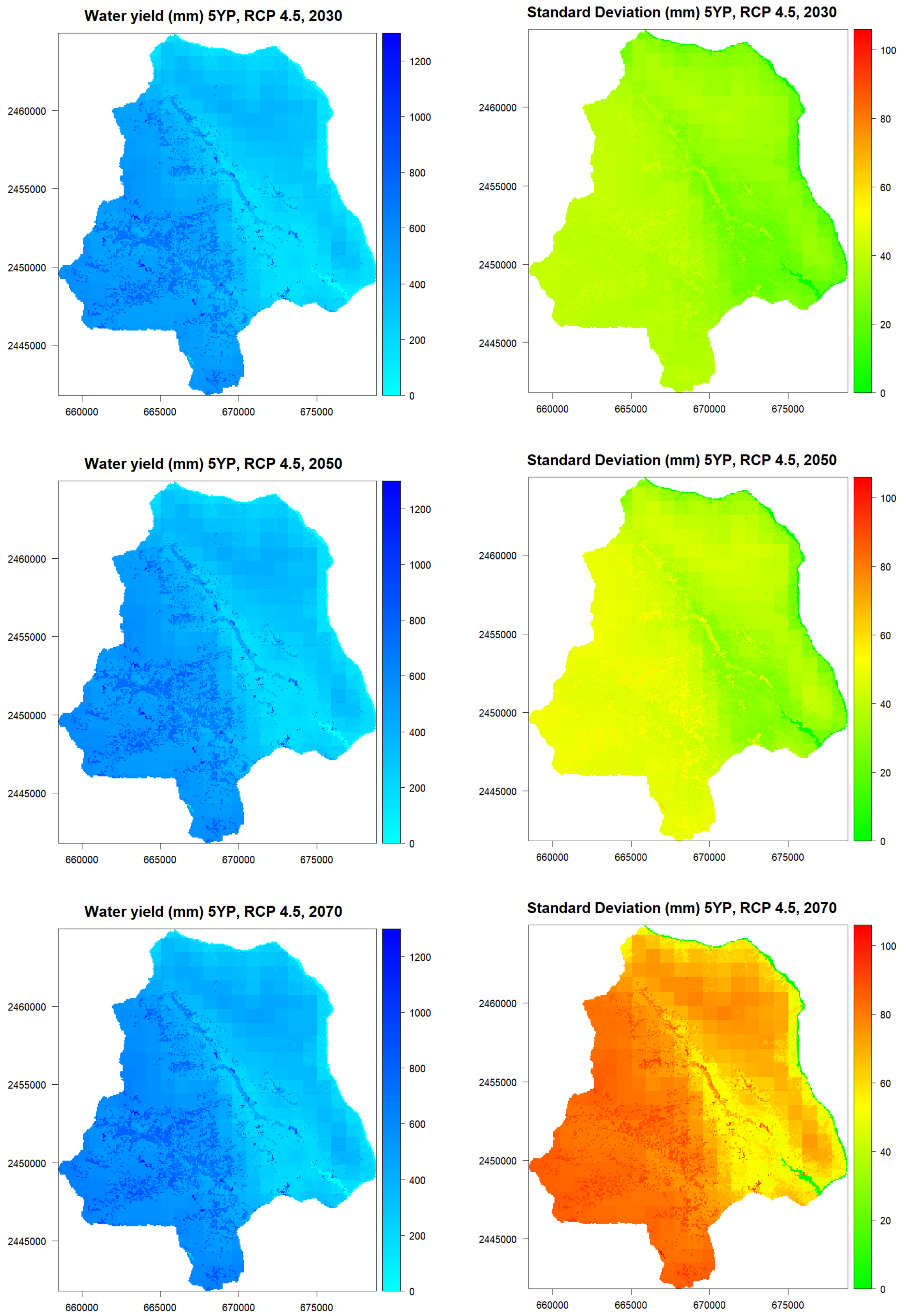


Figure S4.6. Water yield and standard deviation results in Nabanhe Reserve for the 5-Years-Plan scenario (5YP) under RCP 4.5 climate data.

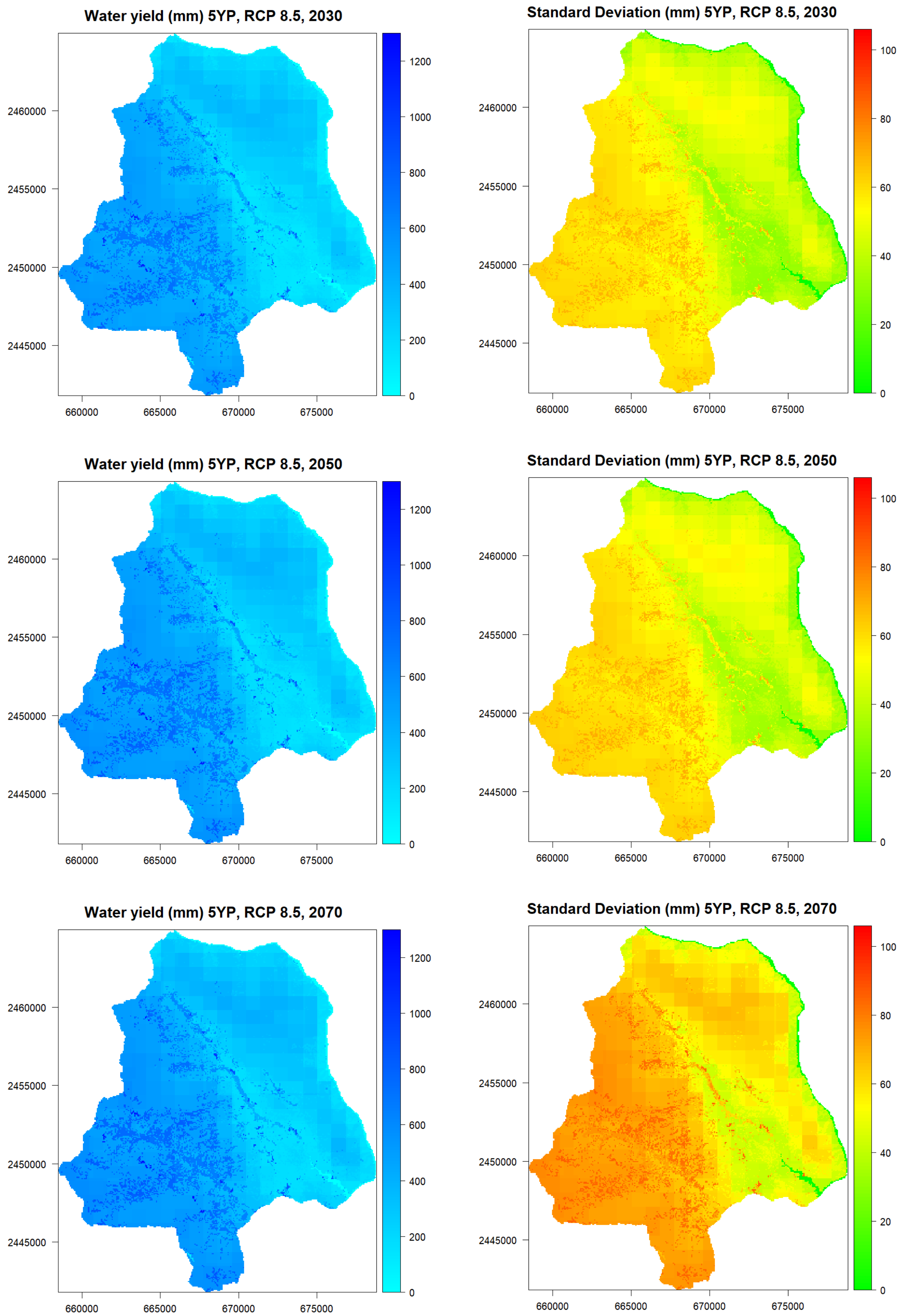


Figure S4.7. Water yield and standard deviation results in Nabanhe Reserve for the 5-Years-Plan scenario (5YP) under RCP 8.5 climate data.

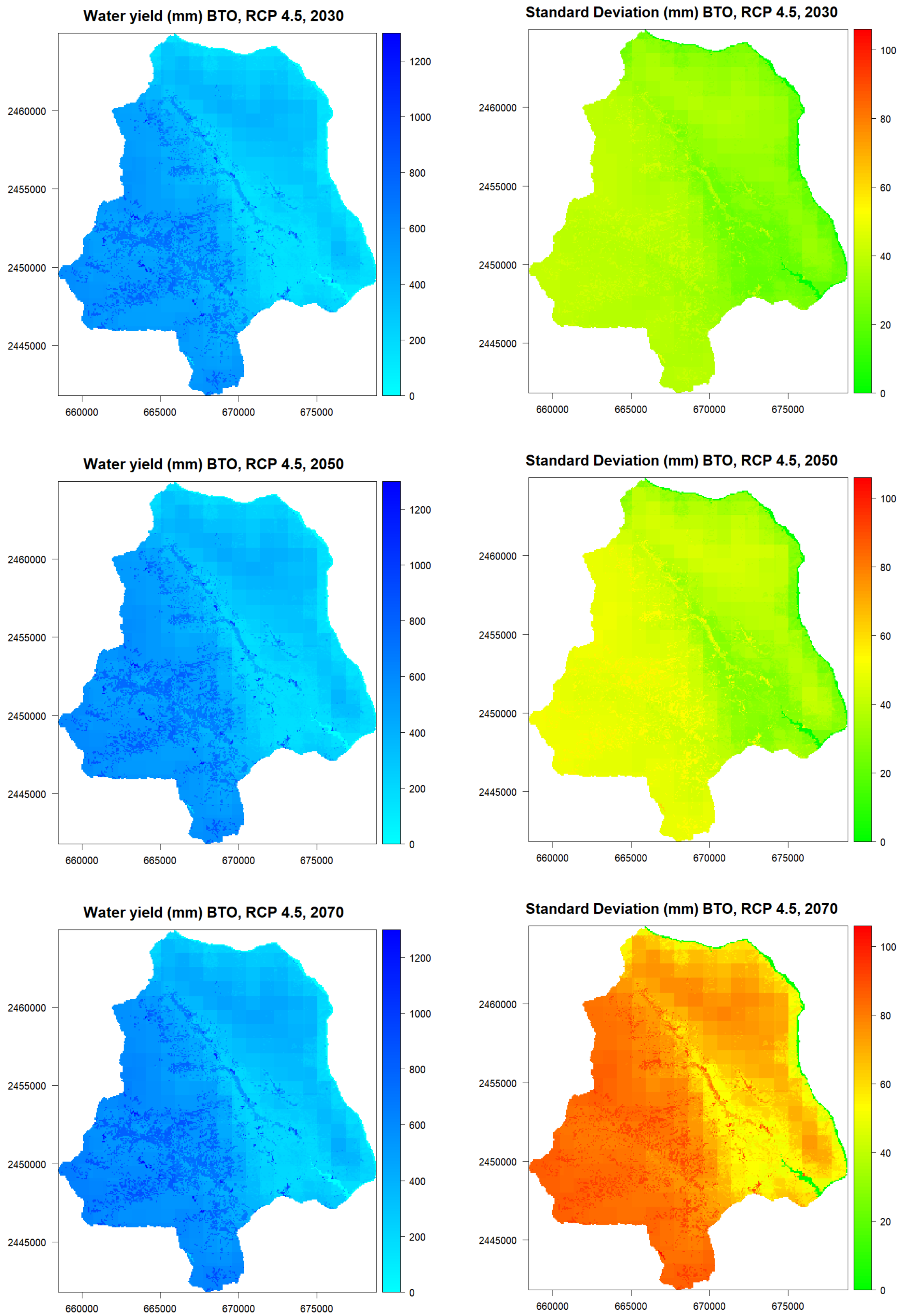


Figure S4.8. Water yield and standard deviation results in Nabanhe Reserve for the Balanced-Trade-Offs scenario (BTO) under RCP 4.5 climate data.

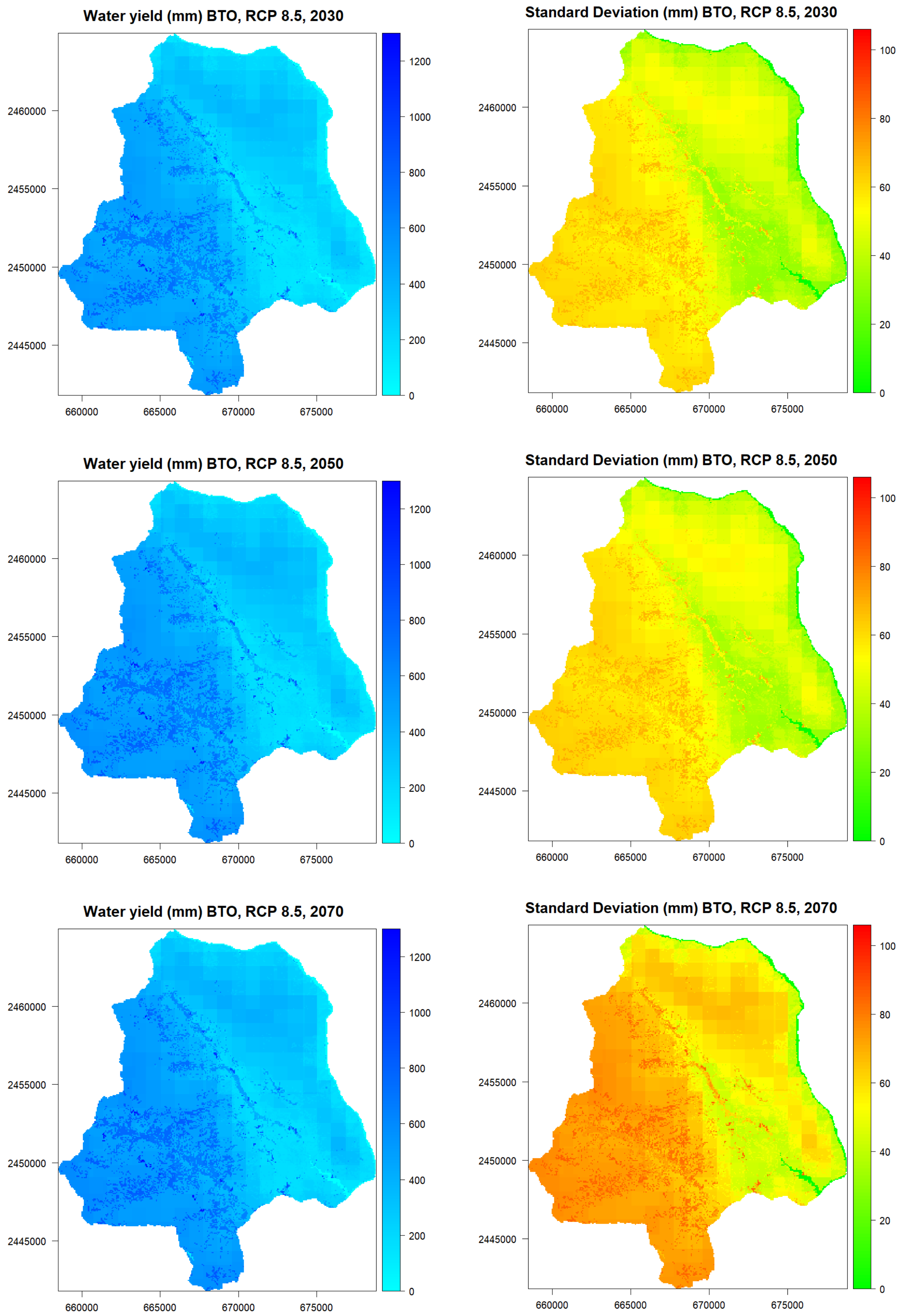


Figure S4.9. Water yield and standard deviation results in Nabanhe Reserve for the Balanced-Trade-Offs scenario (BTO) under RCP 8.5 climate data.

4.6.3 Sediment Export

Table S4.6. Simulation results for sediment export for the land use scenarios and each GCM in Nabanhe Reserve.

	Sediment Export (10^3 t)											
	2030				2050				2070			
	INIT	BAU	5YP	BTO	INIT	BAU	5YP	BTO	INIT	BAU	5YP	BTO
ac 4.5	53.31	60.50	23.81	22.87	53.31	60.50	23.81	22.87	53.31	60.50	23.81	22.87
bc 4.5	53.43	60.64	23.79	22.82	56.51	64.16	25.23	24.19	57.21	64.96	25.55	24.50
cc 4.5	53.06	60.22	23.62	22.65	56.27	63.89	25.14	24.10	62.00	70.35	27.75	26.61
gf 4.5	55.44	62.94	24.74	23.72	56.17	63.77	25.07	24.04	52.91	60.03	23.54	22.58
he 4.5	50.50	57.28	22.41	21.50	58.55	66.50	26.20	25.11	64.33	73.12	28.91	27.70
ip 4.5	55.84	63.39	24.92	23.90	58.47	66.40	26.15	25.07	60.19	68.37	26.96	25.84
mg 4.5	52.11	59.11	23.16	22.21	49.64	56.29	21.99	21.10	51.62	58.58	22.98	22.04
mp 4.5	53.63	60.86	23.87	22.89	55.26	62.72	24.64	23.62	60.73	68.98	27.19	26.06
no 4.5	51.89	58.86	23.05	22.11	54.67	62.05	24.36	23.36	56.46	64.11	25.21	24.17
ac 8.5	50.91	57.74	22.60	21.68	56.20	63.79	25.06	24.03	56.63	64.29	25.27	24.23
bc 8.5	53.55	60.76	23.84	22.86	59.86	68.00	26.81	25.70	62.47	70.98	28.04	26.88
cc 8.5	56.43	64.07	25.22	24.18	56.85	64.54	25.39	24.35	60.38	68.59	27.05	25.93
gf 8.5	53.70	60.94	23.92	22.94	55.43	62.92	24.72	23.71	58.63	66.59	26.23	25.14
he8.5	50.89	57.72	22.58	21.66	53.41	60.60	23.77	22.80	54.23	61.54	24.18	23.18
ip 8.5	45.30	51.33	20.00	19.19	47.53	53.89	21.05	20.20	48.49	54.99	21.50	20.63
mg 8.5	49.40	56.01	21.91	21.02	52.13	59.14	23.17	22.23	53.74	60.98	23.91	22.93
mp 8.5	54.97	62.40	24.51	23.50	57.90	65.75	25.88	24.81	60.55	68.78	27.12	26.00
no 8.5	56.38	64.01	25.18	24.14	58.71	66.68	26.28	25.19	61.81	70.24	27.73	26.58

GCM abbreviations are as follows: ACCESS1.0 (ac), BCC_CSM1.1 (bc), CCSM4 (cc), GFDL CM3 (gf), HadGEM2-ES (he), IPSL-CM5A-LR (ip), MRI-CGCM3 (mg), MPI-ESM-LR (mp), NorESM1-M (no).

Table S4.7. Results of a two-tailed, paired Student's t-test to determine significant differences between sediment export model results. Green values indicate significant differences (p<0.05), red values indicate no significant difference (p>0.05).

p-values, Scenario comparison			
RCP 4.5, 2030	BAU	5YP	BTO
INIT	0.000	0.000	0.000
BAU		0.000	0.000
5YP			0.000
RCP 4.5, 2050	BAU	5YP	BTO
INIT	0.000	0.000	0.000
BAU		0.000	0.000
5YP			0.000
RCP 4.5, 2070	BAU	5YP	BTO
INIT	0.000	0.000	0.000
BAU		0.000	0.000
5YP			0.000
RCP 8.5, 2030	BAU	5YP	BTO
INIT	0.000	0.000	0.000
BAU		0.000	0.000
5YP			0.000
RCP 8.5, 2050	BAU	5YP	BTO
INIT	0.000	0.000	0.000
BAU		0.000	0.000
5YP			0.000
RCP 8.5, 2070	BAU	5YP	BTO
INIT	0.000	0.000	0.000
BAU		0.000	0.000
5YP			0.000

p-values, Time slice comparison		
INIT 4.5	2050	2070
2030	0.052	0.032
2050		0.060
BAU 4.5	2050	2070
2030	0.052	0.032
2050		0.060
5YP 4.5	2050	2070
2030	0.053	0.032
2050		0.059
BTO 4.5	2050	2070
2030	0.052	0.032
2050		0.059
INIT 8.5	2050	2070
2030	0.001	0.000
2050		0.001
BAU 8.5	2050	2070
2030	0.001	0.000
2050		0.001
5YP 8.5	2050	2070
2030	0.001	0.000
2050		0.001
BTO 8.5	2050	2070
2030	0.001	0.000
2050		0.001

p-values, RCP comparison	
INIT 2030	0.575
INIT 2050	0.957
INIT 2070	0.927
BAU 2030	0.575
BAU 2050	0.957
BAU 2070	0.931
5YP 2030	0.573
5YP 2050	0.951
5YP 2070	0.928
BTO 2030	0.570
BTO 2050	0.948
BTO 2070	0.924

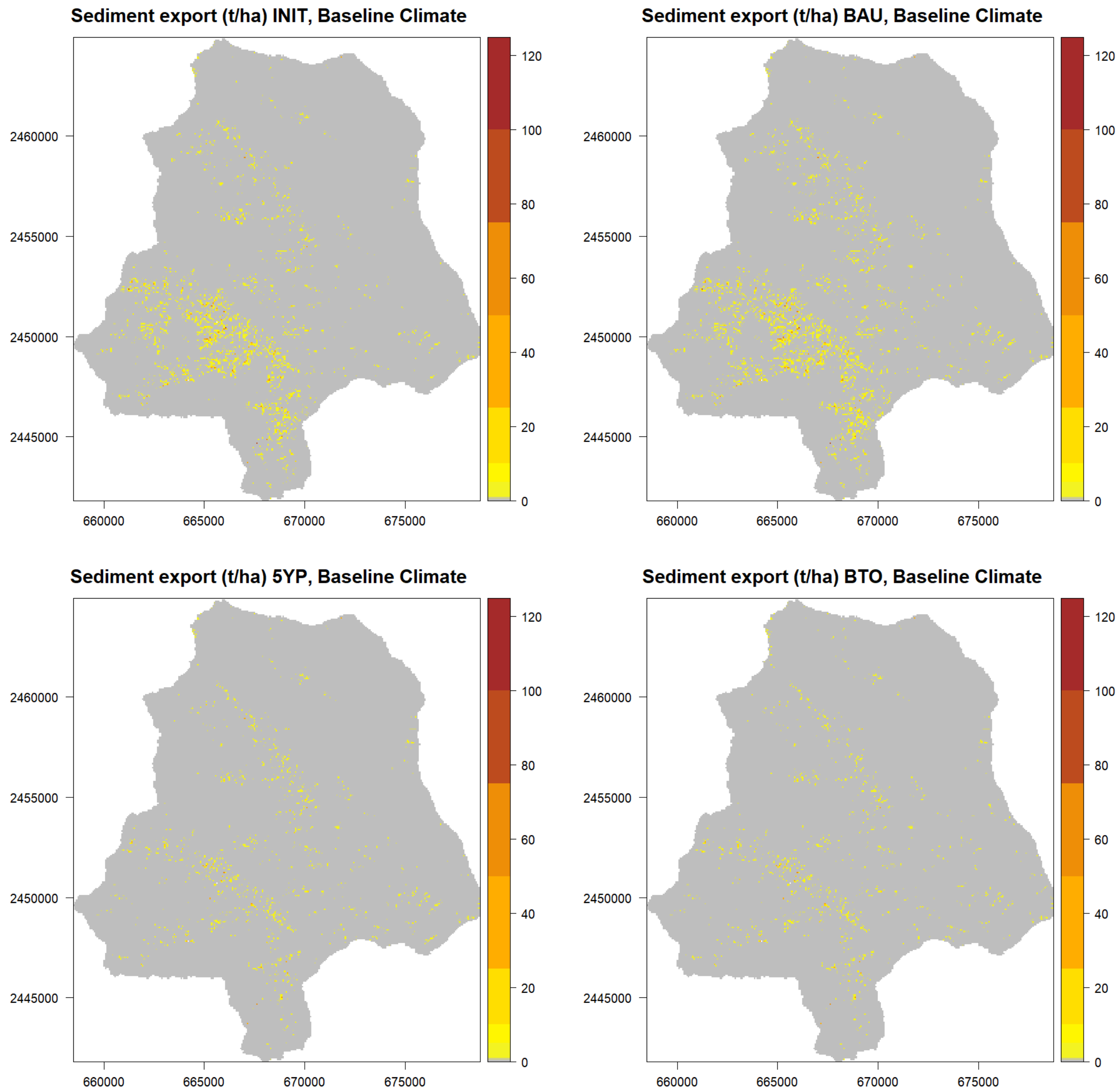


Figure S4.10. Sediment export results for every land use scenario and the baseline climate data. INIT: Initial land use in 2015, BAU: Business-As-Usual, 5YP: 5-Years-Plan, BTO: Balanced-Trade-Offs.

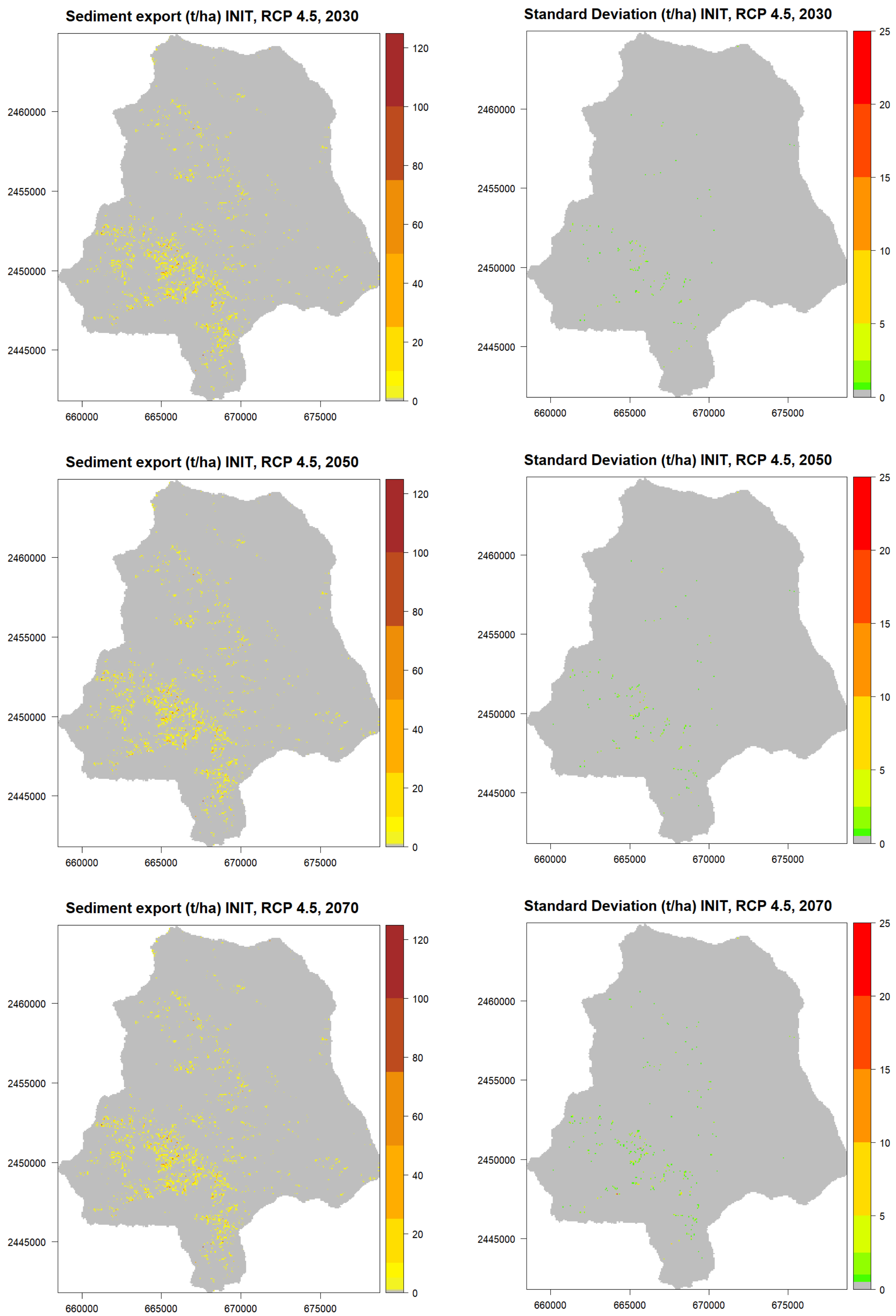


Figure S4.11. Sediment export and standard deviation results in Nabanhe Reserve for the initial land use (INIT) under RCP 4.5 climate data.

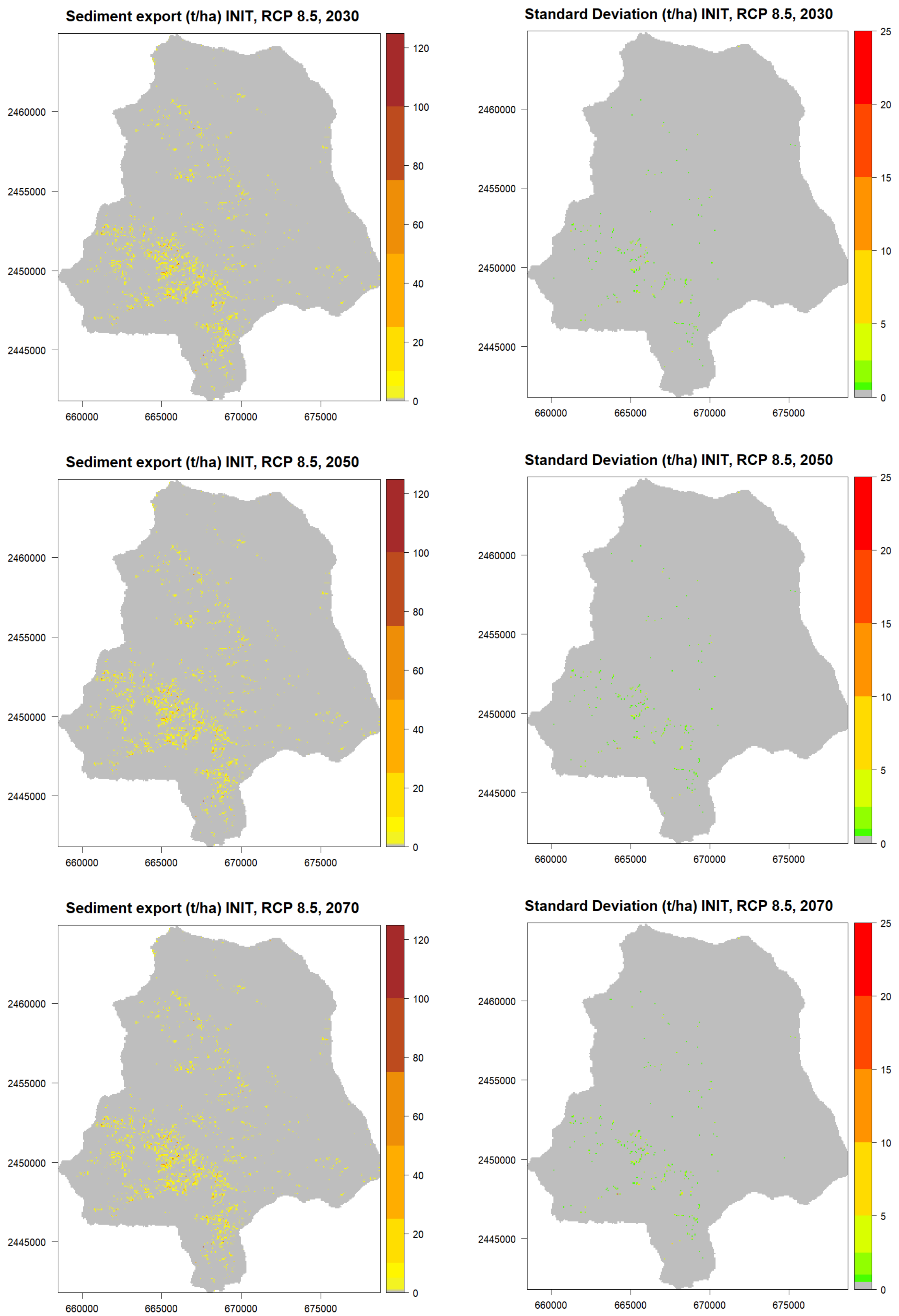


Figure S4.12. Sediment export and standard deviation results in Nabanhe Reserve for the initial land use (INIT) under RCP 8.5 climate data.

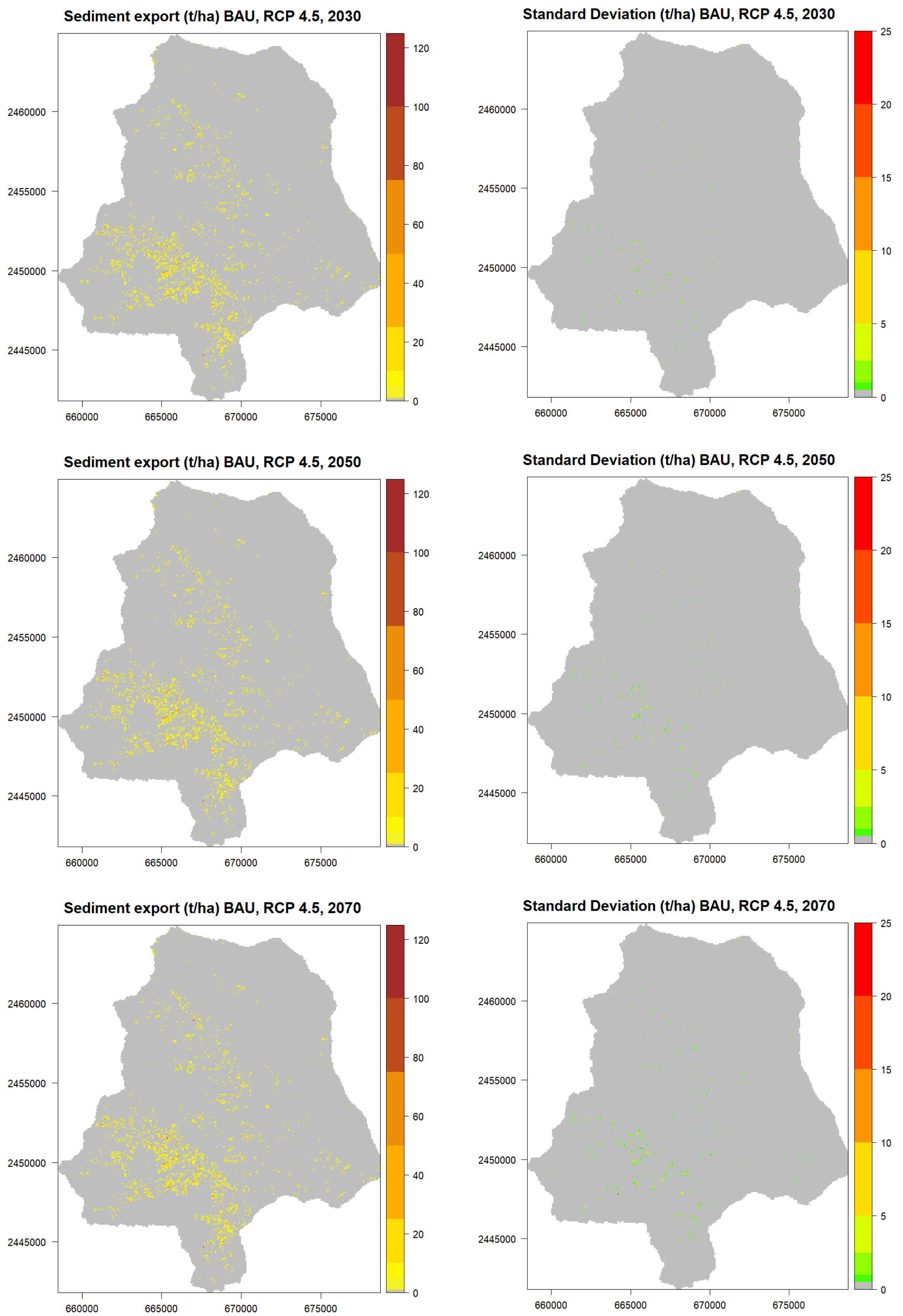


Figure S4.13. Sediment export and standard deviation results in Nabanhe Reserve for the Business-As-Usual scenario (BAU) under RCP 4.5 climate data.

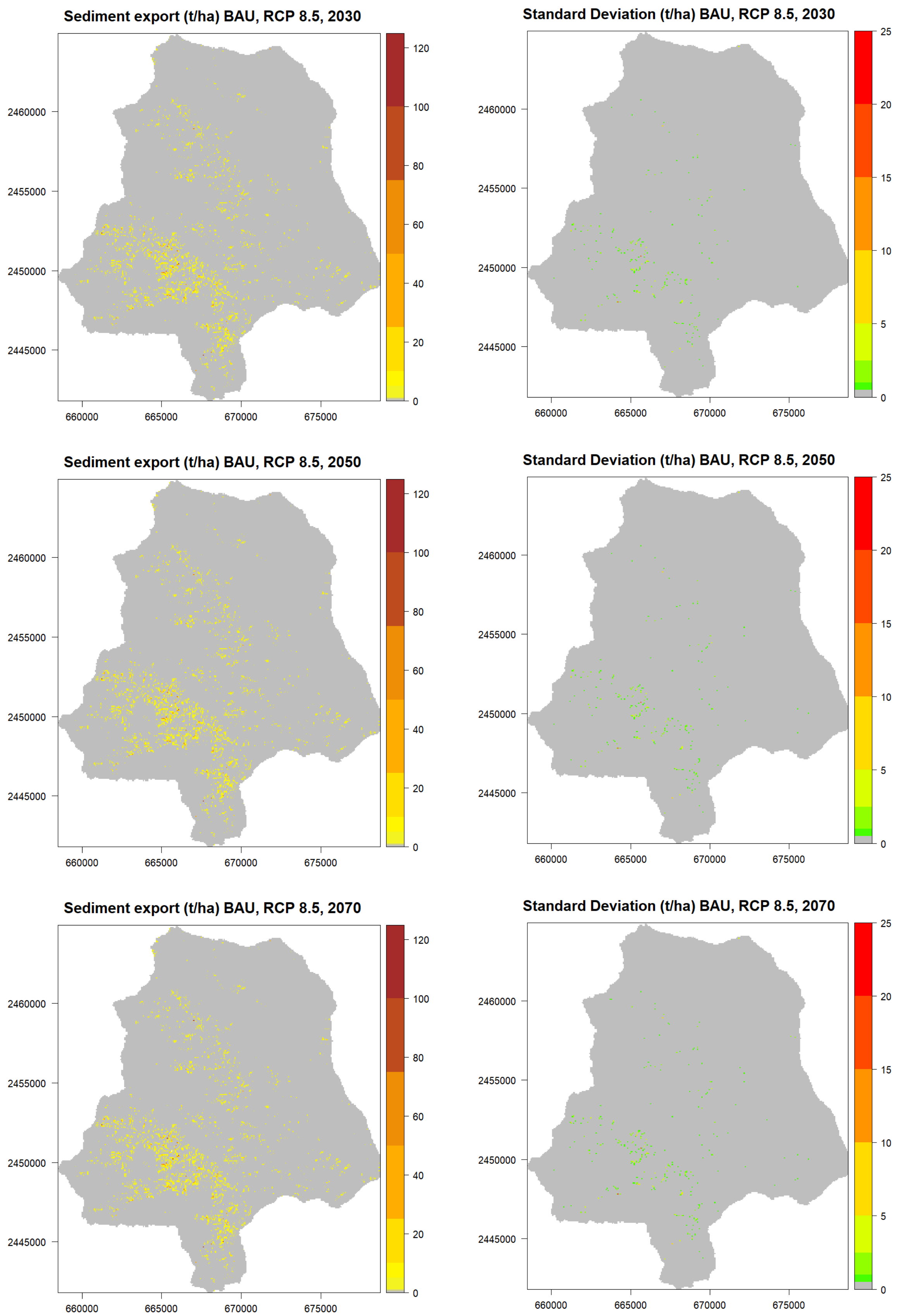


Figure S4.14. Sediment export and standard deviation results in Nabanhe Reserve for the Business-As-Usual scenario (BAU) under RCP 8.5 climate data.

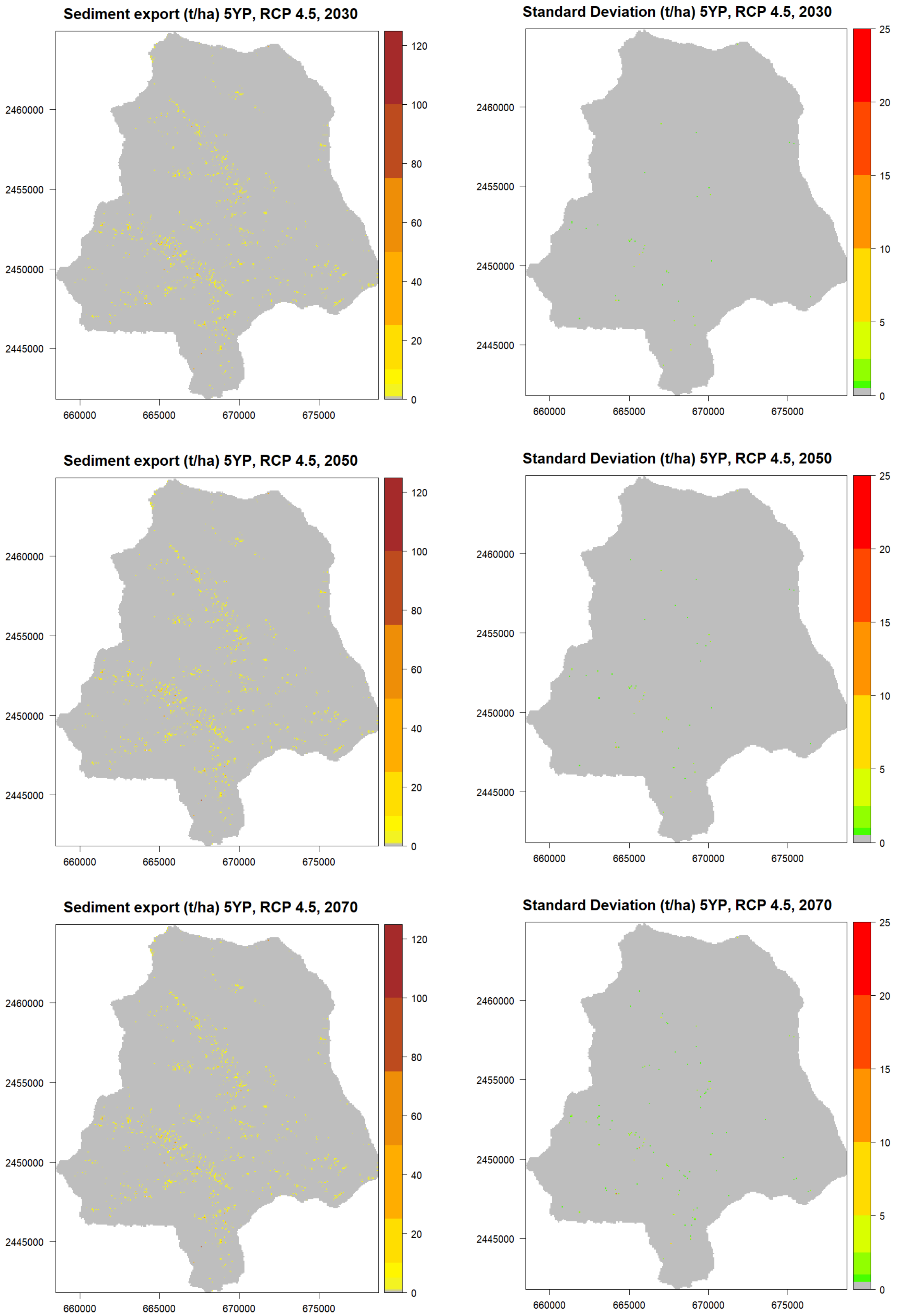


Figure S4.15. Sediment export and standard deviation results in Nabanhe Reserve for the 5-Years-Plan scenario (5YP) under RCP 4.5 climate data.

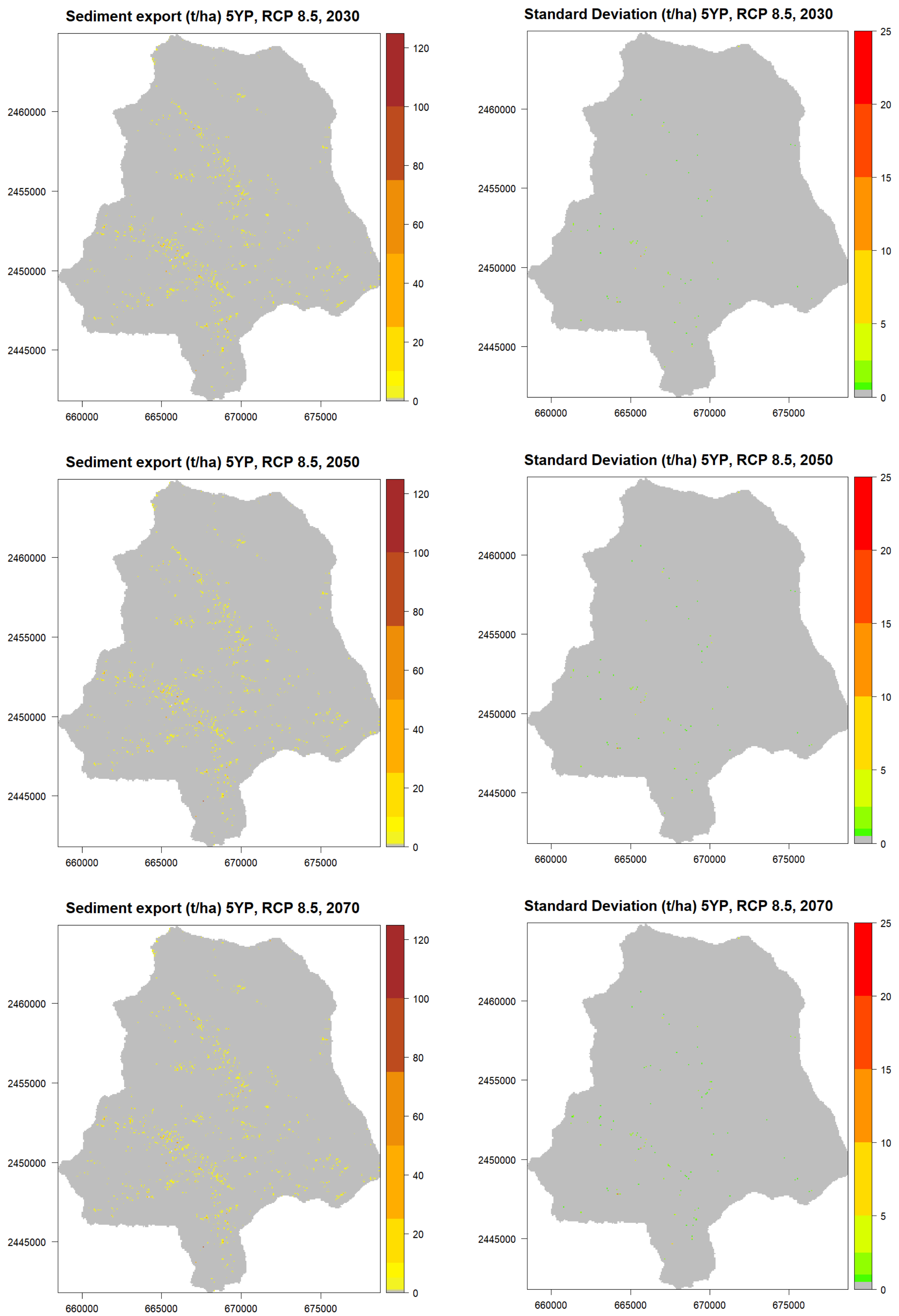


Figure S4.16. Sediment export and standard deviation results in Nabanhe Reserve for the 5-Years-Plan scenario (5YP) under RCP 8.5 climate data.

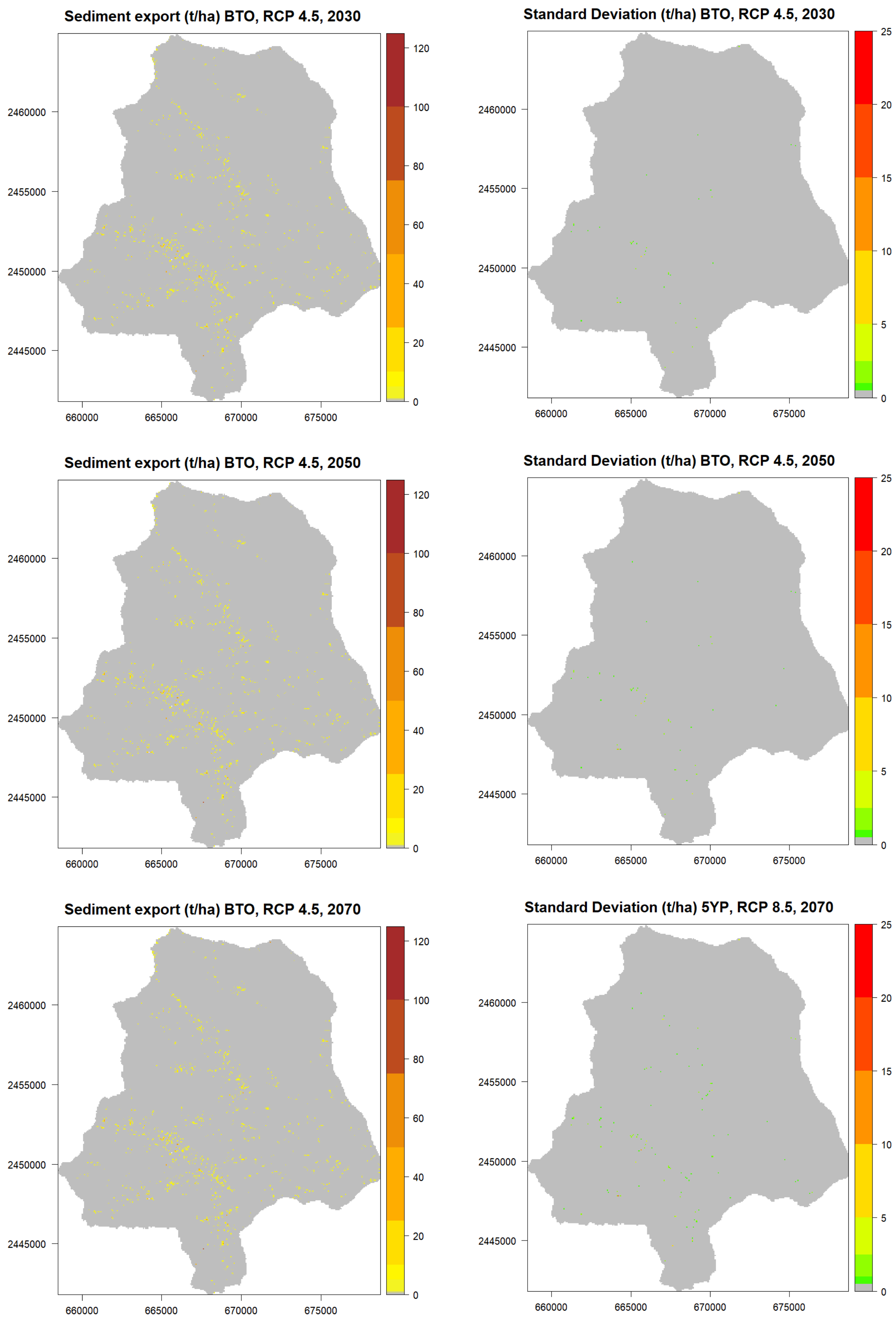


Figure S4.17. Sediment export and standard deviation results in Nabanhe Reserve for the Balanced-Trade-Offs scenario (BTO) under RCP 4.5 climate data.

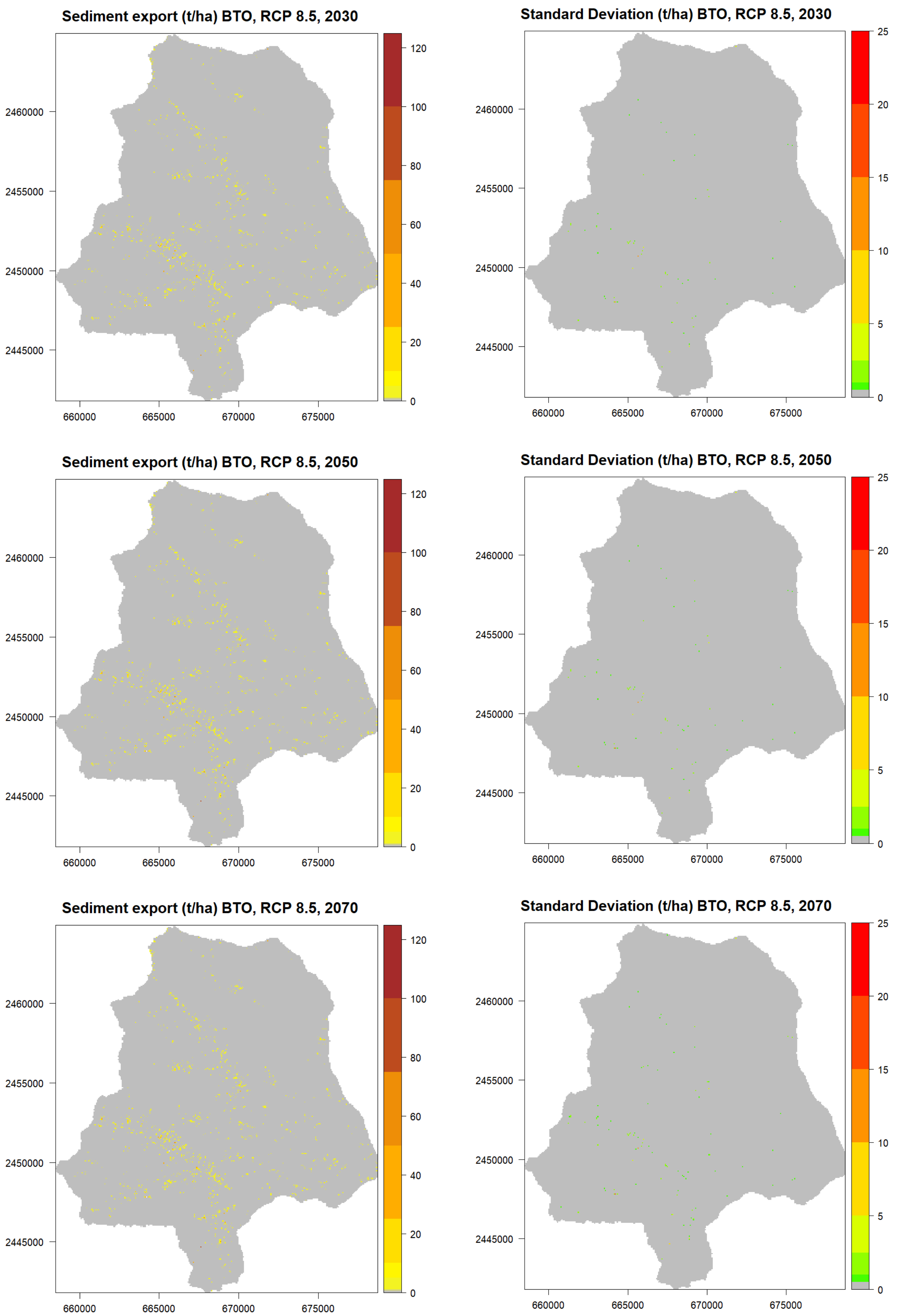


Figure S4.18. Sediment export and standard deviation results in Nabanhe Reserve for the Balanced-Trade-Offs scenario (BTO) under RCP 8.5 climate data.

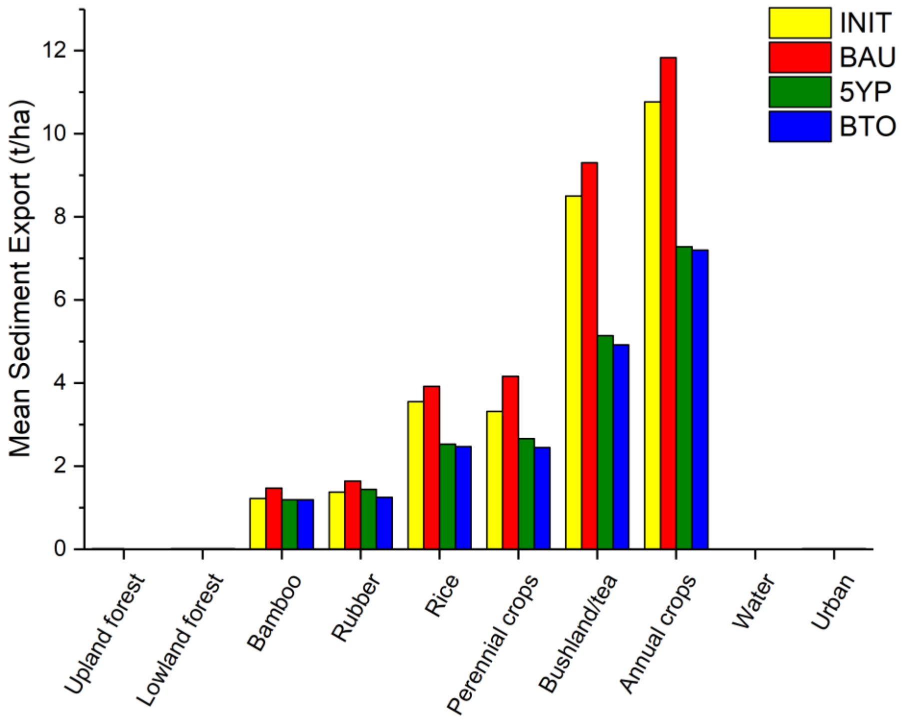


Figure S4.19. Sediment export averaged over every land use category in Nabanhe Reserve for the initial land use (INIT) and baseline climate. We calculated these values by summing the sediment export amounts from each land use category and divided them by the areal extent of the respective land use category in Nabanhe Reserve.

Chapter 5: General Discussion

5.1. Overview

Since the work on this thesis began, more than three years ago, some major steps were made in advancing the field of ESS research with: (1) an ever-growing amount of publications and data bases on ESS [32]; (2) comprehensive blue prints for future ESAs [213]; (3) guidelines and continent-scale ESAs provided and lead by IPBES, an organization which has shaped up to be the ESS-counterpart to the IPCC [214]; (4) the development of new software solutions for modeling ESS in increasingly user-friendly manners, which makes them more likely to be recognized as useful tools for policy advice [215]; (5) the emergence of new approaches to integrate big data, citizen science, and telecoupling into ESAs and the simulation of SES [216,217]. Still, there are also a number of methodological and conceptual inconsistencies [213].

The land use situation in Xishuangbanna Prefecture saw a turning point in recent years. The extensive rubber expansions that dominated Xishuangbannas' landscapes since the turn of the millennium came to a latent halt after the prices for rubber continually decreased since 2011 [27]. New (banana, mango, macadamia) and old (tea) alternatives to rubber are increasingly getting adapted by local farmers in Xishuangbanna, which will require new research and information for policy advice, land use planning and the development of new measures for sustainable land use management [201,218].

The three preceding chapters focused on the expansion of rubber plantations and the ensuing multiple impacts on biodiversity and the supply of ESS in a mountainous watershed in Xishuangbanna Prefecture, Southwestern China. This chapter aims at discussing the findings of the three case studies (Chapter 2-4) in a wider context given by both the aforementioned advancements in the field of ESS research as well as the new situation in Xishuangbanna after the rubber boom. The discussion highlights both the strengths and compromises of the methods applied in this thesis and compares them to similar contemporary research. It discusses some problems in the field of ESS research and demonstrates potential pathways forward to a holistic analysis of SESs.

5.2. Future Pathways for ESS research

5.2.1. Critical Aspects and Blind Spots

Lautenbach et al. [213] conducted a quantitative review with the aim of deriving the prevailing blind spots in ESS research. The authors call attention to five critical aspects that are necessary in order to improve the operationalization of the ESS concept and establish quality standards for future ESS research [213]:

- (I) **Socio-ecological validity of ecosystem data and models**, regarding system boundaries, data sources, indicators, the type and validation of the utilized model, and whether and how uncertainties are quantified;
- (II) **Consideration of trade-offs between ESS**, as well as potential interactions between them;
- (III) **Recognition of off-site effects**, also referred to as telecouplings or teleconnections;
- (IV) **Comprehensive involvement of stakeholders**, regarding both stakeholder types and roles;
- (V) **Relevance and usability of study results for the operationalization of the ESS concept in practice**, regarding the integration of demand and supply for ESS, the inclusion of maps and what kind of variables are mapped, scenario analysis, as well as the inclusion of policy instruments and specific recommendations.

The quantitative review by Lautenbach et al. [213] revealed considerable deficits in the methodologies applied in the reviewed studies spanning across all of the five aspects listed above. Of all the studies reviewed by Lautenbach et al. [213] (n=504 case studies), 86% did not validate model results, and only 49% quantified uncertainties; only 4% considered off-site effects or telecouplings; trade-off analyses were conducted in only 30% of the reviewed studies, only 23% analysed interactions between different ESS, and only 37% of the reviewed studies involved interactions with stakeholders. Regarding the relevance and usability of the study results, only 18% of the studies included both the demand and the supply side of ESS, as the largest share considered solely ESS supply (70%), and the smallest share (12%) focused solely on the demand side of ESS; 31% of the studies mapped ESS; the majority of the studies (70%) treated ESS as static without the consideration of changes over time or scenario analysis [213]. ESAs have the potential to translate scientific results into best practice advice, yet only 33% of the reviewed studies provided any kind of specific recommendations for practice or implementation [213].

5.2.2. Moving beyond the Blind Spots

In the context of the deficiencies found in current ESS studies, the methods applied in this thesis were able to positively address the blind spots prevalent in ESS research to a large degree. The three case studies that make up the main part of this thesis (Chapters 2-4), contributed to the small share of ESAs that: (1) included the analysis of scenarios, in which (2) ESS are not considered as static, but are simulated across time and space, (3) involved stakeholders for both the scenario design as well as the evaluation of modeling results, (4) mapped a number of locally important ESS and compared the trade-offs between scenarios in a spatially-explicit manner, (5) included the quantification of uncertainties through varying input datasets, and (6) derived best practice recommendations from the model results.

However, some of the blind spots were not addressed in a completely satisfactory manner in this thesis. While ESS supply was mapped in a quantitative, spatially-explicit way for each of the five selected service indicators (water yield, sediment retention, carbon storage, rubber yield, and habitat quality), the demand for these ESS was only represented in a qualitative manner from the information received during the stakeholder workshops. Furthermore, plausibility-checks were only performed for parts of the model results (water yield, sediment retention), while other results were impossible to validate, as the model design is based on the upscaling of indicators (e.g. habitat quality). Similarly, interactions between the analysed ESS were impossible to simulate, as each ESS sub-model is run in isolation. This model behaviour is inherent to modular design of InVEST and is only possible to overcome with other modelling approaches. As is the case with the majority of ESAs, the analysis of off-site effects was not included in this thesis. However, toolboxes to analyse off-site effects or telecouplings are now starting to become available [217].

In 2006, Grimm et al. [219] published a concept protocol for the application of individual-based/agent-based models, which proved to be a successful guideline for designing, structuring and developing models and projects in the field of ecology (given that it was cited more than 1400 times by early 2020) [41]. Seppelt et al. [41] aimed for the same effect with their proposed blueprint for ESAs in 2012. Given the overlap of their findings with the blind spots in ESS research reported by Lautenbach et al. [213] in 2019, only little progress seems to have been made in the methodological soundness of ESS research in these years. This is concerning as the number of publications utilizing the ESS concept is increasing each year, whereas methodological consistency remains unchanged [32].

One potential explanation for the enduring blind spots in ESS research is that spatial modeling of ESS is considered as an emerging research field and that the term “ecosystem service” might have been used as a popular science “buzzword” [101]. Another explanation for the lack of methodological consistency in ESS research is that similar disciplinary clusters of ESS studies fail to address the same critical aspects of research [73,213]. Examples for this include a general lack of stakeholder involvement in ESS studies focused on climate regulation, soil retention, water quality, and habitat provisioning, or the low share of studies that focus on water quality, food, and air quality and include mapping of ESS [213]. Researchers with different academic backgrounds focus on different sets of ESS in their research, are guided by different research traditions and may have an unclear perspective of scientific standards present in other disciplines [213]. A solution for this would be truly trans- and interdisciplinary research collaborations that bring together scientists with multiple disciplinary backgrounds in order to holistically analyse the essential aspects of the SES in question [220]. This call has been echoed in the ESS community [32,41,213]. However, in comparison to non-interdisciplinary research, higher scientific, financial and administrative efforts are necessary for such projects to take shape. In addition, real world problems might lead to unplanned compromises and adaptations, which should be clearly expressed and not suppressed by the urge to influence policy [73].

5.2.3. Dynamic Representations of SES

The problem of methodological inconsistencies is present not only in ESS research. Comparable findings were made by Herrero-Jáuregui et al. [220] on the inconsistencies in the scientific use of the concept of SES. While most of the reviewed studies on SES shared common topics (e.g. resilience, sustainability, ESS, governance), the majority did not study SES as a whole, and omitted important social and ecological variables and their feedback loops [220]. The authors call attention to two particular necessities in order to advance the field of research on SES: (1) conscious and agreed efforts of scientists to conduct transdisciplinary research in order to study SES, and (2) the development of methodologies for the true integration of social and ecological data [220].

In other words, the complex and dynamic nature of SES calls for equally complex and dynamic modeling approaches in order to capture the essential interdependencies between the social and ecological sub-systems. For SES, the well-known Drivers-Pressures-State-Impact-Response (DPSIR) framework was originally derived from social sciences and has been adapted for the organization of information about the state of the environment [221]. In the field of ESS, the ESS cascade framework was widely used and has been revised [222,223]. However, the ESS cascade framework was criticised for its linear, or oversimplified view on how human society derives benefits from ESS [32]. In brief, there is a flow from biophysical structures and processes to ecosystem functions to ecosystem services, which provide benefits that are valued (Figure 5.1) [222,223].

This thesis mainly dealt with the first three steps of the ESS cascade; modeling biophysical structures and ecosystem functions to quantify ESS. Chapter 2 features the integration of stakeholder feedback into the scenario development process and the evaluation of ESS. However, the trajectories of land use change and land use management measures in the analysed scenarios remained constant throughout the 25-year simulation period. Such fixed scenario trajectories are useful to assess and compare potential futures, as was done in this thesis. In reality, however, humans are constantly adapting their behaviour and actions according to the consequences of their past actions. This feedback loop should be a focal point in future ESAs in order to come closer to a valid representation of SESs.

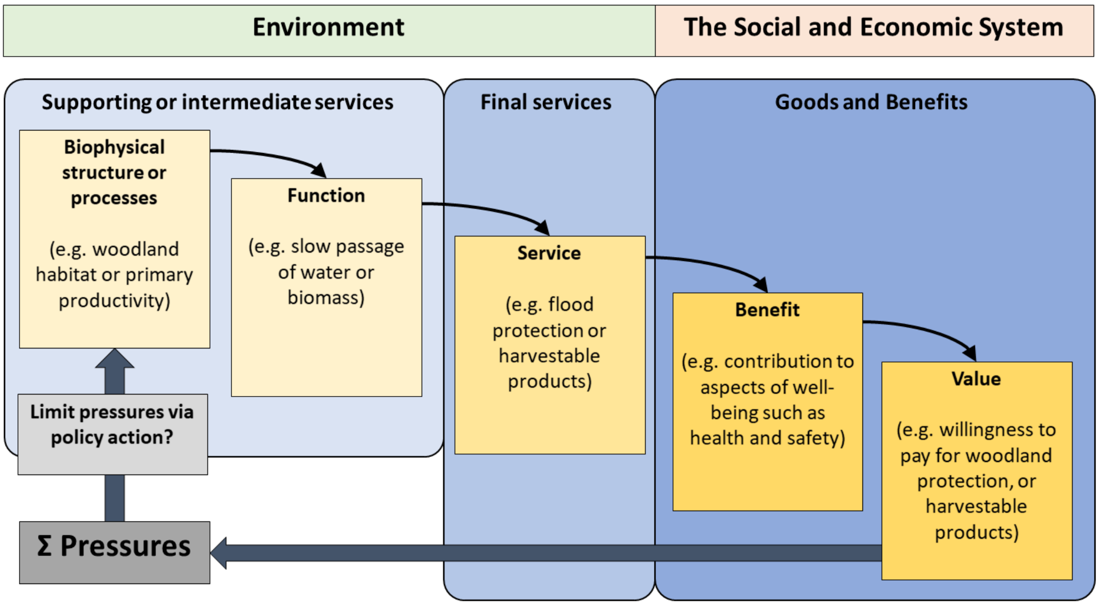


Figure 5.1. The Ecosystem Service Cascade Framework, adapted from Potschin-Young et al. [222] and Potschin & Haines-Young [223].

To realize this, some authors made attempts to integrate ESS into the DPSIR framework [221,224,225], or to merge the ESS cascade with the DPSIR framework in order to better describe the dynamic interactions between the social system and the ecological system [226]. Figure 5.2 depicts one attempt by Nassl & Löffler [226]. It shows the integration of the feedback loop between the social system and the ecosystem through human evolvement and changed rates of ESS supply, as well as the two-way impact of external drivers.

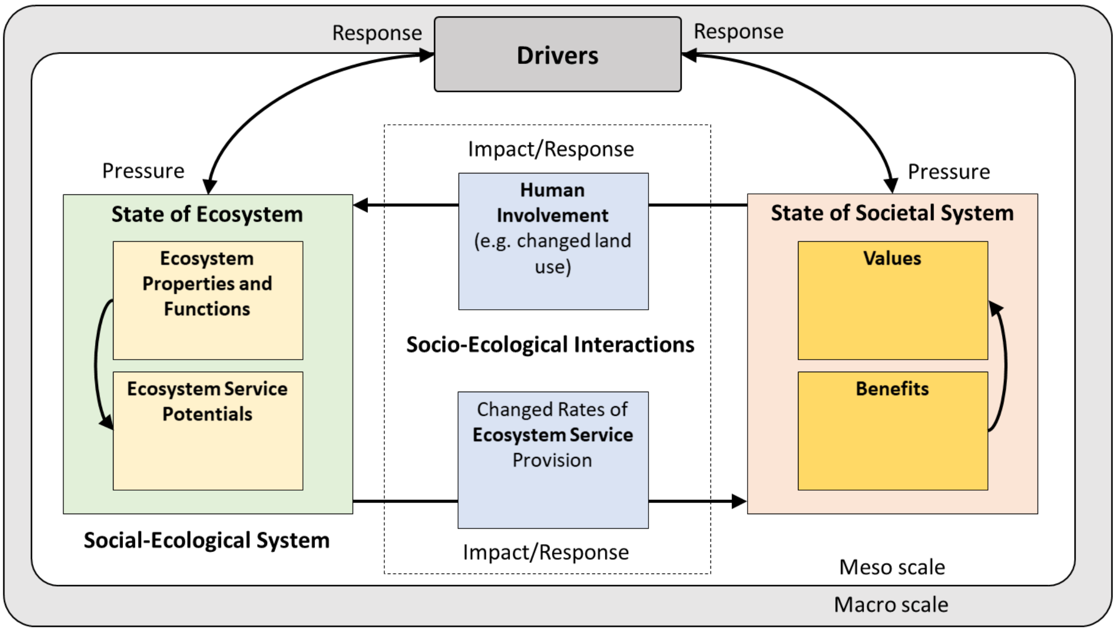


Figure 5.2. This graph shows the combination of the Ecosystem Service Cascade and the Drivers-Pressures-State-Impact-Response Framework in order to integrate the cycle of ecosystem service supply into a societal feedback loop, adapted from Nassl & Löffler [226].

5.2.4. Modeling Solutions

Software solutions for modeling ESS, such as InVEST, are not capable of representing complex feedback loops in a dynamic way. Spatially-explicit ESS models aiming to assess the impact of land use changes and climate changes on ESS and biodiversity have to strike a balance between model complexity and model accessibility in order to be of use in environmental decision making, land use planning or policy design. The most crucial aspects in regard to choosing an appropriate model include data availability, at what areal extent, scale and resolution the model should be applied, and most importantly: to what purpose?

Therefore, it is important to consider whether to focus on highly detailed, small-scale field experiments with dynamic modeling approaches, or to assess ESS on increasingly larger scales and accept the necessity to generalize or omit certain aspects in the process. For this thesis, the scale of the analysis (Nabanhe Reserve) was given by the framework of the SURUMER project in order to satisfy and make use of "common plot, common data" approaches [201]. At the start of this thesis, InVEST was an appropriate choice (among only very few others) to be used for this purpose, as it allows for multidisciplinary simulations at the given spatial scale. However, considerable progress has been made in the past years in developing ESS models further.

On the one hand, new models emerged that allow for the dynamic representation of both the social and the ecological sub-systems, mostly in the field of agent-based modeling [216]. Thus far in this field, models were mostly restricted to small spatial scales, ranging from single farms to small watersheds, because these models are as demanding in the amount and detail of input data as they are in necessary computing power to run, in addition to large time investments for a successful setup [216].

On the other hand, ARIES (Artificial Intelligence for Ecosystem Services) is becoming a flexible framework for the assessment of ESS, that caters to a wide range of user types, depending on the assessment needs and the availability of time and data: "Tier 1" models in ARIES are comparable to InVEST in regard to the simplification of biophysical processes, but can be accessed, parameterized and run as a web browser tool, which is capable of dynamically accessing global datasets (in varying spatial resolutions) for many types of input parameters, depending on the chosen extent of the study area [215]. This is useful as it significantly reduces the amount of time and work needed for rapid ESAs and has the potential to greatly expand the model user base to include non-academic users, e.g. policy makers or non-governmental organisations. (2) "Tier 2" includes more complex models, such as agent-based pollination models, which are too computationally expensive for large scale applications [215]. ARIES has the potential to become the main platform for ESAs, once it leaves the beta testing phase. As of 2017, InVEST was the most used modeling framework for ESS [101]. ARIES is open-source, based on a semantic modeling framework, which allows for the integration and interaction between multiple ESS models across time and space, adheres to the "FAIR guiding principle for scientific data management and stewardship" (scientific data should be findable, accessible, interoperable and reusable), and is planned to be free to use [215].

5.3. The Aftermath of the Rubber Boom

5.3.1. ESS in Rubber-Dominated Landscapes

Häuser et al. [64] showed that the majority of ESS publications regarding rubber plantations concentrated on single or few ESS. This provides only limited information for decision-making, as sound decisions are better made with a holistic picture featuring multiple services from different groups of provisioning, regulating, supporting and cultural ESS. Studies that do not integrate multiple services are not as well-suited for the development of PES schemes or for land use planning in comparison to holistic assessments [64]. Although five ESS, that were considered to be of local importance by stakeholders, were included in this thesis, a number of other aspects had to be omitted from the analysis.

Firstly, it was not possible to consider water quality and nutrient retention in Nabanhe Reserve, due to insufficient field data. The only indicators for water quality in this thesis are the estimated sediment export values. This is a rather crucial omission as the ongoing deterioration of water quality in Nabanhe Reserve and the surrounding areas was a recurring point of discussion throughout the stakeholder workshops [201]. Secondly, agricultural yields of other crops in the study area (e.g. maize or rice) were also not considered. The SURUMER project had a clear focus on rubber cultivation. However, since more than 11% of the areal extent of Nabanhe Reserve is used for crop production (Table 2.1), the inclusion of any information on crop yields could have provided a more holistic picture of provisioning services in the study area. Other examples of omitted provisioning services are timber production and non-timber forest products. In Xishuangbanna, there is a long tradition of collecting plants for traditional Chinese medicine from forests [227]. Furthermore, rubber trees are usually harvested for timber after the end of their economic life cycle [21].

The results shown in Chapter 2-4 provide the biophysical basis for an economic assessment of ESS. The assessment of direct market values is relatively straight-forward for provisioning services, but also for some cultural services like recreation [228]. De Groot et al. [228] compiled a list of methods that are available for the monetary evaluation of indirect market values: (1) avoided cost (e.g. avoided damage by wetlands that provide natural flood control), (2) replacement cost (e.g. building treatment plant for water purification to replace the natural waste treatment provided by marshlands), (3) factor income (e.g. water quality improvements which increase the catch of commercial fisheries), (4) travel cost (e.g. recreational areas which attract visitors from distant areas and how much they are willing to pay for the journey), (5) and hedonic pricing (e.g. increased property values for houses with an ocean view in comparison to identical houses with less attractive scenery) [228]. With contingent valuation, service demands can be assessed with social survey questionnaires to reveal respondents willingness to pay [228]. An economic assessment of ESS values would have allowed for cost-benefit analyses in order to compare scenario outcomes or conduct a more detailed trade-off analysis between ESS values. This was not possible with the indicator-based approach used in this thesis. However, an economic assessment would also have introduced a number of uncertainties and assumptions, given the highly variable prices for rubber, or changing preferences for ESS.

A major point of potential improvement for ESS research is the implementation of long-term of ESS monitoring, as existing monitoring systems have not been designed for the majority of ESS [213]. Due to the end of the SURUMER project, long-term monitoring on the development of ESS is unfortunately not planned for Nabanhe Reserve.

5.3.2. The End of Rubber Expansion in Xishuangbanna

According to recent remote sensing analyses, the rubber boom in Xishuangbanna came to an end, as the area under rubber declined from 24% in 2014 to 21% in 2018 [27]. This is certainly a consequence of the decline of producer prices for rubber which has prevailed since 2011 [27]. At the same time, both the area under tea cultivation in Xishuangbanna as well as the producer prices for tea have increased in China [27,229]. However, due to the initial investment costs of establishing rubber plantations, farmers are inclined to not give up on rubber too quickly, even in the face of dropping prices [201]. After a number of years of low rubber prices, farmers in Xishuangbanna developed several coping strategies: (1) doing business as usual, (2) changing rubber management strategies, and (3) decreasing rubber tapping frequency or stop tapping altogether [218]. Information from the stakeholder workshops indicate that many rubber plantations might also be replaced by mango, banana and macadamia [201]. Rubber farmers with tea areas were not as affected by the rubber price drops in comparison to farmers that specialized in growing rubber [218]. Households with tea additionally benefitted from the infrastructure improvements that were, to a large extent, made possible by the past rubber boom [218]. This is another example of the importance of crop diversification for a better livelihood security. In addition, more diverse landscapes often provide a larger range and amount of ESS supply and have the potential to harbour a higher amount of species [40]. Although the low prices initiated a decrease of areas under rubber, the impact of climate change might again lead to an increase of rubber cultivation in Xishuangbanna. Golbon et al. [17] estimated that by 2050, the area suitable for rubber cultivation in Xishuangbanna may increase from currently 33.5% to 43.7% (under RCP4.5) or 60.1% (under RCP8.5) with high certainty.

5.4. Concluding Remarks and Final Recommendations

This thesis investigated scenarios of land use change and climate change in a rubber-dominated watershed in Xishuangbanna, and analysed how these change processes impact the supply of ESS and biodiversity. The case studies (Chapter 2-4) showed detrimental consequences induced by rubber expansions for all assessed ESS, with the exception of rubber yields. Further continuing the trend of rubber expansions in the study area is not the best option in terms of integrated ESS supply on a landscape scale. Land use planning alternatives, such as rubber expansions restricted to suitable areas only, in combination with reforestation efforts at less suitable locations, may be used to keep crucial ESS intact. Policy regulations at the local level, if properly assessed with spatial models and integrated stakeholder feedback, have the potential to buffer the typical trade-off between agricultural intensification and environmental protection. The implementation of these regulations might still pose a considerable challenge.

The work presented in this thesis had one major advantage in comparison to other ESAs: an overarching project (SURUMER) that was approaching the end of its duration and the resulting amount of research that had been done on sustainable rubber cultivation, mostly in the same study area (Nabanhe Reserve). This meant that a wide range of publications, data and an extensive set of protocols from group discussions and stakeholder workshops were available (or became available) at the time of defining the framework conditions of this cumulative thesis. Furthermore, it also facilitated the parameterization of the multiple InVEST modules and presented the opportunity to apply plausibility checks for some of them. In many tropical and sub-tropical environments, data availability is often insufficient for sound model parameterization, calibration, validation and upscaling modeling results to larger areas. In many cases, this can lead to compromises in the study design. Nevertheless, researchers highlight the need for more ESS studies that implement different spatio-temporal scales in tropical environments [101].

The aforementioned advantage of being conducted at the tail end of a larger research project also represented one of the major disadvantages of this thesis: most of it was performed at the very end of the project runtime of SURUMER, integrating available data and information into the study design and modeling process a posteriori. This approach goes against the recommendations of a number of synthesis studies on how to conduct holistic ESAs [41,213]. Lautenbach et al. [213] conclude that most of the blind spots in ESS research are a result of shortcomings in the initial phases of studies and recommend researchers to pay special attention to the experimental design in this critical phase. Nevertheless, although the major part of the presented research was performed a posteriori, most of the above-listed quality standards in ESS research were addressed in a satisfactory manner in this thesis.

The methods introduced in this thesis can easily be transferred to regions facing comparable land use situations, as the InVEST modeling framework and a large amount of the utilized spatial datasets (such as the IPCC climate projections) are freely available. However, given the multi-disciplinary aspect of the ESS concept, which spans the fields of natural and social sciences, this thesis did not cover the whole range of crucial aspects of rubber cultivation in MMSEA. The economic evaluation for ESS may be the most crucial omission, as the low prices for dry rubber initiated the end of rubber expansion in Xishuangbanna. As has been shown in this chapter, many questions are still open, as are opportunities for science to advance the field of ESS research. Truly multi- and interdisciplinary approaches are necessary in order to holistically assess the complexity of SES with all of the inherent dynamics and feedbacks.

Summary

This cumulative PhD thesis investigates the expansion of rubber (*Hevea brasiliensis* Müll. Arg.) plantations and the ensuing multiple impacts on biodiversity and the supply of ecosystem services (ESS) in a mountainous watershed in Xishuangbanna Prefecture, Southwestern China. In recent decades, large-scale monoculture plantations have expanded at an unprecedented rate throughout the mountainous regions of Southeast Asia. Deforestation and the replacement of traditional swidden agriculture by permanent cultivation systems, such as rubber plantations, have led to substantial declines in the supply of ESS. This may further decrease under the additional environmental pressure from climate change processes such as extended dry periods, rising temperatures or changing precipitation patterns.

One means to better anticipate the impact of future rubber plantation expansions is to develop land use scenarios in cooperation with local stakeholders and simulate their impact on the supply of ESS with spatially explicit ESS models. Up to now, multidisciplinary projects on rubber cultivation, which integrate research on a variety of ESS, have been few and far between. This cumulative PhD thesis intends to fill this research gap.

In recent decades, the study area, the Naban River Watershed National Nature Reserve (or Nabanhe Reserve in abbreviated form) saw the expansion of rubber plantations and the loss of extensive forest areas. Workshops with regional stakeholders resulted in the development of three future land use scenarios for Nabanhe Reserve (2015 – 2040), varying in their degree of rubber expansions, management options and reforestations efforts.

In the first study, the InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) modeling framework was used to analyze the impact of these rubber expansion scenarios on selected ESS: sediment retention, water yield, habitat quality, and carbon sequestration. In addition, a model for assessing potential rubber yields was developed and implemented in ArcGIS. The analysis focused on investigating the percentage deviations of integrated ESS indices in each scenario, as compared to the initial state of 2015 and utilized different statistical weighting methods to include rankings for the preference of ESS from three contrasting stakeholder groups (prefecture administration, tourists, off-site citizens). The business-as-usual scenario (BAU, continuous rubber expansions based on past expansion rates) revealed an increase in rubber yields trading off against all other ESS analyzed. Compared to BAU, the measures introduced in the balanced-trade-offs scenario (BTO, reforestation, reduced herbicide application, riverine buffer zones) reduced the total amount of rubber yield but enhanced habitat quality and regulating ESS (carbon storage, sediment retention and water yield). The study concludes that the integrated ESS indices would be overestimated without the inclusion of the stakeholder groups.

The second study introduced a new method to identify potential tipping points in the supply of ESS. Here, time-series data derived from InVEST have been combined with a sequential, data-driven algorithm (R-method) to identify potential tipping points in the supply of ESS within two contrasting scenarios of rubber expansion in Nabanhe Reserve (BAU and BTO). Tipping points were defined as any situation in which the state of a system is changed through positive feedback as a result of accelerating changes. The tipping point analysis included hydrological, agronomical, and climate-regulation ESS, as well as multiple facets of biodiversity (habitat quality for vertebrate, invertebrate, and plant species). The model results showed regime shifts indicating potential tipping points, which were linked to abrupt changes in rubber yields, in both scenarios and at varying spatial scales. The study concludes

that sophisticated land use planning may provide benefits in the supply of ESS at watershed scale, but that potential trade-offs at sub-watershed scales should not be neglected.

The third study focused on modeling hydrological ESS (water yield and sediment export) in Nabanhe Reserve under multiple scenarios of land use and climate change in order to assess how both drivers influence the supply of these ESS. Three rubber expansion scenarios were analyzed in combination with multiple climate change scenarios using the InVEST modeling framework. As projected climate change varies remarkably between different climate models, datasets of temperature and precipitation changes, derived from nine General Circulation Models of the Fifth Assessment Report of the IPCC (Intergovernmental Panel on Climate Change) were integrated into InVEST in order to capture the uncertainty in climate projections. Simulation results showed that the effect of land use and land management decisions on water yield in Nabanhe Reserve are relatively minor (4% difference in water yield between land use scenarios), when compared to the effects that future climate change will exert on water yield (up to 15% increase or 13% decrease in water yield compared to the baseline climate). Changes in sediment export were more sensitive to land use change (15% increase or 64% decrease) in comparison to the effects of climate change (up to 10% increase). The study concludes that in the future, particularly dry years may have a more pronounced effect on the water balance in Nabanhe Reserve as the higher potential evapotranspiration increases the probability for periods of water scarcity, especially in the dry season.

In conclusion, the studies showed detrimental consequences induced by rubber expansions for all assessed ESS, with the exception of rubber yields. Further continuing the trend of rubber expansions in the study area is not the best option in terms of integrated ESS supply on a landscape scale. Land use planning alternatives, such as rubber expansions restricted to suitable areas only, in combination with reforestation efforts at less suitable locations, may be used to keep crucial environmental functions intact. Policy regulations at the local level, if properly assessed with spatial models and integrated stakeholder feedback, have the potential to buffer the typical trade-off between agricultural intensification and environmental protection. The implementation of these regulations might still pose a considerable challenge. The methods introduced in this Dissertation can easily be transferred to regions facing comparable land use situations, as the InVEST modeling framework and a large amount of the utilized spatial datasets (such as the IPCC climate projections) are freely available.

Zusammenfassung

Die vorgelegte Doktorarbeit befasst sich mit der Ausweitung von Kautschukplantagen (*Hevea brasiliensis* Müll. Arg.) und den daraus folgenden vielfältigen Auswirkungen auf Biodiversität und die Bereitstellung von Ökosystemdienstleistungen (ÖSD) in einem bergigen Wassereinzugsgebiet in der Präfektur Xishuangbanna im Südwesten Chinas. In den vergangenen Jahrzehnten hat der Anteil großflächiger Monokulturplantagen in den Hochlandregionen Südostasiens in einem noch nie dagewesenen Tempo zugenommen. Abholzung und die Ablösung des traditionellen Wanderfeldbaus durch permanente Anbausystem, wie z.B. Kautschukplantagen, haben zu einem erheblichen Rückgang in der Bereitstellung von ÖSD geführt. Diese könnten in Zukunft aufgrund zusätzlicher Belastungen durch Klimawandelprozesse wie ausgedehnte Trockenperioden, steigende Temperaturen oder veränderte Niederschlagsmuster noch weiter abnehmen.

Eine Möglichkeit um die Auswirkungen zukünftiger Ausweitungen von Kautschukplantagen besser abschätzen zu können, besteht darin, in Zusammenarbeit mit verschiedenen lokalen Interessenvertretern Landnutzungsszenarien zu entwickeln und deren Auswirkungen auf die Bereitstellung von ÖSD mit räumlich-expliziten ÖSD-Modellen zu simulieren. Bislang gab es jedoch nur wenige multidisziplinäre Projekte zum Kautschukanbau, die eine Vielzahl von ÖSD berücksichtigten. Die vorliegende kumulative Doktorarbeit soll diese Forschungslücke schließen.

In den vergangenen Jahrzehnten kam es im Untersuchungsgebiet, dem Naban River Watershed National Nature Reserve (oder Nabanhe-Reservat in abgekürzter Form) zu einer rasanten Ausweitung von Kautschukplantagen und dem Verlust weitläufiger Waldflächen. Aus Workshops mit regionalen Interessenvertretern entstanden drei Landnutzungsszenarien für die Zukunft des Nabanhe-Reservats (2015 – 2040), die sich hinsichtlich des Ausmaßes der Kautschukausweitung, verschiedener Managementoptionen und Wiederaufforstungsstrategien unterscheiden.

In der ersten Fallstudie wurde das Model InVEST (Integrated Valuation of Ecosystem Services and Trade-Offs) verwendet, um die Auswirkungen der Landnutzungsszenarien auf vier ausgewählte ÖSD zu analysieren: Sedimentretention, Wasserertrag, Habitat-Qualität und Kohlenstoffbindung. Zusätzlich wurde ein Modell zur Abschätzung potenzieller Kautschukerträge entwickelt und in ArcGIS implementiert. Die Analyse konzentrierte sich auf die Untersuchung der prozentualen Abweichungen der integrierten ÖSD-Indizes in jedem Szenario verglichen mit dem Ausgangszustand von 2015 (Baseline). Weiterhin wurden verschiedene statistische Gewichtungsmethoden benutzt, um die Präferenzen dreier kontrastierender Interessengruppen (Präfektur-Administration, Touristen, Externe Bürger) in der Auswertung der ÖSD Ergebnisse miteinzubinden. Das Business-As-Usual Szenario (BAU, voranschreitende Kautschukausweitung basierend auf Ausweitungsraten der vergangenen Jahre) führte zum Anstieg der Kautschukerträge und zur Verminderung der anderen betrachteten ÖSD. Im Vergleich zum BAU-Szenario zeigte das Balanced-Trade-Offs-Szenario (BTO, Wiederaufforstung, reduzierter Herbizideinsatz, Pufferzonen um die Flüsse im Wassereinzugsgebiet) verringerte Kautschukerträge, jedoch aber Verbesserungen der Habitat-Qualität und der anderen regulierenden ÖSD (Kohlenstoffbindung, Sedimentretention und Wasserertrag). Die Studie kommt zu dem Schluss, dass die integrierten ÖSD Indizes ohne die Einbeziehung der Interessengruppen überbewertet würden.

Die zweite Studie stellt eine neue Methode zur Identifikation potenzieller Kipp-Punkte (KP) in der Bereitstellung von ÖSD vor. Hierbei werden Zeitreihendaten von InVEST mit einem sequenziellen, datengetriebenen Algorithmus (R-Methode) kombiniert, um potenzielle Kipp-Punkte in der Bereitstellung von ÖSD innerhalb zweier gegensätzlicher Landnutzungsszenarios (BAU und BTO)

abzuleiten. Kipp-Punkte wurden hier als Situation definiert, in der der Zustand eines Systems durch sich beschleunigende, positive Rückkopplungseffekte verändert wird. Die Kipp-Punkt-Analyse umfasste hydrologische, agronomische und klimaregulierende ÖSD sowie mehrere Facetten der Artenvielfalt (Habitat-Qualität für Wirbeltiere, wirbellose Tiere und Pflanzen). Die Modellergebnisse zeigten in beiden Landnutzungsszenarien auf unterschiedlichen räumlichen Skalen Regimeverschiebungen, die auf potenzielle Kipp-Punkte hindeuteten und aus abrupten Veränderungen der Kautschukerträge hervorgingen. Die Studie bietet eine Methode zur Risikoverringerung im Überschreiten von Kipp-Punkten in der Bereitstellung von ÖSD in vom Kautschukanbau beeinflussten Wassereinzugsgebieten. Verbesserungen in der Bereitstellung von ÖSD können mit Hilfe von gut geplanten Landnutzungsstrategien auf der Skalenebene von Wassereinzugsgebieten erreicht werden. Potenzielle Trade-Offs auf kleineren Skalenebenen sollten jedoch auch beachtet werden.

Die dritte Studie befasste sich mit der Modellierung hydrologischer ÖSD (Wasserertrag und Sedimentretention) im Nabanhe-Reservat unter verschiedenen Landnutzungs- und Klimawandelszenarien, um zu beurteilen, wie beide Faktoren die Bereitstellung dieser ÖSD beeinflussen. Drei Landnutzungsszenarien wurden in Kombination mit mehreren Klimawandel-Szenarien mit Hilfe von InVEST analysiert. Da prognostizierte Klimaveränderungen verschiedener Klimamodelle oft stark variieren, wurden die für die ÖSD Modellierung benötigten Datensätze hinsichtlich Temperatur- und Niederschlagsveränderungen aus neun General Circulation Models (GCMs) des fünften Reports des IPCC (Intergovernmental Panel on Climate Change) entnommen und in InVEST integriert, um die Unsicherheiten in den Klimaprojektionen zu erfassen. Die Simulationsergebnisse zeigen, dass die Auswirkungen von Landnutzungs- und Landmanagemententscheidungen auf den Wasserertrag im Nabanhe-Reservat relativ gering sind (ein Unterschied von 4% im Wasserertrag zwischen den Landnutzungsszenarien), insbesondere wenn man sie mit den Auswirkungen des bevorstehenden Klimawandels vergleicht (eine 15% Zunahme oder 13% Abnahme des Wasserertrags verglichen mit dem Baseline-Klima). Sedimentexportwerte reagierten sensitiver auf Landnutzungsänderungen (15% Zunahme oder 64% Abnahme) im Vergleich zu den Auswirkungen des Klimawandels (bis zu 10% Zunahme). Die Studie kommt zu dem Schluss, dass sich in Zukunft besonders trockene Jahre stärker auf den Wasserhaushalt im Nabanhe-Reservat auswirken könnten, da die höhere potenzielle Evapotranspiration die Wahrscheinlichkeit für Zeiten der Wasserknappheit erhört, was insbesondere in der Trockenzeit eintreten könnte.

Zusammenfassend zeigten die Studien nachteilige Folgen der Kautschukausweitung in Bezug auf alle betrachteten ÖSD mit Ausnahme der Kautschukerträge. Auf Landschaftsebene ist die zusätzliche Ausweitung von Kautschukflächen nicht die beste Option im Hinblick auf die integrierte ÖSD Bereitstellung. Alternativen der Landnutzungsplanung, wie z.B. die Kautschukausweitung auf geeignete Flächen zu beschränken und andere Flächen wieder aufzuforsten, können genutzt werden, um wichtige Umweltfunktion zu erhalten. Politische Regelungen auf lokaler Ebene haben das Potenzial den typischen Zielkonflikt zwischen landwirtschaftlicher Intensivierung und Umweltschutz zu mildern, sofern sie mit räumlich expliziter Modellierung und dem Feedback von Interessengruppen ausgewertet werden. Die Umsetzung solcher Regelungen könnte jedoch eine beträchtliche Herausforderung darstellen. Die in dieser Dissertation vorgestellten Methoden können leicht auf Regionen mit vergleichbaren Landnutzungssituationen übertragen werden, da sowohl InVEST als auch der Großteil der verwendeten räumlichen Datensätze (wie die IPCC-Klimaprojektionen) frei verfügbar sind.

Curriculum Vitae

Date/place of birth	21 June 1989, Bad Friedrichshall, Germany
Nationality	german
Marital status	unmarried
Address	Breitscheidstr. 91, 70176 Stuttgart
Email	thellmannkevin@gmail.com

Educational Record

2017 – present	University of Hohenheim, Stuttgart, Germany PhD Student at the Institute of Agricultural Sciences in the Tropics (Hans-Ruthenberg-Institut), Scholarship holder in the Graduate School „Water-People-Agriculture“
2013 – 2016	University of Hohenheim, Stuttgart, Germany Earth System Science, Master of Science (GPA: 1.9)
2009 – 2013	University of Hohenheim, Stuttgart, Germany Biobased Products & Bioenergy, Bachelor of Science (GPA: 2.4)
2005 – 2008	Wilhelm-Maybach-Schule, Heilbronn, Germany Abitur (GPA: 2.6)

Employment Record

2016 – 2017	University of Hohenheim, Institute of Agricultural Sciences in the Tropics (Hans-Ruthenberg-Institut), Stuttgart, Germany Scientific staff: Research on the acquisition, preparation and integration of spatial environmental data for multi-disciplinary ecosystem service and biodiversity modeling in the SURUMER project (Sustainable Rubber Cultivation in the Mekong Region)
2015 – 2017	University of Hohenheim, Institute of Soil Science and Land Evaluation, Stuttgart, Germany Research assistant: Tutor for the M.Sc. exercise courses of the modules “Spatial Data Analysis with GIS” and “Environmental Modeling”

Additional Education

August 2018	Karlsruhe Institute of Technology, KIT Campus Alpin, Garmisch-Partenkirchen, Germany Summer School „Ecosystems and Land Use Change“
July 2018	University of Hamburg, Hamburg, Germany Summer School „Climate Change“

Stuttgart, 2020

Kevin Thellmann

References

1. Meyer, W.B.; Turner II, B.L. Land-use/land-cover change: Challenges for geographers. *GeoJournal* **1996**, *39*, 237–240.
2. Rindfuss, R.R.; Walsh, S.J.; Turner II, B.L.; Fox, J.; Mishra, V. Developing a science of land change: Challenges and methodological issues. *Proc. Natl. Acad. Sci. U. S. A.* **2004**, *101*, 13976–13981.
3. Rees, W.G. *Physical principles of remote sensing*; Cambridge University Press, 2013; ISBN 978-0-521-18116-7.
4. Verburg, P.H.; Schot, P.P.; Dijst, M.J.; Veldkamp, A. Land use change modelling: Current practice and research priorities. *GeoJournal* **2004**, *61*, 309–324.
5. Fox, J.; Vogler, J.B.; Sen, O.L.; Giambelluca, T.W.; Ziegler, A.D. Simulating land-cover change in Montane mainland southeast Asia. *Environ. Manage.* **2012**, *49*, 968–979.
6. Myers, N.; Mittermeier, R.A.; Mittermeier, C.G.; Da Fonseca, G.A.B.; Kent, J. Biodiversity hotspots for conservation priorities. *Nature* **2000**, *403*, 853–858.
7. Jarvis, A.; Reuter, H.I.; Nelson, A.; Guevara, E. CGIAR-CSI SRTM – SRTM 90m DEM Digital Elevation Database Available online: http://srtm.csi.cgiar.org/ (accessed on Jan 9, 2020).
8. Free Spatial Data | DIVA-GIS Available online: https://diva-gis.org/Data (accessed on Jan 9, 2020).
9. Fox, J.M.; Castella, J.-C.; Ziegler, A.D.; Westley, S.B. Rubber plantations expand in mountainous Southeast Asia: What are the consequences for the environment? *Asia Pac. Issues* **2014**.
10. Dressler, W.H.; Wilson, D.; Clendenning, J.; Cramb, R.; Keenan, R.; Mahanty, S.; Bruun, T.B.; Mertz, O.; Lasco, R.D. The impact of swidden decline on livelihoods and ecosystem services in Southeast Asia: A review of the evidence from 1990 to 2015. *Ambio* **2017**, *46*, 291–310.
11. Ziegler, A.D.; Bruun, T.B.; Guardiola-Claramonte, M.; Giambelluca, T.W.; Lawrence, D.; Thanh Lam, N. Environmental consequences of the demise in swidden cultivation in montane mainland southeast asia: Hydrology and geomorphology. *Hum. Ecol.* **2009**, *37*, 361–373.
12. Cotter, M.; Häuser, I.; Harich, F.K.; He, P.; Sauerborn, J.; Treydte, A.C.; Martin, K.; Cadisch, G. Biodiversity and ecosystem services-A case study for the assessment of multiple species and functional diversity levels in a cultural landscape. *Ecol. Indic.* **2017**, *75*, 111–117.
13. Ahrends, A.; Hollingsworth, P.M.; Ziegler, A.D.; Fox, J.M.; Chen, H.; Su, Y.; Xu, J. Current trends of rubber plantation expansion may threaten biodiversity and livelihoods. *Glob. Environ. Change* **2015**, *34*, 48–58.
14. Li, Z.; Fox, J.M. Mapping rubber tree growth in mainland Southeast Asia using time-series MODIS 250 m NDVI and statistical data. *Appl. Geogr.* **2012**, *32*, 420–432.
15. Chen, H.; Yi, Z.-F.; Schmidt-Vogt, D.; Ahrends, A.; Beckschäfer, P.; Kleinn, C.; Ranjitkar, S.; Xu, J. Pushing the limits: The pattern and dynamics of rubber monoculture expansion in Xishuangbanna, SW China. *PLoS ONE* **2016**, *11*, 1–15.
16. Langenberger, G.; Cadisch, G.; Martin, K.; Min, S.; Waibel, H. Rubber intercropping: a viable concept for the 21st century? *Agrofor. Syst.* **2017**, *91*, 577–596.
17. Golbon, R.; Cotter, M.; Sauerborn, J. Climate change impact assessment on the potential rubber cultivating area in the Greater Mekong Subregion. *Environ. Res. Lett.* **2018**, *13*, 084002.
18. Cornish, K. Alternative Natural Rubber Crops: Why Should We Care? *Technol. Innov.* **2017**, *18*, 244–255.
19. Priyadarshan, P.M.; Hoa, T.T.T.; Huasun, H.; Gonçalves, P.D.S. Yielding potential of rubber (Hevea brasiliensis) in sub-optimal environments. *J. Crop Improv.* **2005**, *14*, 221–247.
20. FAOSTAT Available online: http://www.fao.org/faostat/en/#home (accessed on Feb 10, 2020).
21. Cotter, M.; Martin, K.; Sauerborn, J. How do “Renewable Products” impact biodiversity and ecosystem services - The example of natural rubber in China. *J. Agric. Rural Dev. Trop. Subtrop.* **2009**, *110*, 9–22.

22. Hora Júnior, B.T. da; de Macedo, D.M.; Barreto, R.W.; Evans, H.C.; Mattos, C.R.R.; Maffia, L.A.; Mizubuti, E.S.G. Erasing the Past: A New Identity for the Damoclean Pathogen Causing South American Leaf Blight of Rubber. *PLoS ONE* **2014**, *9*, e104750.
23. Häuser, I.; Martin, K.; Germer, J.; He, P.; Blagodatsky, S.; Liu, H.; Krauß, M.; Rajaona, A.; Shi, M.; Pelz, S.; et al. Environmental and socio-economic impacts of rubber cultivation in the Mekong region: challenges for sustainable land use. *CAB Rev. Perspect. Agric. Vet. Sci. Nutr. Nat. Resour.* **2015**, *10*.
24. Zhang, J.; Cao, M. Tropical forest vegetation of Xishuangbanna, SW China and its secondary changes, with special reference to some problems in local nature conservation. *Biol. Conserv.* **1995**, *73*, 229–238.
25. Ziegler, A.D.; Fox, J.M.; Xu, J. The rubber juggernaut. *Science* **2009**, *324*, 1024–1025.
26. Xu, J. The political, social, and ecological transformation of a landscape: The case of rubber in Xishuangbanna, China. *Mt. Res. Dev.* **2006**, *26*, 254–262.
27. Zhang, J.-Q.; Corlett, R.T.; Zhai, D. After the rubber boom: good news and bad news for biodiversity in Xishuangbanna, Yunnan, China. *Reg. Environ. Change* **2019**, *19*, 1713–1724.
28. Millennium Ecosystem Assessment *Ecosystems and Human Well-being: Synthesis*; Island Press: Washington, DC, 2005; ISBN 1-59726-040-1.
29. Asah, S.T.; Guerry, A.D.; Blahna, D.J.; Lawler, J.J. Perception, acquisition and use of ecosystem services: Human behavior, and ecosystem management and policy implications. *Ecosyst. Serv.* **2014**, *10*, 180–186.
30. Daily, G.C. *Nature's services: societal dependence on natural ecosystems*; Island Press: Washington, DC, 1997; Vol. Vol. 3;
31. Costanza, R.; D'Arge, R.; De Groot, R.; Farber, S.; Grasso, M.; Hannon, B.; Limburg, K.; Naeem, S.; O'Neill, R.V.; Paruelo, J.; et al. The value of the world's ecosystem services and natural capital. *Nature* **1997**, *387*, 253–260.
32. Costanza, R.; de Groot, R.; Braat, L.; Kubiszewski, I.; Fioramonti, L.; Sutton, P.; Farber, S.; Grasso, M. Twenty years of ecosystem services: How far have we come and how far do we still need to go? *Ecosyst. Serv.* **2017**, *28*, 1–16.
33. TEEB *The Economics of Ecosystems and Biodiversity: Ecological and Economic Foundations*; Kumar, P., Ed.; Routledge: London, Abington and New York, 2012; ISBN 978-0-415-50108-8.
34. About | IPBES Available online: https://ipbes.net/about (accessed on Feb 12, 2020).
35. Gagnon Thompson, S.C.; Barton, M.A. Ecocentric and anthropocentric attitudes toward the environment. *J. Environ. Psychol.* **1994**, *14*, 149–157.
36. McCauley, D.J. Selling out on nature. *Nature* **2006**, *443*, 27–28.
37. Costanza, R.; Chichakly, K.; Dale, V.; Farber, S.; Finnigan, D.; Grigg, K.; Heckbert, S.; Kubiszewski, I.; Lee, H.; Liu, S.; et al. Simulation games that integrate research, entertainment, and learning around ecosystem services. *Ecosyst. Serv.* **2014**, *10*, 195–201.
38. Foley, J.A.; DeFries, R.; Asner, G.P.; Barford, C.; Bonan, G.; Carpenter, S.R.; Chapin, F.S.; Coe, M.T.; Daily, G.C.; Gibbs, H.K.; et al. Global consequences of land use. *Science* **2005**, *309*, 570–574.
39. Rockström, J.; Steffen, W.; Noone, K.; Persson, Å.; Chapin, F.S.; Lambin, E.F.; Lenton, T.M.; Scheffer, M.; Folke, C.; Schellnhuber, H.J.; et al. A safe operating space for humanity. *nature* **2009**, *461*, 472–475.
40. de Groot, R.S.; Alkemade, R.; Braat, L.; Hein, L.; Willemen, L. Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. *Ecol. Complex.* **2010**, *7*, 260–272.
41. Seppelt, R.; Fath, B.; Burkhard, B.; Fisher, J.L.; Grêt-Regamey, A.; Lautenbach, S.; Pert, P.; Hotes, S.; Spangenberg, J.; Verburg, P.H.; et al. Form follows function? Proposing a blueprint for ecosystem service assessments based on reviews and case studies. *Ecol. Indic.* **2012**, *21*, 145–154.
42. Ostrom, E. A General Framework for Analyzing Sustainability of Social-Ecological Systems. *Science* **2009**, *325*, 419–422.

43. The Natural Capital Project *InVEST 3.3.3*; 2016;
44. Sharp, R.; Tallis, H.; Ricketts, T.; Guerry, A.D.; Wood, S.A.; Chaplin-Kramer, R.; Nelson, E.; Ennaanay, D.; Wolny, S.; Olwero, N.; et al. InVEST 3.3.3 User's Guide. The Natural Capital Project: Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund, 2016.
45. Villa, F.; Bagstad, K.J.; Voigt, B.; Johnson, G.W.; Portela, R.; Honzák, M.; Batker, D. A Methodology for Adaptable and Robust Ecosystem Services Assessment. *PLoS ONE* **2014**, *9*, e91001.
46. Boumans, R.; Roman, J.; Altman, I.; Kaufman, L. The Multiscale Integrated Model of Ecosystem Services (MIMES): Simulating the interactions of coupled human and natural systems. *Ecosyst. Serv.* **2015**, *12*, 30–41.
47. Bagstad, K.J.; Semmens, D.J.; Waage, S.; Winthrop, R. A comparative assessment of decision-support tools for ecosystem services quantification and valuation. *Ecosyst. Serv.* **2013**, *5*, 27–39.
48. Thellmann, K.; Blagodatsky, S.; Häuser, I.; Liu, H.; Wang, J.; Asch, F.; Cadisch, G.; Cotter, M. Assessing Ecosystem Services in Rubber Dominated Landscapes in South-East Asia—A Challenge for Biophysical Modeling and Transdisciplinary Valuation. *Forests* **2017**, *8*, 505.
49. Daily, G.C.; Matson, P.A. Ecosystem services: From theory to implementation. *Proc. Natl. Acad. Sci. U. S. A.* **2008**, *105*, 9455–9456.
50. Costanza, R.; de Groot, R.; Sutton, P.; van der Ploeg, S.; Anderson, S.J.; Kubiszewski, I.; Farber, S.; Turner, R.K. Changes in the global value of ecosystem services. *Glob. Environ. Change* **2014**, *26*, 152–158.
51. Metzger, M.J.; Rounsevell, M.D.A.; Acosta-Michlik, L.; Leemans, R.; Schröter, D. The vulnerability of ecosystem services to land use change. *Agric. Ecosyst. Environ.* **2006**, *114*, 69–85.
52. Martínez-Harms, M.J.; Balvanera, P. Methods for mapping ecosystem service supply: A review. *Int. J. Biodivers. Sci. Ecosyst. Serv. Manag.* **2012**, *8*, 17–25.
53. Fox, J.; Castella, J.-C. Expansion of rubber (Hevea brasiliensis) in Mainland Southeast Asia: What are the prospects for smallholders? *J. Peasant Stud.* **2013**, *40*, 155–170.
54. Ahlheim, M.; Börger, T.; Frör, O. Replacing rubber plantations by rain forest in Southwest China—who would gain and how much? *Environ. Monit. Assess.* **2015**, *187*, 1–20.
55. Li, H.; Ma, Y.; Liu, W.; Liu, W. Soil changes induced by rubber and tea plantation establishment: Comparison with tropical rain forest soil in Xishuangbanna, SW China. *Environ. Manage.* **2012**, *50*, 837–848.
56. Wu, Z.-L.; Liu, H.-M.; Liu, L.-Y. Rubber cultivation and sustainable development in Xishuangbanna, China. *Int. J. Sustain. Dev. World Ecol.* **2001**, *8*, 337–345.
57. Liu, H.; Blagodatsky, S.; Giese, M.; Liu, F.; Xu, J.; Cadisch, G. Impact of herbicide application on soil erosion and induced carbon loss in a rubber plantation of Southwest China. *Catena* **2016**, *145*, 180–192.
58. Li, H.; Ma, Y.; Aide, T.M.; Liu, W. Past, present and future land-use in Xishuangbanna, China and the implications for carbon dynamics. *For. Ecol. Manag.* **2008**, *255*, 16–24.
59. Yang, X.; Blagodatsky, S.; Lippe, M.; Liu, F.; Hammond, J.; Xu, J.; Cadisch, G. Land-use change impact on time-averaged carbon balances: Rubber expansion and reforestation in a biosphere reserve, South-West China. *For. Ecol. Manag.* **2016**, *372*, 149–163.
60. Guardiola-Claramonte, M.; Troch, P.A.; Ziegler, A.D.; Giambelluca, T.W.; Durcik, M.; Vogler, J.B.; Nullet, M.A. Hydrologic effects of the expansion of rubber (Hevea brasiliensis) in a tropical catchment. *Ecohydrology* **2010**, *3*, 306–314.
61. Li, H.; Aide, T.M.; Ma, Y.; Liu, W.; Cao, M. Demand for rubber is causing the loss of high diversity rain forest in SW China. *Biodivers. Conserv.* **2007**, *16*, 1731–1745.
62. Meng, L.-Z.; Martin, K.; Weigel, A.; Liu, J.-X. Impact of rubber plantation on carabid beetle communities and species distribution in a changing tropical landscape (southern Yunnan, China). *J. Insect Conserv.* **2012**, *16*, 423–432.

63. Cotter, M.; Berkhoff, K.; Gibreel, T.; Ghorbani, A.; Golbon, R.; Nuppenau, E.-A.; Sauerborn, J. Designing a sustainable land use scenario based on a combination of ecological assessments and economic optimization. *Ecol. Indic.* **2014**, *36*, 779–787.
64. Häuser, I.; Thellmann, K.; Cotter, M.; Sauerborn, J. Ecosystem services and biodiversity of rubber plantations-a systematic review. *CAB Rev. Perspect. Agric. Vet. Sci. Nutr. Nat. Resour.* **2015**, *10*.
65. Pfund, J.-L.; Watts, J.D.; Boissière, M.; Boucard, A.; Bullock, R.M.; Ekadinata, A.; Dewi, S.; Feintrenie, L.; Levang, P.; Rantala, S.; et al. Understanding and integrating local perceptions of trees and forests into incentives for sustainable landscape management. *Environ. Manage.* **2011**, *48*, 334–349.
66. Sohel, M.S.I.; Ahmed Mukul, S.; Burkhard, B. Landscape's capacities to supply ecosystem services in Bangladesh: A mapping assessment for Lawachara National Park. *Ecosyst. Serv.* **2014**.
67. Hu, H.; Liu, W.; Cao, M. Impact of land use and land cover changes on ecosystem services in Menglun, Xishuangbanna, Southwest China. *Environ. Monit. Assess.* **2008**, *146*, 147–156.
68. Liu, S.; Yin, Y.; Liu, X.; Cheng, F.; Yang, J.; Li, J.; Dong, S.; Zhu, A. Ecosystem Services and landscape change associated with plantation expansion in a tropical rainforest region of Southwest China. *Ecol. Model.* **2017**, *353*, 129–138.
69. Bateman, I.J.; Brouwer, R.; Ferrini, S.; Schaafsma, M.; Barton, D.N.; Dubgaard, A.; Hasler, B.; Hime, S.; Liekens, I.; Navrud, S.; et al. Making Benefit Transfers Work: Deriving and Testing Principles for Value Transfers for Similar and Dissimilar Sites Using a Case Study of the Non-Market Benefits of Water Quality Improvements Across Europe. *Environ. Resour. Econ.* **2011**, *50*, 365–387.
70. Koschke, L.; Fürst, C.; Frank, S.; Makeschin, F. A multi-criteria approach for an integrated land-cover-based assessment of ecosystem services provision to support landscape planning. *Ecol. Indic.* **2012**, *21*, 54–66.
71. Atkinson, G.; Bateman, I.; Mourato, S. Recent advances in the valuation of ecosystem services and biodiversity. *Oxf. Rev. Econ. Policy* **2012**, *28*, 22–47.
72. Gos, P.; Lavorel, S. Stakeholders' expectations on ecosystem services affect the assessment of ecosystem services hotspots and their congruence with biodiversity. *Int. J. Biodivers. Sci. Ecosyst. Serv. Manag.* **2012**, *8*, 93–106.
73. Seppelt, R.; Dormann, C.F.; Eppink, F.V.; Lautenbach, S.; Schmidt, S. A quantitative review of ecosystem service studies: Approaches, shortcomings and the road ahead. *J. Appl. Ecol.* **2011**, *48*, 630–636.
74. The Natural Capital Project » How does it work? Available online: https://www.naturalcapitalproject.org/how-do-we-know-it-works/#where-we-work (accessed on Oct 25, 2017).
75. Thompson, J.R.; Wiek, A.; Swanson, F.J.; Carpenter, S.R.; Fresco, N.; Hollingsworth, T.; Spies, T.A.; Foster, D.R. Scenario studies as a synthetic and integrative research activity for long-term ecological research. *BioScience* **2012**, *62*, 367–376.
76. Seppelt, R.; Lautenbach, S.; Volk, M. Identifying trade-offs between ecosystem services, land use, and biodiversity: A plea for combining scenario analysis and optimization on different spatial scales. *Curr. Opin. Environ. Sustain.* **2013**, *5*, 458–463.
77. Li, Z.; Zhang, Y.; Wang, S.; Yuan, G.; Yang, Y.; Cao, M. Evapotranspiration of a tropical rain forest in Xishuangbanna, Southwest China. *Hydrol. Process.* **2010**, *24*, 2405–2416.
78. Wehner, S.; Herrmann, S.; Berkhoff, K. CLUENaban - A land use change model combining social factors with physical landscape factors for a mountainous area in Southwest China. *Ecol. Indic.* **2014**, *36*, 757–765.
79. Aenis, T.; Wang, J.; Hofmann-Souki, S.; Lixia, T.; Langenberger, G.; Cadisch, G.; Martin, K.; Cotter, M.; Krauss, M.; Waibel, H. Research-praxis integration in South China – The rocky road to implement strategies for sustainable rubber cultivation in the Mekong Region. In Proceedings of the River Sedimentation - Proceedings of the 13th International Symposium on River Sedimentation, ISRS 2016; 2017; p. 1343.

80. Aenis, T.; Wang, J. From information giving to mutual scenario definition: Stakeholder participation towards Sustainable Rubber Cultivation in Xishuangbanna, Southwest China. In *Farming Systems Facing Global Challenges: Capacities and Strategies.*; Aenis, T., Knierim, A., Riecher, M.-C., Ridder, R., Schobert, H., Fischer, H., Eds.; Humboldt-Universität zu Berlin, Lebenswissenschaftliche Fakultät, 2016; Vol. 1, pp. 618–625.
81. Naban River Watershed National Nature Reserve Bureau *Naban River Watershed National Nature Reserve (NRWNNR) - Atlas of Ecological Baseline Results*; 666100 Jinghong, Yunnan Province, China: NRWNNRB, 2014.
82. Xu, J.; Grumbine, R.E.; Beckschäfer, P. Landscape transformation through the use of ecological and socioeconomic indicators in Xishuangbanna, Southwest China, Mekong Region. *Ecol. Indic.* **2014**, *36*, 749–756.
83. Yi, Z.-F.; Cannon, C.H.; Chen, J.; Ye, C.-X.; Swetnam, R.D. Developing indicators of economic value and biodiversity loss for rubber plantations in Xishuangbanna, southwest China: A case study from Menglun township. *Ecol. Indic.* **2014**, *36*, 788–797.
84. Marohn, C.; Cadisch, G. Land Use Change Impact Assessment Available online: https://lucia.uni-hohenheim.de/en/85418 (accessed on Oct 10, 2017).
85. Chang, N.-B.; Wen, C.-G.; Wu, S.L. Optimal management of environmental and land resources in a reservoir watershed by multiobjective programming. *J. Environ. Manage.* **1995**, *44*, 144–161.
86. Estrella, R.; Cattrysse, D.; van Orshoven, J. Comparison of Three Ideal Point-Based Multi-Criteria Decision Methods for Afforestation Planning. *Forests* **2014**, *5*, 3222–3240.
87. Uhde, B.; Heinrichs, S.; Stiehl, C.R.; Ammer, C.; Müller-Using, B.; Knoke, T. Bringing ecosystem services into forest planning – Can we optimize the composition of Chilean forests based on expert knowledge? *For. Ecol. Manag.* **2017**, *404*, 126–140.
88. Bhagabati, N.K.; Ricketts, T.; Sulistyawan, T.B.S.; Conte, M.; Ennaanay, D.; Hadian, O.; McKenzie, E.; Olwero, N.; Rosenthal, A.; Tallis, H.; et al. Ecosystem services reinforce Sumatran tiger conservation in land use plans. *Biol. Conserv.* **2014**, *169*, 147–156.
89. Polasky, S.; Nelson, E.; Pennington, D.; Johnson, K.A. The impact of land-use change on ecosystem services, biodiversity and returns to landowners: A case study in the state of Minnesota. *Environ. Resour. Econ.* **2011**, *48*, 219–242.
90. Hamel, P.; Guswa, A.J. Uncertainty analysis of a spatially explicit annual water-balance model: Case study of the Cape Fear basin, North Carolina. *Hydrol. Earth Syst. Sci.* **2015**, *19*, 839–853.
91. Wischmeier, W.H.; Smith, D.D. *Predicting rainfall erosion losses - a guide to conservation planning*; USDA, Science and Education Administration: Hyattsville, Maryland, 1978.
92. Sheikh, A.H.; Palria, S.; Alam, A. Integration of GIS and universal soil loss equation (USLE) for soil loss estimation in a Himalayan watershed. *Recent Res. Sci. Technol.* **2011**, *3*.
93. Waibel, H.; Min, S.; Huang, J. Small scale rubber farming and income risk in Xishuangbanna, China. In Proceedings of the World Congress on Agroforestry; Delhi, 2014.
94. Nguyen, B.T. Large-scale altitudinal gradient of natural rubber production in Vietnam. *Ind. Crops Prod.* **2013**, *41*, 31–40.
95. Beckschäfer, P. Obtaining rubber plantation age information from very dense Landsat TM & ETM + time series data and pixel-based image compositing. *Remote Sens. Environ.* **2017**, *196*, 89–100.
96. Hijmans, R.J.; Cameron, S.E.; Parra, J.L.; Jones, P.G.; Jarvis, A. Very high resolution interpolated climate surfaces for global land areas. *Int. J. Climatol.* **2005**, *25*, 1965–1978.
97. Hoyer, R.; Chang, H. Assessment of freshwater ecosystem services in the tualatin and Yamhill basins under climate change and urbanization. *Appl. Geogr.* **2014**, *53*, 402–416.
98. 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.; et al. Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales. *Front. Ecol. Environ.* **2009**, *7*, 4–11.
99. Ahlheim, M.; Frör, O.; Möller, B.; Zhang, Y.; Xi, W. Welfare Economic Valuation of a Sustainable Rubber Production in Southeast Asia: An Exemplary Study in SW-China. In Proceedings of the

Tropentag 2013 “Agricultural development within the rural-urban continuum”; Stuttgart-Hohenheim, 2013.
100. Roszkowska, E. Rank ordering criteria weighting methods–a comparative overview. *Optim. Stud. Ekon.* **2013**, 14–33.
101. Ochoa, V.; Urbina-Cardona, N. Tools for spatially modeling ecosystem services: Publication trends, conceptual reflections and future challenges. *Ecosyst. Serv.* **2017**, *26*, 155–169.
102. Felipe-Lucia, M.R.; Comín, F.A.; Escalera-Reyes, J. A framework for the social valuation of ecosystem services. *Ambio* **2015**, *44*, 308–318.
103. Likert, R. A technique for the measurement of attitudes. *Arch. Psychol.* **1932**, *22 140*, 55–55.
104. Saaty, T.L. How to make a decision: The analytic hierarchy process. *Desicion Mak. Anal. Hierarchy Process Theory Appl.* **1990**, *48*, 9–26.
105. Schmidt, S.; Manceur, A.M.; Seppelt, R. Uncertainty of monetary valued ecosystem services - value transfer functions for global mapping. *PLoS ONE* **2016**, *11*.
106. Jiang, W. Ecosystem services research in China: A critical review. *Ecosyst. Serv.* **2017**, *26*, 10–16.
107. Knoke, T.; Paul, C.; Hildebrandt, P.; Calvas, B.; Castro, L.M.; Härtl, F.; Döllerer, M.; Hamer, U.; Windhorst, D.; Wiersma, Y.F.; et al. Compositional diversity of rehabilitated tropical lands supports multiple ecosystem services and buffers uncertainties. *Nat. Commun.* **2016**, *7*, 11877.
108. Smajgl, A.; Xu, J.; Egan, S.; Yi, Z.-F.; Ward, J.; Su, Y. Assessing the effectiveness of payments for ecosystem services for diversifying rubber in Yunnan, China. *Environ. Model. Softw.* **2015**, *69*, 187–195.
109. Villamor, G.B.; Le, Q.B.; Djanibekov, U.; van Noordwijk, M.; Vlek, P.L.G. Biodiversity in rubber agroforests, carbon emissions, and rural livelihoods: An agent-based model of land-use dynamics in lowland Sumatra. *Environ. Model. Softw.* **2014**, *61*, 151–165.
110. Kovacs, K.; Polasky, S.; Nelson, E.; Keeler, B.L.; Pennington, D.; Plantinga, A.J.; Taff, S.J. Evaluating the Return in Ecosystem Services from Investment in Public Land Acquisitions. *PLoS ONE* **2013**, *8*.
111. Tan, Z.-H.; Zhang, Y.-P.; Song, Q.-H.; Liu, W.-J.; Deng, X.-B.; Tang, J.-W.; Deng, Y.; Zhou, W.-J.; Yang, L.-Y.; Yu, G.-R.; et al. Rubber plantations act as water pumps in tropical China. *Geophys. Res. Lett.* **2011**, *38*.
112. Giambelluca, T.W.; Mudd, R.G.; Liu, W.; Ziegler, A.D.; Kobayashi, N.; Kumagai, T.; Miyazawa, Y.; Lim, T.K.; Huang, M.; Fox, J.; et al. Evapotranspiration of rubber (Hevea brasiliensis) cultivated at two plantation sites in Southeast Asia. *Water Resour. Res.* **2016**, *52*, 660–679.
113. Cha, Z.-Z.; Lin, Z.-M.; Luo, W.; Li, S.-C.; Luo, X.-H. Sustainable land management practices for rubber plantations in mountainous area of Hainan. *Pedosphere* **2005**, *15*, 404–408.
114. Sánchez-Canales, M.; López Benito, A.; Passuello, A.; Terrado, M.; Ziv, G.; Acuña, V.; Schuhmacher, M.; Elorza, F.J. Sensitivity analysis of ecosystem service valuation in a Mediterranean watershed. *Sci. Total Environ.* **2012**, *440*, 140–153.
115. Yang, D.; Kanae, S.; Oki, T.; Koike, T.; Musiake, K. Global potential soil erosion with reference to land use and climate changes. *Hydrol. Process.* **2003**, *17*, 2913–2928.
116. Zhang, C.; Xie, G.; Liu, C.; Lu, C. Assessment of soil erosion under woodlands using USLE in China. *Front. Earth Sci.* **2011**, *5*, 150–161.
117. Liu, Y.; Luo, Z. A study on estimation of the amount of soil erosion in small watershed based on GIS: A case study in the three gorge area of China. In Proceedings of the Proceedings of SPIE - The International Society for Optical Engineering; 2005; Vol. 6045 II.
118. Shi, Z.H.; Cai, C.F.; Ding, S.W.; Wang, T.W.; Chow, T.L. Soil conservation planning at the small watershed level using RUSLE with GIS: A case study in the Three Gorge Area of China. *Catena* **2004**, *55*, 33–48.
119. Zhu, Z.; Yu, B. Validation of rainfall erosivity estimators for mainland china. *Trans. ASABE* **2015**, *58*, 61–71.
120. Cai, C.; Ding, S.; Shi, Z.; Huang, L.; Zhang, G. Study of applying USLE and geographical information system IDRISI to predict soil erosion in small watershed. *J. Soil Water Conserv.* **2000**, *14*, 19–24.

121. Song, X.; Duan, Z.; Niu, H.; Kono, Y. Estimation of the cover and management factor for modeling soil erosion using remote sensing. *J. Beijing For. Univ.* **2009**, *31*, 58–63.
122. Schönbrodt-Stitt, S.; Bosch, A.; Behrens, T.; Hartmann, H.; Shi, X.; Scholten, T. Approximation and spatial regionalization of rainfall erosivity based on sparse data in a mountainous catchment of the Yangtze River in Central China. *Environ. Sci. Pollut. Res.* **2013**, *20*, 6917–6933.
123. Shangguan, W.; Dai, Y.; Duan, Q.; Liu, B.; Yuan, H. A global soil data set for earth system modeling. *J. Adv. Model. Earth Syst.* **2014**, *6*, 249–263.
124. Fooladmand, H.R. Estimating soil specific surface area using the summation of the number of spherical particles and geometric mean particle-size diameter. *Afr. J. Agric. Res.* **2011**, *6*, 1758–1762.
125. Desmet, P.J.J.; Govers, G. A GIS procedure for automatically calculating the USLE LS factor on topographically complex landscape units. *J. Soil Water Conserv.* **1996**, *51*, 427–433.
126. Borselli, L.; Cassi, P.; Torri, D. Prolegomena to sediment and flow connectivity in the landscape: A GIS and field numerical assessment. *Catena* **2008**, *75*, 268–277.
127. Vigiak, O.; Borselli, L.; Newham, L.T.H.; McInnes, J.; Roberts, A.M. Comparison of conceptual landscape metrics to define hillslope-scale sediment delivery ratio. *Geomorphology* **2012**, *138*, 74–88.
128. Piouceau, J.; Panfili, F.; Bois, G.; Anastase, M.; Dufossé, L.; Arfi, V. Actual evapotranspiration and crop coefficients for five species of three-year-old bamboo plants under a tropical climate. *Agric. Water Manag.* **2014**, *137*, 15–22.
129. Chen, X.; Zhang, X.; Zhang, Y.; Booth, T.; He, X. Changes of carbon stocks in bamboo stands in China during 100 years. *For. Ecol. Manag.* **2009**, *258*, 1489–1496.
130. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *FAO Rome* **1998**, *300*, D05109.
131. Carr, M.K.V. The water relations and irrigation requirements of banana (Musa SPP.). *Exp. Agric.* **2009**, *45*, 333–371.
132. Canadell, J.; Jackson, R.B.; Ehleringer, J.R.; Mooney, H.A.; Sala, O.E.; Schulze, E.-D. Maximum rooting depth of vegetation types at the global scale. *Oecologia* **1996**, *108*, 583–595.
133. Global Aridity and PET Database | CGIAR-CSI. Available online: http://www.cgiar-csi.org/data/global-aridity-and-pet-database (accessed on Oct 20, 2017).
134. Redhead, J.W.; Stratford, C.; Sharps, K.; Jones, L.; Ziv, G.; Clarke, D.; Oliver, T.H.; Bullock, J.M. Empirical validation of the InVEST water yield ecosystem service model at a national scale. *Sci. Total Environ.* **2016**, *569–570*, 1418–1426.
135. Thellmann, K.; Cotter, M.; Baumgartner, S.; Treydte, A.; Cadisch, G.; Asch, F. Tipping Points in the Supply of Ecosystem Services of a Mountainous Watershed in Southeast Asia. *Sustainability* **2018**, *10*, 2418.
136. Bangash, R.F.; Passuello, A.; Sanchez-Canales, M.; Terrado, M.; López, A.; Elorza, F.J.; Ziv, G.; Acuña, V.; Schuhmacher, M. Ecosystem services in Mediterranean river basin: Climate change impact on water provisioning and erosion control. *Sci. Total Environ.* **2013**, *458–460*, 246–255.
137. Grimm, N.B.; Groffman, P.; Staudinger, M.; Tallis, H. Climate change impacts on ecosystems and ecosystem services in the United States: Process and prospects for sustained assessment. *Clim. Change* **2016**, *135*, 97–109.
138. Holling, C.S. Resilience and stability of ecological systems. *Annu. Rev. Ecol. Syst.* **1973**, *4*, 1–23.
139. Walker, B.; Holling, C.S.; Carpenter, S.; Kinzig, A. Resilience, adaptability and transformability in social–ecological systems. *Ecol. Soc.* **2004**, *9*.
140. Biggs, R.; Schlüter, M.; Biggs, D.; Bohensky, E.L.; BurnSilver, S.; Cundill, G.; Dakos, V.; Daw, T.M.; Evans, L.S.; Kotschy, K.; et al. Toward Principles for Enhancing the Resilience of Ecosystem Services. *Annu. Rev. Environ. Resour.* **2012**, *37*, 421–448.
141. Folke, C.; Carpenter, S.; Walker, B.; Scheffer, M.; Elmqvist, T.; Gunderson, L.; Holling, C.S. Regime Shifts, Resilience, and Biodiversity in Ecosystem Management. *Annu. Rev. Ecol. Evol. Syst.* **2004**, *35*, 557–581.

142. Scheffer, M.; Bascompte, J.; Brock, W.A.; Brovkin, V.; Carpenter, S.R.; Dakos, V.; Held, H.; Van Nes, E.H.; Rietkerk, M.; Sugihara, G. Early-warning signals for critical transitions. *Nature* **2009**, *461*, 53–59.
143. Milkoreit, M.; Hodbod, J.; Baggio, J.; Benessaiah, K.; Calderon Contreras, R.; Donges, J.F.; Mathias, J.-D.; Rocha, J.C.; Schoon, M.; Werners, S. Defining tipping points for social-ecological systems scholarship – an interdisciplinary literature review. *Environ. Res. Lett.* **2018**.
144. van Nes, E.H.; Arani, B.M.S.; Staal, A.; van der Bolt, B.; Flores, B.M.; Bathiany, S.; Scheffer, M. What do you mean "Tipping Point"? *Trends Ecol. Evol.* **2016**, *31*, 900–902.
145. Zhang, K.; Dearing, J.A.; Dawson, T.P.; Dong, X.; Yang, X.; Zhang, W. Poverty alleviation strategies in eastern China lead to critical ecological dynamics. *Sci. Total Environ.* **2015**, *506–507*, 164–181.
146. Scheffer, M.; Carpenter, S.; Foley, J.A.; Folke, C.; Walker, B. Catastrophic shifts in ecosystems. *Nature* **2001**, *413*, 591.
147. Rockström, J.; Steffen, W.; Noone, K.; Persson, Å.; Chapin, F.S.; Lambin, E.; Lenton, T.M.; Scheffer, M.; Folke, C.; Schellnhuber, H.J.; et al. Planetary Boundaries: Exploring the Safe Operating Space for Humanity. *Ecol. Soc.* **2009**, *14*.
148. Raworth, K. A safe and just space for humanity: can we live within the doughnut. *Oxfam Policy Pract. Clim. Change Resil.* **2012**, *8*, 1–26.
149. Dearing, J.A.; Wang, R.; Zhang, K.; Dyke, J.G.; Haberl, H.; Hossain, M.S.; Langdon, P.G.; Lenton, T.M.; Raworth, K.; Brown, S.; et al. Safe and just operating spaces for regional social-ecological systems. *Glob. Environ. Change* **2014**, *28*, 227–238.
150. Rocha, J.C.; Peterson, G.D.; Biggs, R. Regime Shifts in the Anthropocene: Drivers, Risks, and Resilience. *PLOS ONE* **2015**, *10*, e0134639.
151. Bruun, T.B.; de Neergaard, A.; Lawrence, D.; Ziegler, A.D. Environmental Consequences of the Demise in Swidden Cultivation in Southeast Asia: Carbon Storage and Soil Quality. *Hum. Ecol.* **2009**, *37*, 375–388.
152. SURUMER Sustainable Rubber Cultivation in the Mekong Region: Development of an integrative land-use concept in Yunnan Province, China Available online: https://surumer.uni-hohenheim.de/90683?&L=1 (accessed on Nov 6, 2018).
153. Wang, J.; Aenis, T.; Hofmann-Souki, S. Triangulation in participation: Dynamic approaches for science-practice interaction in land-use decision making in rural China. *Land Use Policy* **2018**, *72*, 364–371.
154. Rodionov, S.N. A sequential algorithm for testing climate regime shifts: ALGORITHM FOR TESTING REGIME SHIFTS. *Geophys. Res. Lett.* **2004**, *31*, L09204.
155. Bai, Y.; Zheng, H.; Ouyang, Z.; Zhuang, C.; Jiang, B. Modeling hydrological ecosystem services and tradeoffs: A case study in Baiyangdian watershed, China. *Environ. Earth Sci.* **2013**, *70*, 709–718.
156. Min, S.; Waibel, H.; Cadisch, G.; Langenberger, G.; Bai, J.; Huang, J. The Economics of Smallholder Rubber Farming in a Mountainous Region of Southwest China: Elevation, Ethnicity, and Risk. *Mt. Res. Dev.* **2017**, *37*, 281–293.
157. Hossain, M.S.; Eigenbrod, F.; Amoako Johnson, F.; Dearing, J.A. Unravelling the interrelationships between ecosystem services and human wellbeing in the Bangladesh delta. *Int. J. Sustain. Dev. World Ecol.* **2017**, *24*, 120–134.
158. Laurance, W.F. Do edge effects occur over large spatial scales? *Trends Ecol. Evol.* **2000**, *15*, 134–135.
159. Hughes, T.P.; Linares, C.; Dakos, V.; van de Leemput, I.A.; van Nes, E.H. Living dangerously on borrowed time during slow, unrecognized regime shifts. *Trends Ecol. Evol.* **2013**, *28*, 149–155.
160. Jelinski, D.E.; Wu, J. The modifiable areal unit problem and implications for landscape ecology. *Landsc. Ecol.* **1996**, *11*, 129–140.
161. Bagstad, K.J.; Johnson, G.W.; Voigt, B.; Villa, F. Spatial dynamics of ecosystem service flows: A comprehensive approach to quantifying actual services. *Ecosyst. Serv.* **2013**, *4*, 117–125.
162. Hossain, M.S.; Dearing, J.A.; Eigenbrod, F.; Johnson, F.A. Operationalizing safe operating space for regional social-ecological systems. *Sci. Total Environ.* **2017**, *584–585*, 673–682.

163. Polasky, S.; Carpenter, S.R.; Folke, C.; Keeler, B. Decision-making under great uncertainty: environmental management in an era of global change. *Trends Ecol. Evol.* **2011**, *26*, 398–404.
164. Thellmann, K.; Golbon, R.; Cotter, M.; Cadisch, G.; Asch, F. Assessing Hydrological Ecosystem Services in a Rubber-Dominated Watershed under Scenarios of Land Use and Climate Change. *Forests* **2019**, *10*, 176.
165. Newbold, T.; Hudson, L.N.; Hill, S.L.L.; Contu, S.; Lysenko, I.; Senior, R.A.; Börger, L.; Bennett, D.J.; Choimes, A.; Collen, B.; et al. Global effects of land use on local terrestrial biodiversity. *Nature* **2015**, *520*, 45–50.
166. Perrings, C.; Duraiappah, A.; Larigauderie, A.; Mooney, H. The Biodiversity and Ecosystem Services Science-Policy Interface. *Science* **2011**, *331*, 1139–1140.
167. IPBES *Summary for policymakers of the assessment report on land degradation and restoration of the Intergovernmental Science- Policy Platform on Biodiversity and Ecosystem Services*; IPBES secretariat: Bonn, Germany, 2018; ISBN 978-3-947851-04-1.
168. SWAT | Soil & Water Assessment Tool. Available online: https://swat.tamu.edu/ (accessed on Nov 7, 2018).
169. Kharin, V.V.; Zwiers, F.W.; Zhang, X.; Wehner, M. Changes in temperature and precipitation extremes in the CMIP5 ensemble. *Clim. Change* **2013**, *119*, 345–357.
170. Alexander, L.V.; Zhang, X.; Peterson, T.C.; Caesar, J.; Gleason, B.; Klein Tank, A.M.G.; Haylock, M.; Collins, D.; Trewin, B.; Rahimzadeh, F.; et al. Global observed changes in daily climate extremes of temperature and precipitation. *J. Geophys. Res.* **2006**, *111*.
171. Trenberth, K.E.; Dai, A.; Rasmussen, R.M.; Parsons, D.B. The Changing Character of Precipitation. *Bull. Am. Meteorol. Soc.* **2003**, *84*, 1205–1218.
172. IPCC *Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA, 2013;
173. Arunyawat, S.; Shrestha, R. Assessing Land Use Change and Its Impact on Ecosystem Services in Northern Thailand. *Sustainability* **2016**, *8*, 768.
174. Eastham, J.; Mpelasoka, M.; Mainuddin, C.; Ticehurst, C.; Dyce, P.; Hodgson, G.; Ali, R.; Kirby, M. Mekong River Basin water resources assessment: Impacts of climate change. *CSIRO Water Healthy Ctry. Natl. Res. Flagship* **2008**, 153.
175. Shrestha, B.; Babel, M.S.; Maskey, S.; van Griensven, A.; Uhlenbrook, S.; Green, A.; Akkharath, I. Impact of climate change on sediment yield in the Mekong River basin: a case study of the Nam Ou basin, Lao PDR. *Hydrol. Earth Syst. Sci.* **2013**, *17*, 1–20.
176. Zhu, Y.-M.; Lu, X.X.; Zhou, Y. Sediment flux sensitivity to climate change: A case study in the Longchuanjiang catchment of the upper Yangtze River, China. *Glob. Planet. Change* **2008**, *60*, 429–442.
177. Phan, D.B.; Wu, C.C.; Hsieh, S.C. Impact of climate change on stream discharge and sediment yield in Northern Viet Nam. *Water Resour.* **2011**, *38*, 827–836.
178. Trisurat, Y.; Eawpanich, P.; Kalliola, R. Integrating land use and climate change scenarios and models into assessment of forested watershed services in Southern Thailand. *Environ. Res.* **2016**, *147*, 611–620.
179. UNESCO Biosphere Reserves | United Nations Educational, Scientific and Cultural Organization Available online: http://www.unesco.org/new/en/natural-sciences/environment/ecological-sciences/biosphere-reserves/ (accessed on Feb 1, 2019).
180. WorldClim - Global Climate Data | Free climate data for ecological modeling and GIS Available online: http://www.worldclim.org/ (accessed on Oct 20, 2017).
181. Thomson, A.M.; Calvin, K.V.; Smith, S.J.; Kyle, G.P.; Volke, A.; Patel, P.; Delgado-Arias, S.; Bond-Lamberty, B.; Wise, M.A.; Clarke, L.E.; et al. RCP4.5: a pathway for stabilization of radiative forcing by 2100. *Clim. Change* **2011**, *109*, 77–94.

182. Riahi, K.; Rao, S.; Krey, V.; Cho, C.; Chirkov, V.; Fischer, G.; Kindermann, G.; Nakicenovic, N.; Rafaj, P. RCP 8.5—A scenario of comparatively high greenhouse gas emissions. *Clim. Change* **2011**, *109*, 33–57.
183. McSweeney, C.F.; Jones, R.G.; Lee, R.W.; Rowell, D.P. Selecting CMIP5 GCMs for downscaling over multiple regions. *Clim. Dyn.* **2015**, *44*, 3237–3260.
184. Bi, D.; Dix, M.; Marsland, S.; O'Farrell, S.; Rashid, H.; Uotila, P.; Hirst, A.; Kowalczyk, E.; Golebiewski, M.; Sullivan, A.; et al. The ACCESS coupled model: description, control climate and evaluation. *Aust. Meteorol. Oceanogr. J.* **2013**, *63*, 41–64.
185. Dix, M.; Vohralik, P.; Bi, D.; Rashid, H.; Marsland, S.; O'Farrell, S.; Uotila, P.; Hirst, T.; Kowalczyk, E.; Sullivan, A.; et al. The ACCESS coupled model: documentation of core CMIP5 simulations and initial results. *Aust. Meteorol. Oceanogr. J.* **2013**, *63*, 83–99.
186. Xin, X.; Zhang, L.; Zhang, J.; Wu, T.; Fang, Y. Climate Change Projections over East Asia with BCC_CSM1.1 Climate Model under RCP Scenarios. *J. Meteorol. Soc. Jpn. Ser II* **2013**, *91*, 413–429.
187. Gent, P.R.; Danabasoglu, G.; Donner, L.J.; Holland, M.M.; Hunke, E.C.; Jayne, S.R.; Lawrence, D.M.; Neale, R.B.; Rasch, P.J.; Vertenstein, M.; et al. The Community Climate System Model Version 4. *J. Clim.* **2011**, *24*, 4973–4991.
188. Donner, L.J.; Wyman, B.L.; Hemler, R.S.; Horowitz, L.W.; Ming, Y.; Zhao, M.; Golaz, J.-C.; Ginoux, P.; Lin, S.-J.; Schwarzkopf, M.D.; et al. The Dynamical Core, Physical Parameterizations, and Basic Simulation Characteristics of the Atmospheric Component AM3 of the GFDL Global Coupled Model CM3. *J. Clim.* **2011**, *24*, 3484–3519.
189. The HadGEM2 Development Team: G. M. Martin; Bellouin, N.; Collins, W.J.; Culverwell, I.D.; Halloran, P.R.; Hardiman, S.C.; Hinton, T.J.; Jones, C.D.; McDonald, R.E.; McLaren, A.J.; et al. The HadGEM2 family of Met Office Unified Model climate configurations. *Geosci. Model Dev.* **2011**, *4*, 723–757.
190. Dufresne, J.-L.; Foujols, M.-A.; Denvil, S.; Caubel, A.; Marti, O.; Aumont, O.; Balkanski, Y.; Bekki, S.; Bellenger, H.; Benshila, R.; et al. Climate change projections using the IPSL-CM5 Earth System Model: from CMIP3 to CMIP5. *Clim. Dyn.* **2013**, *40*, 2123–2165.
191. Yukimoto, S.; Adachi, Y.; Hosaka, M.; Sakami, T.; Yoshimura, H.; Hirabara, M.; Tanaka, T.Y.; Shindo, E.; Tsujino, H.; Deushi, M.; et al. A New Global Climate Model of the Meteorological Research Institute: MRI-CGCM3: Model Description and Basic Performance. *J. Meteorol. Soc. Jpn.* **2012**, *90A*, 23–64.
192. Giorgetta, M.A.; Jungclaus, J.; Reick, C.H.; Legutke, S.; Bader, J.; Böttinger, M.; Brovkin, V.; Crueger, T.; Esch, M.; Fieg, K.; et al. Climate and carbon cycle changes from 1850 to 2100 in MPI-ESM simulations for the Coupled Model Intercomparison Project phase 5: Climate Changes in MPI-ESM. *J. Adv. Model. Earth Syst.* **2013**, *5*, 572–597.
193. Bentsen, M.; Bethke, I.; Debernard, J.B.; Iversen, T.; Kirkevåg, A.; Seland, ø.; Drange, H.; Roelandt, C.; Seierstad, I.A.; Hoose, C.; et al. The Norwegian Earth System Model, NorESM1-M – Part 1: Description and basic evaluation of the physical climate. *Geosci. Model Dev.* **2013**, *6*, 687–720.
194. Data - CCAFS Climate Available online: http://www.ccafs-climate.org/data_spatial_downscaling/ (accessed on Nov 6, 2018).
195. ESRI *ArcGIS 10.3.1*; Environmental Systems Research Institute: Redlands, CA, USA, 2015.
196. Zomer, R.J.; Bossio, D.A.; Trabucco, A.; Yuanjie, L.; Gupta, D.C.; Singh, V.P. *Trees and water: Smallholder agroforestry on irrigated lands in Northern India.*; International Water Management Institute: Colombo, Sri Lanka, 2007; p. 47.
197. Zomer, R.J.; Trabucco, A.; Bossio, D.A.; Verchot, L.V. Climate change mitigation: A spatial analysis of global land suitability for clean development mechanism afforestation and reforestation. *Agric. Ecosyst. Environ.* **2008**, *126*, 67–80.
198. Hargreaves, G.H.; Allen, R.G. History and Evaluation of Hargreaves Evapotranspiration Equation. *J. Irrig. Drain. Eng.* **2003**, *129*, 53–63.

199. Hamel, P.; Chaplin-Kramer, R.; Sim, S.; Mueller, C. A new approach to modeling the sediment retention service (InVEST 3.0): Case study of the Cape Fear catchment, North Carolina, USA. *Sci. Total Environ.* **2015**, *524–525*, 166–177.
200. Zhang, L.; Hickel, K.; Dawes, W.R.; Chiew, F.H.S.; Western, A.W.; Briggs, P.R. A rational function approach for estimating mean annual evapotranspiration. *Water Resour. Res.* **2004**, *40*, W025021–W02502114.
201. Cadisch, G.; Aenis, T.; Ahlheim, M.; Asch, F.; Azizi, N.; Bai, J.; Blagodatsky, S.; Cotter, M.; Frör, O.; Harich, F.K.; et al. *Sustainable Rubber Cultivation in the Mekong Region (SURUMER)*; Cadisch, G., Langenberger, G., Blagodatsky, S., Eds.; GRIN Verlag: Munich, Germany, 2018; ISBN 978-3-668-83051-6.
202. R Core Team *R: A language and environment for statistical computing*; R Foundation for Statistical Computing: Vienna, Austria, 2016.
203. OriginLab Corporation *OriginPro 2017*; OriginLab Corporation: Northhampton, MA 01060 USA, 2017.
204. Bajracharya, A.R.; Bajracharya, S.R.; Shrestha, A.B.; Maharjan, S.B. Climate change impact assessment on the hydrological regime of the Kaligandaki Basin, Nepal. *Sci. Total Environ.* **2018**, *625*, 837–848.
205. Plangoen, P.; Babel, M.; Clemente, R.; Shrestha, S.; Tripathi, N. Simulating the Impact of Future Land Use and Climate Change on Soil Erosion and Deposition in the Mae Nam Nan Sub-Catchment, Thailand. *Sustainability* **2013**, *5*, 3244–3274.
206. Xiao, Y.; Xiao, Q.; Ouyang, Z.; Maomao, Q. Assessing changes in water flow regulation in Chongqing region, China. *Environ. Monit. Assess.* **2015**, *187*.
207. Liu, H.; Yang, X.; Blagodatsky, S.; Marohn, C.; Liu, F.; Xu, J.; Cadisch, G. Modelling weed management strategies to control erosion in rubber plantations. *CATENA* **2019**, *172*, 345–355.
208. Min, S.; Huang, J.; Bai, J.; Waibel, H. Adoption of intercropping among smallholder rubber farmers in Xishuangbanna, China. *Int. J. Agric. Sustain.* **2017**, *15*, 223–237.
209. van Soesbergen, A.; Mulligan, M. Uncertainty in data for hydrological ecosystem services modelling: Potential implications for estimating services and beneficiaries for the CAZ Madagascar. *Ecosyst. Serv.* **2018**, *33*, 175–186.
210. Pessacg, N.; Flaherty, S.; Brandizi, L.; Solman, S.; Pascual, M. Getting water right: A case study in water yield modelling based on precipitation data. *Sci. Total Environ.* **2015**, *537*, 225–234.
211. Fan, H.; He, D.; Wang, H. Environmental consequences of damming the mainstream Lancang-Mekong River: A review. *Earth-Sci. Rev.* **2015**, *146*, 77–91.
212. Lu, X.X.; Li, S.; Kummu, M.; Padawangi, R.; Wang, J.J. Observed changes in the water flow at Chiang Saen in the lower Mekong: Impacts of Chinese dams? *Quat. Int.* **2014**, *336*, 145–157.
213. Lautenbach, S.; Mupepele, A.-C.; Dormann, C.F.; Lee, H.; Schmidt, S.; Scholte, S.S.K.; Seppelt, R.; van Teeffelen, A.J.A.; Verhagen, W.; Volk, M. Blind spots in ecosystem services research and challenges for implementation. *Reg. Environ. Change* **2019**.
214. Assessing knowledge | IPBES Available online: https://ipbes.net/assessing-knowledge (accessed on Feb 24, 2020).
215. Martínez-López, J.; Bagstad, K.J.; Balbi, S.; Magrach, A.; Voigt, B.; Athanasiadis, I.; Pascual, M.; Willcock, S.; Villa, F. Towards globally customizable ecosystem service models. *Sci. Total Environ.* **2019**, *650*, 2325–2336.
216. Lippe, M.; Bithell, M.; Gotts, N.; Natalini, D.; Barbrook-Johnson, P.; Giupponi, C.; Hallier, M.; Hofstede, G.J.; Le Page, C.; Matthews, R.B.; et al. Using agent-based modelling to simulate social-ecological systems across scales. *GeoInformatica* **2019**.
217. Tonini, F.; Liu, J. Telecoupling Toolbox: spatially explicit tools for studying telecoupled human and natural systems. *Ecol. Soc.* **2017**, *22*, 11.
218. Slothuus, C.F.; Schmidt-Vogt, D.; Mertz, O. Navigating between Tea and Rubber in Xishuangbanna, China: When New Crops Fail and Old Ones Work. *Land* **2020**, *9*, 22.

219. Grimm, V.; Berger, U.; Bastiansen, F.; Eliassen, S.; Ginot, V.; Giske, J.; Goss-Custard, J.; Grand, T.; Heinz, S.K.; Huse, G.; et al. A standard protocol for describing individual-based and agent-based models. *Ecol. Model.* **2006**, *198*, 115–126.
220. Herrero-Jáuregui, C.; Arnaiz-Schmitz, C.; Reyes, M.; Telesnicki, M.; Agramonte, I.; Easdale, M.; Schmitz, M.; Aguiar, M.; Gómez-Sal, A.; Montes, C. What do We Talk about When We Talk about Social-Ecological Systems? A Literature Review. *Sustainability* **2018**, *10*, 2950.
221. Rounsevell, M.D.A.; Dawson, T.P.; Harrison, P.A. A conceptual framework to assess the effects of environmental change on ecosystem services. *Biodivers. Conserv.* **2010**, *19*, 2823–2842.
222. Potschin-Young, M.; Haines-Young, R.; Görg, C.; Heink, U.; Jax, K.; Schleyer, C. Understanding the role of conceptual frameworks: Reading the ecosystem service cascade. *Ecosyst. Serv.* **2018**, *29*, 428–440.
223. Potschin, M.B.; Haines-Young, R.H. Ecosystem services: Exploring a geographical perspective. *Prog. Phys. Geogr. Earth Environ.* **2011**, *35*, 575–594.
224. Kandziora, M.; Burkhard, B.; Müller, F. Mapping provisioning ecosystem services at the local scale using data of varying spatial and temporal resolution. *Ecosyst. Serv.* **2013**, *4*, 47–59.
225. Müller, F.; Burkhard, B. The indicator side of ecosystem services. *Ecosyst. Serv.* **2012**, *1*, 26–30.
226. Nassl, M.; Löffler, J. Ecosystem services in coupled social–ecological systems: Closing the cycle of service provision and societal feedback. *Ambio* **2015**, *44*, 737–749.
227. Ghorbani, A.; Langenberger, G.; Feng, L.; Sauerborn, J. Ethnobotanical study of medicinal plants utilised by Hani ethnicity in Naban River Watershed National Nature Reserve, Yunnan, China. *J. Ethnopharmacol.* **2011**, *134*, 651–667.
228. de Groot, R.S.; Wilson, M.A.; Boumans, R.M.J. A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecol. Econ.* **2002**, *41*, 393–408.
229. Su, S.; Wan, C.; Li, J.; Jin, X.; Pi, J.; Zhang, Q.; Weng, M. Economic benefit and ecological cost of enlarging tea cultivation in subtropical China: Characterizing the trade-off for policy implications. *Land Use Policy* **2017**, *66*, 183–195.

List of Abbreviations and Acronyms

5YP	5 Years Plan (Scenario)
ARIES	Artificial Intelligence for Ecosystem Services
BAU	Business As Usual (Scenario)
BMBF	German Federal Ministry of Education and Research
BTO	Balanced Trade Offs (Scenario)
CC	Climate Change
DEM	Digital Elevation Model
ESA	Ecosystem Service Assessment
ESF	Ecosystem Function
ESS	Ecosystem Service(s)
EW	Equal Weights
FAIR	Findable, Accessible, Interoperable, Reusable
GCM	General Circulation Model
GIS	Geographic Information System
HQ	Habitat Quality
INIT	Initial Land Use (2015)
InVEST	Integrated Assessment of Ecosystem Services and Trade-Offs
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IPPC5	The Fifth Assessment Report of the Intergovernmental Panel on Climate Change
K_c	Transpiration Coefficient
LUCIA	Land Use Change Impact Assessment
m.a.s.l.	meters above sea level
MEA	Millennium Ecosystem Assessment
MIMES	Multiscale Integrated Model of Ecosystem Services
MMSEA	Montane Mainland Southeast Asia
NR	Nabanhe Reserve
NRWNNR	Naban River Watershed National Nature Reserve
PAWC	Plant Available Water Content
PES	Payments for Ecosystem Services
PET	Potential Evapotranspiration

PET_a	Annual Potential Evapotranspiration
PET_m	Monthly Potential Evapotranspiration
RA	Extraterrestrial Radiation
RCP	Representative Concentration Pathway
ROC	Rank-Order Centroid Weight
RR	Inverse (or Reciprocal) Weight
RS	Rank Sum Weight
RSI	Regime Shift Index
SEA	Southeast Asia
SES	Socio-Ecological System
SURUMER	Sustainable Rubber Cultivation in the Mekong Region
SW	Sub-Watershed
SWAT	Soil and Water Assessment Tool
TD	Daily Temperature Range
TEEB	The Economics of Ecosystems and Biodiversity
T_{mean}	Monthly Mean Temperature
TP	Tipping Point
USLE	Universal Soil Loss Equation
WTP	Willingness to Pay