Ecosystem services for communities in forest frontiers

An assessment of nature's benefits to local stakeholders under different land use and tenure systems in a tropical frontier landscape in Myanmar

Inaugural dissertation

of the Faculty of Science,

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Mélanie Feurer

from Kirchberg SG

Supervisor of the doctoral thesis:

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Prof. Dr. Zoltan Balogh

Summary

In recent decades, intact forest landscapes in the tropics have been severely degraded and large areas have been converted to large-scale agricultural concessions or smallholder farms, often both. So-called forest frontiers are affected by multiple interrelated drivers of change including population growth, global consumption patterns, crop booms, infrastructure development, and international and national policies. In Myanmar's border areas, frontier landscapes have been formed by decades of civil war and a rapidly opening economy inviting agricultural investments in recent years. Various claims on land have then shaped the landscape and led to the establishment of oil palm concessions on the one hand and protected areas on the other hand. Such changes in land use frequently cause trade-offs between nature's goods and services provided and the types of stakeholders benefiting from them, with rural communities often on the losing end. Limited recognition of customary land rights and imposed restrictions on access to land and its resources negatively affect their livelihoods and well-being.

Although human-nature interrelations in the form of ecosystem services have become a priority in research for development, there is still limited knowledge on how rural communities experience trade-offs and how they adapt to new risks and opportunities in forest frontiers. This thesis aimed to understand how local communities in a frontier context in Myanmar's Tanintharyi Region benefit from a mosaic of land uses and cope with a changing resource base. To identify the multiple types of benefits, we used and evolved recent advances in land system science to value, model, and map outcomes of different provisioning, regulating and cultural services for local stakeholders. Considering the challenges in data-scarce regions, we used a combination of methods to acquire both qualitative and quantitative data. Further, we analyzed the impact of different land use and tenure schemes on local communities' ability to access and benefit from ecosystem services.

We found that local communities in Myanmar's southern forest frontier benefit from many ecosystem services provided by the variety of land uses present in a mosaic landscape. Remaining forest complexes and mangroves support biodiversity, regulating services, and several non-timber forest products. Outcomes for local stakeholders decreased to some extent with the establishment of protected areas and restricted access but increased with the introduction of community forestry. On agricultural lands, rural land users mainly benefit from mixed plantations that provide a balanced set of ecosystem services including commercial and subsistence crops. However, oil palm concessions run by private companies adversely affect local people's access to lands and related benefits and even cause disservices such as water pollution. Apart from these challenges, our results also show that local communities have found many ways to adapt to socio-political and ecological changes and even profit from new market opportunities. Some of nature's resources have already been replaced by man-made alternatives. Overall, we found that much of the remaining demand for nature's products and services is met across Myanmar's Tanintharyi Region, but with critical exceptions in urban spaces and rapidly developing areas near roadsides. Land tenure and zoning arrangements were identified as determining factors for local communities' ability to benefit from natural resources for their livelihoods and human well-being.

This thesis is embedded in land system science and contributes to a better understanding of the role and perspectives of rural communities in forest frontier landscapes and their capacity to adapt to trade-offs from land use change. It further shares advances in complex ecosystem services modelling and mapping in a data scarce region.

Table 1 below presents the list of scientific papers produced within the scope of this doctoral thesis.

Table 1 List of scientific papers in the frame of the thesis

	Title	Authors	Journal	Status	doi
I	**Community forestry for livelihoods: Benefiting from Myanmar's mangroves**	**Feurer M**, Gritten D, Than MM	Forests	Published (2018)	https://doi.org/10.3390/f9030150
II	**Local perspectives on ecosystem service trade-offs in a forest frontier landscape in Myanmar**	**Feurer M**, Heinimann A, Schneider F, Jurt C, Myint W, Zaehringer, JG	Land	Published (2019)	https://doi.org/10.3390/land8030045
III	**Sustainable development under competing claims on land: Three pathways between land-use changes, ecosystem services and human well-being**	Schneider F, **Feurer M**, Lundsgaard-Hansen LM, Myint W, Nuam CD, Nydegger K, Oberlack C, Tun NN, Zaehringer JG, Htun AM, Messerli P	The European Journal of Develop-ment Research	Published (2020)	https://doi.org/10.1057/s41287-020-00268-x
IV	**Quantifying local ecosystem service outcomes by modelling their supply, demand and flow in Myanmar's forest frontier landscape**	**Feurer M**, Zaehringer JG, Heinimann A, Naing SM, Blaser J, Celio E	Journal of Land Use Science	Published (2020)	https://doi.org/10.1080/1747423X.2020.1841844
V	**Ecosystem services for local stakeholders: Mapping supply, demand, and flow – and identifying mismatches – at regional scale in Myanmar**	**Feurer M**, Rueff H, Celio E, Heinimann A, Blaser J, Htun AM, Zaehringer JG	Ecosystem Services	Submitted (2021)	

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Part I Research context and synthesis

1 Background

1.1 Introduction

Tropical forest landscapes provide valuable ecological functions and are often hotspots of biodiversity (Myers et al. 2000). Moreover, they are integral to the livelihoods of rural communities (Angelsen et al. 2014; Rasmussen et al. 2017). Forest-dependent people usually collect non-timber forest products (NTFP) and, in many areas, practice shifting cultivation as a traditional form of natural resources management (Dressler et al. 2017).

Forest frontiers, also called agricultural frontiers, agriculture-forest landscapes, or frontier landscapes, are landscapes exposed to resource appropriation due to the abundance of land and shortage of alternative economic opportunities (Meyfroidt et al. 2018). They often experience rapid changes. Between 1990 and 2019, 17% of intact forest landscapes in the humid tropics were lost, and one tenth of the remaining tropical moist forest is currently in a degraded state (Vancutsem et al. 2021). A large share of intact forest loss can be attributed to fragmentation (Potapov et al. 2017). Forest frontiers are subjected to interrelated drivers of change including population growth, national and international policies, changing consumption patterns and cash crop booms resulting essentially from global demand (Scales 2011; Vliet et al. 2012; Brando et al. 2013). Up to 90% of rapid commodity crop expansion in the tropics take place in previously forested areas wherever ecological, technical and political conditions support this (Meyfroidt et al. 2014). In frontiers with access to markets, swidden landscapes thus slowly give way to either large-scale intensive agriculture through commercial land acquisitions or to mosaic landscapes through smallholder conversion to permanent agriculture (Vliet et al. 2012; Messerli et al. 2015). Forest frontiers are also present in coastal areas, where intact mangrove forests are consistently lost to make way for aquaculture, rice farming or oil palm plantations (Richards and Friess 2016).

Even though forest fragmentation is predominantly seen as detrimental for biodiversity and the functionality of ecosystems (Wilson et al. 2016; Potapov et al. 2017), other studies found that mosaic landscapes actually deliver multiple benefits and believe they can take a critical function in sustainable development (Zaehringer et al. 2016; Law et al. 2017; Pinillos et al. 2020). Yet, changes in land use can cause trade-offs between the goods and services provided (Verburg et al. 2014; Mora et al. 2016) and the types of stakeholders benefiting from them, in particular where power relationships limit access for certain groups (German et al. 2014; Schoneveld 2014; Felipe-Lucia et al. 2015b). Overlapping interests and claims on land are major causes of conflict in many Southeast Asian countries (To et al. 2015; Maryudi et al. 2016; Dhiaulhaq et al. 2017). For smallholders, limited recognition of customary land rights is a main challenge restricting their access to natural resources (Kmoch et al. 2021). As various actors including governments, private companies and investors, non-governmental organizations, and especially local land users have a stake in frontier landscapes, balancing trade-offs in an increasingly dynamic competition for land resources is critical (Verburg et al. 2015).

Studies have shown that trade-offs can be mitigated if rural communities are given access to land and are included in decision-making and management (Gritten et al. 2015; Daw et al. 2016). For example, conservationist-driven plans to create large protected area networks on half the earth's area could negatively affect the livelihoods of the 1 billion people living in and off these natural resources (Schleicher et al. 2019). On the other hand, rights-based approaches such as community forestry schemes or community-managed protected areas can more effectively contribute to conservation where they include management plans for sustainable resource use (Porter-Bolland et al. 2012; Ellis et al. 2017). In agriculture, land tenure security encourages more productive and environmentally sound farming practices including tree planting and reduces the need for smallholders to clear new forest lands (Higgins et al. 2018; Kubitza et al. 2018). The concept of land governance (Sikor et al. 2013) is thus central to effectively address local, regional, and global challenges.

Human-nature relationships have become a priority in the search for solutions to achieving multiple global goals of biodiversity conservation, climate change mitigation, economic development, food security and human well-being (UN 2015). The 2030 Agenda for Sustainable Development also recognized the importance of tenure and people's access to natural resources (ibid.). In response, land system science, which has developed over the past 25 years at the interface of social and biophysical systems, has shifted its focus from understanding specific systems and system changes towards applying this knowledge to design stakeholder-inclusive sustainable transformations (Verburg et al. 2015). Ecosystem services (ES), described by Costanza et al. (2017), is a key concept of land system science to assess the benefits from various land uses and the impact of land use change on the well-being of different stakeholders. The ES concept was first introduced in 1997 (Costanza et al. 1997) and has achieved wide acceptance since the Millennium Ecosystem Assessment (MEA 2005) with a specific aim to connect science with policy through the integration of multiple types of knowledge on human-nature relations. ES research has added crucial methodological advances to understand socio-ecological interactions and provide recommendations to the fundamental changes needed for sustainable development (Costanza et al. 2017). Recent analytical progress was also made with the emergence of the telecoupling framework, which includes spatial, institutional, and temporal scales in the analysis of socio-ecological systems and land use change (Friis et al. 2016). However, the impact of increased telecoupling on smallholders and reciprocal flows have so far received limited attention (Dou et al. 2020). Likewise, owing to challenges in valuing and comparing different types of services for different stakeholders, locally relevant ES remain a neglected issue in policymaking (Pandeya et al. 2016).

Another element in forest frontiers that has been largely disregarded is the potential of humans to adapt to a changing environment in transitional contexts (Thornton et al. 2019). While rural communities themselves are agents of change in small-scale agricultural expansion, they also play an active role where land transitions are imposed on them. Various studies have shown that local communities can demonstrate a remarkable resilience and capacity to adapt to changing political, environmental, and economic risks and opportunities (Imperiale and Vanclay 2016; Alam et al. 2017; Asfaw et al. 2018). Although local adaptation potentials to changing conditions have been intensively researched in connection with climate change (Lebel 2013; Nkoana et al. 2018), it has been insufficiently explored in the complex context of tropical forest frontiers, telecoupling processes, and ES trade-offs.

In this thesis, I apply current ES valuation approaches and further develop them to account for local communities' perspectives on how they benefit from various land uses and tenure schemes and adapt to changing landscapes, comparing several types of services. The thesis thus contributes to the understanding of human-nature interactions through the lens of ecosystem services, local trade-offs experienced from landscape transitions, and anticipated impacts at the regional level.

1.2 Study context

1.2.1 Land resources in Myanmar

This thesis focuses on Myanmar, a Southeast Asian country that is home to diverse ecosystems and significant natural resources on a total land surface of 68 million ha (FAO 2021). In its border regions, the country contains numerous forest frontiers undergoing land cover transitions. Between 2002 and 2014 alone, Myanmar lost 2 million ha of intact forests, with major losses of up to 1.2% annually in border areas (Bhagwat et al. 2017). These forest frontiers have been formed by decades of civil war and isolation from the outside world. During the military regime from 1962 to 2011, the border regions were largely controlled by ethnic armed groups and also served as a refuge for internally displaced people. Forced migration and the relocation of remote forest villages to more controllable areas along the main road were also common (South and Jolliffe 2015). While both the military and ethnic armed groups benefited from illegal cross-border trade of timber as main source of income, there were no large-scale investments in forest lands at that time (Woods 2016). This changed when the military regime started the democratization process around 2010 and established a nationwide ceasefire agreement in 2015 with several ethnic armed organizations including the Karen National Union (KNU) in Myanmar's South. With the takeover of the civilian government in 2011 and the issuance of several reforms, the country has opened up to the international community and strongly pushed for agricultural investments in border areas. Foreign direct investment has concentrated on extractive industries and the energy sector and regularly induced militarization and displacement in frontier regions (Oo et al. 2020). Deforestation in Myanmar in the form of infrastructure development, timber extraction, and expansion of commercial agriculture is thus driven by complex drivers including land policies, national economic investments, private concessions, and social issues related to land tenure and civil war (Lim et al. 2017). In a contrasting development, opportunities for both forest resources and local people's livelihoods have evolved through the establishment of community forestry, a priority of the Forest Department since 1995 (Tint et al. 2011).

Since 1953, all land in Myanmar is property of the state. Land is broadly classified as farmland, forest land, virgin, vacant and fallow land and other according to Oo et al. (2020). Farmland is under the Ministry of Agriculture and Irrigation (MoAI) and is further subdivided into paddy land, flooded land (oilseeds, vegetables), garden land (orchards, vegetables), nypa land, taungya land (shifting cultivation), and other land not suitable for paddy rice. Forest land under the Ministry of Natural Resources and Environmental Conservation (MoNREC) is categorized as reserved forest area (production), protected public forest (conservation) and public forest land that is often under customary shifting cultivation. As an additional category, virgin, vacant and fallow lands fall under the jurisdiction of MoAI and refer to lands without intact forest cover that have either never been cultivated or later abandoned. A large share of customarily managed land, in particular land used for shifting cultivation, falls under this definition. Local communities in these areas have weak tenure security and are vulnerable in the face of land acquisitions through concessionaires, as their lands can be allocated for industrial agricultural development. Zoning broadly distinguishes between areas under the responsibility of either the General Administration Department (GAD) under MoAI and the Forestry Department (FD) under MoNREC. But these zoning arrangements often do not correspond to current land use. FD and GAD lands are in many areas not clearly demarcated and sometimes overlap. FD lands consist of managed forests or agricultural land with farmers paying annual taxes. Land under GAD includes settlements or croplands that are mostly under customary land tenure. Since 2012, these lands can be registered to obtain formal land certificates, but information on the current extent of such formal land titles is limited. Reliable data in terms of zoning is only available in some regions for protected areas (PA), community forests, and different types of concessions.

Even though a more participatory National Land Use Policy was developed and approved in 2016, there is not yet a National Land Law to implement it. A participatory assessment conducted by RECOFTC (2018) identified Myanmar's forest governance status as weak, with low scores for cross-sectorial coordination, benefit-sharing incentives, law enforcement, and measures to address corruption. It stressed that land tenure is a major issue limiting resource access for local communities.

1.2.2 Embedment of thesis and study sites

This thesis focuses on a specific forest frontier in southern Myanmar (Figure 1). Tanintharyi Region, a long stretch of land situated between Thailand and the Andaman Sea, is home to large intact forest complexes in the remote uplands along the border to Thailand. Shifting cultivation is still common in some of the remote areas (Schmid et al. 2021). In the lower altitudes that are close to the main roads and more densely populated, these forests transition into a mosaic landscape consisting of degraded forest lands, smallholder mixed plantations with rubber or cashew and betelnut, larger private rubber plantations, and oil palm concessions (Bhagwat et al. 2017). Coastal areas are dominated by mangroves and paddy fields on flat terrain. Across the region, households have different-sized home gardens providing them with fruit and vegetables. There are two PAs covering approximately 200 000 ha in Tanintharyi Region, and two more national parks have been proposed but are on hold. Since the early 1990s, close to 800 000 ha of oil palm concessions have been granted to companies, both in reserved forest lands and on villagers' plantations (Woods 2016). However, due to unfavorable conditions to grow, process and transport oil palm, revenues have remained low and several concessions have not fulfilled their potential. By 2019, only 15% of concession lands were actually planted with oil palm (Nomura et al. 2019). While private actors engage in timber exploitation, oil palm and rubber plantations, mining or aquaculture, local communities use the land for mixed subsistence and commercial farming. Similar to other forest frontier regions (German et al. 2014; Messerli et al. 2015), major challenges in Tanintharyi are the contrasting land claims from various actors.

Livelihoods in the selected study sites are largely rural and linked to natural resources. In remote upland areas, local communities practice shifting cultivation under customary land arrangements mainly for subsistence purposes. Communities with better market access generally get their income from plantation crops such as rubber, betelnut, and cashew as well as from small businesses and trading. Previously, forested areas and roadsides were used for herding cattle, however, this is not common anymore. Most households keep some chickens or a pig. Cattle and buffalo only remain in rice-producing areas. In flat lands suitable for paddy production, most smallholders grow rice with interspersed palm trees. Fisheries are the main source of income in coastal areas. Tourism, while still underdeveloped, is increasingly promoted in Tanintharyi's archipelagos. Due to limited opportunities for well-paid jobs within the region, out-migration is common. While some young people from rural areas move to regional cities or Yangon to look for jobs, labor migration to Thailand is much more common. In turn, laborers from Ayeyarwady Region arrive in Tanintharyi.

Tanintharyi Region is home to various ethnic groups, including the ethnic majority of Bahmar, Dawei (a subgroup of Bahmar), and ethnic minorities of Karen, Mon, and a few smaller groups. Some areas within Tanintharyi are under dual administration, with both the government and the KNU representing the local Karen people. However, limited information is available on respective spatial extents.

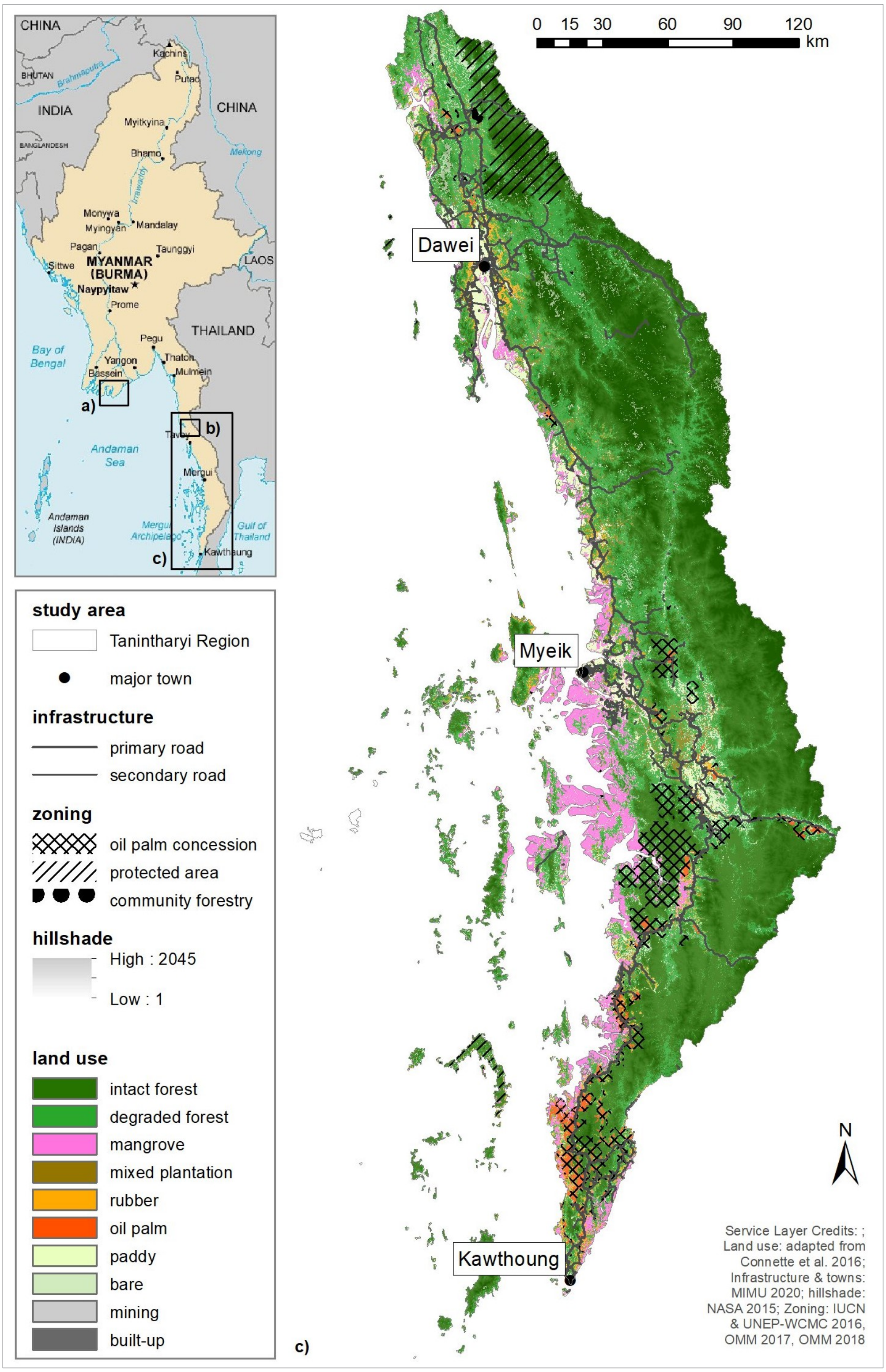

Figure 1 Map of the thesis' study areas; a) Pyapon township, Ayeyarwady Region, b) Yebyu township, Tanintharyi Region, c) Tanintharyi Region

A first study area of this thesis was in a post-frontier context in the Ayeyarwady Delta and included four villages in Pyapon township (see Figure 1, a). In this area, mangrove deforestation for the establishment of paddy fields to meet the regime's rice quota had been widespread until 2011 (Webb et al. 2014). But due to continued flooding and consequent salinization of these low-lying paddy fields, they soon became unproductive. In response, efforts were made since the late 1990s to restore these lands through the planting of mangroves coupled with a community forestry scheme with active participation of local communities. This area was also strongly affected by Cyclone Nargis, which devastated the delta and killed an estimated 140 000 people in 2008 (UNEP 2009). The communities had to adapt to the changing conditions in the aftermath of the cyclone. This part of the research was carried out as an activity within the project '*Scaling Up Community Forestry (SUComFor)'* under the lead of The Center for People and Forests (RECOFTC), which was implemented between 2015 - 2017. The project aimed to demonstrate how community forestry can contribute to empowerment, benefit-sharing, climate change adaptation, and the promotion of democratic principles at grassroots level. It had a total of seven study sites across Myanmar, among them one in northern Tanintharyi, which was the focal area of my thesis.

The main part of my field research was then carried out in several villages in Yebyu township in northern Tanintharyi in the frame of the research project '*Managing telecoupled landscapes for the sustainable provision of ecosystem services and poverty alleviation'* under the Swiss programme for research on global issues for development (r4d programme). The project ran from 2015 - 2021 and was led by the Center for Development and Environment (CDE) in collaboration with ETH Zurich and with local partners in Myanmar, Laos and Madagascar. This thesis was embedded in WP 1.2, which aimed to model ES flows under telecoupled land uses. The study area in Yebyu township (Figure 1, b) is located along the main road through Tanintharyi. It is near the Tanintharyi Nature Reserve with adjacent community forests and also includes oil palm concessions, gas companies and some mining areas.

Later, I expanded my research to the entire Tanintharyi Region (Figure 1, c). This included travels to the towns of Dawei, Myeik and Kawthaung and visits to several rural communities that benefit from different landscapes and land uses. This regional research part was embedded in the '*OneMap Myanmar'* project, which is led by CDE and has a close collaboration with different interest groups including the Land Core Group in Myanmar. OneMap Myanmar aims to improve country-wide accuracy and availability of data on land use, land cover, and land tenure. Working closely with different stakeholders including relevant ministries, civil society, non-governmental organizations and local communities, the initiative combines official sources with public contributions and participatory mapping. One of the initial focal areas was Tanintharyi Region. Therefore, the project had accumulated several spatial datasets on the region's biophysical properties, land uses, zoning arrangements, infrastructure, and socio-economic indicators. This thesis contributed to the project by combining these datasets with qualitative data from the field and using them to spatially assess ES for local communities at the regional level.

1.3 Key challenges and research objectives

The overarching problem I aimed to address with this thesis is the limited understanding of the role of local communities in shaping forest frontier landscapes and their perspectives on the benefits provided by various land uses present in frontiers. This is not only due to smallholders' low representation compared to more powerful stakeholders in global sustainability discussions but also a result of scientific challenges to analyze the complex relationships that local communities have with nature in a telecoupled world. Therefore, this thesis aims to respond to several key challenges related to the Myanmar context and forest frontier landscapes in general, local stakeholders' dynamic roles in natural resource management and use, and scientific assessments thereof.

Knowledge gaps related to the institutional context of forest frontiers in Myanmar and local communities' adaptation

Specific challenges in Myanmar are the overlapping land claims, zoning arrangements and responsibilities between different government and ethnic institutions. In these power struggles over land, local communities and their customary rights are often disregarded. Even though there are ongoing land reforms, including a multi-stakeholder process that led to the 2016 National Land Use Policy and recognizes customary land tenure, there are still many gaps to implementation. As basis for these processes, the roles and needs of local stakeholders in this transitional context need to be understood. Research needs to go beyond assessing specific benefits that local communities obtain from certain land uses and trade-offs they experience if land use changes. Bennett et al. (2015) emphasizes the need to understand the relative importance and interaction of biophysical and social components over time and space. Research thus needs to acknowledge and incorporate additional factors that shape local land users' decision-making and adaptation to a transitioning frontier landscape. This thesis aims to understand how local communities in the context of Myanmar's forest frontiers benefit from natural resources provided by various land uses and how they adapt to a changing resource base under consideration of ecological, economic, political, and cultural variables.

Research challenges related to accessibility and stakeholder representation

For data collection, a main challenge in frontier regions is accessibility. The researchers' access to local communities can be restricted due to their remoteness and lack of infrastructure and transport. It can also be restricted due to political or cultural circumstances. In Tanintharyi, research permits have to be obtained before visiting any rural communities. Research permits are only issued in well-accessible areas and zones under control of the government. Arguably, that means that any assessments of local perspectives are based mainly on communities that are more connected, accessible, have benefited from governmental programs or international projects, and usually belong to the main ethnic groups. Another challenge is the issue of scale. Small-scale or local assessments, also called case studies, have the advantage of taking place in fairly homogenous areas and accounting for the majority of stakeholders. This leads to a more in-depth and participatory knowledge generation. On the other hand, case studies alone are limited in their ability to draw conclusions for the wider study area.

Methodological challenges for assessing local perspectives and flow of ecosystem services

Acknowledging the importance of spending time with rural communities to understand their perspectives and realities on the one hand and quantifying and upscaling these findings on the other hand, the challenge is to find a way to combine different types of knowledge in ES assessments and be able to draw conclusions from local to regional scale and beyond. Even though various valuation methods for ES exist (Gómez-Baggethun et al. 2016), they are rarely applied in integrated assessments needed for local analyses and decision-making support (Pandeya et al. 2016). Costanza et al. (2017)

name the inconsistency of valuation approaches and lack of institutional frameworks as limiting factors in ES research. Standardized models still face limitations in their transparency of variables and respective calculations, the number and type of services included (particularly cultural services), and options to incorporate qualitative data (Bagstad et al. 2013; Sharps et al. 2017). While assessing ES demand is restricted in the standardized tools, analyzing flow is even more challenging. ES models have only recently started to include flows in the form of spatial movements (Baró et al. 2016; Schröter et al. 2018; Schirpke et al. 2019). The role of institutional access to natural resources through zoning and tenure schemes has so far been neglected in ES assessments and is particularly important for local stakeholders in frontier landscapes. Using more flexible and transparent models can facilitate the inclusion of the different dimensions of supply, demand, and flow. Developing model rules based on different types of stakeholder knowledge is a possibility to upscale local perspectives in the form of qualitative data. Obviously, data-scarce regions pose further challenges to assessing and valorizing ES (Pandeya et al. 2016). In Myanmar's Tanintharyi Region, similar to other frontiers in developing countries, data availability and accuracy are weak. This also applies to spatial data. One particular problem is that overlapping responsibilities of different government institutions and low coordination between them hinders systematic data collection at larger scales. Another issue is that land use and additional variables, e.g. property rights, infrastructure, access to markets, or population, are highly dynamic in frontier landscapes. This makes it difficult to generate accurate data that reflects realities on the ground and is still useful in a few years' time. For these regions, using models that can easily be updated is highly recommended (Landuyt et al. 2013). In this thesis, I therefore aim to further evolve recent advances in ES valuation for data-scarce regions with new models that combine qualitative and quantitative data and include aspects of demand and flow with a focus on local stakeholders.

Bridging science and policy

Finally, one remaining challenge is the question of how gained knowledge can be translated into transformational impact on the ground. Land system science as an interdisciplinary platform can support the bridge between science and policy (Verburg et al. 2015). Especially in frontier contexts, ES analyses can make trade-offs more transparent and thus be useful for policymakers (Costanza et al. 2017). Bennett et al. (2015) recommend that ES research needs to be transdisciplinary for designing research for sustainability. Costanza et al. (2017) stress the need to effectively communicate results to the public and to clearly identify different outcomes related to potential policies. While modelling provides a knowledge base of dynamic socio-ecological systems and related trade-offs, mapping supports policymakers in understanding these links between landscapes and human well-being (Burkhard and Maes 2017). In this regard, maps need to be robust, transparent and stakeholder relevant (Willemen et al. 2015). This aims to contribute to the application challenge by spatially assessing the multifaceted impacts of different land use and tenure schemes on local communities in tropical forest frontiers and providing respective policy recommendations based on scientific findings.

2 Approach and methodology

This chapter gives an overview of the relevant concepts and the approach I took to investigate the above stated challenges. It briefly describes the main methods and tools that were used in the course of this research. More detailed descriptions can be found in the methodology sections and annexes of the respective papers.

2.1 Theoretical framework

My research was based on two main theoretical frameworks that are commonly used for assessing socio-ecological systems, human-nature interrelations, and associated livelihoods of rural communities: The Sustainable Livelihoods Assessment (SLA) and the Ecosystem Services (ES) concept. The SLA (IFAD 2011) focuses on the livelihoods of rural household under consideration of five livelihood assets (natural, physical, financial, human, social). We used this framework in *Paper I* to analyze how and to what extent mangrove community forests contribute to the livelihoods and livelihood strategies of different households within rural societies. For *Papers II – V,* we used the ES concept (Costanza et al. 1997), which focuses on the natural capital and its contribution to people's well-being. It refers to the wider landscape context and considers not only nature's products but also non-material services that contribute to human well-being beyond livelihoods, distinguishing between provisioning, regulating and cultural services. The concept became popular with the Millennium Ecosystem Assessment (MEA 2005) and is still the most prominent framework for assessing the multiple benefits that people get from natural and man-made systems (Costanza et al. 2017). The cascade model implies that final services rely both on ecosystem capacity and on people's needs (Haines-Young and Potschin 2012). Building on this, I consider final ES outcomes to be the result of supply, demand, and flow. ES supply hereby refers to the goods and services supported by a certain land use, whereas ES demand refers to local people's use and perceived value thereof (Burkhard and Maes 2017). ES flow refers to people's access to these services (Villamagna et al. 2013; Schröter et al. 2014).

2.2 Data collection

My research was guided by an explorative study design that started with qualitative data collection and then moved towards quantification. At village-level, first in the Ayeyarwady Delta and later in Tanintharyi Region, I used Participatory Action Research (PAR) tools (Angelsen et al. 2011) to collect qualitative data during several months between 2015 - 2020. Key tools included transect walks, focus group discussions, resource mapping, and informal interviews. The aim was to get an understanding of local livelihoods and use of natural resources, main land use practices, historical land use changes, and current challenges. In a next step and complementary to this, I carried out household surveys with semi-structured questionnaires that built upon previous learnings. These served to quantitatively assess livelihood assets and strategies across villages. In Tanintharyi Region, standardized questionnaires in group interviews were additionally used for the social valuation (Felipe-Lucia et al. 2015a) of benefits in the form of ecosystem services per land use. Later, I expanded the perspective to the regional level and carried out interviews with several key informants from civil society and government institutions working with different communities on land issues across Tanintharyi Region. The aim was two-fold: First, talking to different types of local actors gave a more diversified view of current challenges associated to land use and tenure rights. Second, by way of representation, these interviews at least partly allowed for the integration of the perspectives of local communities that were otherwise not accessible to us, such as some Karen villages in remote and secluded areas or the Moken living in the archipelagos of the Andaman Sea. For the regional level, additional secondary spatial datasets were acquired, including land use, zoning (oil palm and mining concessions, community forestry, protected areas), biophysical (slope, soil type, rainfall, etc.), and socio-economic data from the OneMap Myanmar project and online sources.

2.3 Model development

Continuing the efforts to quantify ES outcomes for local communities at regional level, I developed models for nine ES relevant in the study area: subsistence foods, commercial products, fuelwood, medicinal plants, biodiversity, climate regulation, water regulation, environmental education, and cultural identity. I decided to use Bayesian networks (BN), which are probabilistic models based on causal dependencies (Kjærulff and Madsen 2008). They are able to include different knowledge types and especially qualitative data and are therefore useful in data-scarce regions (Burkhard and Maes 2017). All models were constructed with the commercial software Netica (version 6.05). Model development followed an iterative process during a period of approximately two years, where new data from key informant interviews supported the continuous updating and calibration of the models. In a last step, models were validated with twelve scientific international experts who are familiar with both the study area and the ES concept. All nine models included ES supply mainly based on land use and biophysical factors, ES demand based on socio-economic factors, and ES flow based on distance and access rights for local communities.

2.4 Data analysis and mapping

A structured content analysis (Bernard et al. 2017) was carried out for the qualitative data. I transcribed, coded, and analyzed all data from PAR tools using the MaxQDA software (version 2018). The quantitative data from household surveys was analyzed with R statistical software (version 3.4.1.), by applying mostly descriptive statistics. The ES models were analyzed in Netica. For that, I first did a sensitivity analysis which aimed at identifying the most relevant variables for ES supply, demand, and flow. Based on these key variables, I then applied different scenarios to test their impact on ES outcomes. In a final step, I carried out a spatial analysis of ES for Tanintharyi Region. After cleaning the available spatial datasets in ArcGIS (version 10.6.1) and verifying their consistency with the models' input variables, I linked the data with the models using the online tool gBay (Stritih et al. 2020). Outputs were produced as raster files that show probability distributions of supply, demand, and flow values for each ES. These were then used to map ES and identify supply/demand mismatches for local stakeholders across Tanintharyi Region. Mismatch areas were hereby understood as areas with unsatisfied demand (supply < demand).

3 Key insights from research papers

I started my research by assessing livelihoods in a few villages situated in a specific mangrove post-frontier landscape (*Paper I*) and then moved to a second, current, frontier landscape with upland forests, smallholder plantations and agricultural concessions. Recognizing that a broader perspective was needed to account for the various material and non-material benefits that people obtain from nature and to assess trade-offs, I adopted the ecosystem services framework (*Paper II*). Connecting these findings with other studies that investigated underlying land transformations, different claims on land as well as local perceptions on human well-being, we investigated potential pathways to sustainability at district-level (*Paper III*). I then moved on to assess ES outcomes for local stakeholders across the entire region, which included all land uses and tenure systems encountered before. Aiming to quantify the supply, demand, and flow of ES, I developed new models based on both qualitative and quantitative data (*Paper IV*). Finally, I combined these models with spatial data to map ES outcomes and identify mismatches for local communities (*Paper V*). The research process is illustrated in Figure 2.

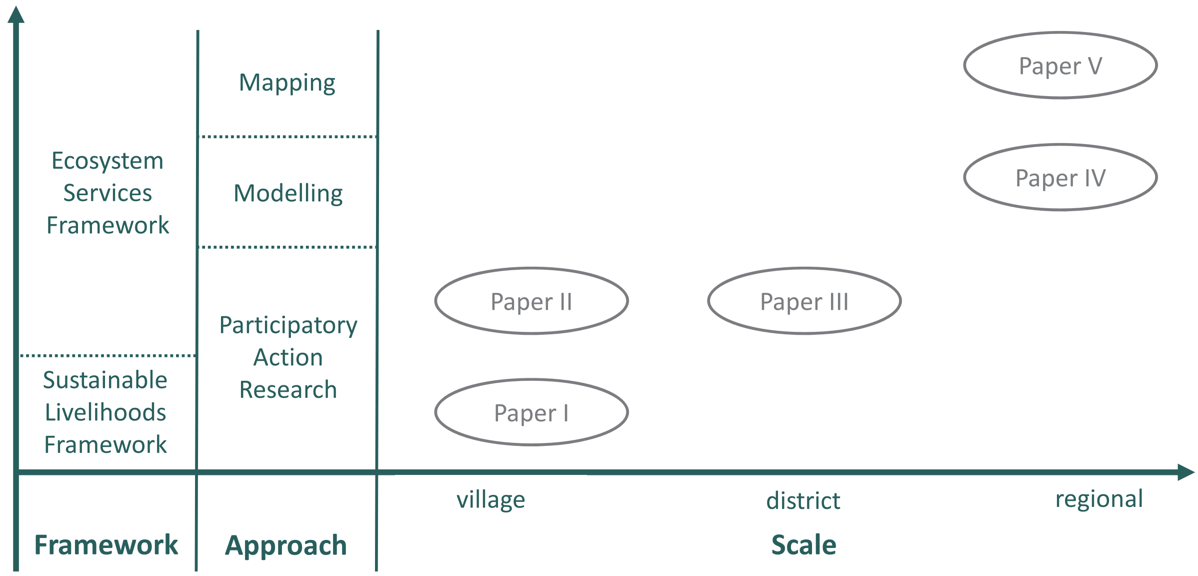

Figure 2 Illustration of research process and scientific papers according to the applied framework, methodological approach, and spatial scale

Step by step, the research results presented in this chapter contributed to a better understanding of the key challenges for local communities in tropical frontier landscapes and potential pathways towards achieving higher benefits for all stakeholders through more inclusive land policies in such forest frontiers. Papers I - III mainly contribute to the understanding of rural communities in Myanmar, their benefits from natural resources, and local adaptation processes to landscape transitions and trade-offs. Papers IV - V then focus more on the methodological advancement of ES research. Paper III specifically aims to frame sustainable development pathways, but all papers contribute to a certain extent to the science-policy bridge, as they assemble insights into different land tenure schemes and recommend policy measures that can apply to tropical forest frontier contexts beyond the study area.

3.1 Community forestry and livelihoods

With the awareness that rural communities not only depend on forest resources for their livelihoods but that, in fact, they play a central role in the protection and sustainable management of forest landscapes (Porter-Bolland et al. 2012), community forestry (CF) has increasingly been recognized by governments across Asia and the Pacific as a key mechanism for more inclusive land policies. In forest frontiers, CF is often used in buffer zones of protected areas to allow local communities the use of forest products and prevent them from interfering with the conservation of remaining natural forests. In degraded areas, CF is also used to restore unproductive lands with the support of local land users. But although CF is widely recognized for its potential to provide ecosystem services (Paudyal et al. 2015) and support forest-related livelihoods, some studies have found that it can fail to benefit the poorest households within communities (Parajuli et al. 2015; Moktan et al. 2016). Furthermore, previous studies have focused on CF user groups (CFUGs) only but neglected non-members of those groups.

In *Paper I*, we aimed to address this research gap by assessing whether and how different households within a community can benefit from CF. The study was carried out in Myanmar's Ayeyarwady Delta, which experienced extensive land use changes in the past due to the conversion of mangrove forests into paddy fields and, more recently, into shrimp or salt farms. In response to a gradual degradation of paddy fields, these were later restored with mangrove plantations under CF management.

> Paper I
>
> **Community forestry for livelihoods: Benefiting from Myanmar's mangroves**
>
> Feuer M, Gritten D, Than MM, 2018. Community forestry for livelihoods: Benefiting from Myanmar's mangroves. Forests, 9 (3), 150. https://doi.org/10.3390/f9030150

Our findings in this case study demonstrate that, under the right conditions including mutual trust relationships within communities and with government agencies, adequate regulatory rules for the collection of forest products and equitable benefit-sharing mechanisms, CF can support the livelihoods and well-being of entire communities and is not restricted to certain households within a community. From a total of 110 interviewed households (thereof 50 members of the CFUG) in four villages, we found that 91% regularly use mangrove products. These include both subsistence products such as fuelwood, small timber, fish or medicinal plants, and commercial products such as mud crab or nypa leaves. This study further revealed the benefits that land users obtain from homegardens. These diverse systems provide multiple products as well as other services that enhance household resilience. Especially poorer and landless households rely on natural resources in their livelihood strategies in addition to casual labor. Both men and women in poor households collect forest products, in contrast to wealthier households, where women are mainly housewives. While we found no obvious link between CF membership and wealth, we did find a connection between CF membership and the contribution of mangrove products to household income. While mangrove products account for 36% of total income from CF members, they account for only 15% of non-member's income. Among the poorest CF member households, up to half of their income stems from mangrove products. In addition to livelihood support, the mangrove CF areas also provide local communities with ecosystem services, in particular storm and flood protection. In times of hardship or after extreme events, the mangroves provide a safety net, which is especially vital for the poor.

This paper contributed to the debate on community forestry as a pro-poor approach. In agreement with a global comparative analysis on environmental income (Angelsen et al. 2014), our findings indicate that natural resources can reduce income inequality and that households with low agricultural output rely more on forest products. We can assume that improved access to natural resources, e.g. in the form of CF, is particularly important for landless people and those with formerly limited access to agricultural lands. In forest frontiers landscapes, rural communities often receive complementary benefits from agricultural and forest activities (ibid.).

3.2 Ecosystem service trade-offs

In the Ayeyarwady Delta, I investigated local communities' benefits from forests and other land uses at a time when deforestation had largely halted, and the land use distribution was more or less stable at a state of low mangrove cover (post-frontier context). Tanintharyi Region, on the other hand, is still in a process of transition. Natural forests and smallholder mixed plantations have already partly been replaced by oil palm concessions and private rubber plantations, leading to a shift in livelihoods and culture. So, while diverse landscapes have the potential to provide several livelihood options and multiple ecosystem services (Law et al. 2017), inequitable land use changes can generate trade-offs that adversely affect the well-being of local land users. In the context of forest frontiers, trade-offs are often linked to governance and occur when different stakeholders hold divergent claims on land (Howe et al. 2014). Myanmar's outdated and incoherent land classification systems fail to accommodate customary land tenure (Woods 2016) and weaken local land user's decision-making. Inherently, rural communities are most vulnerable in the face of top-down land use decisions. However, limited information is available on how local communities experience and react to the trade-offs from changes in land use and associated ES bundles.

With *Paper II*, we wanted to bridge this knowledge gap and complement existing ES research by using social valuation techniques to assesses local smallholders' perspectives in terms of land use, ES trade-offs from land use change and local adaptation processes.

Paper II

Local perspectives on ecosystem service trade-offs in a forest frontier landscape in Myanmar

Feurer M, Heinimann A, Schneider F, Jurt C, Myint W, Zaehringer JG, 2019. Local perspectives on ecosystem service trade-offs in a forest frontier landscape in Myanmar. Land, 8 (3), 45. https://doi.org/10.3390/land8030045

In a case study involving three villages in northern Tanintharyi, we found that local land users value forests in particular for their ability to provide a broad portfolio of ES, including several regulating and cultural services as well as subsistence products in the form of fuelwood, wild foods and medicinal plants. Shifting cultivation, previously important for growing rice for subsistence, was mostly abandoned due to a lack of land after agricultural expansion and the establishment of a protected area nearby. Instead, we found that local communities prefer more commercial agricultural lands such as mixed agroforestry with cashew and betelnut trees or rubber plantations, which were found to almost fulfill local ES demand entirely. At the time of the research, rubber was the main source of income and fuelwood for rural households. When planting rubber, smallholders can further obtain legal rights to their land, which assures that they can access ES benefits in the long term. As a result, most smallholders kept some mixed plantations and converted the remaining lands to rubber. Oil palm concessions that were established approximately twenty years ago were strongly condemned by local communities, as they lost access to these lands and experienced not only ES decline but even disservices such as water contamination, air pollution, and biodiversity loss. We also found trade-offs between regulating and provisioning commercial ES when forests were converted into small-scale agricultural plantations. Generally, rural communities adapted rather well to land use changes by modifying their use of ES based on availability and other factors such as changing markets, knowledge, or tenure rights. Improved infrastructure simultaneously gives them more options to substitute products, for example by replacing herbal remedies with modern medicine. Still, we identified one key problem in the study area: the gradual loss in the regulation of water flows, which in frontier landscapes can only be fully maintained through intact forest ecosystems. Adequate forest zoning and management is thus vital for areas with key hydrological functions. In terms of ES bundles, the study concludes that revising current land laws to grant more legal rights to local people and ensuring their participation in land governance is crucial to sustainably enhance local well-being.

Contributing to the efforts to value ES from different stakeholder perspectives, we demonstrated that social valuation techniques are highly valuable for understanding local communities' perception on various land uses, related ES, and trade-offs in forest frontiers. Nonetheless, some services such as water regulation should be assessed at larger scale and quantified in order to draw conclusions on the sustainability of a landscape.

3.3 Pathways between land use change, ecosystem services, and human well-being

After having analyzed ES trade-offs in a specific area in two village tracts, I expanded my focus to the district level and collaborated with fellow researchers working in the same general study area to bring together and synthesize our findings on land use changes, ecosystem services, human well-being and the role of different actors in land use decision-making.

Competing claims on land and responsible management of natural resources are at the core of several current development challenges, particularly in tropical forest frontiers and countries undergoing political and economic transitions (Prescott et al. 2017; Smith 2018). Land system science faces the dilemma of complexity and dynamics; thus, studies often focus on single components within a socio-ecological system but fail to consider all actors at different levels, power relationships, or governance challenges. In an attempt to overcome these shortcomings and contribute to middle-range theories of land system change (Meyfroidt et al. 2018), *Paper III* used an integrative perspective to investigate the links between stakeholder interactions, land use changes, and sustainable development outcomes in northern Tanintharyi and identify priority areas for sustainable land governance in Myanmar.

Paper III

Sustainable development under competing claims on land: Three pathways between land-use changes, ecosystem services and human well-being

Schneider F, Feurer M, Lundsgaard-Hansen LM, Myint W, Nuam CD, Nydegger K, Oberlack C, Tun NN, Zaehringer JG, Tun AM, Messerli P, 2020. Sustainable development under competing claims on land: Three pathways between land-use changes, ecosystem services and human well-being. The European Journal of Development Research, 32 (2), 316-337. https://doi.org/10.1057/s41287-020-00268-x

We identified three main land use developments that affected communities in northern Tanintharyi in the past two decades: establishment of a protected area (Tanintharyi Nature Reserve); conversion to oil palm; conversion to rubber and mixed plantations. The main actors in these trajectories were the government that implemented the TNR and granted oil palm concessions to companies, the military that supported the enforcement of such land deals, the Karen National Union (KNU) that opposed these deals but eventually gained control over part of the TNR and also apply their own land policy, the related palm oil and gas companies that exploit natural resources for profit but also support village development projects, and the local land users that were mainly involved in the acquisition of land for rubber and mixed cashew and betelnut plantations. We found that the loss in ES for local communities not only resulted from changing land uses but more importantly also from changing governance systems that limit local people's rights to resources. Despite an overall decrease in ES, human well-being generally increased after the civil war in the early 1990s due to improved infrastructure and more income generation from smallholder plantations that allowed people to invest in better housing, education, and health care. Our findings indicate that, particularly in complex forest frontier landscapes, impacts on local well-being depend not simply on land use changes but also on political stability, governance systems and the agency of the different actors involved. Indeed, positive effects were more likely where villagers were able to co-drive land use pathways and invoke their own claims on land. We conclude with four priority areas for sustainable land governance in Myanmar: 1) consider the role of armed conflict and include land issues in peace dialogues, 2) create strong land governance arrangements that include both land sharing and land sparing approaches for enhanced ES outcomes, 3) secure land tenure and enable local communities' access to land, and 4) support broader transformation regarding accountability, know-how and hidden power relations between different dominant actors. This paper contributed to the theories around land system change under telecoupling.

After having gained in-depth knowledge of the situation of local communities regarding land resources in a specific case study area and discussing the implications for sustainable development pathways in northern Tanintharyi, I decided to broaden the scope further to the regional level while also attempting to quantify ES outcomes for local stakeholders.

3.4 Modelling the supply, demand, and flow of ecosystem services

Quantitative ES assessments often use only one indicator per service and fail to account for the complexity of socio-ecological systems. Thus, modelling approaches to ES quantification that include several variables have become more popular and include standardized frameworks such as InVEST (Sharp et al. 2020) or ARIES (Villa et al. 2014). However, their ability to integrate locally relevant variables and qualitative data is limited (Bagstad et al. 2013). Bayesian networks (BN) allow for both and are particularly useful in data-scarce regions (Burkhard and Maes 2017). Still, previous models have remained limited either in terms of scale, ES types, or dimensions for ES outcomes including supply, demand, and flow, as well as related indicators. With the objective to investigate the actual benefits that enhance the well-being of the local population, I considered these as a function of supply, demand, and flow (Villamagna et al. 2013; Mouchet et al. 2014; Schirpke et al. 2019; Vallecillo et al. 2019). As seen in the previous paper, adding these different dimensions supports the examination of underlying mechanisms and eventual impacts on local communities.

With the aim to evolve contemporary modelling approaches, *Paper IV* presents the development and application of BN models for nine ES in Tanintharyi Region. The paper further investigates how ES outcomes change for local stakeholders according to various land use and tenure scenarios at different spatial scales.

Paper IV

Quantifying local ecosystem service outcomes by modelling their supply, demand and flow in Myanmar's forest frontier landscape

Feurer M, Zaehringer JG, Heinimann A, Naing SM, Blaser J, Celio E, 2021. Quantifying local ecosystem service outcomes by modelling their supply, demand and flow in Myanmar's forest frontier landscape. Journal of Land Use Science, 19 (2), 1-39. https://doi.org/10.1080/1747423X.2020.1841844

Based on our models and considering Tanintharyi Region as a whole, we found on an indicative range from 1 to 5 the highest scores for water regulation (3.6) and biodiversity (3.5) and the lowest score for commercial products (2.3). This reflects the overall high forest cover of the region and limited commercial opportunities from agriculture for local communities. In line with earlier findings from the study villages, our results indicated that even though the supply of multiple ES is highly linked to land use, there are additional decisive factors that influence ES outcomes for local stakeholders in a forest frontier context. We found that local demand for ES strongly depends on people's use of natural products and the availability of alternatives. Further, flow is particularly affected by zoning and land tenure. In concession lands or protected areas, local communities usually cannot benefit from potentially provided ES due to access restrictions. Using scenarios, we were able to detect more significant impacts of land use and tenure changes where applied to a small-scale homogenous landscape compared to the fairly heterogenous landscape of the entire Tanintharyi Region. This is not surprising, as ES outcomes from regional scenario analysis are somewhat diluted in combination with many other factors playing a role and being highly diverse across the region, including e.g. population density or market access. Using a small-scale reserved forest landscape with a mean outcome score of 3.2 for nine ES as baseline, local scenarios showed that benefits for local stakeholders increased if community forestry was established (3.4). On the other hand, ES benefits strongly decreased if the area was converted into an oil palm concession (2.4), with particularly negative effects on local livelihoods and cultural identity. If forests were converted to smallholder plantations in a third scenario, overall ES did not change much (3.1) but instead we found a shift towards slightly lower regulating services and fuelwood availability and much higher benefits from commercial products. We conclude that while forests are good sources of ES, mixed tree crop plantations can be just as important land uses in remote areas where communities have few alternative sources of income.

This paper contributed to the advancement of modelling techniques for ES assessments. While models are useful land science tools to inform decision-makers on the potential impacts of policy changes, adding maps can support policymakers in better understanding the links between ecosystems, society, and human well-being (Burkhard and Maes 2017). In forest frontiers like Tanintharyi, characterized by data scarcity, overlapping land claims and frequent land use changes, ES mapping is particularly challenging but also an opportunity to include the perspectives of local stakeholders and increase transparency, two often neglected aspects in mapping studies (Willemen et al. 2015). Following this, the next step in this research was a spatial analysis of the developed models for Tanintharyi Region.

3.5 Regional-scale mapping of ecosystem services

With increasing relevance of spatial assessments during the past decade, several studies have mapped the supply of and demand for ES and identified corresponding budgets or mismatches (Burkhard et al. 2012; Chen et al. 2020). Other studies also mapped ES flows (Baró et al. 2016; Schirpke et al. 2019). Recommended best practices for ES mapping are robustness (e.g. by considering a wide range of variables), stakeholder inclusion, and transparency, in particular by reporting map uncertainties (Willemen et al. 2015). These are all important aspects to be considered in dynamic tropical forest frontiers. In the tropics, a few notable mapping studies were done (e.g. Forio et al. 2020; Pinillos et al. 2020; Ramirez-Gomez et al. 2020), but they either excluded the dimension of flow or focused on a few ES with limited relevance for local communities.

Opposed to this, *Paper V* specifically analyses locally important ES in Tanintharyi Region in terms of supply, demand, flow, and supply/demand mismatches. We mapped nine ES by updating the recently developed models - described in the previous paper – with regional spatial data. This paper aims to assess current ES outcomes for local stakeholders, identify problematic areas with high mismatches and/or flow limitations, and contextualize findings considering land use and land tenure options.

Paper V

Ecosystem services for local stakeholders: Mapping supply, demand, and flow – and identifying mismatches – at regional scale in Myanmar

Feurer M, Rueff H, Celio E, Heinimann A, Blaser J, Htun AM, Zaehringer JG, [submitted]. Ecosystem services for local stakeholders: Mapping supply, demand, and flow – and identifying mismatches – at regional scale in Myanmar.

Our results show a high supply of multiple ES, namely fuelwood, medicinal plants, biodiversity, climate regulation, and cultural identity, across Tanintharyi Region. Subsistence foods are provided to a lesser extent, as rice is only grown in shifting cultivation areas and paddy fields, although homegardens also provide some fruit and vegetables. In contrast, the supply of commercial products and environmental education is overall limited. This is problematic as both are highly demanded by local stakeholders, resulting in strong imbalances across the region. In cities with high population densities, the demand for these and most other ES cannot be covered, even if surrounding areas provided multiple ES. We identified hotspots of supply/demand mismatches in urban areas as well as in degraded forest areas along roadsides that are rapidly being developed. From a total of nine ES, up to eight and three were mismatched in urban and rapidly developing areas, respectively. Mismatches were also found in oil palm concessions, which provide few ES for local stakeholders next to limiting their access to these lands. Overall, mixed landscapes consisting of remaining patterns of natural forest and smallholder agricultural plantations showed a maximum of one mismatched ES, which speaks for the value of mosaic landscapes. To contextualize how mismatches are linked to land use and land tenure, we zoomed in to two study sites, A) the rapidly developing earlier case study villages in northern Tanintharyi and B) a coastal town surrounded by paddy fields and mangroves. We confirmed that mismatches not only relate to land use but are strongly linked to zoning and land tenure arrangements including concessions, protected areas, and community forests. Protected areas and concession lands, although pursuing very different goals, both serve more powerful stakeholders while presenting local communities with high ES mismatches and limited access (flow) to these natural resources. Community forestry, if managed well, is most promising both in terms of ES flow and limited mismatches.

Our results support insights on how local stakeholders perceive and benefit from natural resources and related ES. This is complementary to existing knowledge on the global value of ES such as carbon sequestration or biodiversity. We also highlighted the importance of mapping supply/demand mismatches and flows, as these particularly affect the livelihoods and well-being of local communities. Securing land rights for local land users is key to ensuring effective ES outcomes and sustainable development in Tanintharyi Region as in other forest frontier landscapes.

4 Synthesis and outlook

This thesis contributed to the understanding of how rural communities in Myanmar's southern forest frontiers manage their lands and benefit from various natural resources. We found that smallholder lands are highly diverse and provide both subsistence and commercial products. Only if a household has additional lands do they invest in purely commercial plantations such as rubber. Many households still gather a range of wild products, even in areas where agriculture has become dominant. Considering their previous experiences with civil war, land grabs, and Cyclone Nargis in the delta, sustained use of natural resources could be a safety net to cope with future threats. In view of climate change and increased risks of heat waves, storms, floods, landslides and crop failures, rural communities are well aware of the value of forests and mangroves in mitigating these dangers. Nonetheless, the undisputable reality is that even though rural communities value nature, their primary concern is making a living and providing better opportunities for their children, be it in agriculture or other sectors. Infrastructure development and improved market access provide opportunities that are quickly embraced by these communities, as the example of rubber demonstrates. Other natural resources are being substituted with newly available alternatives. Traditional herbal remedies have largely been replaced by modern drugs, fuelwood and charcoal in urban areas have given way to electric and gas stoves, and rice and other foods are more often bought on the market nowadays. We found that even education has shifted from traditional learning in nature to on-screen information. Thus, assumingly, economic and technological development can reduce the demand for ecosystem services (Carpenter et al. 2006). Yet, science has given little attention to rural communities' adaptation prospects beyond livelihoods or scenarios involving the substitution of certain services. This is certainly an aspect that deserves more in-depth research.

Still, natural resources are important assets particularly for the poor and forest-dependent people. Our findings correspond to the middle-range theories of land system change presented by Meyfroidt et al. (2018). In response to reduced land availability and uncertainties associated with more intensive land uses such as rubber, some communities have already returned to practicing shifting cultivation in the protected area's buffer zone. This need for a safety component in tropical frontiers is expected to remain important (Vliet et al. 2012). In our case, land grabs and imposed zoning arrangements have negatively affected the livelihoods of rural communities, particularly those in Tanintharyi Region. The establishment of oil palm concessions on forested or farmed lands has not only deprived local smallholders of their access to associated benefits, but also led to broader disservices such as soil compaction, sediment accumulation, water contamination, and air pollution. While the accounting of disservices is contested in ES research (Harrison et al. 2014), regional tipping points must be considered, leading up eventually to the level of planetary boundaries (Steffen et al. 2015). Clean water supply is a major issue. Even though we found currently high regulating services at regional level, it is not clear what happens if deforestation and forest degradation continue at the same pace (Schmid et al. 2021). In protected areas, local communities experienced declines in provisioning and cultural services due to the restricted access but no limitations for regulating services. The results of this thesis thus contribute to the still limited understanding of how different large-scale zoning schemes affect ES outcomes for local communities (Intralawan et al. 2018; Kim et al. 2018; Roy et al. 2018).

Recently, a surge in studies on land governance processes in Myanmar was observed (Mark 2016; Suhardiman et al. 2019; Mark and Belton 2020). This thesis supports the discussion through the lens of ecosystem services to give a more multifaceted account of local stakeholders' needs and perspectives. On reserved forest land, some acres of farmland per household are allowed in return for annual taxes. On agricultural land, formal land certificates are issued. However, land registration is a burdensome process for smallholders and certificates are partial to certain crops. It seems that reserved forest land is comparatively less affected by large-scale developments. Supporting other studies (Birch et al. 2014; Santika et al. 2019), we found that community forestry, established on reserved forest lands (or certain virgin lands) for 30 years, shows great potential for increasing local communities' tenure security, livelihoods, and ecosystem services under the right conditions. These include strong participation and decision-power of communities, equitable benefit-sharing mechanisms, and adequate regulations on collecting forest products. Having seen the important contribution of traditional shifting cultivation to various ecosystem services, the recognition of customary rights is vital. While we were not able to fully explore shifting cultivation landscapes, they seem to be expanding in Tanintharyi Region (Schmid et al. 2021). Our findings generally point in the same direction as a recent study that linked declining swidden agriculture with ES losses for rural households across Southeast Asia (Dressler et al. 2017). Apart from these more remote areas within mosaic landscapes, the realities of frontier crop booms, not only driven by private investors but also by smallholders' imitation behavior (Junquera and Grêt-Regamey 2019), need to be considered in policies for sustainable development. Several measures are needed for smallholders to benefit from these booms without risking their livelihoods and benefits from surrounding forests and mixed plantations. First, land certification processes require simplification and certificates need decoupling from certain crops to increase local land use options for diversification and sustainable land management practices. Second, increased capacity-building to improve the quality of smallholder products can provide households with better income security in telecoupled markets.

To broaden the view, what can be recommended for sustainable land use planning in tropical frontiers beyond the Myanmar context? Considering ongoing land zoning debates, the results of this thesis tentatively support the recommendations of Law et al. (2017) that mixed land sparing and sharing policies are most effective in supplying multiple ES in tropical mosaic landscapes. However, while they propose a minimum of one third of the land area under conservation, this thesis suggests that strict conservation can do more harm than good. Protected areas need to account for local people's needs and acknowledge their capacities to manage natural resources sustainably (Porter-Bolland et al. 2012). Indigenous conservation areas should be recognized and promoted (Garnett et al. 2018). With community forestry contributing to the achievement of multiple sustainable development goals (Jong et al. 2018), protected areas should at the minimum be accompanied by community-managed buffer zones and conditionally allow for traditional long-fallow shifting cultivation. Aside from achieving biodiversity conservation and regulated water supply, rural households need to benefit commercially from forest products, for example through non-timber forest products value chains (Harbi et al. 2018). As pointed out in this thesis, there is a critical lack of education extending from forest to agricultural management. In addition to secure tenure, more comprehensive extension systems could catalyze a transition towards sustainable intensification of agricultural lands and reduced forest clearing (Jayne et al. 2019). Importantly, also non-governmental organizations and the private sector provide educational services. Although in our study area oil palm concessions had largely negative impacts on local livelihoods and ecosystem services, companies did at least contribute to agricultural extension. In other countries, concessions were found to enhance economic growth and poverty alleviation under the right circumstances including good governance and smallholder tenure security (Sayer et al. 2012). To conclude, tropical forest frontiers need governance processes that sufficiently recognize customary land rights and that adequately design zones for protected areas or commercial agriculture based on biophysical suitability, ecological value, smallholder rights, stakeholder needs, infrastructure, and markets. Above all, land use diversification is key to ensuring a sustainable transformation of forest frontiers while minimizing ES trade-offs.

In addition to supporting the science-policy link, a main ambition of land system science, this thesis has contributed to the methodological advancement of ES valuation and communication. Specifically, it has applied and evolved current techniques to model and map ecosystem services in a data-scarce region. Compared to similar assessments using modelling approaches, I was able to incorporate a larger number of biophysical, political, and socio-economic variables and demonstrated their effects on local ES outcomes in terms of supply, demand, and flow. Compared with earlier research in tropical frontier landscapes, this thesis compared a larger number of ES comprised of provisioning, regulating, and cultural services. This allowed the identification of the multiple benefits that people get from a landscape. The potential uses of the ES models developed and presented in this thesis can further be exploited. They could, in a next step, be used to analyze ES bundles and the relative importance of biophysical or socio-economic drivers such as land use, land tenure or zoning arrangements, which would allow us to better understand synergies and trade-offs across landscapes (Spake et al. 2017). Spatial modelling of policy scenarios, as done in an Indonesian forest frontier (Law et al. 2017), could be a progress towards informing policymakers. Added value to ongoing reform processes including the development of a National Land Law in Myanmar can be generated if specific proposed or expected policy scenarios are assessed. The flexibility of Bayesian networks further allows for rapid updating of models so that these could be applied at other scales, in other regions, or analyzed in time steps. Specifically, Bayesian networks can cover temporal patterns in ES assessments (Rau et al. 2020), which is particularly critical in highly dynamic forest frontier landscapes.

In order to capitalize on the results of this thesis, the ecosystem services models developed will be used for further spatial and temporal analyses in the context of Tanintharyi Region. I envision using the models to identify ES bundles, synergies and trade-offs across different land uses and land tenure schemes. These findings can then be employed to test diverging scenarios and their impact on local livelihoods and ES outcomes. To make results more accessible to various stakeholders, they will be communicated through different channels. Lastly, a main objective is to make the models publicly accessible so that they can be adapted and applied in other tropical forest frontier contexts for comparison purposes.

To conclude, a final word on the current situation in Myanmar. The presented research was carried out during the period of the civilian government and the thesis was finalized just after the military coup on 1st February 2021. Although we cannot predict future pathways, it is clear that land issues will again be at the core of interests and reform processes once the situation steadies in either direction. This research has laid the foundations to support scenario analyses to assess the impacts on local communities and human well-being at the forest frontier. The past has shown us how land is used as a commercial asset and bargaining chip of powerful stakeholders during decades of military regime. That is one scenario. But there is another path visible now, not that of a centralized quasi-democracy, but that of an inclusive federal democracy. In that scenario, local communities will take center stage in managing and governing land.

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Part II Research papers

Paper I: Community forestry for livelihoods: Benefiting from Myanmar's mangroves

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Article

Community Forestry for Livelihoods: Benefiting from Myanmar's Mangroves

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Abstract: It is well known that in many rural communities in the developing world, forests, particularly those under community management, are important for people's livelihoods. However, studies on the contribution of forests to the income of different households within a community are rare, including the poorest households and how non-members of the community forestry user group (CFUG) benefit from those resources. This paper compares livelihood strategies and the use of a mangrove CF by different community members in Myanmar. Utilizing a livelihoods approach, data were collected through a household survey (n = 110) and various participatory tools. The significance of CF for people's livelihoods was clearly demonstrated, with as many as 91% of households depending on CF products to varying degrees. Livelihood strategies are largely determined by financial assets and road access. Strategies include large levels of dependence on natural resources such as homegardens and CF. Substantial differences were found for CF's contribution to total income depending on CF membership (p = 0.004) and wealth (p = 0.022). Non-members benefit mostly through subsistence products. The poorest households were found to get the highest income shares (36%) from CF. This leads to the conclusion that with an inclusive process to membership, CF has the potential to reduce poverty.

Keywords: community forestry; livelihoods; mangroves; membership; Myanmar

1. Introduction

Forest resources often contribute substantially to the well-being of rural communities in many developing countries, in particular to the poorest households and especially during times of hardship [1–3]. While the contribution of environmental products and services to rural livelihoods is widely documented [4,5], their significance within forest-dependent communities remains insufficiently explored [6].

In recent decades, the increased recognition of the importance of forests for rural communities, and their record in managing these forests sustainably, especially compared to state forest management, has resulted in the emergence of community forestry (CF). Areas under CF have been increasing throughout the Asia-Pacific, particularly in China, Nepal, the Philippines and Vietnam [7], but also in other countries in the region, though at a slower pace. For example, in 2001, the government in Myanmar set a target of 919,000 ha under CF management by 2030. As of 2016, 12% of the target had been achieved [8].

With its significant natural resources and diverse ecosystems across a land surface area of 68 million ha [9], Myanmar used to be a comparatively well-off country in Southeast Asia, including being viewed as the rice bowl of the region. However, particularly in the fertile region of the Ayeyarwady Delta, this came at the cost of its forests. It was found that between 2002 and 2014, intact forest decreased by 22.5% [10]. Mangrove forests have particularly suffered, with one study observing a decrease of 64% in the Delta's mangrove cover between 1978 and 2011, attributing this mainly to agricultural expansion [11]. Another important driver, since 1972, was fuelwood collection for charcoal production [12]. The impact of the mangrove loss was particularly felt in 2008, when Cyclone Nargis struck the country, taking the lives of an estimated 140,000 people, killing livestock and damaging paddy fields in the long term. The cyclone was particularly destructive in the Ayeyarwady Delta [13].

Keeping in mind the protective function of mangrove forests [14–16], the Forest Department with the assistance of non-governmental organizations (NGOs) responded by increasing their reforestation efforts along Myanmar's coast. In order to ensure the support of the local communities, plantation establishment was coupled with community forest management plans, as outlined in the Community Forestry Instruction (CFI) [17]. As of 2017, there were 3840 community forestry user groups (CFUGs) in the country [18].

Though CF is widely viewed as having great potential to address poverty and support sustainable livelihood development for forest-dependent peoples, there are also contrasting opinions on whether it tangibly benefits the poorest within a community [19–22].

The mangrove plantations in Myanmar's Delta are a good example of how local people are expected to manage and benefit from CF. However, until now, the impact of such mangrove community forests in Myanmar on the well-being of local households has not been investigated, although studies in other Asian countries show the importance of mangroves for livelihoods [23–25]. Previous studies on community forestry and livelihoods focus on the community members who are directly involved in the CF management. Yet, considering the fact that people living in the vicinity of forests have used them in one way or another since the beginning of civilization, it would be arbitrary to believe that only members of the formally-registered CFUG use them actively. Rather, it could be assumed that the majority of households benefit from the mangroves at least for subsistence purposes. Another study described such evidence of subsistence and small-market uses of mangroves in Cambodia, Colombia, Fiji, Sri Lanka and Venezuela [26]. However, it does not refer to mangrove utilization of different members within a community.

This paper aims to address this gap in the scientific literature by comparing the use of community forests by members and non-members of a CFUG in Myanmar's delta area. It investigates the criteria on which households base their livelihood strategies and assesses the differences between CFUG members and non-members regarding mangrove utilization. Findings will support decision-making in the development of CF in Myanmar and beyond, based on the gained knowledge of different member households within rural communities, their characteristics, CF membership status and their use of community forests. Specifically, the following questions will be examined: (a) Which livelihood strategies do different households within the communities have? What are their characteristics? (b) How are the CFUGs organized? (c) What are the main differences between CF members and non-members? (d) Does CF membership and wealth influence forest use?

2. Materials and Methods

2.1. Study Area

The low-lying Ayeyarwady Delta in southwest Myanmar is strongly influenced by numerous hydrological factors. The first factor is freshwater, which flows from different river systems towards the Andaman Sea. The second involves tides carrying saline water from the sea. Roughly three ecological zones can be distinguished: the saline water zone, the brackish water zone and the fresh water zone. There is a distinct wet season between May and October, when almost all of the annual rainfall (1867 mm) occurs [27]. During the rainy season, many areas experience temporary flooding.

The main income for people in the Ayeyarwady Delta used to be from forest and agriculture [28]. Nowadays, the main income sources in the lower Delta are casual labor (70%), employed farm work

(12%), farming (11%) and fishing (11%), with additional income generation from the sale of poles, seeds and fuelwood sourced from mangroves [29]. For this study, the focus is on the brackish water zone, where most people rely on mangrove community forests for their livelihood and, to a lesser extent, on the above-mentioned activities. Unfortunately, there are no livelihood statistics for the lower Delta.

The forests in the study area have been mostly cleared or heavily degraded in recent years. Only since around 2000 have reforestation efforts increased the mangrove area. Nowadays, practically all forests in the area are mangrove plantations under community management.

Four study villages in the southern part of Pyapon Township were chosen according to three criteria—presence of a CF; accessibility; availability of baseline data—and with the aim to select communities with a range of site conditions. The characteristics of the selected villages are described in Table 1. Two of the villages (B,D) are situated directly along the main road, while the other two (A,C) are more remote.

Table 1. Characteristics of the study villages (CFUG = community forestry user group, hh = households).

	A	B	C	D
Population (No. of hh)	97	199	93	334
CFUG (No. of member hh)	43	50	40	74
CF area (ha)	124	120	140	150
CF since (y)	2001	2001	2001	2003
CF certificate (yes/no)	Yes	Yes	Yes	No

2.2. Framework

The sustainable livelihoods approach (SLA) [30] was chosen as the overall framework for the research as it puts people at the center and assesses complex decisions and livelihood strategies of the households (Figure 1). While livelihood is the sum of household assets and activities [31], livelihood strategy in this study is considered the sum of activities contributing to household income plus additional subsistence activities.

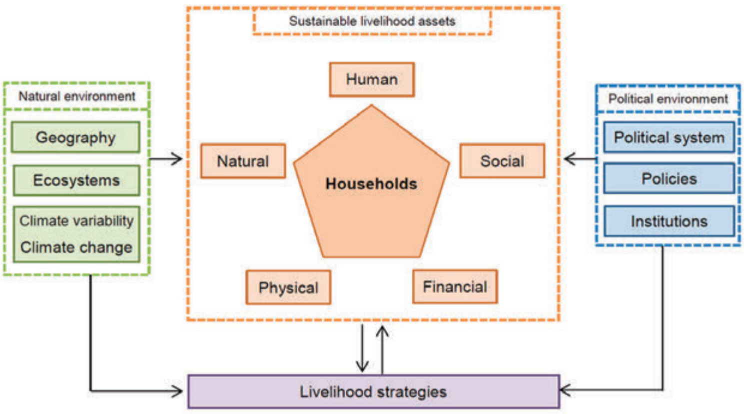

Figure 1. Sustainable livelihoods framework (adapted from [30]).

A livelihoods perspective is crucial for this research, as it includes not only income-generating activities, but also subsistence use of resources. This is of particular importance for natural resources, which are seen as common goods, such as community forests. Some advocate an analysis of forest products use in relation to different livelihood strategies [32,33], and the SLA helps to address this through consideration of the natural and political environment, which both highly influence the study area and people's land use decisions.

2.3. Methods

The research followed various steps. Background reading was conducted to provide a foundational understanding on local livelihoods and the relevance of mangroves and community forests. Additional information was collected during preliminary discussions with diverse stakeholders in-country and on site.

Fieldwork was conducted during five weeks in the study villages. It was divided into two parts to combine qualitative with quantitative information. Qualitative data were collected by means of various participatory research tools [34,35]. They include transect walks, key informant interviews, unstructured informal interviews, resource mapping, historical mapping, seasonal calendar, wealth ranking and several focus group discussions in each village. The key informants were village leaders, village elders, CF chairmen, teachers and staff from different local NGOs and the Forest Department. As many social groups as possible were represented, involving the criteria of gender, age, ethnicity, livelihood activities and CF membership. All of the previously-mentioned tools were applied in each of the four villages and produced comparable results. Data triangulation was ensured through the combination of tools and cross-checking of information. Qualitative information was then backed up with a survey using a standardized and pre-tested questionnaire, which provided quantitative household data. The survey was carried out through face-to-face interviews with a total of 110 households (25 in the smaller two and 30 in the larger two villages). All participants were randomly selected from a list of households provided by the village leaders. Out of the 110 households, 50 were CFUG members. Households are regarded as a unit in the study area. Even though the men usually do the physical work in the CF, women are involved in management decisions and often accompany their husbands to the forest. They both have knowledge about their livelihood activities. The women take the role as household head in cases where the husband is deceased or away for seasonal work. The interviews were held either with the husband, wife or eldest son or daughter.

The field research was conducted jointly with local research assistants, who were previously trained in forest ecology and management and know the context in the study villages and the communities personally.

A results-sharing workshop, as part of a regular multi-stakeholder Community Forestry National Working Group meeting, was held at the end of the data collection period with participants from national research institutes, the Forest Department, different civil society organizations and village representatives. The preliminary results were discussed, and feedback from the stakeholders was included in the analysis.

Qualitative data from interviews and focus groups were interpreted through a content analysis. Quantitative data from the survey were put in an Excel file, and some of the categorical variables were revised in order to reduce the number of categories for interpretation. Due to some missing values, the sample size for analysis varied between 100 and 110. Data were analyzed using the statistical program R (v3.4.1. R Foundation for Statistical Computing, Vienna, Austria) for descriptive statistics and statistical tests. Permutation *F*-tests were chosen due to the zero-inflation of the data. All graphs were produced with the R software.

3. Results

3.1. Livelihood Strategies and Household Characteristics

According to the SLA framework, livelihood strategies are highly influenced by the households' assets. Many of those assets are similar for all community members in the study area. Human assets are rather low due to low level of education (the average adult left school at the age of 10–11) and limited health care. Social assets include good networks within and between communities, mainly inclusive decision-making processes (83% of households participate in village meetings), but often a lack of strong leadership. Physical assets in all villages are limited, i.e., no connection to the electricity grid, limited phone coverage and internet connection and very basic infrastructure. Regarding physical assets, however, the government has recently shown strong commitments to improve the situation in the Ayeyarwady Delta. While financial assets are generally low, more opportunities have come up recently with microfinance institutions (59% of households have already used it). Natural assets consist of the community forests, farmland and homegarden land. Although people can make use of the land, no formal land titles are given except for the CF.

The study revealed various livelihood systems in the study sites. They usually consist of different combinations of one or more income-generating activity. Nonetheless, four main household strategies can be distinguished (summarized in Table 2). They can be characterized according to the corresponding main livelihood activity.

Table 2. Main livelihood strategies of target communities in the Ayeyarwady Delta. NTFPs, non-timber forest products. (CF = community forestry).

	(A) Casual Labor	(B) Natural Resources	(C) Small Business	(D) Homegarden
Main livelihood	Casual labor	Natural resources	Small business	Homegarden (>1 ha)
Other livelihoods	Natural resources	Livestock	-	Rice farming and CF
Households (No.)	22	25	26	26
CF members	5	16	9	14
Non-CF members	17	9	17	12
Very poor	20	9	3	18
Poor	0	9	6	2
Medium	0	4	11	4
Rich	0	0	3	1
CF use	Sale and subsistence	Sale (and subsistence)	Subsistence	Sale and subsistence
CF products	NTFPs	NTFPs	NTFPs	Timber and NTFPs
	Low income	Low–middle income	Middle income	Poor–high income
Households Characteristics	Men and women work as casual labor and collect NTFPs together	Men and women work on the farm, men tend cattle, women look after chicken and pigs	Women stay at home and look after shops, men have businesses concerned with a trade	Men work on the farm and in the forest, women are housewives or help out on the farm
	Landless, some farmland	Some farmland, often CF	Mostly landless	Homegarden, often CF

- Strategy A covers mainly landless households that focus on casual labor. This includes day jobs such as road construction, farm work, mangrove planting, as well as seasonal jobs on fishing boats. However, as opportunities for casual labor are often scarce, households following Strategy A often get additional income from natural resources such as forest products. Sometimes, they also do small-scale fishing or farming.
- Another strategy, Strategy B, of poorer households is to focus solely on natural resources. Most of them are members of the CFUG, and all use the CF primarily for income generation. Usually, they also have some farmland and keep livestock around their homes.
- Strategy C includes all households with a small business (e.g., shopkeepers, traders, mechanics or carpenters). These households can obtain a comparatively good income from their businesses and seldom have additional livelihood activities.
- The fourth group of households follows Strategy D. They own several hectares of homegarden with a variety of annual crops (vegetables, betel leaves) and perennials (coconut, betel nut, banana and other fruit trees), which are highly productive. The owners consume some of the produce themselves, and sell the rest at local markets. For additional income, many D households also have CF plots, which they manage actively.

Eleven households do not follow any of the main livelihood strategies described in Table 2. Some of them live from one person having full-time employment (usually as a teacher), while others rely on remittances. Some also have a mixed strategy.

Household strategies are contingent on the availability of the above-described livelihood assets. They are not linked to household size or gender balance. Households following livelihood Strategy A, B, C or D can roughly be characterized by their wealth status. Generally speaking, poorer community members often follow Strategy A or B, relying on casual labor and natural resources out of necessity, while C households with an average-sized income were able to start a small business. D households are a bit of an exception. Although, typically, wealthier community members have homegardens, there are also numerous poor households following this strategy. This result indicates that homegardens, as well as CF and other natural resources are relevant for different groups within a community. Other particularities are reflected in the fact that the women of D, as well as C households do not commonly seek jobs outside of their homes. They are either housewives or help in the family business (including selling products from their homegardens). Shopkeepers (Strategy C) are mostly women. In poorer households, both men and women have to work in casual labor or collect forest products for sale.

In the communities, a total of 91% of households collect mangrove products. They use the CF at least partly for subsistence. Subsistence products are fuelwood, posts, poles, nypa (*Nypa fruticans*) for housing, vegetables, fish, as well as plants with medicinal properties. Both A and D households also use mangroves for income. However, while the generally wealthier D households sell timber and fuelwood, the poorer A households generate income from non-timber forest products (NTFPs). Although wealth status seems to be a key factor influencing strategic livelihood choices, other factors also play a role. One of them is the location. While in villages with direct road access, the majority of households run a small business (Strategy C), the households in more remote villages commonly rely on natural resources (Strategies A and B). Village location has a particularly significant influence on the income from CF ($p = 0.000$), whereas the two more remote villages get considerably higher contributions of CF to total income. On the other hand, migration factors showed no relation to livelihoods in this study.

3.2. Community Forestry User Groups

The community forests in the Ayeyarwady Delta follow a CF model that differs from other CF in the country. The members of the CFUGs had decided at the beginning that they wanted to have individual rather than collective 'ownership' for the specific plantation plots. The model includes 'individual ownership' and 'collective management'. People prefer this because they have no other possibility to own private land as individuals. All land is in a demarcated reserved forest area under the Forest Department. Although the villagers have been using this land for decades, they are perceived as encroachers. Once they agree to plant mangroves on their 'encroached land', they can receive formal land tenure for it. Even though the CF certificate allows only for a 30-year use and does not give formal ownership, the individual CFUG members and their plots are listed at the Forest Department. After the 30-year period, the CFUG can apply for a 30-year extension. When establishing CF, all plots are demarcated and allocated to the members according to their household size and human resources. The CF members are responsible for managing their plots in terms of silvicultural practices. Often, they hire casual labor for this work. The members are promised the full benefit of the timber once the plantation is mature. Before that point, they can harvest small timber for posts and poles. All other mangrove products, including fuelwood and other NTFPs can be freely used by any other person (CF members and non-members alike). In addition, all villagers are allowed to collect mangrove seeds no matter who owns the individual plot. As a consequence, the number of forest users is much higher than the number of actively-participating CFUG members. Meanwhile, the CF area is enlarged every year with new plantations. They are open to new members. There are also former CF members, who have dropped out due to low short-term profitability and given their plots informally to other members.

According to different members of the communities, there is no conflict within the CFUG or with non-members within the villages. There are, however, occasional conflicts with people from other villages who steal small timber and fuelwood from their community forests. On the other hand, they report that since the introduction of CF, illegal logging has decreased.

CF membership and active participation are often related to availability. There is little noticeable gender dynamic to participation. According to some of the more influential CF members, poorer households are less likely to participate in the CFUGs, as they are more occupied with their daily livelihoods. Richer households, on the other hand, have more leisure time to engage in community groups and social gatherings. This is also reflected in the fact that CF members engage in more village-level organizations (mean = 2.4, standard deviation = 2.1) than non-members (mean = 1.4, standard deviation = 1.8). However, this finding is not evidence enough for a connection between CF membership and wealth status.

3.3. Differences between CF Members and Non-Members

This study found very little difference in the wealth status of CF members and non-members based on the participatory wealth ranking, although there is a tendency that non-CF members are slightly wealthier. However, the highly congruent wealth distribution (Figure 2) shows that community forestry in the study sites is inclusive and allows all members of the communities to participate in the CFUG.

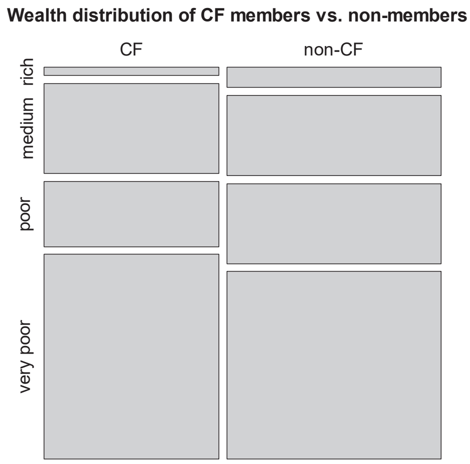

Figure 2. Wealth distribution of CF member vs. non-member households (n = 100).

The equal wealth distribution could also suggest that CF membership is not, or not in the short period of time since CF establishment, the only factor that can lift households out of poverty. This is partly due to the fact that poverty alleviation was not the main goal in establishing the CF, but rather a hoped-for side effect of nature restoration. Mangrove plantations are the best-known strategy to restore degraded farmlands in the area and make them not only more productive, but also more resilient. Positive effects on poverty will thus only appear in the long term. It remains to be seen whether the wealth distribution within communities will change once the mangroves are mature for timber harvesting. Currently, CF members and non-members have similar incomes.

Nevertheless, a closer look at different households' livelihood activities and forest-related benefits is necessary before a conclusion can be drawn on the relation between CF membership, wealth and subsistence and commercial use of the mangroves.

3.4. Influence of CF Membership and Wealth on Income from CF

The condition of different households seems not so different as they have similar livelihood assets, as described in Section 3.1. Some disparities are only found for social assets (community participation), part of the natural assets and, possibly, financial assets.

Livelihood strategies consist of several activities (Table 2) for both CF and non-CF households. However, this study found substantial differences between CF members and non-members concerning the contribution of different activities to total income. Not surprisingly, this is particularly visible for the collection and sale of forest products. The effect of CF membership on the contribution of CF products to total income is significant (p = 0.004). When adding up all income activities and their shares to the families' revenues, major differences can be detected in all major income sources except homegardens (Figure 3). While mangrove products make up the bulk of the income (36%) for CF members, for non-members, the share is only 15%. This also indicates why the former are so willing to participate in the CFUG, while the latter have other priorities.

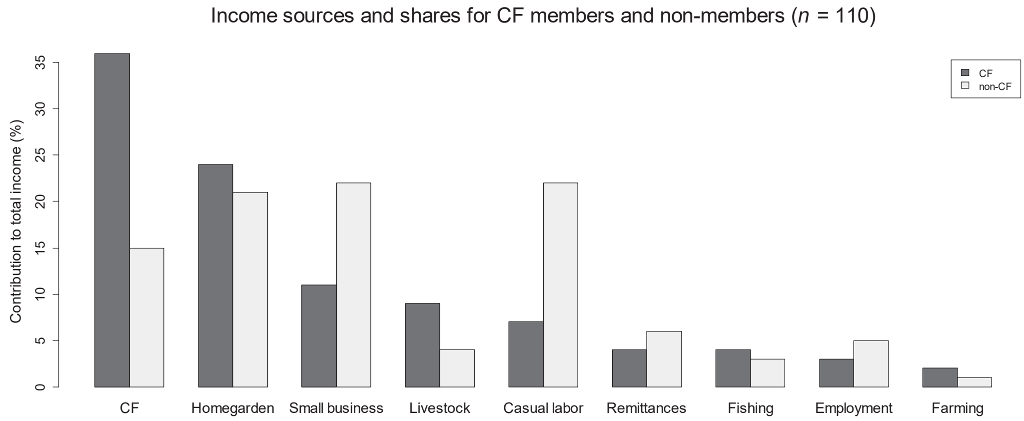

Figure 3. Income sources and shares for CF members and non-members.

According to the findings, non-members derive most of their income from small businesses, as well as casual labor and homegardens. Reliance on small businesses is in line with livelihood Strategy C, where households have few other income sources. They seldom use the community forests for commercial purposes.

It is also notable that casual labor seems to be much more pronounced in non-CF households (Figure 3). This can be partly explained by the fact that the category 'casual labor' includes seasonal labor for eight months. Six of the households, including one CF member household, have seasonal labor as their main income. For those getting their income from daily labor, however, non-membership in the CFUG should not be equated with non-use of CF. However, many of the interviewed people, especially the poorer ones, confirmed that they live from both daily labor and CF non-timber forest products. This strategy allows them a high degree of flexibility. When the labor market is good and well-paid jobs can be found, they choose to work as laborers. On other days, when there are limited job opportunities, they go to the mangroves to collect NTFPs. In turn, in less favorable situations, such as during low tide, they would rather work day jobs, even if they do not pay much. According to the villagers, the daily income is approximately the same, depending on the circumstances.

Significant results (p = 0.0218) were found regarding the influence of wealth on CF income. The contribution of mangrove CF to the incomes of different wealth groups is depicted in Table 3.

Table 3. Contribution of CF to total household income for different community groups.

	Wealth Group				
	Very Poor	**Poor**	**Middle Income**	**Rich**	**Ø**
CF members	0.47 (n = 25)	0.19 (n = 8)	0.31 (n = 11)	0.20 (n = 1)	0.38 (n = 45)
Non-CF members	0.21 (n = 28)	0.06 (n = 12)	0.12 (n = 12)	0.27 (n = 3)	0.16 (n = 55)
Mean (Ø)	0.33 (n = 53)	0.11 (n = 20)	0.21 (n = 23)	0.26 (n = 4)	0.26 (n = 100)

With an average income share of 33%, the poorest households rely most on the CF. Looking at the importance of CF for the poor, the potential for poverty reduction seems highly likely. Although also wealthier people get substantial income from the CF, a higher number of respondents would be needed to confirm this. With a higher income from CF, households are more likely to participate in the CFUG. This is particularly true for the very poor.

Subsistence use of mangroves, on the other hand, was reported to be important by all households. Among the various mangrove NTFPs, some are much more relevant to the local people than others. Therefore, a closer analysis of the individual products and their use was carried out.

3.5. Use of Community Forests

The study found that almost all households (91%) use wood and NTFPs from the CF area, irrespective of whether they own forest plots or not. Timber can only be used by the individual plot owners, but everyone else can collect unlimited amounts of fuelwood for subsistence and other NTFPs, so the mangroves are likely to be overused in time. From 105 responding households, 96 said that they use at least one product. On average, two types of products are collected from the CF by each household. In most cases, timber from the CF plantations cannot yet be used, as trees are too young. Most of the wood is therefore used for posts or poles and branches for fuelwood. Since all households use traditional stoves for cooking, the main product from the mangroves is fuelwood. However, out of 85 households collecting fuelwood, only 17 sell it for income generation.

The second most important product from the mangroves is the mud crab (*Scylla serrata*), which breeds at the roots of the mangroves. For most villagers who collect crabs, they have the highest priority compared to all other forest products. This is explained by the high market potential. For more than ten years, villagers have been selling crabs to traders who transport them to Yangon and further afield to China. Especially big crabs fetch a high market price of approximately 1 US$ each. Of the 41 households catching crabs, 39 sell them to traders. Small crabs are either fattened and then sold or consumed directly by the families. It was found that the collection of crabs is an important livelihood activity across the communities, irrespective of the people's wealth status or participation in the CFUG. Another important CF product for semi-subsistence is nypa palm, in particular for poor households and women. They profit from the sale of thatched nypa for roofing. Woven nypa is locally used not only for roofing, but also for the walls of the houses. The palm sap is popular for wine production. The sweet seeds of the fruit are cherished for local consumption.

Concerning the differences in CF use by members and non-members, it was found that small timber (posts and poles) is used mostly by households who have their own plots. The reason for these different priorities is that the members can sell these items, while non-members are only permitted to use small timber for subsistence purposes. The first timber will be ready for harvesting in approximately 10–15 years. While all in all, little timber is used yet, posts and poles are important secondary sources of livelihoods. All other NTFPs have similar priorities for CF members and non-members (Figures 4 and 5). This picture is expected to change in the next decade, when trees reach a girth of 25–30 cm. Once timber is mature for harvest, it will likely become a priority for the CF households. It can be assumed that it was the main reason for them to engage in community forestry in the first place.

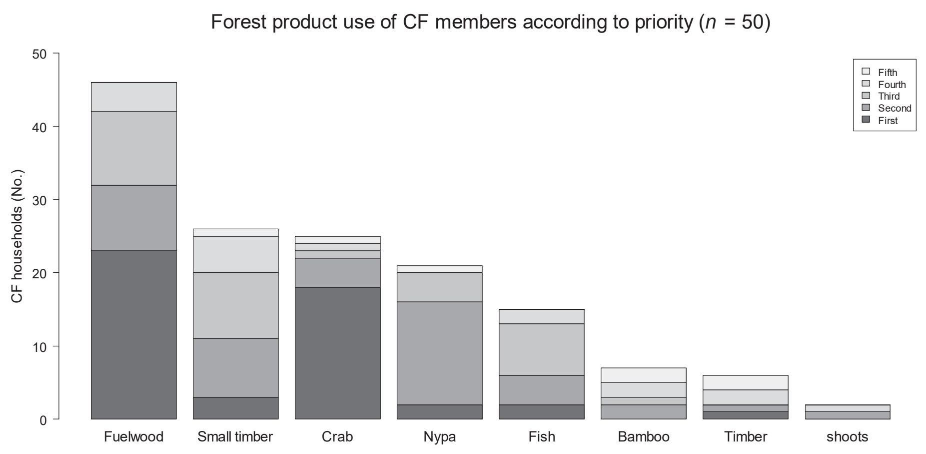

Figure 4. Use and importance of mangrove products by members of the CFUG.

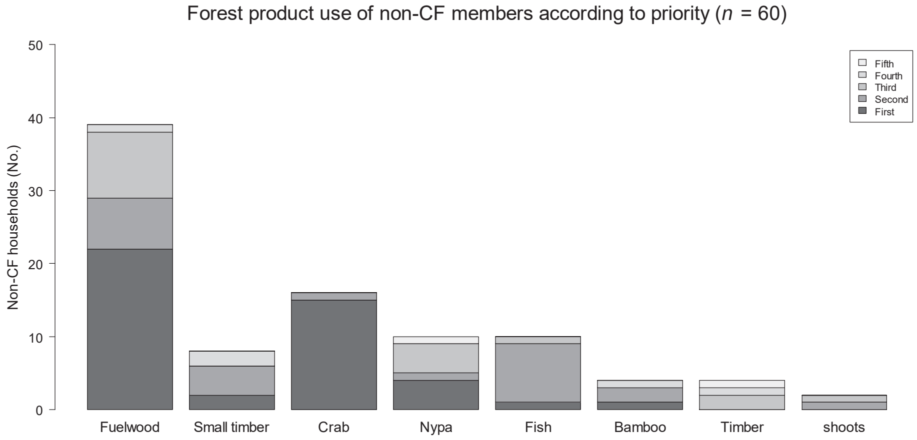

Figure 5. Use and importance of mangrove products by non-members of the CFUG.

Fuelwood is used more by CF members (92% of households) than non-members (65%, Figures 4 and 5). A possible explanation is that non-members, who go less often to the CF, prefer to take fuelwood from their homegardens. They can take fallen branches (e.g., from coconut) from other homegardens for subsistence purposes, provided that they have sought permission from the owner beforehand. Crab collection also has a higher priority among the CFUG. This could indicate that membership could possibly bring advantages for crab collectors. However, current data are not enough to confirm this argument.

In addition to the main CF products illustrated in Figures 4 and 5, minor products can be found in some of the mangrove areas and are generally used for subsistence. They include clams, snails and shrimp, as well as a type of climbing plant, which is used in a local curry dish.

Non-material goods also contribute to local livelihoods in a wider sense and improve their non-financial assets, in particular the natural assets. The community as a whole benefits from the ecosystem services provided by the established mangrove plantations. The protection they provide from storms and floods is well known. Experiences from Cyclone Nargis show that mangroves are an important safety net in the aftermath of natural disasters. After the cyclone, the forests were degraded due to overuse by the local population. They mainly used small timber to rebuild houses, fuelwood, as well as NTFPs as a source of income. For poorer households, the mangrove forests are even more important as a safety net, as they do not have many other resources to fall back on. The role of the forests as a safety net is not connected with CF membership. With Cyclone Nargis in 2008, the experience was that in times of need, the remaining resources are used by everyone. People also mentioned the cultural and spiritual value of the mangrove forests and their fauna and flora. Medicinal plants gathered in the forest can be used to treat stomach ache, fever, injuries and snake bites and thus have a positive impact on the local population's health. These examples show that CF potentially improves additional sustainable livelihood assets, such as human assets, of all people.

4. Discussion

Using case studies, this research contributes to the understanding of livelihood strategies of people living in mangrove areas, including their interaction with CF. It particularly shows their high level of reliance on the mangrove forests. Interestingly, the study reveals only small differences in the characteristics and livelihoods of households who are members of the CFUG and those who are not.

Differences in the use of CF are more attributed to income and not as much to subsistence. In terms of income, CF members get a higher share from the forest, while non-members get more from casual labor and small businesses. In the past, with expanding mangrove cover, there has been an increased collection of NTFPs for subsistence and sale for both members and non-members.

Therefore, in addition to CF membership, there are other factors that determine the livelihood strategy of a household.

4.1. Other Determinants of Livelihood Strategy Choices

As few people in the lower Ayeyarwady Delta obtain further education, livelihood strategies are mostly determined by the given circumstances such as location (i.e., remoteness) and corresponding income opportunities. Although wealth status plays a role, a substantial contribution to decisions concerning livelihood is road infrastructure in the study area. CF is much more important in those villages with no direct access to a main road. This was also found by a study in Indonesia, where improved road access led to higher economic diversity [36]. From this point, it could be argued that as infrastructure improves, CF loses its importance. However, this assumption is rather precarious. First of all, even with the possibility to start a small business, not all households are equipped or would have the desire to do so. Many of them still rely on casual labor and, as these jobs are not always available, on natural resources, with mangroves at the forefront. As time invested in livelihood activities is also believed to be an important factor, CF provides double benefits with commercial and subsistence products being collected at the same time. Secondly, non-material benefits from the mangrove forests, in particular mitigation of extreme weather events, are highly valued by the local people and also receive particular attention from outside stakeholders. Thirdly, the safety net function remains for all households, even for business owners, although to a lesser extent [37]. Inferring from this, CF will somewhat remain a priority in the livelihoods of many households, even if other opportunities arise from infrastructure development. Government investment in physical assets such as connection to the mobile phone network and electricity grid could even open the door for new markets and value-added CF products. Social factors, such as household-level decision-making and gender, have not come up as a major issue in discussions with diverse community members, and a more thorough examination would be needed to draw conclusions on their influence on livelihood strategies. However, considering that in the study area, decisions are made within households and women-led households are just as likely to be members of the CF, gender is assumed to play a lesser role than in other regions.

4.2. Impact of Community Forestry on Poor vs. Wealthy Households

The findings support the belief that a CF approach can be highly beneficial for rural communities, in particular those living in remote areas. This result also agrees with different studies, which show that environmental resources can reduce income inequality [2,38].

The majority of the interviewed households benefit directly from the CF plantations. However, while the results show a clear contribution of CF to the income and subsistence of the poor, they cannot fully confirm that CF is per se a pro-poor approach. Rather, it suggests that, at least in the study area, all households have an opportunity to profit from the community forests. Yet, it is difficult to judge whether the benefits come from the fact that they have mangrove plantations or from the fact that said plantations are under community management.

The landscape has changed dramatically in the past. Thirty years ago, mangrove forests were abundant, but mostly used for charcoal production. Fifteen years ago, deforested areas were used for rice production, but later flooded and rendered unproductive. Nowadays, mangroves are increasing again, but used for different purposes, which are mostly related to new marketing opportunities of crab. While nowadays, crabs consequently have the highest priority among the NTFPs, this was not the case a few decades ago. Timber at that time was not available to the communities, as it belonged to the government. Thus, revenues from timber, once the CF plantations are mature after 5–10 years, will possibly be the determining factor for the impact of CF on different households.

Land tenure is still an unresolved issue in many parts of Myanmar. Community forestry is one possibility for the local population to receive secured access, management and use rights over forested land for a certain time period. It can be assumed that this is one of the reasons why communities are interested in CF. In the near future, though, the revised Community Forestry Instruction in 2016 is expected to create more commercial opportunities for the CFUGs.

4.3. Reasons for Participating in the CFUG

In order to establish CF, community members need to reach a consensus. For those households not participating in CF, the constraints are likely linked to uncertainties regarding long-term benefits. As it is, the current system of the CFUG gives minimal additional short-term benefits to its members. The main benefits, i.e., income-generation through the sale of NTFPs such as crab or nypa, are accessible to members and non-members alike. It is thus reasonable to believe that many of them do not think it a worthwhile investment, especially considering the limited income from timber in the short term. The lack of opportunities for communities making a living from timber and the deterrent of CFUG membership and forest investment is an issue in many countries in the region [39].

For those who participate in the CFUG, an assumption could be that they do so partly to receive financial gains from the sale of timber. However, this would not fully explain the high involvement of community members in some villages in the CFUG. There are also social factors connected to participation and inclusion in the decision-making processes. A factor that should not be neglected is also that the local people indeed care about the mangrove forests and are willing to invest time in proper management if they can.

Other benefits from CF participation that have not been discussed stem from the fact that it can be an opener for other foreign aid programs, and this has been an issue in some countries such as Nepal [7,40]. Oftentimes, development organizations prefer to work with village groups that are already well organized. In the study area, the core people within the CFUG also served as contact persons and were sometimes employed by international organizations working in the region. However, a more detailed analysis of the reasons for choosing to become a CF member is suggested to complement this study.

Another remaining question is whether more households (especially poorer ones) should be encouraged to participate in the CFUGs. The current livelihood situation shows no direct need for that to increase income generation opportunities, although that may change in the next decade with the harvesting of timber. An argument for the inclusion of all households would be a more coordinated use of resources. Another reason is that many CFUGs are useful platforms for information sharing, though this varies from community to community, an issue that is also found in Nepal [7]. As long as only some of the users are active members of the CFUG, there are limited opportunities to discuss a fair and sustainable yield of NTFPs from the community forests. Such arrangements are necessary to avoid future shortages of those resources and ensuing implications for the people's livelihoods.

4.4. Recommendations for Community Forestry Development

- Before establishing the CFUG, a clear communication about the benefits and the rights of members vs. non-members is necessary. This would also need to be continuously updated once the CFUG is established.
- Trust building is needed between the local communities and the government. This will make people more secure about their forest land tenure and help them make decisions in favor of a sustainable management of the CF, including investing time and money in their land.
- Regulatory rules for collecting NTFPs and timber need to be in place to guarantee long-term benefits for all users; the revised CFI will support this, but clear guidelines for its implementation are needed. More research on sustainable management of NTFPs is required to provide communities with such information.
- To decrease poverty, community forestry alone is not a solution. Additional income opportunities are required that reduce people's reliance on forests, and this needs to also consider the other livelihood assets (e.g., education, access to electricity, roads).

5. Conclusions

The study found that the livelihood strategies of the people living at the study sites in the lower Ayeyarwady Delta can be divided into four main groups. The four strategies according to the corresponding main activity are: (A) casual labor; (B) natural resources; (C) small business; (D) homegarden. The key determinants of which strategy a household follows are road access and job opportunities, human assets and land availability. The poorer households usually follow Strategies A, B and D, while the wealthier tend to follow C and D. Although income generation and subsistence use of CF products differ within these strategies, a total of 91% of all households use the CF in one way or another.

The CFUGs' members have their own plots within the forest area. They decide on the mangrove species and manage the plantations for a period of 30 years. When trees are mature, they will benefit from the sale of the timber, with this potentially being more significant with the more favorable regulatory environment through the recently revised CFI. All other villagers, members and non-members alike are allowed to use non-timber forest products for subsistence and commercial purposes. The most important products are fuelwood for subsistence and mud crab and nypa palm for sale.

While CF-members and non-members have similar livelihood activities, CF members get most income from the CF (on average 36%) and non-members from small business, casual labor and homegardens. Additionally, this study found high effects of CF membership ($p = 0.004$) and wealth ($p = 0.0218$) on the contribution of CF products to total income. With an average share of 33%, the poorest households depend most on the mangrove CF. Non-monetary benefits such as the mangroves' function as a safety net were experienced to be more substantial for poor households in the past, due to a limited availability of other, mainly financial, assets. In conclusion, this study pointed out that while CF is important for the majority of community members, there are considerable differences concerning its use and revenues depending on the CF membership and wealth status of a household. Inclusiveness of different community groups in the CFUG and widespread use of NTFPs for income and subsistence in the study area demonstrate that CF has the potential to greatly reduce poverty.

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Paper II: Local perspectives on ecosystem service trade-offs in a forest frontier landscape in Myanmar

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Article

Local Perspectives on Ecosystem Service Trade-Offs in a Forest Frontier Landscape in Myanmar

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Abstract: Extensive land use changes in forest frontier landscapes are leading to trade-offs in the supply of ecosystem services (ES) with, in many cases, as yet unknown effects on human well-being. In the Tanintharyi Region of Myanmar, a forest frontier landscape facing oil palm and rubber expansion, little is known about local perspectives on ES and the direct impact of trade-offs from land use change. This study assessed the trade-offs experienced with respect to 10 locally important ES from land user perspectives using social valuation techniques. The results show that while intact forests provide the most highly valued ES bundle, the conversion to rubber plantations entails fewer negative trade-offs than that to oil palm. Rubber plantations offer income, fuelwood, a good microclimate, and even new cultural identities. By contrast, oil palm concessions have caused environmental pollution, and, most decisively, have restricted local people's access to the respective lands. The ES water flow regulation is seen as the most critical if more forest is converted; other ES, such as non-timber forest products, can be more easily substituted. We conclude that, from local perspectives, the impact of ES trade-offs highly depends on access to land and opportunities to adapt to change.

Keywords: ecosystem service; trade-offs; adaptation; social valuation; frontier landscape; Myanmar

1. Introduction

The benefit of a landscape is more than the sum of its products. Particularly in rural areas of the tropics, the services provided by land—such as soil conservation, an agreeable microclimate, or spiritual values—are integral to local people's well-being. The concept of ecosystem services (ES), defined as the benefits people obtain from nature [1], has gained attention in research since the Millennium Ecosystem Assessment [2]. It is based on the idea that each ecosystem or habitat provides a certain set of supporting, provisioning, regulating, and cultural services for human well-being [2]. More recent concepts refrain from using supporting services as a separate type and rather see them as underlying functions for the supply of final ES [3,4]. A set refers to a 'bundle' of ES that 'repeatedly appear together across space or time' [5]. Land use is a potential spatial reference for such ES bundles.

Regulating and provisioning ES in particular have been studied more extensively in land use research [6]. Comprehensive assessments that include all three or even four service types (as e.g., [7]) are lacking, since cultural ES are often left out or studied separately. Moreover, studies often do not consider the changes in ES over time. It has been suggested that ES assessments consider temporal dynamics in addition to spatial patterns [8] and distinguish between supply and demand, among other factors [9]. Even when local people manage to adapt their use to a lower ES supply, their demand may remain.

It is crucial to take into account different stakeholders, as changes in the provision of ES occurring as a result of changes in land use or land management practices are closely linked to governance. As such, ES trade-offs often take place in situations where there are competing claims and interests of stakeholders [6]. They are mostly found among provisioning and regulating services and less so with cultural services [10]. However, it is still difficult to find studies on linkages between trade-offs and their ultimate impact on human well-being [6].

The social, or socio-cultural, approach was originally used for cultural services only but is now gaining attention in research [11] for the comparison of different types of services [12] or the assessment of ES bundles and has been increasingly used (e.g., [13,14]). In terms of ES, socio-cultural values are defined as 'the importance people, as individuals or as a group, assign to [. . .] ES' [15]; they express both material and non-material well-being. Thus, ES are determined by people's preferences according to the cultural and institutional context they live in Ref. [16]. These perspectives of local stakeholders assessed with social valuation techniques bring together cultural, economic, and ecological considerations in ES assessments. Qualitative and deliberative research methods have gained importance in developing countries [17] and countries with limited data availability [18].

ES trade-offs are particularly obvious in landscapes experiencing large-scale land acquisitions and fast land use changes, as is the case in many tropical countries with formerly large forest tracts. In these areas, so-called forest frontier [19] or agricultural frontier [20] landscapes, forests are increasingly being threatened by cash crop expansion [19] and the traditional livelihoods of people living within and near their borders are at stake. Forest-dependent communities, including shifting cultivators, can lose their natural assets and be forced to find alternative livelihoods. Furthermore, the loss of ES, such as climate and water regulation, can disturb further aspects of their lives. As agricultural expansion into forest frontiers is not only driven by a growing population but also by changing consumption patterns and international markets [19,21], ES trade-offs often have negative consequences for local stakeholders [6].

In Southeast Asia, two dominant patterns of land acquisition in forest frontier landscapes have been identified as large forestry-related acquisitions and smaller agriculture-related acquisitions [22], with the former often occurring under the pretext of agricultural or industrial development [23]. One of Myanmar's few remaining forest frontiers, Tanintharyi Region, is affected by both [24]. Before 2010, the country had undergone 50 years of military regime and civil war, and forests in border areas, such as Tanintharyi, had been a refuge as well as a source of livelihood (in addition to a few mixed plantations with betelnut and cashew) for the local people. However, in the past 20 years, the area has increasingly become a hotspot for large-scale land acquisitions for oil palm or rubber on the one hand and conservation activities on the other, frequently hand-in-hand [21]. In addition to a major deforestation period between 1997 and 2004 [25], a government-supported rubber boom that began in 2007 has been motivating private investors and smallholder farmers to grow rubber plantations on former forest and mixed plantation land [26]. Outdated and incoherent land classification systems fail to account for the customary land use rights of local communities [27]. The current land law from 2012 gives farmers the opportunity to apply for official land titles if their land is classified as agricultural land [27]; however, these use rights are usually restricted to a few selected commercial crops. This is one of the reasons why shifting cultivation has mostly stopped and traditional mixed plantations are now only present in small areas. By 2013, more than one-third of Tanintharyi's land surface had been allocated for agribusiness concessions intended for oil palm [27]. Concessionaires often do not respect traditional land rights or boundaries of permanent forest estates [27]. Consequently, local communities have little say in the use of land, even though they suffer the most from the dwindling ability of the landscape to provide ES. However, no comprehensive ES assessments covering several land uses and services have been carried out in Myanmar.

This study aims to identify local people's perspectives on the values of a variety of ES [12] provided by different land uses within the landscape. It tries to complement existing research by concentrating on land use ([28] or [29]) and by analysing bundles of ES instead of separate services [3]. Rural households often find ways to cope with changes in the supply of natural resources and associated services [30]. We aim to show by means of a case study not only the impacts of land use change and ES trade-offs, but also the adaptation measures that local communities adopt to enhance their livelihoods and well-being. The study was guided by the following research questions: (a) How are ES perceived and what do people consider the attributes of ES in a forest frontier context? (b) To what extent are bundles of ES provided by each land use? (c) What are the ES trade-offs deriving from land use change from forest to rubber and oil palm? (d) How do local people adapt to these trade-offs?

2. Materials and Methods

2.1. Theoretical Framework

This study is embedded in land system science, which addresses transformations in landscapes with a combined perspective of environmental and social systems thinking and aims at producing knowledge for sustainable development [31]. The ES concept presents implicit links to sustainability [32]. It is also a means to explore the relations between nature and humans. Hence, we are using the ES framework as a conceptual lens to investigate the benefits people obtain from nature. The Intergovernmental Platform on Biodiversity and Ecosystem Services emphasizes the need for normative frameworks in ES research [16]. This study's theoretical framework builds on the cascade model [33], which is widely used in ES research [3] and distinguishes between the ecological (supply) and socio-economic (demand) side [11]. As such, it connects biophysical structures and functions to human well-being (Figure 1). We adapted the model to focus the biophysical lens on land use (in the way that mapping approaches often do [34]), and the socio-economic and cultural lenses on human well-being.

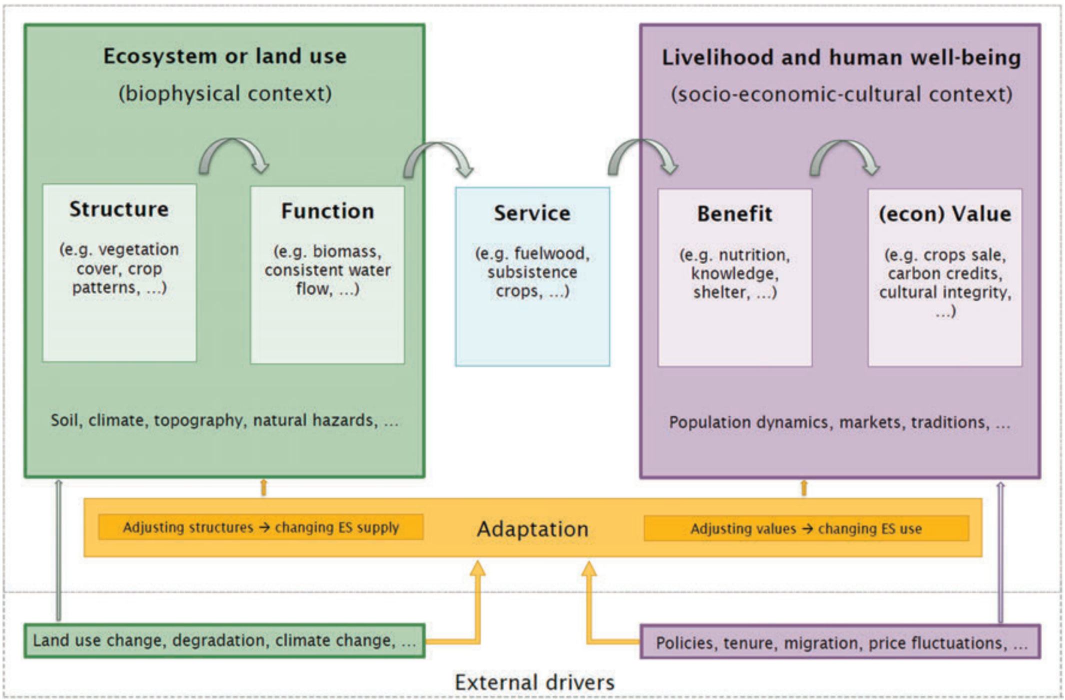

Figure 1. The cascade model for ecosystem services and adaptation (adapted from [33]).

The adapted framework further includes the aspect of adaptation to external drivers, which influence the biophysical or socio-economic system and thus the final services. This reflects the fact that people also react to a changing ES supply, either by adjusting land use or land use practices or by substituting products to satisfy demands. The framework highlights the dynamic nature of ES supply and demand.

2.2. Study Area

We selected the Tanintharyi Region of Myanmar as a study site due to its exemplary but under-researched characteristics as a forest frontier landscape. Myanmar is among the top three countries with the greatest annual net forest loss since 2010 [35]. We chose three villages in the northern part of Tanintharyi for their vicinity to the Tanintharyi Nature Reserve and their experience with conversion to both oil palm and rubber (Figure 2).

Figure 2. A map of the study villages in Yebyu Township, Tanintharyi Region, Myanmar (sources: ESRI [36], MIMU [37,38]).

Village A has over 200 households and is situated next to the main road, on land classified as agricultural. This land classification means that many farmers were able to acquire land titles and often invest in private rubber plantations. Village A also has a community forest. Villages B and C are situated on land classified as a forest reserve [27], which means they cannot obtain land titles. They have been heavily affected by oil palm concessions. Village B has around 40 households and Village C, the most remote of the three, has only 20 households. Most of the research was carried out in the three villages, with some additional expert interviews conducted in the wider study area.

2.3. Ecosystem Services Classification

The study differentiated between three ES types: provisioning, regulating, and cultural [3]. Supporting services were not considered as individual types, but rather seen as functions within the cascade (Figure 1). We used an original list of 22 ES, based on the Common International Classification of Ecosystem Services (CICES, [4]) and adapted to the local context using information from the literature and prior knowledge. While some of these ES are already used, others may take on greater relevance in an uncertain future. To ensure that the spectrum of ES types was represented, several cultural services were included in the analysis although they were challenging to attribute to specific land use categories.

2.4. Social Valuation

Interpretive methods are effective in uncovering the reasons behind the valuation of certain ES by land users [39]. This is particularly important for ES that are perceived differently by land users or other stakeholders. With our focus on local land users' perspectives, we decided to use social valuation techniques for ES [40]. Such techniques have been found to be the most suitable way to value a wide range of ES [12] in line with the cascade model (Figure 1). The social valuation approach is based on societal values for ES, in contrast to the ecological approach, which measures ecosystem functions, and the economic approach, which assigns monetary values to the benefits from ecosystems [40]. There are two steps in social valuation: First, the identification of valuable ES to stakeholders and second, the ranking of these stakeholders' preferences or values according to a scoring system [40].

2.5. Data Collection

The research was guided by an explorative study design [41]. Data collection took place over five weeks using a participatory research approach. The methodology consisted of a total of four transect walks, 16 focus group discussions (FGDs), and 27 semi-structured key informant interviews, which ensured triangulation. This is depicted in Table 1. For the interviews, a purposive sampling design [42,43]—i.e., a selective sampling by the researcher's judgement and substantive criteria, in this case according to a participant's knowledge on specific land uses—was applied to develop a typology of land user cases in the villages and agricultural specialists at the regional and national level.

Table 1. An overview of methods per village and topic.

Place	Transect Walks	Focus Groups	Key Informant Interviews					
			Forest	Rubber	Mixed	Oil Palm	Rice	Lime
Village A	2	5	2	1	1	-	1	1
Village B	1	5	1	1	1	1	1	-
Village C	1	6	1	1	2	1	2	-
Regional	-	-	2	-	-	1	-	-
National	-	-	-	1	1	1	2	1
Total	**4**	**16**	**6**	**4**	**5**	**4**	**6**	**2**

In each village, data collection started with one general FGD on land use and land use change, followed by a transect walk with some of the participants, including the village head. We then carried out the rest of the FGDs on specific land uses and land use practices, followed by the key informant interviews. Each FGD was held at the village level and involved around 10 people. Diverse participants were selected according to the following criteria: main livelihood activity, wealth, gender, and age. Topics focused on land use, land management practices for each land use, and land use change, and served to understand the activities of ES beneficiaries [15]. We held key informant interviews on the existing land uses and their supply of ES, focusing on one land use in each interview. This was repeated in all villages where the respective land use is present and with other relevant key informants at the regional (plantation managers) and national (researchers) level. To assess the importance of a specific land use for the supply of ES, we gave interviewees a list of 10 ES and asked, "How important is land use A for the supply of ecosystem services 1–10 at the landscape level, ranging from not important to very important, and how do you use it?". Follow-up questions then revealed how certain services were understood and valued, and how demand and actual use are related to supply. For example, for fuelwood from mixed plantations, the follow-up questions were: "How much fuelwood do you get from mixed plantations? Is it enough to cover your needs? How is the quality of the fuelwood? Do you prefer fuelwood from betelnut or cashew trees?". In total, the interviews included six on forests, four on rubber, five on mixed plantations, four on oil palm, six on rice, and two on lime. Taking extensive field notes was indispensable during all interviews.

2.6. Data Analysis

After all data were collected, we transcribed field notes from transect walks and texts from focus groups and interviews and applied a thematic coding system [41] based on land uses and ecosystem services. Following an explorative approach, we developed further codes on drivers of change after reading through the transcripts. A structured content analysis [41] followed. The qualitative content analysis built the foundation for the ES scoring process [44]. Additionally, we carried out a coding query using all transcripts to find links between ES and drivers of change, interpreting more than two overlaps as a rather strong link.

2.7. Scoring System

In order to systematically analyze and compare data, we carried out a scoring process based on a qualitative content analysis [41]. We assigned each ES a supply score from 0 to 3 depending on the quantity and quality supplied by respective land uses building on the criteria outlined below. For the analysis of trade-offs, we continued with the 10 most highly valued ES based on the following determinants: supply and demand scores, adherence to specific land uses, data availability from interviews, and a balance of representative ES for all ES types. Table 2 describes the supply scoring criteria for these 10 ES in detail.

Table 2. The ecosystem service (ES) supply scoring criteria for the 10 selected ES.

ES		Description	Scoring Criteria for ES Supply
Provisioning	Subsistence crops	Crops for subsistence include mainly rice, vegetables, and fruit.	0 = no subsistence crops planted 1 = some subsistence crops planted intermittently 2 = some subsistence crops planted continuously 3 = subsistence crops dominate land use (LU)
	Commercial crops	Commercial crops are sold raw or after primary processing.	0 = no commercial crops planted 1 = some commercial crops planted 2 = medium-income commercial crops dominate 3 = high-income commercial crops dominate LU
	Livestock	Livestock products include meat, eggs, leather, and manure.	0 = no livestock present 1 = sometimes livestock present (mostly chicken) 2 = livestock present (chicken or cattle) 3 = livestock dominant (cattle)
	Wild plants	Wild plants are for nutrition or medicine. No plant materials are discussed.	0 = no wild plants 1 = few wild plants present 2 = wild plants present, but low diversity 3 = abundant and highly diverse wild plants
	Fuelwood	Fuelwood includes small trees and branches used for cooking.	0 = no material for fuelwood present 1 = some low-quality fuelwood present 2 = much fuelwood present with different qualities 3 = abundant fuelwood of high quality
Regulating	Water flow	Water is used locally (regulation of below-surface water flows).	0 = no contribution or disturbance to water flow 1 = limited contribution to water flow 2 = improved water flow 3 = high contribution to water flow and quality
	Biodiversity	Biodiversity refers to the maintenance of nursery populations and habitats for domestic and wild species.	0 = destruction of biodiversity (pollution) 1 = low biodiversity 2 = good agrobiodiversity 3 = high biodiversity overall
	Microclimate	Regulation and improvement of the microclimate (air flow, temperature).	0 = disturbance of a healthy microclimate 1 = common microclimate 2 = agreeable microclimate 3 = very agreeable microclimate and high C-seq.

Table 2. *Cont.*

ES		Description	Scoring Criteria for ES Supply
Cultural	Education	Education is the land use contribution to the knowledge base of children and adults.	0 = not important for education 1 = part of education (parent to child) 2 = important for education and training 3 = many opportunities for continued education
	Cultural identity	Embedment in local culture includes traditions, religion, spiritual value, and connectivity.	0 = no cultural value, no cultural products 1 = some products used traditionally 2 = LU and products important to cultural identity 3 = LU strongly embedded in culture

LU, land use; C-seq, carbon sequestration.

The aim of the social valuation was to obtain, for each ES, six supply scores (one for each land use) and one demand score. It is understood that ES demand is influenced by the landscape and ES availability but does not change between land uses. This allows for a direct comparison between ES supply and the contribution to local demand for each land use. Demand is defined as "the amount of a service required or desired by society" [45], whereby the rural poor in developing countries are usually more reliant on the use of local ES [46]. Thus, demand is reflected in direct use, indirect use, potential benefit, and the intrinsic value that people attribute to a service [47]. Accordingly, the scores for ES demand are based on the qualitative content analysis according to the following criteria:

0 = people do not use this ES directly and do not see a benefit or value
1 = people see a benefit or value but do not use it directly
2 = people use it directly or indirectly
3 = ES is essential for livelihoods and human well-being [46]

During the interviews, villagers also explained about past, current, and sometimes even future demand, which allowed us to detect trends.

3. Results

3.1. The Tanintharyi Landscape and Local Perspectives on Ecosystem Services

In Tanintharyi Region, most land used to be covered with natural forests. Local communities remember that they derived various regulating and cultural services from their environment at the time. However, they also actively used forest lands for shifting cultivation for subsistence as well as livestock herding, benefiting from an immense variety of provisioning services. Later, with the introduction of mixed plantations of cashew, betelnut, and minor crops, farmers felt they could still benefit from many ES, including additional commercial crops. However, they were not able to benefit from ES in the early 1990s, a time during the country's long-running civil war in which the local communities were often hindered from accessing their fields. Today, many of the interplanted annual crops, such as vegetables or herbs, are still used for subsistence or semi-subsistence. Intercropping is done both in traditional mixed plantations as well as in new rubber plantations during the first years before the canopy closes.

The impact of losing certain ES became evident to the local people with the allocation of oil palm concessions in the study area. They observed soil compaction and water pollution, and, being banned from areas designated for oil palm, experienced a loss of provisioning and cultural services. Cattle herders had to make sure that no cattle entered those areas, an additional risk that made them decide either to reduce the number of cattle or to stop herding altogether; today, the ES 'livestock' mainly refers to small livestock, such as pigs, chicken, and ducks. The view of globally highly significant ES—such as carbon sequestration or biodiversity—has increased locally since the arrival of different organizations trying to raise awareness and press for forest conservation. Nonetheless, these ES do not have the same priority for the local population as those that directly contribute to their livelihoods and well-being, such as 'water flow' and 'microclimate', two regulating services that are perceived as very important. Most villagers derive their drinking and non-drinking water from pipes connected to the water catchment area in the mountains, while others rely on small wells or fetch water from the stream. Of these options, the mountain water is valued most highly. Microclimate, too, is directly felt by the villagers: with the loss of forests, they are experiencing increased heat during the dry season. Farmers also believe that changes in the microclimate and seasonal water availability could be affecting productivity of their cashew and betelnut plantations. In terms of education, local people perceive some land uses to be more valuable because they provide the opportunity for training. This is the case for rubber, where companies provide farmers with specific technical training, and for community forests, where the user groups are trained in sustainable forest management and use by non-governmental organizations. Other land uses, particularly those with cultural importance, such as forests or rice production, are an integral part of parental teaching and therefore offer educational benefits to children.

3.2. Bundles of Ecosystem Services for Each Land Use

Each of the land uses in the study area delivers a certain bundle of ES, including provisioning, regulating, and cultural services. The scores according to Table 2 illustrate to what extent a certain land use provides bundles of 10 selected ES according to local perspectives (Figure 3).

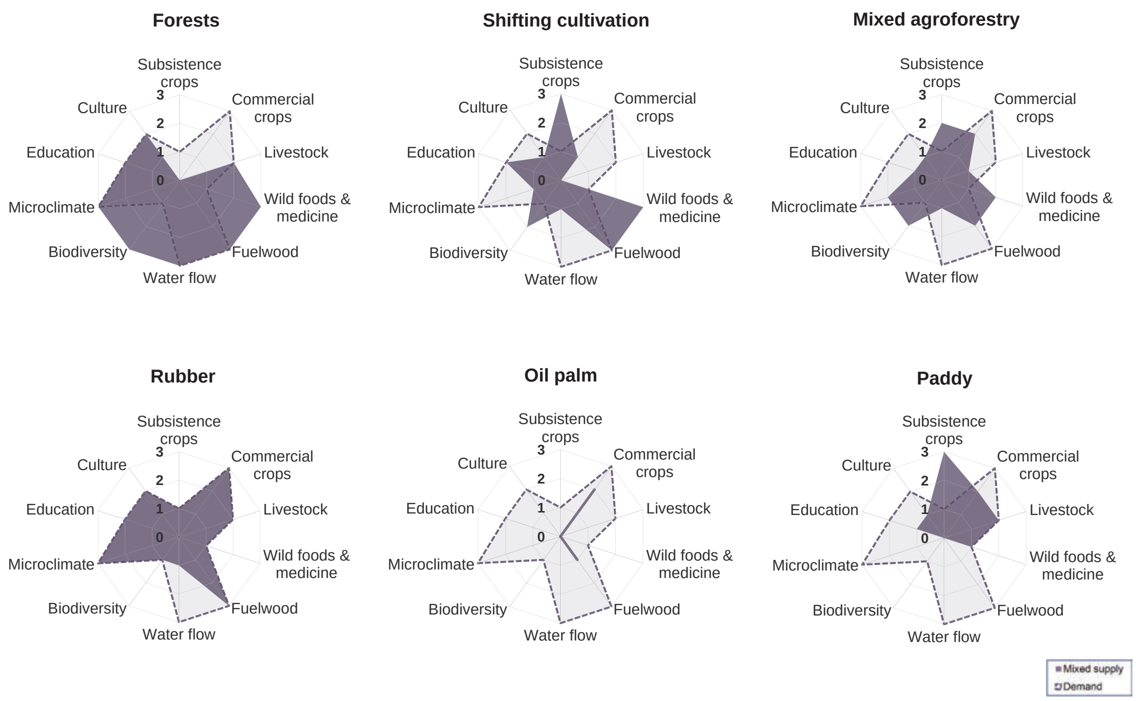

Figure 3. Local perspectives on ecosystem service bundles provided by different land uses in a forest frontier landscape in Tanintharyi, Myanmar.

Intact forests provide many regulating ES as well as non-timber forest products. Cultural services are tied to the forest ecosystem, which explains the strong connection with nature that has been observed with people living in the Tanintharyi forest frontier. However, forests that are not used for shifting cultivation lack opportunities for subsistence and especially commercial crops, which are highly favored by local communities. This seems to be one of the reasons why rubber plantations have become very popular even for smallholders in the recent past. In fact, rubber plantations seem to fulfil local ES demand almost entirely. Compared with other land uses, rubber is the main source of income for smallholders (as owners and/or tappers) and also provides fuelwood for household use. One reason is that farmers obtain tenure rights and have access to the benefits. Furthermore, rubber is also often associated with poultry production. Unlike other tree crops, the roots of rubber are not damaged by chickens, and rubber tappers living within plantations appreciate the additional income opportunity. Interestingly, these good financial opportunities mean that local people are beginning to assign important cultural values to rubber plantations. This indicates that cultural services, but also other ES, can change quite rapidly over time and are adapted to the context. People also recognize that rubber cultivation—requiring specific new production skills—brings opportunities for training and education. Capacity-building related to rubber cultivation and primary processing is supported by the government and private companies.

Mixed plantations are recognized by land users to provide a balanced bundle of ES, but important services, such as commercial crops or fuelwood, are supplied less than in other land uses (Figure 3). This is reflected in many farmers' decisions to convert them to rubber. Most farmers keep a few low-input traditional mixed plantations with cashew and/or betelnut while concurrently investing in rubber since 2007. Oil palm plantations on the other hand, mainly owned by investors, are experienced by local communities as having detrimental effects on the supply of ES in the study region. From their perspectives, oil palm plantations provide limited ES because benefits are not accessible to them. While they do provide potential benefits in the form of commercial palm nuts, these go only to the companies. Further, several people stated that the companies' dominating practices lead to disservices for the entire landscape, such as water contamination, air pollution, and a loss of biodiversity. Lastly, paddy rice cultivation, limited to a few flat areas, provides a fairly different set of ES compared to the other land uses. Paddy fields are the main providers of the region's staple food (previously, shifting cultivation too). While upland rice could produce enough for household consumption, paddy fields often yield a surplus for the market. However, considering that the total rice production area is limited in Tanintharyi Region, much of the rice consumed is produced in other regions of Myanmar. Paddy fields can also be important for grazing livestock, especially cattle and buffalo, during the dry season.

The findings reveal that one service—the regulation of water flows—can only be provided fully if forests are intact. This is a major concern throughout the study area. With the water catchment area in the mountains as the primary source of water, these forested lands have ensured an intact hydrological cycle in the past. Local people feel that none of the current land uses are able to maintain water flows to the same effect (Figure 3).

3.3. Ecosystem Service Trade-Offs from the Main Land Use Changes

In terms of land area, the most relevant land use changes in the forest frontier landscape of Tanintharyi Region are the conversion from forests to mixed plantations (in the distant past), oil palm (20 years ago), and rubber (since 2007). The resulting trade-offs (Figure 4) are especially felt for locally used ES.

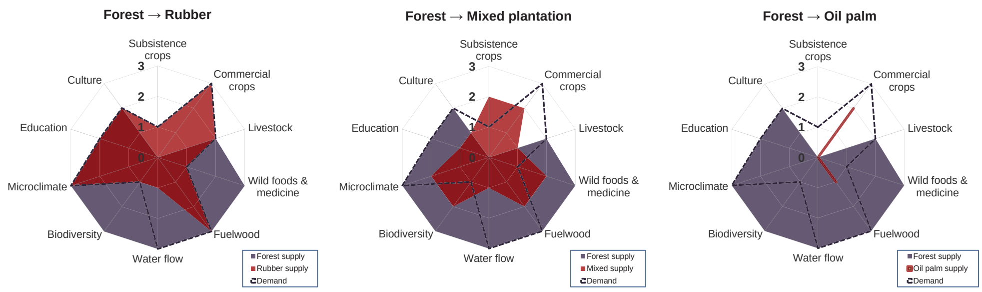

Figure 4. The ecosystem service trade-offs in a forest frontier landscape in Tanintharyi, Myanmar.

We found obvious trade-offs between regulating ES and provisioning ES for income generation (i.e., commercial crops) when forests are converted to any form of agriculture. Comparing the three main types of land use change from forest, however, there are vast differences in the trade-offs. First, oil palm. In terms of the total supply of ES, conversion to oil palm has been experienced most negatively.

We found a decline in all ES apart from an increase in commercial crops, which benefits only a small set of stakeholders. This is especially alarming for locally important services, such as the regulation of water flows or microclimate. Second, mixed plantations. The conversion to mixed plantations has had both positive and negative effects on the provided ES bundle. The big difference compared to oil palm is that no ES was lost completely for the local population. Instead, almost the same bundle of ES is supplied, but to a lesser extent. Third, rubber. In terms of serving local people's needs, the trade-offs are lowest when forests are converted into rubber plantations (Figure 4). There is a continued supply of fuelwood, for example, that rubber farmers can use themselves or sell to other villagers. Rubber plantations also cover almost all needs for regulating and cultural services.

While the study area has seen no oil palm expansion in the last two decades, forests and mixed plantations are still being converted into rubber plantations. This is causing a strong decrease in the supply of water flow regulation, microclimate, and biodiversity services: developments that local land users fear will have a negative impact on their future well-being. In our study, they assigned high demand to the ES of water flow and microclimate and expressed concern about the overall loss of intact forests. On the other hand, the financial opportunities for farmers gained by converting forests into rubber plantations cannot be underestimated. Increased income can have multiple positive effects on local communities' livelihoods and well-being. However, the results clearly show that there is one unresolved issue connected with the trade-offs: the regulation of water flows. Each of the three most prominent land use changes leads to a significant decline in this ES. Local communities feel that only intact forest ecosystems are fully able to maintain a healthy water flow (Figure 4). However, they fear that because of their limited land use decision-making power, more forests in the upland water catchment area could be converted in the future. An additional concern is that interruptions to the hydrological cycle are usually not recognized straight away but only become evident over a longer period.

3.4. Changing Demand

The study showed that both the use of and the demand for ES are not constant over time. During focus group discussions and key informant interviews, people compared past with current use and even mentioned potential future benefits and their expected value. Thus, people seem to adapt not only their direct use but also their overall demand depending on availability in the landscape and other factors, such as tenure and access, markets, knowledge, and emotional patterns. Furthermore, in- and out-migration, which is widespread in Tanintharyi, potentially influences the overall demand for ES. However, our data do not provide enough evidence linking migration with specific ES. Table 3 shows demand trends and the links between drivers and ES demand according to how often they were specifically mentioned and found relevant (if mentioned 1–2 times → +, if mentioned 3 or more times → ++).

Along with supply trade-offs between subsistence and commercial crops, the demand for subsistence crops as an ES has also decreased. For one, people can buy food for their household at affordable prices on local markets. (While a few people expressed worries about food shortages, they had not yet experienced these. Although people expect the demand for subsistence crops to remain low, this could change rapidly in the case of a sudden escalation of conflict or limited market access.) For another, the enhanced cultivation of commercial crops (rubber but also minor crops, such as lime or cocoa) has been accompanied by improved infrastructure and market access. The demand for wild foods and medicine depends on availability of commercial substitute products. A decline in direct use is leading to a loss of knowledge on which wild plants are edible or have medicinal properties; this is also further affecting overall demand. Nonetheless, several land users explained that they want to keep wild plants in their plantations because of potential future benefits.

Table 3. The change and drivers of change for the ecosystem service demand in Tanintharyi, Myanmar.

	Past Demand	Current Demand	Future Demand	Drivers of a Changing ES Demand			
				Tenure	Market	Knowledge	Emotion
Subsistence crops	High	Low	Low	-	++	-	+
Commercial crops	Medium	High	High	++	++	+	+
Livestock	High	Medium	Medium	+	++	+	++
Wild foods and medicine	High	Medium	Medium	-	++	+	-
Fuelwood	High	High	High	-	-	-	-
Water flow	Medium	High	High	-	-	+	-
Biodiversity	Low	Low	Medium	+	+	++	+
Education	Medium	Medium	Medium	-	+	++	-
Cultural identity	Medium	Medium	Low	-	+	-	++

- = no link; + = rather weak link; ++ = rather strong link.

We found that the need for water flow maintenance is consistently high and that the effects of a disturbed hydrological cycle may become even more evident in time. For local land users, it is difficult to place a value on biodiversity as a service because often it holds many indirect or potential benefits that are not yet recognized. Benefits are also linked to other ES and could include insects for pollination for agricultural production, plants with medicinal traits, or drought-resistant crop varieties, to name but a few. So, in local perspectives, the value of the ES biodiversity includes many potential uses. As knowledge on biodiversity increases, biodiversity is likely to be more appreciated, both at the local and the global level. If eco-tourism develops in the region, which is an option favored by most of the interviewed villagers, the accompanying financial opportunities would cause biodiversity as a service to be valued much more highly.

Education and cultural identity services are difficult to assign to specific land uses, although some land uses offer additional educational benefits; access to these ES is more specifically linked to physical (i.e., distance to school) and financial (i.e., ability to pay school fees) factors within the area than to the supply from elements of the landscape. Accordingly, the link to land use should not be taken as given, as cultural values assigned to specific land uses were found to also change over time but need to be assessed in their actual context. This is one way for local communities to adapt to the trade-offs they face (Figure 1).

3.5. Local Adaptation Processes

In Tanintharyi, people had to adapt to different environments and living situations several times during and after the civil war, which was most acute in the early 1990s. They also adapted to changes in the availability of land area and the expansion of oil palm plantations by intensifying their mixed cultivation plots, giving up cattle, and seizing opportunities from external initiatives to establish community forestry (e.g., village A) or to attend training sessions and receive seedlings for new crops (e.g., lime, cocoa, elephant foot yam). Changing ES use is another way of adapting to trade-offs in ES supply. This is possible for all services that can be exchanged with commercial goods. Accordingly, subsistence crops are substituted with food bought on the market, and medicinal plants can be replaced by pharmaceutical pills and visits to formal clinics. Nonetheless, local people believe in the value of wild plants and potential medicinal uses, so they let them grow on their land to avoid future vulnerability.

We found that livestock as an ES has changed in form since local people had to give up their cattle 20 years ago due to a lack of grazing land and the ban on entering oil palm concession areas. Cattle are less important today because of their incompatibility with current land uses and land tenure, even though people still have a strong emotional connection to livestock herding (Table 3). In contrast, there is a growing local market for poultry products, mainly for eggs. Even new opportunities to use chicken manure as a fertilizer in rubber plantations are evolving, and people are adapting to this by keeping chicken and pigs. They provide similar benefits, including income generation, risk aversion and stability, and manure. While they may not provide mechanical labor, as was usually the main value of cattle, farmers no longer need this as there are fewer paddy fields within the landscape.

Adaptation can also entail people changing their land use or land use practices. One example in the study area is village B. The land users reacted to a loss of forests and shifting cultivation, diversifying their mixed plantations to balance out the supply of ES. The villagers tend to manage their farms to resemble natural forest ecosystems: the farms provide the same benefits, such as biodiversity, microclimate, and factors for forming cultural identity, while at the same time supplying more provisioning ES, such as subsistence and commercial crops or fuelwood.

4. Discussion

4.1. The Ecosystem Services Framework in Practice

Using the cascade model [33] as a framework proved useful for analyzing all aspects of an ES, although the distinction between functions and services was sometimes challenging. Nevertheless, the cascade helped us to consider the relationships between the supply and the demand side of ES [3]. In addition, looking at ES along the cascade with local communities improved communication between land users and researchers and supported the inclusion of both ecological and socio-economic and cultural aspects in the discussion [3]. Even though the CICES framework was useful for obtaining a well-structured and comparable list of ES, several adjustments had to be made for it to fit the local context. This highlights how important it is to consider local settings and understandings of ES before starting an assessment [48]. The early separation between subsistence and commercial crops was essential, especially as it is a major reason for land use changes and one of the main trade-offs for local land users in the study area. This suggests that differentiating between subsistence and commercial crops adds an important aspect to ES research.

Social valuation as a method has proven to be well-suited for comparing bundles of different types of ES across land uses and could be further promoted [6,9]. Having more studies with a similarly comprehensive list of ES would support the out-scaling of the results. Recognizing that social valuation was an important first step in assessing ES trade-offs at the local scale, we propose ensuing studies that quantify and map ES at a larger scale to address policy-makers and achieve an impact on landscape planning [15,49]. The promoted value pluralism approaches hereby promise holistic assessments for a sustainable development [16,50,51].

Adaptation processes have gained attention mainly in relation to climate change research. However, they are also relevant where other factors influence socio-ecological systems or landscapes, as this study has shown. Adding adaptation to the framework allows researchers to illustrate the dynamics of ES supply and demand, to confirm that ES are not static in time and space, and to discuss the role of humans in ecosystem processes. This study demonstrates that not all declines in ES supply necessarily have a negative impact on livelihoods and well-being. On the contrary, land use change and ES trade-offs often bring new opportunities. This has been illustrated by the new cultural value assigned to rubber plantations or the emergence of chicken farms on small patches of land. As seen in this research, both physical characteristics of the landscape and people's valuations change in time. Thus, including changing demands and adaptation processes in ES assessments can move ES research forward.

4.2. Ecosystem Service Trade-Offs in a Forest Frontier Landscape

We found a distinct shift from subsistence crops and wild foods towards commercial crops. The conversion in Tanintharyi from forest and shifting cultivation to commercial crops is frequent in other forest frontiers that had previously been used for shifting cultivation. Such landscapes are often subject to large-scale conversions of forests for the cultivation of commercial crops [21,52] and sometimes driven by interests in timber [22]. In Southeast Asia, the major commodities are rubber and palm oil, and similar ES trade-offs can be expected in other forest frontiers. Our findings supplement a review [53] that found that rubber expansion in the Mekong Region negatively affects the supply of water and climate regulation services. Further, it states that rubber as a single crop poses high risks to the livelihoods of local farmers. On the other hand, small-scale farmers often opt for diversification strategies [54] and their land use decisions are based not only on economic considerations but also on the environmental, cultural, and political context [55,56]. This has also been observed in our study area. Rubber cultivation in Tanintharyi started only recently, even though it had been cultivated in the neighboring Mon State for nearly a century [26], and there were no farmers in our study area who depended solely on rubber. Nevertheless, rubber plantations do pose a potential threat for local agricultural systems and human well-being where their expansion advances into intact forest landscapes and crucial water flows are interrupted. A biophysical mapping of the landscape and hydrological processes will thus be highly useful to assess these risks in more detail. Impacts of oil palm expansion have been described mostly for Indonesia and Malaysia and include the positive potential as commercial crops and the negative effects on subsistence crops, wild foods, water quality and quantity, climate regulation, biodiversity, and cultural services [57]. The results are mostly in line with our findings. However, the commercial potential is not accessible to local farmers. Even for the private sector, financial gains from palm oil are limited because of low productivity in Myanmar [58]. Due to this, only 19% of the allocated concession areas have been planted [27] and investors are sometimes planting rubber as the more profitable crop instead [56]. According to a study [59], forest conversions to oil palm have negative effects on remaining forests because they increase pressure on them (displacement of fuelwood collection, timber harvesting, etc.). This was not observed in the case study site but may well be an important issue in other forest frontier landscapes. There are multiple possibilities as to why it did not occur in the study area: The opportunity to collect fuelwood from rubber plantations, the conservation status of the remaining forest, and the community forestry initiatives, which promote a sustainable protection and use of forested lands.

Our results also indicate that the extent to which ES trade-offs occur and affect local people's well-being highly depends on the inclusion of the local population in the land use development process, their rights and access to resources, and common regulations for managing ES at the landscape level. It appears that the current legal framework on land governance does not adequately consider the needs of local land users, as many are struggling to obtain tenure rights for their customary lands. A large part of the negative trade-offs from oil palm conversion is thus because local people are prevented from entering the lands and using it for multiple purposes, such as growing subsistence crops or rearing livestock. Several studies proposed that negative trade-offs can be mitigated if forest-dependent communities participate in decisions and are actively engaged in land management [60], if people's access to ES is ensured [61], if forest land regulations are simplified [62], if land management rules are negotiated with all stakeholders [63], and if strategies and policies are directed towards a minimization of ES trade-offs in the landscape [64].

4.3. Outlook for Tanintharyi Region

In the forest frontier landscape of Tanintharyi Region, our findings suggest that local people prefer having diverse land uses, as this allows for a balanced ES supply.

On the one hand, forest conservation is necessary in the water catchment area. Uncontrolled expansion of rubber has proved to endanger long-term water supply in other areas of the Mekong Region [53], and signs that this could also occur in the study area are already being observed by the local communities. A close monitoring of this development and the implementation of forest conservation measures thus seems necessary, especially where water sources are threatened. However, one might question whether a state-protected area and the strong land-sparing approach is the right pathway in terms of maintaining ES bundles. Community forestry schemes coupled with management plans for a sustainable use of resources arguably contribute more to conservation [65–67] and the provision of a holistic bundle of ES. Studies have even shown that community forests in Myanmar can also reduce disparities by contributing to the livelihoods of different subgroups within a community [68]. Inclusion of local people's perspectives is a major advantage and prerequisite for community forests.

On the other hand, agricultural land uses, especially rubber and mixed plantations, are crucial for local livelihoods. The main importance of mixed plantations seems to be the aspect of diversification and risk minimization for resilience, particularly for smallholder farmers. A study in China found that land use choices and agrobiodiversity depend on ethnicity, wealth, land tenure, and rubber farming experience, among others [54], and similar patterns have been observed in our study area. As yet, Myanmar's land governance system and limited tenure rights for farmers in classified reserved forest areas [56] do not allow for adequate local land use decisions. However, with the expansion of commercial plantations leading to improved infrastructure and markets, these developments may improve local people's well-being in several dimensions. Nonetheless, while the farmers' interest to grow commercial crops is expected to remain high, a distinction between different types of crops should be made. Generally, an exaggerated dependency on one crop alone is a high risk [54]. Furthermore, in Myanmar, the land registration process to obtain formal land tenure requires farmers to stipulate the intended land use, which influences farmers' land use decision. For officially recognized commercial crops, such as rubber, this is much easier.

This study confirmed that a landscape with a variety of land uses can provide a more balanced bundle of ES, whereas concentration on one land use always entails major trade-offs. Maintaining heterogeneity and connectivity in the landscapes is important to provide a larger portfolio of ES [3]. We therefore opt for a combination of land-sparing and land-sharing approaches in the given landscape [69,70]. To balance ES supply and demand in the studied forest frontier landscape, several options for improving existing land uses could be developed, including integrated animal husbandry with poultry, optimized agroforestry combinations [71,72], sustainable oil palm cultivation [73,74] with an outgrower scheme, or increased use of bamboo. Further investigations of these options could add to a sustainable landscape management strategy and enhanced human well-being.

5. Conclusions

This study documented the perspectives of local land users on ecosystem service trade-offs in a Myanmar forest frontier landscape with significant expansion of commercial plantation crops. We found that the regulation of water flow is experienced as the main challenge and that this ES is strongly associated with intact forest lands. For areas with important hydrological functions, adequate forest management planning and the prevention of conversion to other land uses are thus vital. More studies are needed to assess water flows at the regional level. Nevertheless, local land users in the study area still benefit to a certain extent from many of the regulating and provisioning services, even when areas are converted from forests to rubber or mixed plantations of cashew and betelnut. Benefits include the supply of wild foods, medicinal plants, and fuelwood, and the regulation of microclimate and biodiversity. While forests are important for local cultural identities and support water flows, biodiversity, and various timber and non-timber forest products, rubber plantations offer income and provide ES such as fuelwood, an agreeable microclimate, and even new cultural values. Mixed plantations are appreciated for their balanced ES bundles and low-risk cultivation. On the other hand, trade-offs are experienced most negatively in local communities where forests are converted into oil palm plantations. These are associated with disservices to water flows and other regulatory functions by reportedly polluting nearby rivers with agricultural chemicals. Local people's restricted access to these lands further exacerbates their perspectives on trade-offs.

To enhance local benefits from ES, we argue that it would be crucial to revise the legal framework of land governance, to grant enhanced land rights to local people, and ensure their participation in land deal processes. We found that the people adapt their use of ES according to landscape transitions and other factors, such as changing markets, knowledge, or tenure rights. Improved infrastructure, which goes along with agricultural investment in forest frontier landscapes, not only brought better opportunities for selling commercial crops but also substituted certain ES, such as subsistence crops, wild foods, and medicinal plants. Local adaptation processes can in turn also influence the landscape (through changing land use or land management practices) as well as the demand for formerly important services, such as wild plants for food and medicine.

In terms of ES research, we have demonstrated that social valuation is well-suited for assessing local stakeholders' perspectives and for comparing bundles of different ES types across land uses in a region with limited prior data availability. Our results provide a good basis for further research to quantify and map ES on a larger scale in Tanintharyi Region. More generally, this study also contributes to the understanding of ES trade-offs in tropical forest frontier landscapes and the potential impact of these trade-offs on local livelihoods and human well-being. It has shown that even though bundles of ES are linked to specific land uses, they are not necessarily lost when land uses change. Our findings highlight the need to include local stakeholders in land governance and in the optimization of land management practices in forest frontiers. Holistic ES assessments such as this with more in-depth qualitative and additional quantitative studies can contribute to formulating sustainable land management strategies for functioning ecosystems and human well-being; as such, they are crucial instruments for policy-makers to assess the impact of land use changes and the resulting trade-offs for the local population.

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Paper III: Sustainable development under competing claims on land: Three pathways between land-use changes, ecosystem services and human well-being

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SPECIAL ISSUE ARTICLE

Sustainable Development Under Competing Claims on Land: Three Pathways Between Land-Use Changes, Ecosystem Services and Human Well-Being

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Abstract

Competition over land is at the core of many sustainable development challenges in Myanmar: villagers, companies, governments, ethnic minority groups, civil society organisations and non-governmental organisations from local to the international level claim access to and decision-making power over the use of land. Therefore, this article investigates the actor interactions influencing land-use changes and their impacts on the supply of ecosystem services and human well-being. We utilise a transdisciplinary mixed-methods approach and the analytical lens of the social-ecological systems framework. Results reveal that the links between land-use changes, ecosystem services and human well-being are multifaceted; For example ecosystem services can decline, while human well-being increases. We explain this finding through three different pathways to impact (changes in the resource systems, the governance systems or the broader social, economic and political context). We conclude with implications of these results for future sustainable land governance.

Keywords Claims on land · Sustainability · Ecosystem services · Human well-being · Myanmar

Résumé

La lutte pour la terre est au centre de plusieurs défis de développement durable au Myanmar : les villageois, les compagnies, le gouvernement, les groupes ethniques minoritaires, les organisations de la société civile et non-gouvernementales – du niveau locale au niveau internationale – réclament l'accès à la terre, et le pouvoir de prendre des décisions sur son utilisation. Cette étude enquête les interactions parmi

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les acteurs qui influencent les changements d'utilisation de la terre, et leur impact sur le bien-être humain et la provision de services d'écosystème. On utilise une approche transdisciplinaire aux méthodes mixtes, et le cadre analytique des systèmes socio-écologiques. Les résultats montrent que les liens entre les changements dans l'utilisation des terres, les services d'écosystème, et le bien-être humain sont polyvalents. Par exemple, les services d'écosystème peuvent baisser et le bien-être humain monter. Nous expliquons cela a travers de trois différentes voies d'impact (changements dans les systèmes des ressources, les systèmes de gouvernance, ou le contexte sociale, économique et politique plus large). On conclut avec les implications de ces résultats pour la future gouvernance durable des terres.

Introduction

In 2015, the same year that the Myanmar people elected a new civilian government after nearly 60 years of military dictatorship, Myanmar representatives also endorsed the global UN 2030 Agenda for Sustainable Development. The 2030 Agenda constitutes a development vision negotiated by the global community, which is aligned around '5 Ps' (people, planet, prosperity, peace and partnership) and 17 sustainable development goals (SDGs) embracing social, environmental and economic dimensions (United Nations 2015). In 2018, sustainability goals and strategies were further specified by the Myanmar government in the Sustainable Development Plan (GoM 2018). However, implementation of these sustainability visions is not an easy task because there are not only synergies but also fundamental trade-offs between different goals such as conservation of biodiversity (SDG 15) and food security (SDG 2). Different actors usually have quite distinct visions of how these trade-offs should be resolved (Zaehringer et al. 2019).

As the use of land is key for many of these goals, competing claims on land are at the core of many related development disputes (Sachs 2018; Smith 2018; Zaehringer et al. 2019). Villagers, companies, governments, ethnic minority groups, civil society organisations (CSOs) and non-governmental organisations (NGOs) from local to international level compete for access to and decision-making power over the use of land based on different arguments such as livelihoods security, place of belonging, economic assets, habitat for flora and fauna and territorial sovereignty (Franco et al. 2015; Li 2014; Meyfroidt et al. 2018). The fundamental changes in land use and governance occurring in recent years in Myanmar can be seen as the materialisation of the power relationships among the actors involved. Resulting land-use changes include deforestation, establishment of large commercial monoculture plantations (oil palm, rubber, maize), special economic zones and increasing presence of NGOs concerned with the conservation of Myanmar's forests, which belong to the global hot spots of biodiversity (De Alban et al. 2019; Mark 2016; Scurrah et al. 2015; Tarkapaw et al. 2016; Woods 2015).

Hence, whether Myanmar can successfully advance towards the 2030 Agenda will strongly depend on how the multiple and competing claims on land are governed in the future.

The overall goal of this article is to investigate the links between recent land-use changes and sustainable development outcomes to identify leverage points and priority areas of concern for a more sustainable land governance in Myanmar. In particular, we aim to investigate how actor interactions shape land-use changes and how these changes impact on the supply of ecosystem services and human well-being. Investigation of the transformation from forest and shifting cultivation to protected areas and oil palm and rubber/mixed-crop plantations in Northern Tanintharyi highlights three pathways to impact shaped by the varying involvement of characteristics of the resource systems, the governance systems and the broader social, economic and political context.

Myanmar under Competing Claims on Land and Development Visions

During the military regime, the Myanmar government followed different socialist, communist and capitalist development visions in succession. It established a highly centralised, regulated and authoritarian state to govern the land. Instruments included agricultural master plans such as the Self-Sufficiency Plans of the 1990s. Granting of large-scale land concessions to protected companies ('cronies') was an important means to boost economic development (Fujita and Okamoto 2006; Gum Ja Htung 2014; Thein et al. 2018; Woods 2011, 2015). Moreover, land concessions were also granted for protected areas to conserve precious forests. However, as many of these government-initiated agricultural and conservation concessions were implemented in ethnic minority areas, they might also have served to extend control over these territories (Gum Ja Htung 2014; Woods 2011, 2019).

The transition to a semi-civilian government after 2011 brought a new focus on peacebuilding and economic development according to liberal principles. This changed development vision resulted in various law and policy reforms, including reformulation of the Farmland Law and the Vacant, Fallow and Virgin Land Management Law in 2012 that introduced land-use rights to attract domestic and international investments in land. As a consequence, a further wave of large-scale land acquisitions for oil palm, rubber and other commercial crops began (Fairhead et al. 2012; Woods 2015).

The land development vision of the former military regime was often in conflict with the interests and visions of ethnic minority groups and local communities. As shown by Franco et al. (2015), local communities—besides economic progress—often stress the importance of personal and community well-being based on subsistence agriculture, maintenance of identities as farmers and connections to ancestors and spirits. Under the military regime, many small-holder farmers lost access to their lands cultivated under customary land-use systems due to the land acquisitions implemented as a consequence of the military's development strategies.

Many of these developments also continued after the transition to the civilian government under the National League for Democracy (NLD) that was elected 2015 (Thein et al. 2018).

Current debates on development in Myanmar are shaped by three competing perspectives of what land-related development visions should be (Franco et al. 2015):

first, the perspective that prioritises capital-intensive large-scale monoculture agriculture and industry projects based on (neo-)liberal values (Woods 2015); second, the view that labour-intensive and small-scale traditional farming, grazing and forestry practices should be recognised, protected and promoted (LIOH 2015); and third, the perspective that calls for protection and conservation of the rich natural environment including forests, waters and biodiversity (FFI 2019).

The Myanmar Sustainable Development Plan (GoM 2018) tries to address all three perspectives, and unlike previous strategies, it considers collaboration between public entities, the private sector and the civil society as crucial. It includes a section entitled 'Improve land governance and sustainable management of resource-based industries ensuring our natural resources dividend benefits all our people'. In this section, historical mismanagement and opacity of land management are explicitly recognised and considered as widespread causes of Myanmar's underdevelopment and degradation of ecosystems such as forests and mountain areas. The plan also expresses the objective to implement 'a more effective and transparent management regime, which must include continued engagement with affected communities' and seeks to strengthen 'rural households' land tenure, property rights and related enforcement capacities'. However, the overall orientation of the Myanmar Sustainable Development Plan heavily focusses on rapid growth, economic stability and private sector integration. Effective governance and sustainable management of natural resources are introduced primarily as essential means to sustain economic growth—people's well-being is only mentioned later.

Land Systems, Ecosystem Services and Human Well-Being

Land system science is at the forefront of research aiming to generate much-needed knowledge that can help to find land-related pathways towards sustainable development (Zaehringer et al. 2019). Land system science considers land as a social-ecological system encompassing dynamics and activities related to the human use, as well as its drivers and consequences (Reenberg 2009; Turner et al. 2007; Verburg et al. 2013). To analyse the consequences for sustainable development, land system scientists operationalise sustainability from a perspective of inter- and intra-generational justice and stress the importance of integrating various actor perspectives (in particular of local communities) (Zaehringer et al. 2019). From this perspective, sustainable development of land systems requires that people living today and in the future can lead a good life, while protecting the environment.

The concepts of ecosystem services (ES) and human well-being support this operationalisation. The concept of ES captures the benefits people receive from the environment (Costanza et al. 1997; Daily 1997), including provisioning (e.g. crops and wild plants), regulating and maintenance (e.g. microclimate) and cultural services (e.g. educational values) (Haines-Young and Potschin 2018). Land-use change is often regarded as the main driver for changing ES supply. Human well-being is a multidimensional concept, and various approaches have been suggested for its conceptualisation and analysis. In recent years, a shift occurred from focussing on human well-being in terms of basic needs to a broader conception of well-being in terms of capabilities (Alkire 2002; Robeyns 2005). Accordingly, human well-being can be defined as the freedom people have to live a life they value (Abunge et al. 2013).

To capture the link between land-use changes, ES and human well-being, the 'cascade-model' proposed by Haines-Young and Potschin (2010) has become very popular. It conceptualises the link between these elements as a chain of causality from biophysical structures and processes, functions, services, benefits and values. While the model has been substantially adapted in recent years, e.g. by differentiating the causal relations and involving various feedback loops (e.g. Daw et al. 2016), it still strongly assumes a sequential causal relation between the elements mentioned. However, there is increasing evidence indicating that these links between land-use changes, ES and human well-being are more complex and multifaceted (Horcea-Milcu et al. 2016) and that ES cannot simply be equated with people's claims on land. Consequently, land system scientists have increasingly called for more nuanced understandings and for highlighting questions of land governance (Verburg et al. 2015; Zaehringer et al. 2019). Land governance relates to the norms and rules of interaction between different actors involved in land use and the resulting power relationships (Biermann et al. 2009; Graham et al. 2003; Rist et al. 2007). It encompasses land tenure, access to land, land-use decision-making, customary practices and formal and informal policies and laws. The analysis of the actors' agency is seen as particularly important as it can yield insights into who has the power to shape the future of land use (Eakin et al. 2014; Lundsgaard-Hansen et al. 2018; Westley et al. 2013).

However, although land system scientists have started to stress the need for better integration of actors' perspectives, agency and governance questions into research on land systems, there are hardly any frameworks that provide guidance for this endeavour. Indeed, studies investigating the above-mentioned aspects usually focus on individual components of the land system; for example research on land-use changes often fails to consider the actors' agency and power relationships, and studies on land governance generally neglect questions about the ecological potential that certain land uses have to provide ES. This finding also applies to land research in Myanmar. Most studies focus on individual components of the land systems such as oil palm concessions (Nomura et al. 2019), rubber sustainability (Kenney-Lazar et al. 2018), agricultural expansion (Woods 2015), ocean and land grabbing (Barbesgaard 2019), land cover shifts (De Alban et al. 2019), deforestation (Lim et al. 2017), ecosystem services (Feurer et al. 2019), human well-being (Nydegger 2018), land-use decision-making (Lundsgaard-Hansen et al. 2018) and land-use reforms (Mark 2016), but there are very few studies that link these elements.

In this article, we argue that an integrative perspective is needed to better understand how land-use changes and sustainability outcomes in terms of ES and human well-being are linked. This requires systematic integration of knowledge on land-use system dynamics and actors' agency.

To tackle this knowledge gap, we adopt the social-ecological systems framework (SESF) (Ostrom 2009). The SESF is a template for diagnosing sustainability challenges by investigating explanatory relationships between resource and governance systems linked through focal action situations. The framework has been designed to build generalisable statements for theory and policy, while recognising contextual differences between cases (McGinnis and Ostrom 2014). The SESF is one of the most widely adopted approaches to study social-ecological systems. It has been applied to understand social and ecological performance in specific land uses such as forestry and pasture land, but to date it has not been systematically applied to study land-use changes (Partelow 2018). We consider the SESF as a suitable framework for our study as it allows us to combine the systems perspective popular in land system sciences with an actor perspective highlighting actors' agencies and governance. This further enables the integration of insights from various disciplines (Marshall 2015).

To investigate the links between land-use changes, ES and human well-being, we ask two main research questions:

(a) How do actor interactions shape land-use changes?
(b) What is the role of these land-use changes for ES supply and human well-being?

Method

Conceptual Framework

As stated above, to address our research questions, we adopted the SESF introduced by Elinor Ostrom and colleagues (Ostrom 2009). At the heart of the SESF are the focal action situations in which actors make decisions and interact with each other and the concerned governance and resource systems. The governance systems define and set rules for the actors, which interact in the action situations. The resource systems involve resource units, which give inputs to the interactions. Sustainability outcomes are regarded as the result of these actor interactions. The focal action situations are embedded in the broader social, economic and political context and related ecosystems (McGinnis and Ostrom 2014; Partelow 2016).

Figure 1 shows how we operationalised the SESF for the study of sustainability outcomes related to land-use changes: Land uses such as forestry, shifting cultivation or commercial plantations are our focal resource systems. The land-use changes represent changes in the resource systems over time. The sustainability outcomes of concern in this study are ES and human well-being. These are seen as characteristics of the resource units and the actors, respectively. ES categories were identified through adapting the Common International Classification of Ecosystem Services (Haines-Young and Potschin 2018) and involve subsistence crops, commercial crops, livestock, wild plants, fuelwood, water flow, biodiversity, microclimate, educational values and cultural identity. Human well-being was understood from the perspective of Nussbaum's capability approach (Nussbaum 2011), covering the dimensions of life expectancy, bodily health, bodily integrity (e.g. free movement, security), senses, imagination and thought (e.g. education), emotions (e.g. family relations), practical reason (e.g. liberty of conscience), affiliation (e.g. non-discrimination, free speech), other species, play and control over one's environment (e.g. property rights, participation in decision-making).

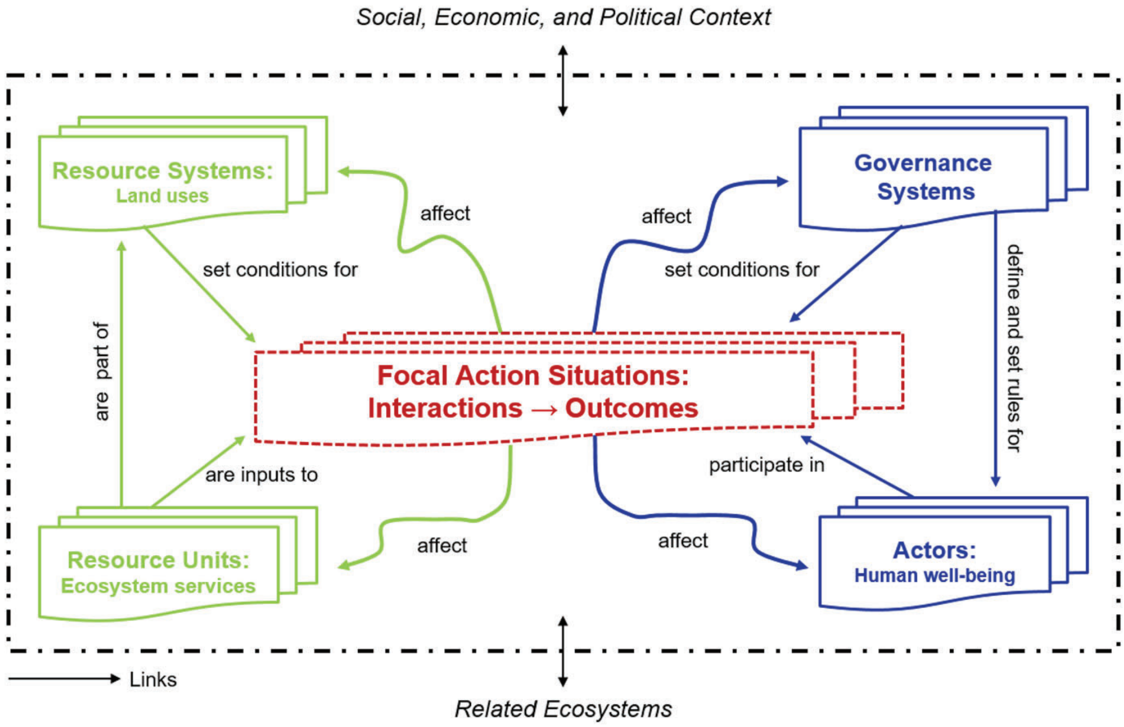

Fig. 1 Revised social-ecological systems framework adapted for the analysis of land-use changes (adapted from McGinnis and Ostrom 2014)

The links between land-use changes and sustainability outcomes in terms of ecosystem services and human well-being are mediated by the actor interactions taking place in the focal action situations. These, in turn, are shaped by the resource and governance systems and the broader context. To consider the temporal dynamics of land-use changes, we trace the actor interactions and their outcomes over the whole time period of the observed changes. By doing so, we distinguish two key phases of different context conditions: the time of the military government and the time after the transition to the new (semi-)civilian government starting in 2011/12 (Cole et al. 2019).[1]

Case Study Region

The research was conducted in northern Tanintharyi Region, southern Myanmar, in villages located in the surroundings of Tanintharyi Nature Reserve (TNR), the planned Dawei special economic zone (SEZ), the Yadana and Yetagun gas pipelines and the oil palm concessions (Fig. 2). The region was selected as it is a site where multiple actors from local to international level compete for access to land (villagers, companies, governments, ethnic minority groups, CSOs and NGOs).

Both the Myanmar government and the Karen National Union (KNU), the main local ethnic political group, claim sovereignty over parts of these areas and were

[1] As we use the framework for the synthesis of a transdisciplinary project, we use the first tier components, but not the second and third tier components defined by the SESF.

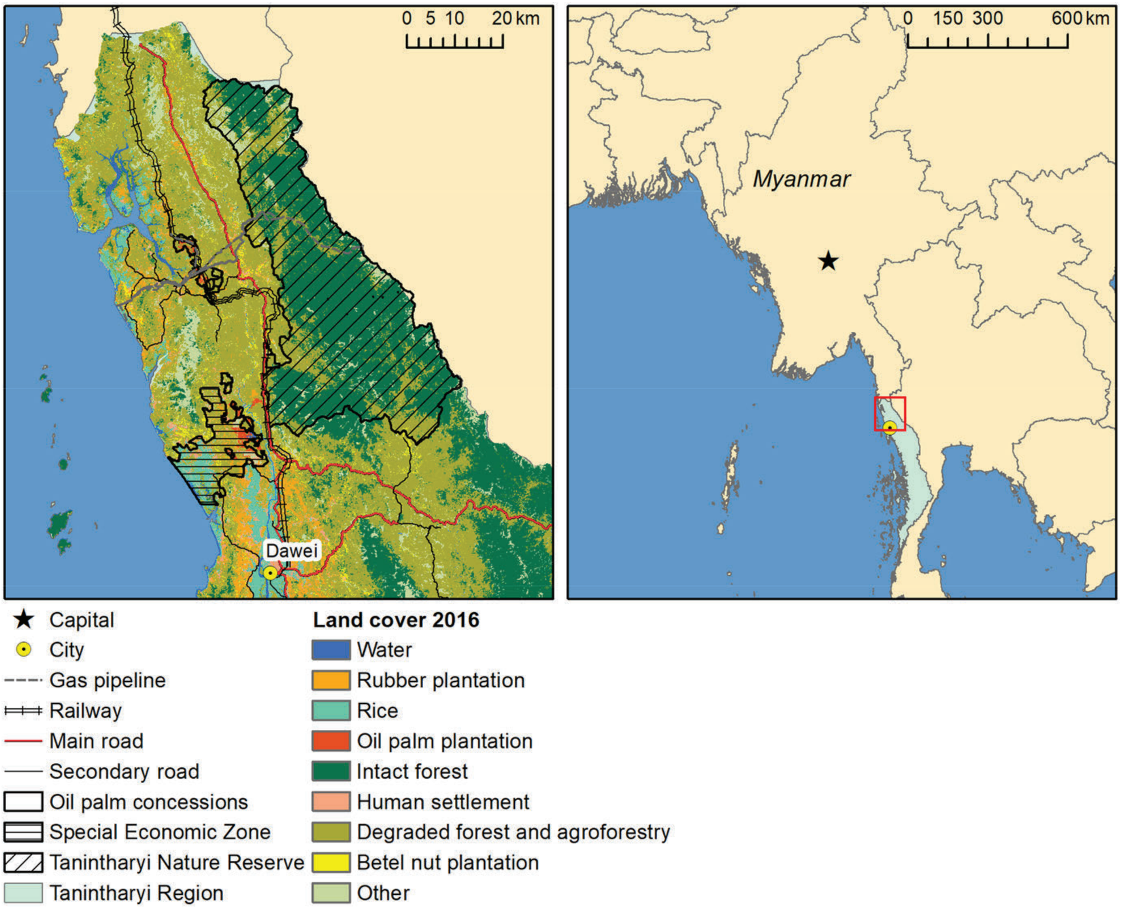

Fig. 2 Overview of study area, northern Tanintharyi Region, Myanmar. Data sources: (Schmid 2018)

involved in armed conflicts until the recent past. Many villages are located in the so-called mixed control area, and almost all villagers were in some way (involuntarily) involved in the civil war. Active fighting was most intense in the 1990s and early 2000s and came to an end with the cease-fire agreement of 2012.

Villagers are mostly farmers, but some also operate smaller businesses. They belong to the Bama, Karen or Mon ethnic groups. Due to the long-lasting civil war and the poor infrastructure, the region became quite isolated and without easy access to markets. Consequently, many villagers migrated to Thailand, although the region also experienced considerable influx of landless immigrants from other regions of Myanmar. At the time of writing, foreigners still need a special permit to visit the villages.

The specific social-ecological system constellation might be unique, considering the great diversity of Myanmar, but the multi-level multi-actor situation is also widespread in many other regions of Myanmar.

Methods

This research is the result of a synthesis effort of the project Managing Telecoupled Landscapes. The project investigated sustainable landscape management from a transdisciplinary perspective (Pohl and Hirsch Hadorn 2007); i.e. researchers from natural and social sciences worked together with societal actors involved in the issue to jointly co-produce new knowledge relevant for more sustainable development. The overall project began with a 1-year inception phase, where we established the Switzerland–Myanmar partnership and jointly framed the key features of the study. It was followed by a 3-year empirical research phase, during which researchers from different disciplines (geography, biology, environmental sciences, economics, agriculture and forestry management) implemented their methods and finally engaged in synthesis activities. The research team involved three senior researchers, two post-docs, three graduate students and four research assistants. The Myanmar senior researcher led the overall project implementation. The Swiss senior researchers and post-docs supervised the different empirical studies and the synthesis endeavour. The post-docs, students and assistants (four of them from Myanmar) designed and implemented the studies. The fieldwork was conducted in tandem by Swiss and Myanmar researchers who worked together closely. Swiss students were partly located in Myanmar (from 3 months to 3 years).

The original research that we synthesised for this article was based on a mixed-methods approach and involved interviews, surveys, focus group discussions, participatory mapping and document review conducted in a series of joint field missions. A first 2-week field mission served to select suitable case study villages, to start collaboration with villagers and to gain an initial understanding of the local situation. In this mission, we also identified the most important land-use changes from the perspectives of the villagers, which were the basis of the following research.

The later missions lasting between 1 week and 3 months were dedicated to the following research themes: land-use changes, ecosystem services, human well-being, actors and agency. Land-use changes were further investigated through a combination of high-resolution satellite imagery with participatory mapping workshops and extensive field walks with villagers knowledgeable about the past changes (Zaehringer et al. 2020). Changes in regard to ES and human well-being were analysed through 16 focus groups and 27 expert interviews on ES supply (Feurer et al. 2019), and 6 focus groups and 52 standardised interviews for human well-being (Nydegger 2018). In both cases, the assessment included elements the local villagers considered as important, how they rated the current status/development of these elements and what has influenced change over time. Issues of actor interactions, including governance arrangements, were addressed by all these methods, but in addition, specialised focus groups (9 in total), interviews with local villagers, companies, CSOs, NGOs and government representatives (92 in total) and a literature review (grey literature, policies, reports) were conducted (Lundsgaard-Hansen et al. 2018). More details on the methods used for data collection and analysis can be found in the research publications mentioned above.

To integrate the empirical knowledge generated by the different study teams, we used a dialogue method approach. Dialogue methods help structure group conversation processes that aim to ‘jointly create meaning and shared understanding about real-world problems by bringing together knowledge from relevant disciplines’ (McDonald et al. 2009, p. 5). They highlight conversation criteria such as active listening, equal participation and mutual probing of assumptions (Franco 2006;

McDonald et al. 2009). Furthermore, the empirical research products were used to substantiate the insights generated.

Hence, a key part of the actual synthesis was elaborated in a 4-day workshop by all researchers involved in the project (except two assistants). First, the researchers presented their key findings using predefined guiding questions related to the SESF components. Second, the three most dominant land-use changes (in terms of area and impact perceived by villagers) were selected based on the results of participatory mapping and focus group discussions and explored in depth. Sub-groups of researchers discussed how the actor interactions and other factors of the resource and governance systems affected the land-use changes, which actors could enforce their claims on land, what outcomes were observed and how they related to each other. The insights were visualised on flip-charts through causal loop diagrams and written down in short texts. The diagrams were then presented to and refined by the whole group. By doing so, knowledge of different participants could be collected and integrated.

After the workshop, the first author further prepared the insights generated according to the SESF and systematically reviewed all existing project outputs (including informal field reports) regarding additional insights that might have been overlooked during the workshop. This analysis was based on procedures of qualitative content analysis (Flick 2005). For each land-use change, she scrutinised the workshop documents and project publications regarding information specifying the SESF key components and their interrelations. To answer the first research question (How do actor interactions shape land-use changes?), she systematised the documented actor interactions, including the actors involved, their claims on land as well as the relevant elements of the governance and resource systems. To answer the second research question (What is the role of these land-use changes for ES supply and human well-being?), she compared the findings from the ES and well-being studies that report on the SESF outcome components resource units and actors. Based on this overview, she identified the key pathways to impact and the roles land-use changes play for ES and well-being. The findings were verified by the whole research team through several feedback rounds.

Results

This section is structured using the two research questions. Insights from the literature review are cited; all other information is based on our own empirical work.

How Actors' Interactions Shape Land-Use Changes

In the following, we investigate the action situations related to the three most important land-use changes in terms of impact and spatial extension: (1) implementation of the protected public forest TNR, (2) conversion to oil palm and (3) conversion to rubber and mixed-crop plantations.

Implementation of the Protected Public Forest TNR

Implementation of the protected public forest TNR was a contested project, mainly shaped by actor interactions involving the government's forest department, oil and gas companies, the military and the KNU—all campaigning with different claims on land. Villagers and NGOs became involved only in the later stages.

In 1996, the forest department officially recognised the TNR to conserve a recognised biodiversity hotspot based on the 1992 Forest Law and the 1995 Forest Policy, but they could not formally establish it until security and financial concerns were settled. At the time, the wider area was largely controlled by an ethnic political organisation, the KNU, which claimed sovereignty over the area and disapproved the establishment of the TNR. Forest department staff could only start to implement the protected area once the military gained control and created a 'safe' environment in the conflict area.

However, it is most likely that the military's activities were not primarily aimed at biodiversity conservation, but at control of the land in the region for economic activities and territorial sovereignty (Barbesgaard 2019; Woods 2019). In particular, they protected oil and gas companies (Total, PTT-EP, Petronas), which started to take up business in the region in the 1990s to explore and extract off-shore natural gas for export to Thailand.

Oil and gas company activity was also critical for solving the financial issues. To compensate the Myanmar government for the construction of pipelines crossing the biodiversity-rich forests (right of passage) and to tackle reputational risks—the companies have been accused of collusion in human rights abuse—they agreed to finance the TNR through a public–private partnership based on a voluntary contract (Pollard et al. 2014). According to our interviews, villagers were not involved in the decision to establish the TNR. They were only informed later in the course of the TNR implementation.

The government transition and the cease-fire agreement of 2011/12 influenced the TNR-related focal action situation in two ways. First, the improved security situation allowed the forest department to further implement the TNR rules at the western park boundaries, thereby strengthening the claim for conserving biodiversity. For patrolling the deeper forest, however, the TNR rangers need to coordinate their patrols with the KNU as a matter of respecting the cease-fire agreements, because at the present time, the KNU still holds sole control over large parts of the TNR area including several Karen villages that lie within the protected area. Having their own perspectives on sustainable land management (2015 Land Use Policy), the KNU does not accept the TNR rules defined by the Myanmar government and continues to allow the use of the area for subsistence and commercial crop production. Second, community rights, already formally established in the 1995 Forest Policy, became more widely known and implemented. In 2013, an international NGO aiming to empower local people for community-based sustainable forest management started to support the villagers in applying for community forestry certificates. These certificates allow for communal uses for 30 years, and since a law revision in 2016, also for minor commercial uses.

Conversion to Oil Palm Plantations

The conversion from forest, shifting cultivation and perennial plantations of cashew and other crops to oil palm monoculture was mainly driven by the former military government's self-sufficiency policy and palm oil companies' business interests (crony companies and smaller regional companies). It was highly disapproved by other actors such as local villagers and the KNU. Further actors such as the regional government, CSOs and foreign aid providers became relevant in recent years.

The self-sufficiency plan was intended to reduce the country's dependency on imported products and to satisfy the increasing demand of the domestic population for cheap edible oil (Woods 2015). To implement this plan, the government granted oil palm concessions to crony companies. Our research shows that, in most cases, villagers were not involved in the oil palm development and had resentments against the companies. Being extraordinarily poor and heavily affected by still ongoing military oppression, villagers often did not dare to oppose the companies because they were afraid of their relationship with the military. The KNU also strongly disagreed with the oil palm expansion, but they could not stop the development either due to the military's superior power. In some other cases, smaller regional companies or entrepreneurs applied for small- to medium-scale land-use permits to establish an oil palm business of their own accord. In these cases, the companies and local villagers usually respected each other's activities.

The government transition of 2011 brought one new development to the oil-palm-related action situation. In 2016, the Regional Chief Minister created multi-stakeholder platforms (MSP) that aimed to review the oil palm concessions and to redistribute uncultivated land. The MSP is facilitated by the foreign aid and central government supported OneMap project. The MSP has—for the first time since the outbreak of civil war many decades ago—brought actors from different societal factions to one table: government representatives of various departments, palm oil companies, CSOs, village representatives and the KNU. While concessions have been revoked in a few cases, the multi-stakeholder process is highly challenging due to the multiple claims of the actors involved and currently seems to be blocked. This might also be an indication that the former power relationships still largely persist (for more information see Bächtold et al. in this special issue).

Conversion to Rubber and Mixed-Crop Plantations

The Myanmar government also played an important role in the conversion to rubber monoculture and mixed-crop plantations (mainly cashew and betel nut but also other crops such as lime or cacao), but in contrast to the other two land-use changes, villagers and smaller regional companies and entrepreneurs from nearby towns also played a key role in and welcomed the conversion.

Once the most severe phases of the civil war with food insecurity, lack of transport and market access, as well as widespread violence had subsided, local communities started to complement their subsistence-oriented farming activities with commercial activities to increase their income and satisfy their livelihoods. But it was only in around 2005/2006 when the Myanmar government pushed the rubber market in the context of their 2000–2030 Master Plan for the Agriculture Sector and abolished the government quotas that increasing numbers of villagers and entrepreneurs from nearby towns engaged in the business—until then, 45% of private harvest was reserved for the government (Woods 2015). Entrepreneurs were attracted due to the great promise of the crop (it was perceived as 'white gold', even though it did not turn out as such later) and the easy access to land. Unlike oil palm, rubber was not regulated through concessions but through different mostly customary land rights and the KNU land policy. Entrepreneurs generally accepted these rights and policies. Some villagers acted as land brokers and unofficially organised the land deals. As a consequence, within only a few years, land turned into a pricey and scarce resource.

The government transition of 2011 fostered a veritable production boom, through which shifting cultivation was mostly abandoned (at least in the government-controlled areas). This was for two reasons: first, the decrease in armed conflicts enabled the villagers to regain mobility as they could access their plots and the market places again due to better security; second, the legal reforms replacing the customary-dominated land tenure system with formal land certificates created a legal land market (Kenney-Lazar et al. 2018; Woods 2015). Land users can obtain land use certificates (e.g. Form 7) if they can prove that they cultivate crops on their land. This encouraged many villagers to convert shifting cultivation systems into permanently cultivated cropland. Moreover, it is likely that entrepreneurs from nearby towns were motivated by rubber not only as a valuable commodity, but also as a land-claiming strategy in the context of land speculation against the background of the announced Dawei special economic zone strongly promoted by the governments of Myanmar and neighbouring countries. Indeed, only a few rubber plantations are professionally managed and none of the actors interviewed had succeeded in producing good-quality rubber or achieved a satisfactory income from rubber.

The Role of Land-Use Changes for ES and Human Well-Being

ES Supply and Use

The analysis of local actors' perspectives showed that, compared with the 1990s, when the landscape in northern Tanintharyi was dominated by forest and shifting cultivation, today, the supply of many ES have declined while a few have increased (mainly commercial crops such as rubber, cashew, betel nut and lime). The general decline in the supply of regulating ES such as biodiversity, water flow and regulation of microclimate, as well as a decline in the provisioning of wild plants, fuelwoods and livestock can be explained by an overall loss of intact forest landscapes. Hence, it is directly attributable to the changing resource systems. But in other cases, new rules and regulations have narrowed villagers' access to and use of ES in the remaining forests and also in company-owned oil palm plantations. Thus, the decline in ES supply is not only the consequence of the changing resource systems, but of the changing governance systems too.

The three land-use changes played different roles for ES supply and use. In the case of the TNR implementation, many regulating ES could be maintained through protecting the forest and vulnerable ecosystems. Forest cover is clearly higher within the TNR than outside, but satellite images also show various signs of logging and crop production activities inside the protected area, pointing to the fact that deforestation could not be stopped completely (Pollard et al. 2014). Provisioning ES related to subsistence use are also often still available, but due to the TNR regulations, they cannot be readily accessed any more by the local communities along the western boundary—with the exception of some community forest areas.

ES trade-offs caused by land-use changes are most pronounced for the conversion of forests to oil palm plantations, as their chemical-intensive management has particularly negative consequences for many regulating ES, such as water flow and biodiversity. Additionally, access to provisioning ES from oil palm plantations, such as firewood and livestock, are socially differentiated. While many villagers do not have access to them due to company regulations, company-related actors such as (mostly migrant) plantation workers do. The only ES that increased is commercial crop production for the companies. But, ironically, despite Tanintharyi Region being the most suitable region for oil palm cultivation within Myanmar, the climate and environmental conditions are not appropriate enough for effective oil palm production and yield. Thus, palm oil companies cannot compete with those in Malaysia and Indonesia. Consequently, the established oil palm plantations are not very profitable and the actually planted areas are often much smaller than the granted concessions.

The conversion from forest to rubber and mixed-crop plantations decreased the overall supply of ES, but it substantially increased the provisioning services of commercial and subsistence crop production. The cultural services also shifted. Having strong connections with nature, local communities attribute many cultural ES to forest ecosystems. But also shifting cultivation is deeply embedded in their culture, and more recently, they started to assign cultural values to rubber and mixed-crop plantations (e.g. betel nut) as they allow them to generate income and acquire a different way of life. Consequently, considering the conversion of forests/shifting cultivation into rubber or mixed-crop plantations, trade-offs between different ES seem almost balanced in the perspectives of local communities. Villagers can obtain more income from commercial crops as a solid and diversified subsistence base (except for rice). Nevertheless, while interviewees generally accepted a slight decrease in biodiversity, climate regulation and cultural services, limited water supply, which is affecting agricultural production and human well-being most directly, was considered at risk if forests in important water catchment areas are cut down.

Human Well-Being

According to the perspective of the villagers, the human well-being situation has generally improved since the land-use conversions started in the 1990s—but not necessarily to satisfactory levels and not for all people. Elements that improved included, in particular, life expectancy, bodily health including nutrition, bodily integrity including housing and security, options for education, free speech and living together as a family, as well as the capability to control their environment through access to land and income opportunities. However, many people still live under adverse conditions and struggle with basic livelihood issues. They also deplored lost access to land, water and forest resources.

The changes in human well-being can partly be explained through the changes in the land-use-related resource systems and ES. For example, deforestation reduced the water flows, which negatively affected crop production and drinking-water quality, which again negatively affected well-being related to human health and nutrition.

In many other cases, however, human well-being dimensions were improved or worsened through changes in the land-use-related governance systems (e.g. new use regulations) or the broader social, economic and political context. In particular, interviewees often highlighted the significance of the ending of the civil war. During the war, where the military and the KNU were fighting for sovereignty over the region to implement their claims on land, people heavily suffered and were deprived of many basic capabilities needed to lead a good life. They regularly had to hide in the forest, plantations were destroyed, public services such as clinics and schools were scarce, and free movement was impossible due to fighting, movement control, lack of infrastructure such as roads and few motorbikes and cars. Human rights violations were also reported. It was particularly challenging for the Karen villages, which suffered heavily from the military's counter-insurgency activities. Hence, once the immediate violence threatening people's lives and bodily integrity stopped, they could take up again basic activities such as accessing and cultivating their fields, visiting relatives and friends and the construction of infrastructure, such as roads, transport and electricity.

Investigation of how well-being was affected by the three land-use changes revealed diverse outcomes. The TNR implementation affected, in particular, villagers at the western park boundaries, as they were officially prohibited to use various forest-based ES. While villagers benefiting from commercial crops could compensate this loss more easily, people not owning land were affected more strongly. When the community forestry rights became more widely known and implemented through the help of an NGO and the TNR management itself, the situation started to improve again (but the community forestry products are still not ready to be harvested).

Conversion to oil palm plantations heavily affected the well-being of the people using these lands. While most concessions of crony companies were granted on land that official records classified as so called 'waste land' or reserved forest land, i.e. land that is officially not used for agricultural activities, interviews revealed that these lands were in fact often claimed by villagers for subsistence and commercial crop production, grazing or collection of wild plants or firewood. Hence, as a consequence of the oil palm concessions, villagers lost their lands and thereby their capability to achieve various land-based well-being dimensions such as nutrition, participation in the community life and control over their environment. Moreover, human rights violations have been reported.

Conversion to rubber and mixed-crop plantations, which were co-driven by the local communities' struggle to generate income opportunities, led to an overall increase in human well-being, despite an overall decrease in ES. While most ES decreased, commercial crop production increased and thereby the villagers' financial resources. As a consequence, people could substitute benefits they formerly received from the environment with other products. For example, while forest products such as fuelwood, timber, wild food and medicine became scarcer, people started to use concrete and metal to build their houses, and they were able to buy medicine and food on the market. This might also be the reason why we could not observe extensive negative effects from giving up subsistence rice production: villagers usually obtain enough money from the sale of their commercial crops and have a secured access to markets to buy rice.

Moreover, the increasing rush on land due to all three land-use changes has intensified land scarcity. Consequently, there is a widespread fear among villagers of losing their land or not being able to extend their agricultural fields for new family members due to the general land-rights insecurity. As work and income opportunities of local communities are still strongly based on agricultural activities, not owning land is a major challenge and affects many well-being dimensions.

Discussion and Conclusion

Our research aims to explore the link between recent land-use changes and sustainable development in Myanmar through an interdisciplinary synthesis effort. In particular, we investigated how actors' interactions shaped land-use changes and the role of these land-use changes in ES supply and human well-being in northern Tanintharyi. The generated results contribute to ongoing wider developments of middle-range theories in land system science (Meyfroidt et al. 2018), as well as to identify pathways for more sustainable development in Myanmar.

Contributions to Middle-Range Theories Linking Land-Use Changes, ES and Human Well-Being

Adopting the SESF as an analytic lens to study how land-use changes translate into ES and human well-being, we found that, until the 1990s, the action situations around land in northern Tanintharyi were shaped by local villagers and their ethnic organisations, who claimed the forested land for subsistence use and maintenance of their livelihoods and identities, mostly in shifting cultivation systems. Since then, increasing numbers of other actors from regional to international level have entered the action situations (different entities of the central and regional government, companies, NGOs and CSOs), leading to three main land-use changes: (1) implementation of the protected public forest TNR, (2) conversion to oil palm, and (3) conversion to rubber and mixed-crop plantations. Shifting cultivation for subsistence rice production has been widely abandoned, and larger areas of intact forest can only be found in the TNR and along the border with Thailand. These results confirm findings of other recent land-use-change studies in Myanmar (De Alban et al. 2019; Lim et al. 2017; Woods 2015).

The land-use changes investigated were driven by different actor constellations. Their claims on land were shaped by heterogeneous commercial, conservation and political interests. Depending on the actors' agencies and prevailing power relations, some actors were more successful than others in implementing their claims. While local communities played an active role in the conversion to rubber and mixed-crop plantations, decisions on the two other changes—implementation of the protected area TNR and conversion to oil palm plantations—were mainly taken by powerful actors at places and scales beyond the local systems (in particular, national and international companies and the former military government), making it difficult for villagers to realise their own development aspirations.

But consequences for ES and their link to human well-being are complex and multifaceted. While the three land-use changes resulted in a decline of many ES, in particular regulating services such as biodiversity and water flow, overall, human well-being improved for many people—though not for all.

Hence, our empirical research challenges models that relate land-use changes, ES and human well-being in a linear way, in particular, the widespread belief that deforestation will lead to a decline in the well-being of people due to a decline in ES supply (Raudsepp-Hearne et al. 2010). In contrast, we found that multiple ways exist to explain the relation between land-use changes, ES and human well-being.

Referring to the SESF, they can be divided into three different pathways to impact. The interactions between specific actors are key in all of them, but depending on the action situation, the characteristics of the resource systems, the governance systems or the broader social, economic and political context are decisive for their outcomes. For example, deforestation leading to a decrease in ES supply of wild plants and livestock, which in turn decreases human well-being of dependent villagers, can be understood as a change in the resource system leading to a change in the resource units (ES) involved, which in turn negatively effects the well-being of certain actors.

However, whether this change effectively translates into negative well-being impacts depends on the agency of the actors involved and the ruling governance system. In general, we observed that positive well-being effects were more likely in cases where villagers could co-drive the land-use change and thereby enforce their own claims on land. For example, deforestation for mixed-crop plantations often decreased overall ES supply but increased commercial crops. As a consequence, villagers having use rights for these lands can substitute benefits they formerly received from the forest with other products. This decoupling of ES and human well-being is a trend that has often been observed in countries of the Global North (Horcea-Milcu et al. 2016), but also seems to be relevant for countries of the Global South (Urech et al. 2015). People tend to adjust valuations of some services over time. Valuations of ES are changing with the peoples' changing needs, expectations and interactions with nature. Thus, future research on the link between land-use changes, ES and human well-being must reflect on a more constructivist and less positivist logic (Raudsepp-Hearne et al. 2010; Urech et al. 2015).

Moreover, in many cases, it is not the land-use changes and related ES that influence human well-being, but the broader socio-political processes involved in the land-use competition. Indeed, the termination of the active fighting between the Myanmar military and the KNU and the activities of the oil and gas companies might be the main reasons for the increased well-being of the local communities. The peace agreement ended more than six decades of civil war that undermined human well-being, and it created favourable conditions for local communities to engage in agriculture or other economic development. The complex ways armed conflicts can influence land-use changes and human well-being have also been raised by Baumann and Kuemmerle (2016), but despite the significance of the topic, it represents an underexplored topic in land system science.

Implications for Sustainable Development

Since the government transition starting in 2011/12, several windows of opportunities emerged in northern Tanintharyi Region, in particular allowing people to re-engage in economic and political activities, lead a life in peace and furthermore increase their well-being. However, current social, economic and political developments dominated by market liberalisation and the opaque power situations in place including the unclear role of the military today, also raise questions regarding future sustainable development. It currently seems that economic claims on land and interests of national and international investors are clearly valued more highly than local villagers' interests and customary rights on land (Franco et al. 2015; KHRG 2018; Mark 2016). This is reflected in the recent 2018 revision of the controversial Vacant, Fallow and Virgin Land Management Law, where the opportunity to strengthen community land rights was overlooked in favour of an strengthened process of market liberalisation (41 INGOs and CSOs 2018), and in the stagnating palm oil concession redistribution process (Bächtold et al. same special issue).

Moreover, considering the projected continued deforestation rates and the related decline in ES, it is unclear whether and to what level human well-being can continue to improve in the future, in particular as regulating services such as water flows and biodiversity are much less likely to be substituted (Raudsepp-Hearne et al. 2010). This is relevant in particular because land is becoming increasingly scarce.

Fostering land-use management that is favourable for the well-being of local communities and maintenance of ES in the long term—a precondition for implementing the 2030 Agenda as well as the Myanmar Sustainable Development Plan—is a truly challenging task. Our findings related to the three pathways to impact point to four priority areas of concern:

- Considering the key role the armed conflict between the Myanmar government and the KNU played in land-use changes, sustained peace might be the single most important factor enabling local communities to enhance human well-being. Moreover, to protect ES in the whole region—inside and outside of the TNR—enhanced peace dialogues between the Myanmar government and the KNU must include land-use issues. But sustained peace in itself might not stop ongoing deforestation processes.
- Therefore, strong land-governance arrangements need to be negotiated, simultaneously strengthening ES proliferation and human well-being. These can include

measures that foster ES and human well-being in the same areas, e.g. community forestry or sustainable mixed-crop plantations, but might also include measures that fully protect intact forests in certain areas, while fostering profitable commercial crop production in others, e.g. professionalisation of rubber production. Moreover, to reduce livelihood dependency on land, the creation of alternative, not-land related or exploiting income opportunities must be developed.

– But today, peoples' livelihoods still strongly depend on land, so securing local communities' access to land is key. Land insecurity also increases the risk of deforestation (Robinson et al. 2014). However, land titling is no panacea. It might also cement existing or produce new inequalities, rendering the villagers even more vulnerable, because—in times of crisis—they might sell their land for short-term money, having less land afterwards (Dwyer 2015).
– However, negotiation and implementation of more promising land-governance arrangements also require broader transformations, namely regarding government accountability and know-how, hidden power relationships between dominant actors from businesses, government and other powerful actors such as the military, as well as widespread societal phenomena related to established fear, mistrust and prejudices towards other actors and ethnic groups.

In short, taking into account the three pathways to impact between land-use changes, ES and human well-being, we argue that future research should deepen the understanding of actors' agencies and power relationships related to land-use changes, including the role of the armed conflict (Woods 2019). Moreover, more emphasis should be placed on what practices and leverage points might effectively foster fundamental transformations of the current social-ecological systems towards more sustainable development.

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Compliance with Ethical Standards

Conflict of Interest All authors declare that they have no competing interests.

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Paper IV: Quantifying local ecosystem service outcomes by modelling their supply, demand and flow in Myanmar's forest frontier landscape

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ARTICLE

Quantifying local ecosystem service outcomes by modelling their supply, demand and flow in Myanmar's forest frontier landscape

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ABSTRACT
In complex tropical forest frontier landscapes, ecosystem service (ES) models are essential tools to test impacts of different land schemes on people. Considering several factors of supply, demand and flow and focusing on local stakeholders, we developed nine ES models using Bayesian networks and applied them in different land scenarios in Myanmar's Tanintharyi Region. We found land use and tenure as well as demand for specific products to be the key factors determining final ES outcomes. While forested lands have high regulating and overall balanced ES bundles, mixed agricultural lands provide subsistence and commercial products as well as better environmental education opportunities. By contrast, commercial agricultural concessions strongly limit ES outcomes for local communities. As our models reveal more distinct impacts of land policy scenarios in a homogeneous setting, where demand is better accounted for, we recommend their use for spatially explicit analyses of forest frontier landscapes.

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Introduction

Nature, as part of both natural and anthropogenic landscapes, contributes to people's lives in various forms. The impacts of its changing use are particularly evident in tropical forest frontiers, where remaining forests face pressure from agricultural development. While intact forest landscapes provide a disproportionately high amount of ecosystem functions including carbon sequestration and water regulation (Potapov et al., 2017), commercial agriculture increases income in areas with good market access, and multifunctional land uses enhance livelihoods and adaptive capacity of rural communities (van Vliet et al., 2012). In a multifunctional tropical forest landscape, mixed policies supporting both land sparing and land sharing were suggested as most effective for achieving multiple ecosystem services (Law et al., 2017). However, as valuation of and comparison between these services remain challenging, they are often neglected in policymaking (Pandeya et al., 2016).

In this context, the conceptualization of ecosystem services (ES) has gained attention in research and policy (MEA, 2005). The ES framework describes how ecological structures and processes lead to benefits and values for human well-being (Groot et al., 2002). ES *supply* thus refers to the goods and services provided by a landscape, whereas ES *demand* refers to people's use and perceived value

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thereof. Services can be supplied both by natural ecosystems or man-made landscapes (Potschin et al., 2016) and therefore both must be considered. *Demand* is defined as 'the amount of a service required or desired by society' (Villamagna et al., 2013). In addition, ES *flows* determine whether services can be accessed and thus used by society. Flows can be seen as the spatial movements of ecosystem-derived materials and other services from a providing to a benefiting area or actor (Schröter et al., 2018), leading to actual service production and use (Schirpke et al., 2019; Vallecillo et al., 2019; Villamagna et al., 2013). In this study, ES flows are understood as people's access to services based on various enabling conditions including biophysical, spatial, social and political factors.

Modelling approaches to ES emerged around ten years ago but face several challenges, including high complexity and poor measurability (Landuyt et al., 2013). While most ES assessments use one indicator for each service, modelling approaches usually contain a variety of factors and indicators. ES research has strongly benefited from emerging frameworks at landscape scale such as the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) (Sharp et al., 2020) or the Artificial Intelligence for Ecosystem Services (ARIES) (Villa et al., 2014), which aim to standardize assessments. While InVEST uses biophysical data and provides output maps in biophysical or economic terms, ARIES uses several underlying process models to produce benefit flow maps showing sources and beneficiaries of ES. Even though both frameworks are valuable for standardized land use planning, disadvantages include the pre-determined services with few cultural services included, moderate transparency, weaknesses in incorporating spatial demand and limited overall ability to account for qualitative data (Bagstad et al., 2013; Sharps et al., 2017; Vigerstol & Aukema, 2011). A promising approach to ES modelling is the use of Bayesian networks (BN) with underlying conditional probabilities as described by Aguilera et al. (2011). A key feature is that they operate with probabilities, which is expedient especially for models where results are expressed in values. A further advantage is the possibility of integrating different types of knowledge sources such as biophysical data, expert and local knowledge and earth observation data, particularly in data-scarce regions. BN have thus become a popular technique to model ES and predict supply within a landscape (Burkhard & Maes, 2017). With regard to indicators, different BN studies used water availability, farming practices (Dang et al., 2019), land cover (McVittie et al., 2015) or topography (Grêt-Regamey et al., 2013) for supply; presence of people (Stritih et al., 2018), rural population (Kleemann et al., 2018) or available substitutes (McVittie et al., 2015) for demand; and distance to road (Grêt-Regamey et al., 2013) or government permissions (Smith et al., 2018) for flow. But, until now, most models have remained limited either in terms of scale (small study area or focus on one ecosystem), ES types (provisioning, regulating, cultural), dimensions for ES outcomes (supply, demand, flow) or number of indicators thereof, due to the complexity of socio-ecological systems as well as limited data availability (Schirpke et al., 2019). Nevertheless, developing complex models with several input factors influencing ES supply, demand and flow are necessary for examining underlying mechanisms. Subsequently, demonstrating potential model applications to identify options for enhanced ES bundles in a landscape is just as important in view of policy development.

The identification of key factors that have a positive leverage effect on multiple ES is particularly important in forest frontier contexts with competing claims on land and its products and services. In Myanmar's Tanintharyi Region, cropland expansion into primary and secondary forests is driven by private rubber plantations and oil palm concessions (de Alban et al., 2019; Zaehringer et al., 2020), which often conflict with traditional land rights or the boundaries of the permanent forest estate (Woods, 2016). Only few people benefit commercially from such agricultural expansion. Furthermore, conservation efforts in the same region aim to maintain biodiversity and other globally important ES (Pollard et al., 2014). As shown by Feurer et al. (2019), because of these land use changes in Tanintharyi, landless people and smallholders have lost access to locally important products and services and gained only few economic opportunities. Impacts were especially negative where these land use changes were connected to tenure insecurities and disputes limiting their access to land and corresponding ES. Nevertheless, people were often able to adapt to diminishing ES supplies by substituting certain products, lowering their demand for a certain service and reducing their dependence on nature. These dynamics underline the necessity of analysing multiple factors to predict ES outcomes and identify promising scenarios for local communities to benefit from natural and human-made landscapes, both at local and at regional scale.

The present study addresses these issues by developing comprehensive models for supply, demand and flow of nine ES in Tanintharyi Region. We identified key factors with a leverage effect in forest frontier landscapes and tested them in scenarios at a regional scale (Tanintharyi Region) with a highly heterogeneous landscape and at a local scale with a homogenous forest landscape. The study was guided by the following research questions:

(1) What are the key factors that influence the supply, demand and flow of nine ES?
(2) Based on the models, what are the ES outcomes for local stakeholders across Tanintharyi Region?
(3) How do the ES outcomes change according to agricultural and forest-based scenarios at regional and at local scale?

To conclude, we discuss the potential of the developed models to inform policymakers of optimized ES outcomes considering supply, demand and flow at different spatial scales.

Materials and methods

Study area

Tanintharyi Region in southern Myanmar is a long stretch of land located between the Andaman Sea and Thailand (Figure 1). It extends over a total area of approximately 4.3 million ha and is a forest frontier landscape including intact dipterocarp forests with high biodiversity value in remote hilly areas, degraded primary and secondary forests, and an increasing number of agricultural plantations in the more populated areas (Bhagwat et al., 2017). Some of the forest lands are used for shifting cultivation by local communities, whereas others are protected areas. The predominant perennial crops are rubber, betel nut and cashew. In addition, almost 800 000 ha of oil palm concessions have been allocated to companies in the past 20 years (Woods, 2016). A second important landscape context in Tanintharyi is the coastal stretch including archipelagos in the Andaman Sea. This area is mostly covered with mangroves and people's main livelihood is related to fishery. Between the two landscapes there is a stretch of flat land mainly used for paddy rice production.

Spatial zoning is an important regulating element in terms of land use and land tenure in Myanmar. Zoning broadly distinguishes between areas under the responsibility of either the General Administration Department (GAD) or the Forestry Department (FD). Under both departments, there are several land uses and tenure systems. In Tanintharyi, spatially explicit data are available for the following zones: (forest) protected areas, community forests (CF), oil palm concessions, mining concessions and the special economic zone (SEZ), which is reserved for infrastructure development and a planned deep sea port. The remaining area is under the control of either the FD or the GAD. If under the FD, it can be managed forest (permanent forest estate) or agricultural land where farmers pay annual taxes to the FD. If under GAD regulations, it can be settlements or croplands, which are either under customary land tenure or registered with land use certificates. Tanintharyi has three urban centres and a total population of 1.4 million people (DOP, 2014), with most of the villages concentrated along the main road. The forested hills near the Thai border are only sparsely populated.

Major challenges for sustainable development in Tanintharyi Region are posed by the different claims on natural resources from various actors. While private investors and companies are engaged in timber exploitation, large-scale agricultural plantations, mining or aquaculture, local communities use the land for planting perennial crops, vegetable gardens or rice. On agricultural land, the number of smallholder land use certificates has strongly increased in recent years (Lundsgaard-Hansen et al., 2018). In some forest areas, including mangroves, CF have been established to give formal user rights to communities for 30 years (Feurer et al., 2019). These contrasting developments influence the provision of ES and rural communities' access to them. At the same time, infrastructure improvements after the civil war have increased job opportunities, facilitated market development and improved access to imported foods,

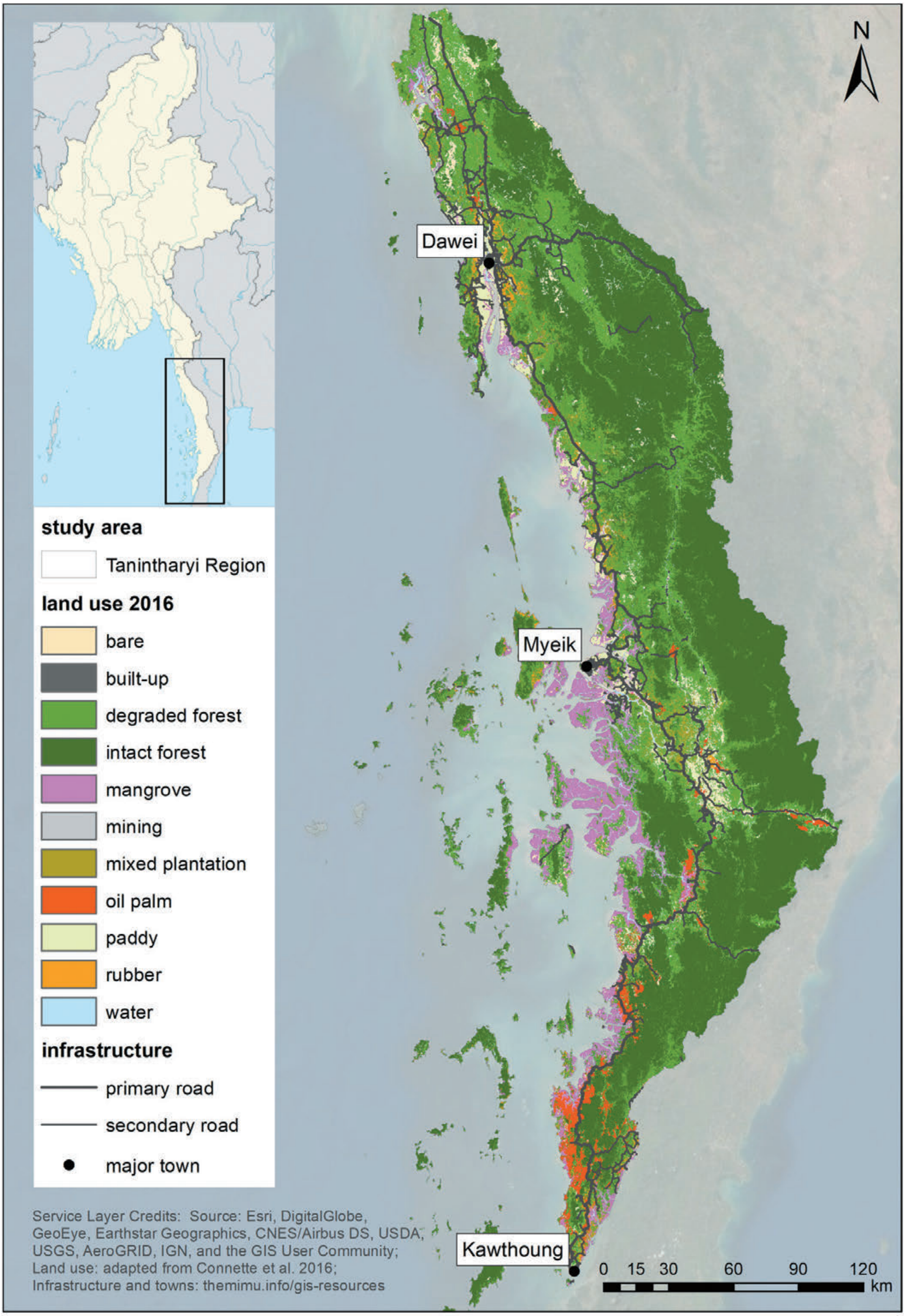

Figure 1. Overview of the study area and land use (Connette et al., 2016) in Tanintharyi Region, Myanmar, in 2016.

modern medicine and other goods, thus reducing people's dependence on nature and changing their demand for ES.

Theoretical framework

This study used a framework touching on different prevalent concepts in ES research. It is based on the common notion that ES are only achieved when (i) there is a potential 'supply' from the ecosystem or land use and its underlying processes and functions, and (ii) there is a 'demand' and people benefit directly or indirectly (Burkhard & Maes, 2017; Groot et al., 2010; Mouchet et al., 2014). Taking into account the difference between potential and actual supply and demand, we added 'flow' as a precondition for final outcome (Schirpke et al., 2019; Schröter et al., 2018; Villa et al., 2014; Villamagna et al., 2013). We use the term 'outcome' similarly to 'ES benefit' in Villa et al. (2014) and analogous to other studies (Dade et al., 2019; Mace et al., 2012; Olander et al., 2018) to describe final ES that are not only potentially provided (supply) but also enabled (flow), desired and used (demand). We thus assume that for assessing final ES outcomes, models need to include three aspects: ES supply, ES demand, and ES flow (Figure 2). In this study, all ES models followed this principle. On the supply side, our starting point was land use under consideration of local management practices. Our focus was specifically on local stakeholders.

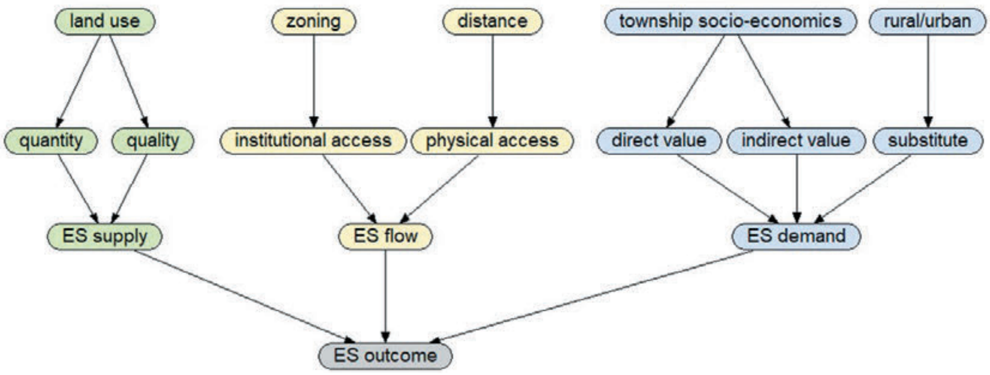

Figure 2. Theoretical framework and basic structure for ecosystem service (ES) model development; diagram produced using Netica (version 6.05).

ES classification and selection

Aiming to cover all ES types (provisioning, regulating, cultural), we selected ES based on classes from the Common International Classification of Ecosystem Services (CICES) (Haines-Young & Potschin, 2018), adapting them to the local context. Selection was done in several steps including a literature review and focus group discussions with local land users in three villages in northern Tanintharyi that together cover all relevant land uses, zones as well as three ethnic groups (Burmese, Karen, Mon). Finally, we chose nine ES (Table 1) according to the following criteria (in this order): link to dominant land uses, relevance for rural communities (based on a ranking exercise in three villages with 20 community members each), suitability (including secondary data availability) for modelling, and relevance for policymakers (literature-based). In this study, biodiversity – sometimes conceptualized as underpinning other services, as conflicting with them or as a service itself (Mace et al., 2012; Schröter et al., 2016) – was considered a regulating service and defined accordingly (Table 1).

Table 1. List of nine selected ecosystem services and description.

Ecosystem service		Description
Provisioning	Subsistence foods	All crops, wild foods, meat and fish used for consumption in the household, for guests or for religious ceremonies
	Commercial products	All products from nature used for income generation (including timber, non-wood forest products, cash crops, meat and fish)
	Fuelwood	All plant parts which are used for cooking fuel, either as fuelwood or as charcoal
	Medicinal plants	All wild plants with known medicinal properties
Regulating	Biodiversity	The diversity of animals, plant species and varieties including agrobiodiversity, related products and pollination services
	Climate regulation	Regulation of microclimate and global climate including carbon sequestration
	Water regulation	Regulation of water flow including associated services such as clean water supply
Cultural	Environmental education	The contribution of nature to education, environmental and agricultural knowledge generation and exchange
	Cultural identity	The contribution of nature to cultural identity, including cultural products supplied by different land uses

Bayesian (belief) networks and software

Bayesian (belief) networks (BN) as probabilistic models based on causal dependencies (Kjærulff & Madsen, 2008) were chosen for their ability to include different knowledge types and demand factors in data-scarce regions (Burkhard & Maes, 2017). This seemed relevant as we focus on locally relevant ES. Our BNs include root nodes (input variables without parent nodes), several levels of intermediary nodes (structuring the BN) and end nodes (output variables). All nodes possess discrete states (possible values) and are linked to other nodes with arrows showing causalities. A child node has causal dependency on its parent node(s). Relationships are defined by conditional probability tables (CPTs). ES models in this study were implemented using the commercial software Netica (version 6.05) for constructing and analysing BNs.

Model development

We developed nine ES models following an iterative process using several steps (Pollino et al., 2007) in three main phases: (a) defining model structures with nodes and states, (b) populating and parameterizing CPTs, (c) validating final models. An overview of these phases in model development is given in the next three paragraphs. Appendix I describes all steps in detail.

For each model, the first step was to develop the structure, including root, intermediary and end nodes as structuring elements and following the theoretical framework (Figure 2) using the Delphi-method (Okoli & Pawlowski, 2004). We first did a literature review and subsequent individual interviews with 15 experts from various institutions (including non-governmental organizations, civil society organizations, research institutions and governmental bodies) active in the study area. After findings were consolidated into draft structures, a set of discrete states was defined for each node based on recognized classifications or combined information from literature and expert interviews. In the end, all nodes and states were verified through follow-up interviews discussing the printed model structures with the above-mentioned experts and village representatives (final model structures in Appendix II, Figures A2–A10).

After finalizing the structure, we parameterized each model by populating and calibrating the CPTs differently according to the type of node using both secondary data (GIS layers, census data, literature review) and primary data (interviews, survey, field observations). Specifically, we used spatial data for the root nodes and population census data for twenty nodes connected to the 'township' root node. For intermediary nodes, we elicited rules (Appendix III, Table A2) based on triangulated data from field observations during a total of three months between 2017 and 2020, the 15 expert interviews taking place over three weeks in 2019, as well as reflections stemming from a comprehensive literature review. Thirteen nodes were subjected to a household survey (n = 40) using a standardized questionnaire (Appendix IV), asking, e.g., 'Do you trust in herbal medicine?' The distribution of responses (e.g., 93% 'yes', 7% 'no') was set as conditional probability for the respective node. For the nine continuous end nodes ('ES outcome') discretized into five states, we elicited rule-based CPTs under consideration of existing ES concepts (Groot et al., 2002; Schirpke et al., 2019; Villamagna et al., 2013) and a standardized survey with 12 additional experts using values of supply, demand and flow of ES. These experts had a scientific background and were familiar with ES and natural resource use in the Southeast Asian context. Resulting from this, the final 'outcome' was defined as the average score of its parent nodes 'supply', 'demand' and 'flow', with uncertainties accounted for through additional probabilities within the range of the minimum and maximum values of each of parent node.

Finally, we administered two validation approaches. As suggested and described by Kleemann et al. (2018), we applied first an extreme-condition test to confirm the operational validity of each parameterized model checking model outputs given most extreme inputs. Secondly, we conducted a face validity test with the 12 scientific experts. Based on a standardized survey including illustrations of the model structures, the experts had to rate the conditional score for supply, demand and flow of each ES based on the direct parent nodes or, where needed for contextual reasons, the parent nodes to those. On average, expert ratings were 5.2% lower than model values across all ES (Appendix V). The highest differences were found for medicinal plants (−14.7%), climate (−11%) and water regulation (−10.4%). Generally, experts gave lower values for supply (−8.8%) and demand (−8.7) and slightly higher values for flow (+1.9%).

Sensitivity analysis for ES indicators

After model development and evaluation, we did a second sensitivity analysis using the Sensitivity to Findings function in Netica for the 'ES outcome' node for the nine parameterized models. For each model, the nodes were then ranked from highest to lowest mutual information (MI). We considered all nodes with MI > 0.01 under the supply, demand and flow paths, subsequently identifying the key factors with MI ≥ 0.1, to answer the first research question.

ES outcomes

Nine ES outcomes predicted on a discrete scale from 1 (no outcome) to 5 (very high outcome), were computed in Netica with the most recent geodata available for Tanintharyi Region for the root nodes (Appendix VI, Table A4), (a) using the actual distribution of land uses in 2016 across the region as soft evidence (50% intact forest, 28% secondary forest, 6% mangrove, 2% mixed plantation, 2% rubber, 3% oil palm, 4% paddy, 5% other) and (b) using hard evidence for each individual land use. In addition to the resulting probability distributions, weighted averages were calculated and used as ES outcome scores.

Regional and local scenarios

Two regional and three local scenarios were constructed and applied in Netica, based on hypothetical but likely scenarios according to common developments in forest frontier landscapes. The regional scenarios were established by the authors, based on triangulated information from literature, field observations and the 15 regional expert interviews, while the local scenarios correspond to actual developments experienced and documented in three focus groups in northern Tanintharyi on land use changes in the past 20 years. These scenarios are representative of similar developments across Tanintharyi at the forest frontier (Bhagwat et al., 2017). At regional scale, the baseline (R0) was the most recent spatially explicit land use data for Tanintharyi Region (Connette et al., 2016). Two hypothetical scenarios were decided on based on most likely developments according to experts

Table 2. Characteristics of regional and local scenarios

		Regional			Local			
Values based on		literature, field observation, expert interviews			case study, focus group discussions, field observation			
Scenario		R0 Current situation	R1 Agricultural expansion	R2 Forest conservation	L0 Forested landscape	L1 Community forestry (CF)	L2 Small-scale agriculture	L3 Oil palm concession
Description		current land uses and zoning in Tanintharyi Region	concessions for oil palm and rubber, expansion of smallholder agriculture	forest conservation and restoration with protected areas and CF	mostly intact forest landscape, partly used for shifting cultivation	CF certificate, restored degraded areas, some agroforestry plots	forest conversion to mixed plan-tations and rubber, no land tenure	agricultural concession, conversion to oil palm and processing plant
Land use (%)	**Intact forest**	50	40	70	80	85	10	5
	Secondary forest	28	0	10	15	10	5	5
	Mangrove	6	4	8	0	0	0	0
	Mixed plantation	2	6	4	0	5	70	0
	Rubber	2	20	2	0	0	10	0
	Oil palm	3	6	2	0	0	0	80
	Paddy	4	16	3	0	0	0	0
	Bare	5	5	0	5	0	5	5
	Mining	0	1	0	0	0	0	0
	Built-up	1	2	1	0	0	0	5
Zoning (%)	**Protected area**	5	5	40	0	0	0	0
	Oil palm concession	7	22	2	0	0	0	100
	Mining concession	0	1	0	0	0	0	0
	SEZ	0	1	0	0	0	0	0
	Community forestry	0	1	17	0	100	0	0
	Other	87	70	41	100	0	100	0
Other variables		existing datasets (Appendix VI)	population density ↑, distance to village ↓	distance to forest ↓	existing datasets, low population density (hard evidence)			

* All percentages were rounded so that sums may not always be 100%. In R0, no value is 0 but rather < 0.5

and our own field observations: agricultural expansion and intensification (R1) and forest conservation and restoration (R2). R1 includes more agricultural areas (particularly rubber) and concession land. R2 includes the restoration of degraded secondary forests and conservation in increasing numbers of protected areas and community forests. At local scale, the baseline (L0) consisted of an exemplary rural forest landscape without formal land tenure and low population density. The three scenarios defined by previous land use changes in northern Tanintharyi were community forestry (L1), expansion of small-scale agriculture (L2), and conversion to an oil palm concession (L3). Table 2 gives an overview of all scenarios and specific model updates giving soft evidence for land use and zoning.

Results

Key factors for ES outcomes

Our nine ES models include up to 30 factors (nodes) each. The relevance of each node, represented through its mutual information (MI) with the respective ES outcome, is depicted in Table 3 for the

Table 3. Main nodes and their relevance for the outcomes of nine ecosystem services based on mutual information (sensitivity analysis carried out in Netica, MI = mutual information).

Ecosystem service		Supply			Flow			Demand		
		Node	MI	mean	Node	MI	mean	Node	MI	mean
Provisioning	Subsistence foods	food amount	0.38	0.42	distance to village	0.13	0.13	consumption frequency	0.23	0.32
		land use	0.32					price of food	0.06	
		food type	0.25					population density	0.04	
		subsistence value	0.13					township	0.04	
	Commercial products	type of product	0.28	0.28	market access	0.02	0.04	access to food	0.02	0.51
		revenue	0.26					type of product	0.45	
		selling price	0.25					expected revenue	0.44	
		land use	0.17							
		land use intensity	0.05							
		price stability	0.05							
		input costs	0.04							
	Fuelwood	fuelwood quantity	0.32	0.34	physical access	0.06	0.09	use of fuelwood	0.12	0.18
		land use	0.31					use in cooking	0.08	
		fuelwood quality	0.26					township	0.04	
								population density	0.04	
	Medicinal plants	land use	0.06	0.07	plant knowledge	0.26	0.26	current use	0.26	0.38
								use frequency	0.23	
								future value	0.12	
Regulating	Biodiversity	species diversity	0.13	0.13	access to products	0.11	0.17	planted crop	0.11	0.15
		land use	0.11		distance to village	0.07		ntfps	0.10	
		agrobiodiversity	0.04					use of products	0.10	
	Climate regulation	air quality	0.13	0.16	distance to village	0.04	0.10	air quality value	0.13	0.19
		tree cover	0.11							
		land use	0.11							
		carbon storage	0.11							
		net ghg emissions	0.10							
		climate mitigation	0.10							
		non ghg emissions	0.05							
	Water regulation	water quality	0.09	0.24	water source	0.07	0.13	household use	0.10	0.17
		water pollution	0.08		township	0.07		population density	0.07	
		water quantity	0.08					type of product	0.06	
		land use	0.07					agricultural use	0.03	
		water purification	0.05					crop requirements	0.03	
		water retention	0.04							
		precipitation	0.03							
Cultural	Environmental education	vocational trainings	0.48	0.86	zoning	0.04	0.06	livelihood knowledge	0.03	0.04
		land use	0.09							
		community groups	0.03							
		local knowledge	0.02							
	Cultural identity	land use	0.14	0.16	products access	0.03	0.06	cultural product use	0.33	0.44
		cultural value	0.13		ancestral land	0.02		annual product use	0.27	
		old cultural value	0.13		zoning	0.02		cultural products	0.17	
		traditional products	0.13					nature in culture	0.02	
		traditional land use	0.10							

most important nodes (MI > 0.01). Comparing the respective contributions of supply, demand and flow to ES outcomes across nine models, we found supply overall to be the most important (mean = 0.30), closely followed by demand (mean = 0.26). Specifically, supply is particularly defining for the outcome of subsistence foods, fuelwood, climate, water and environmental education, which varies widely in different areas of Tanintharyi. In contrast, demand highly influences the outcome of cultural identity, commercial products and medicinal plants, most of which are found on many land use types but used only selectively. The influence of flow factors is highest for medicinal plants, as knowledge is a crucial requirement for using them. Overall, flow has comparably low MI (mean = 0.12), which can be partly explained by the lower number of states (three) as against supply and flow (five).

Considering key factors, land use stands out as the single most important node. It is represented in all models and is particularly relevant (MI ≥ 0.1) for subsistence crops, commercial products, fuelwood, biodiversity, climate and cultural identity (Table 3). In addition, several other factors are directly linked to land use. The vital role of land use for ES outcomes is not surprising, given that it represents the natural and human-made ecosystem and its functions. In terms of demand, there is no single key factor, but some patterns emerge. One key node pattern reflects actual use of specific products (e.g., consumption frequency of subsistence foods or use of cultural products). Other patterns, such as the availability of alternatives (e.g., imported food, alternative cooking stoves, modern medicine) or intrinsic values have lower impacts on outcomes. In terms of flow, physical access appears to have slightly more influence on outcomes than institutional access for subsistence foods and fuelwood, though institutional factors are also relevant (MI > 0.01) for commercial products, fuelwood, water regulation and cultural identity. This is rather surprising, as zoning and corresponding rules and regulations have been reported by local communities as highly affecting their livelihoods and well-being. It can be assumed that, due to a combination of weak law enforcement and high uncertainties related to land tenure, the models do not sufficiently account for this. Thus, rural communities have access to land and its products but only informally. As this might change in the future, zoning should still be considered an important factor for ES outcome.

ES outcomes for Tanintharyi region and individual land uses

Currently, the most probable outcomes for all nine services are between low and high levels (Figure 3). We found the highest outcome scores for water regulation (3.6) and biodiversity (3.5). The lowest outcome by far is for commercial products (2.3). No clear pattern appears between provisioning, regulating and cultural ES types. When comparing individual land uses, two clusters can be distinguished. The first cluster includes forest-related land uses (intact forest, secondary forest, mangrove) and smallholders' mixed plantations, which are extensively managed and often quite diverse. This cluster provides a broad and well-balanced set of ES with most at medium to high levels but some deficiencies in commercial and educational services. Mangroves are an exception with fisheries contributing greatly to commercial outcomes and frequent mangrove conservation trainings enhancing environmental education, leading to an overall balanced ES bundle. The second cluster involves intensively managed agricultural land uses (rubber, oil palm, paddy) with more heterogeneous ES outcomes. Both rubber and oil palm plantations have limited cultural value and provide few subsistence foods. On the other hand, they offer opportunities for agricultural training from companies aiming for high-quality products and from NGOs aiming to enhance rural livelihoods. Since perennial crops dominate agricultural lands, these still provide relatively high levels of regulating services such as climate regulation and biodiversity, especially where farmers manage them extensively and with few chemical inputs. In comparison, paddy fields provide very low levels of regulating services but are important for subsistence and cultural identity, as rice is both a staple food and a product donated in religious ceremonies. Considering that for commercial products demand is highly relevant for outcome, agricultural land uses are expected to be more important in highly populated areas of Tanintharyi.

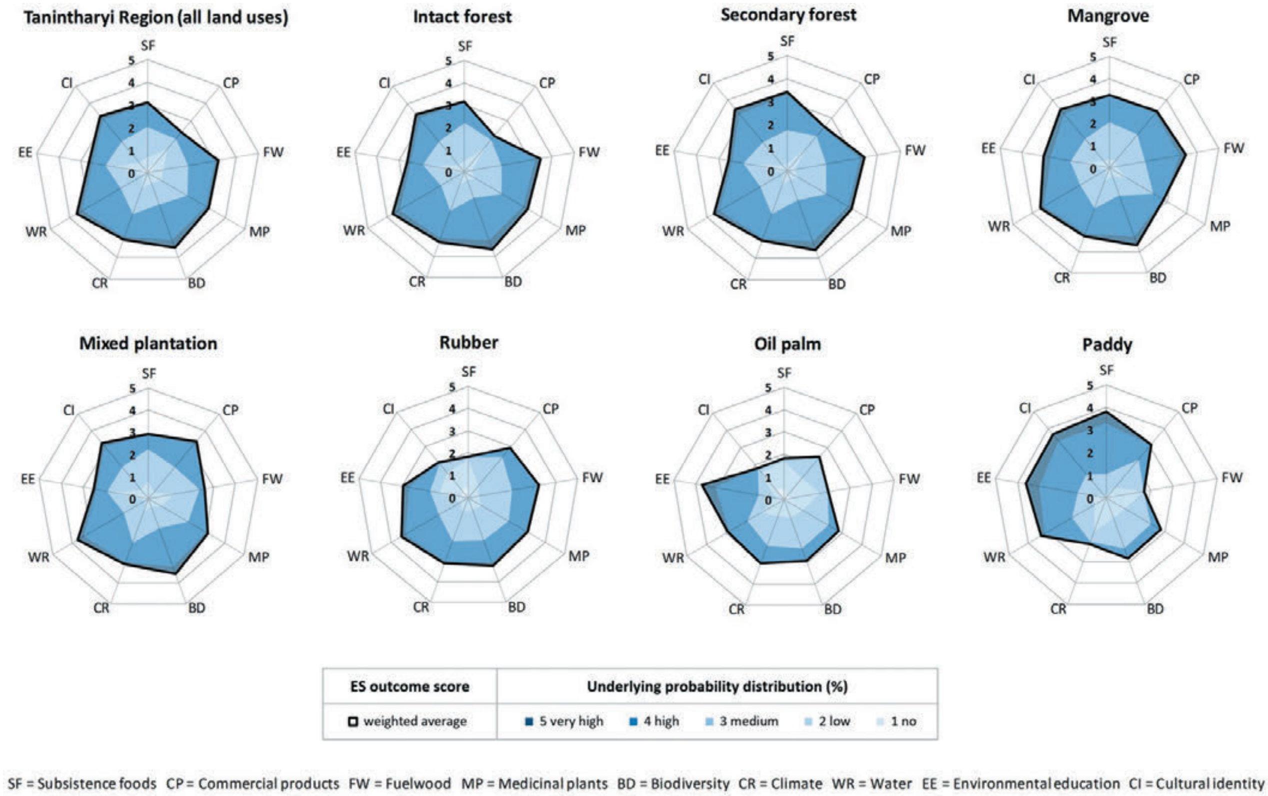

Figure 3. Ecosystem service outcome scores based on weighted average and underlying conditional probability distributions from Bayesian networks for Tanintharyi Region (land use distribution according to Connette et al. (2016) and for each land use separately.

The underlying probability distributions (Figure 3) provide an indication of the extent to which individual ES can be influenced within a certain land use. For example, if good agricultural practices are promoted for rubber, it will be possible to achieve high regulating ES as there are high probabilities of scoring 4. However, there will still be a limited supply of subsistence foods, which has zero probability of a score higher than 3 and thus can only be achieved with other land uses, namely paddy or upland rice fields. On the other hand, for all land uses and ES there is always a risk of low outcomes, as demand may be low. Therefore, policies trying to optimize ES outcomes would need to consider spatial distributions of supply, demand and flow to make sure that the rural communities can indeed benefit from the relevant ES.

Model application using scenarios at regional and local scale

Applying the models through scenarios based on different land use and zoning settings, we found that at the regional level, the models predict few differences for either scenario (Figure 4), with agricultural expansion and intensification (R1) having slightly lower mean outcomes (3.08) than forest conservation and restoration (R2) (3.20). It can be noted that the outcome of R2 is very similar to the current situation, but it includes also larger areas of community forestry, which is always accompanied by training from the FD and NGOs and thus increases environmental education. Turning to the local perspective and a specific, rather homogenous, forest landscape, differences between the scenarios are much more accentuated. In a forested landscape, ES outcomes increase if CF is introduced (L1) (3.36) and decrease if forest is converted to croplands. While small-scale agriculture including rubber and mixed plantations (L2) still provides relatively high outcomes (3.14), the conversion to oil palm (L3) is more detrimental (2.37), especially in terms of cultural identity. Additionally, the comparison of all five scenarios shows that commercial products remain low except for L2, which indicates that especially at regional level, income for rural communities

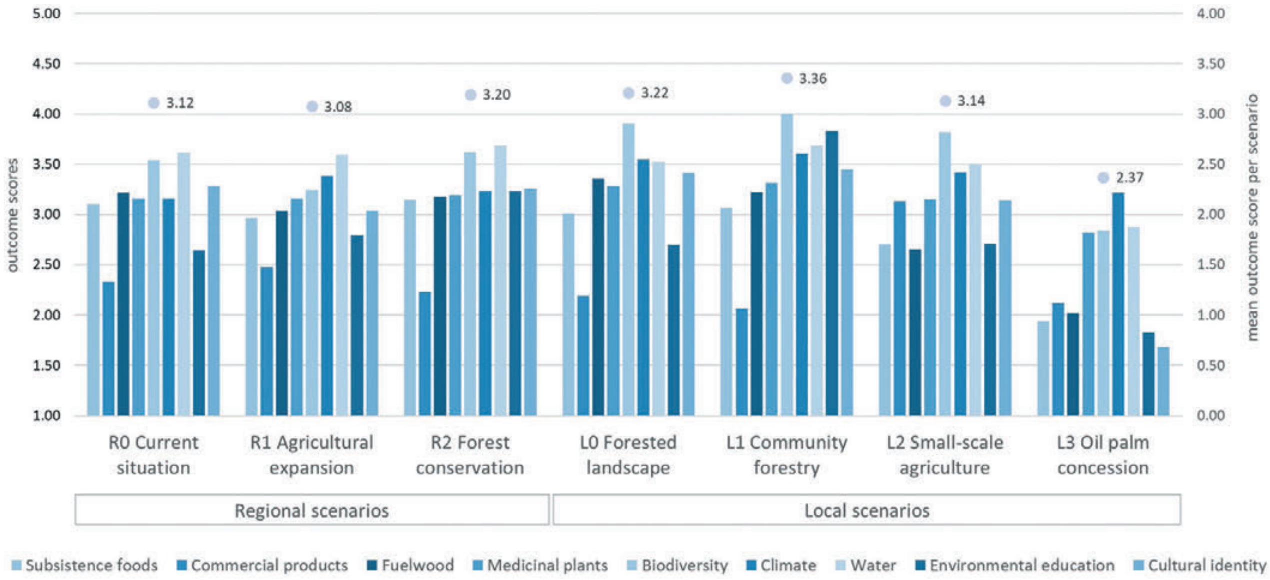

Figure 4. Modelled ecosystem service outcome scores based on supply, demand and flow in two regional and three local scenarios in Tanintharyi Region.

cannot be improved by steering land use and tenure alone. It is thus possible that investigating additional factors such as intensity of land use management or quality of processing practices would have a higher effect specifically for commercial outcomes.

These findings suggest that the models, as an approximation of the complex reality on the ground, can predict the impact of certain land use and zoning policies on ES outcomes more effectively at the local scale, which is less heterogeneous than the entire region. Demand, which has a high influence on outcomes, is difficult to account for at regional scale. The regional scenarios thus cannot respond to the question of whether supply meets demand. On the contrary, while regional-level land use decisions may have negligible effects on overall ES outcomes, local communities in specific areas may be highly impacted in terms of their livelihoods and well-being.

Discussion

In line with a previous review (Landuyt et al., 2013), we found the use of Bayesian networks highly suitable for modelling ES, particularly as our study is located in a data-scarce region (ibid) and involves different types of ES (Shaw et al., 2016). BN's probability distributions indicate to what extent certain ES can be enhanced, which can be a useful basis for designing targeted intervention strategies. Compared to existing ES models (InVEST, ARIES), our models include a broad set of ES, which had been defined together with local stakeholders, and diverse (in particular many qualitative) factors contributing to ES outcomes. They thus provide a more detailed representation of local circumstances, actual demand and benefits for local communities. As the perspective was on these communities, our results did not account for the global relevance of some ES. But based on different actors' contested objectives, scenarios can be defined in a participatory way and used to discuss different ES outcomes from potential policies and interventions. In Myanmar, such an application is a promising opportunity due to ongoing land reforms and the existence of a multi-stakeholder land platform (Bächtold et al., 2020).

According to Norton et al. (2016), larger-scale studies are useful for targeting action, especially when assessing several ES. However, when zooming in to smaller-scale landscapes, our models were able to predict ES outcomes in a more differentiated way. More extreme but rather unrealistic scenarios, such as the conversion of the entire forest complex into rubber plantations, may have led to more compelling results of ES impacts at regional level. Nonetheless, our findings suggest that at regional level it is difficult to optimize ES outcomes based on land use and tenure factors alone, and demand cannot easily be steered with one single factor in our models. A spatially explicit representation of ES supply, demand and flow should thus come as a next step for applying the models. As suggested by Landuyt et al. (2013) and implemented in various studies, e.g., recently in Stritih et al. (2020), spatially explicit modelling through the combination of BN and geographic information systems also presents an opportunity for Tanintharyi Region for more targeted policy and interventions. As BNs can be updated and adjusted as soon as new information becomes available, it is possible to adjust the models to other areas of Myanmar or the wider region either by modifying relevant nodes and states or by updating CPTs. The expert model validation (Appendix V) serves as a reference for potential differences in other areas of Southeast Asia. Generally, the high conformity rate between BN and expert responses implies that the models are applicable in the wider region with slight adjustments. For example, experts with experience outside of Myanmar rated ES outcomes of oil palm slightly higher, which may result from better growing conditions (Saxon & Sheppard, 2014) or better inclusion of local communities. Further, some of the experts rated physical access as more relevant compared to the models, as infrastructure and road access are known to encourage the use of forest products and conversion from forest to croplands (Barber et al., 2014). Improved physical access may have various more long-term impacts on supply, demand and flow ES. In the sparsely populated Tanintharyi Region, this is yet to be seen.

Overall, our study suggests that to optimize ES outcomes, several aspects of supply, demand and flow should be considered. Land use and actual product use being key factors that correspond to similar findings on ES indicators (Meacham et al., 2016; Schirpke et al., 2019). In contrast, these studies also point to zoning aspects as key indicator, which did not show in our results and implies a need for further investigation. Our models show that a large-scale conversion of forests to agriculture would not necessarily increase local revenues from commercial products. Instead, sustainable intensification to increase crop yields or measures to improve quality could be preferred options (Pretty & Bharucha, 2014). This would at the same time allow remaining forests to keep providing valuable ES bundles (Ahammad et al., 2019; Emerton & Aung, 2013). But while rubber, oil palm and paddy generally had more diverging ES outcomes than forests or mixed plantations, different types of agricultural practices need to be investigated more deeply to make a clear statement on their relevance for ES. Shifting cultivation as an integral part of secondary forest areas has not yet been sufficiently considered in other ES assessments. Complementary to studies documenting the role of shifting cultivation in rural livelihoods in Southeast Asia (Cairns, 2017; Dressler et al., 2017; Fox et al., 2014), our results show that these secondary forest landscapes provide nearly the same amount of regulating services of intact forests and additionally contribute to subsistence foods. At the same time, shifting cultivation plots are often transformed by local land users into mixed plantations, which include betel nut, cashew, a variety of fruit trees and annual crops. They provide the commonly known benefits of agroforestry systems (such as improved agrobiodiversity, carbon sequestration or income diversification) and are crucial for rural people's subsistence and income generation. Indeed, because it provides more subsistence and commercial products while retaining reasonable levels of regulating services, local people see agroforestry as a complementary or even better source of ES than forests (Feurer et al., 2019; Muhamad et al., 2014).

If the aim is to enhance ES outcomes for local communities, it seems crucial to consider land tenure and zoning. The apparent low sensitivity of the 'institutional access' factor stands in contrast to several studies documenting local communities' constrained access to natural resources in protected areas (Pollard et al., 2014; TRIP NET, 2016) or agricultural concessions (Feurer et al., 2019; Thein et al., 2018; Woods, 2016) and the fact that improved land tenure security encourages sustainable management practices (Higgins et al., 2018). Although our ES models did not sufficiently account for that at regional scale, the local scenarios revealed that establishing CF may enhance overall ES outcomes, whereas transferring land to a company negatively affects rural communities' benefits from these lands. Recognizing the administrative hurdles and multiple stakeholder claims on land (Lundsgaard-Hansen et al., 2018), it seems nonetheless a viable option to improve land registration processes, issue more land certificates to local land users and allocate additional CF.

As we found demand factors to be highly relevant for ES outcomes, efforts to enhance supply need to consider demand in the respective locations. Spatially explicit modelling can help to identify supply/demand (mis)matches and devise targeted intervention strategies. For the forestry sector, this effectively means that strict forest conservation measures should be complemented with local forest use where feasible. For example, near villages CF may be the best option, whereas in remote areas nature reserves can protect primary forests from agricultural conversion and ensure regulating ES for downstream users. Alternatively, promoting valorisation of selected forest products may be crucial for long-term ES outcomes where forest-dependent communities are present (Gritten et al., 2015). In Tanintharyi's coastal area, clear policies need to be established and enforced to protect remaining mangroves and support rehabilitation in selected sites in order to secure the valuable ES bundles provided by them, as shown in our results. For the agricultural sector, investments should consider areas with high population density and good access to markets to ensure flow and demand. While our scenarios support other studies in the assumption that any form of concession will reduce ES outcomes for local stakeholders (Baird & Fox, 2015; Kenney-Lazar, 2012), it should be mentioned that oil palm production in Tanintharyi is currently not even profitable for investors (Saxon & Sheppard, 2014) and more diverse landscape trajectories should be considered.

Conclusions

This study presented an ecosystem service modelling approach using Bayesian networks and considering multiple supply, demand and flow factors. We determined that land use has the highest impact on multiple ES and suggests that further decisive factors are land tenure and demand for natural resources, in particular for local stakeholders. Using scenarios, we found that differences in ES outcomes from changes in land use and land tenure are much more pronounced in a homogenous (local) landscape than at regional scale in the present context of Tanintharyi Region. In a forest landscape, overall ES outcomes increased with the introduction of community forestry but decreased with the expansion of small-scale agriculture. The 'oil palm concession' scenario, on the other hand, had particularly negative effects on local communities' livelihoods and cultural identity. Thus, while forests are important sources of ES, agricultural land uses, especially mixed tree crop plantations, can be equally or more beneficial where rural communities depend on those products for income generation. In existing croplands, sustainable intensification and product quality improvements could improve livelihoods further. We conclude by suggesting that the new ES models are land use science tools with considerable potential to inform policymaking. In view of the ongoing land reform processes in Myanmar, such models could play a critical role in multi-stakeholder platforms by facilitating discussions on contested issues and different scenario outcomes. Overall, the consideration of spatial scales is crucial when applying the models. In a next step we recommend applying the models in a spatially explicit manner, which will allow the identification of supply/demand mismatches at the regional level. This – and considering access factors – would enable more targeted policies and interventions to be designed for enhanced ES outcomes and, finally, the sustainable development of a forest frontier landscape.

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Appendix

Appendix I. Steps in model development

Phase (a) Defining model structures with nodes and states

For each model, the first step was to develop the structure, following the basic structure of the theoretical framework and using the Delphi-method (Okoli & Pawlowski, 2004). We first did a literature review and subsequent individual interviews with 15 experts from various institutions (including non-governmental organizations, civil society organizations, research institutions and governmental bodies) active in the study area. All selection criteria are detailed in Table A1.

After findings were consolidated into draft structures, a set of discrete states were defined for each node aiming for as many states as needed but as few as possible. For the parent nodes to 'ES outcome' we used an ordinary scale consisting of a scale from 1 to 5 for the nodes 'ES supply' and 'ES demand' and a scale from 1 to 3 for 'ES flow', which involves fewer options due to a lower number of input nodes. This allows for consistency across the nine models and makes them comparable at the level of supply, demand and flow. For nodes with available spatial data, states were defined according to the respective datasets after having prepared the geodata so that categories fit the desired content. For the other nodes, states were either defined by using recognized classifications (e.g., soil types) or combining information from literature and expert interviews.

In the end, all nodes and states were verified in a second round of interviews with the above-mentioned experts as well as with representatives from two villages in the study area using the printed consolidated draft model structures as discussion material.

Phase (b) Populating and parameterizing CPTs

As a fourth step, we parameterized each model by filling in the CPTs and calibrating them in several rounds, using a variety of both secondary data (GIS layers, population census data, literature review) and primary data (interviews, survey, field observations) collected during a total of three months in the field between 2017 and 2020. For a total of 54 root nodes (some repeating), available spatial data were compiled and processed into raster datasets with relevant states for the respective nodes using ArcGIS. For each dataset, the states' distribution across Tanintharyi Region was calculated and inserted as probability distribution for the corresponding root nodes. For intermediary nodes, three types were distinguished depending on the availability and quality of secondary data. The first type (n = 20) was based on township-level census data and CPTs were populated according to the distribution in the corresponding parent node 'township', which is spatially explicit. The second type (n = 27) had good literature information which determined the probability distributions. For the third type (n = 105) we used triangulated information from field observations, key informant interviews and reflections stemming from a comprehensive literature review as a basis to elicit rules for populating CPTs. Key informants included the same 15 experts from local institutions who were interviewed regarding the model structure. The interviews took place during three weeks in 2019. The elicited rules included shifts between classes of either 10%, 25% or 50% depending on the parent nodes. These were found to be most suitable for handling uncertainties according to experts. All rules are found in Appendix III. After the first parameterization, all intermediary

Table A1. Selection criteria for interviews with local stakeholders (n = 15).

Selection criteria	Number of interviewees
Institutional diversity	3 government representatives: Forest Department (FD), Environmental Conservation Department (ECD), Tanintharyi Nature Reserve Project (TNRP) 1 Karen National Union (KNU) 4 non-governmental and civil society organizations: 3x Worldwide Fund for Nature (WWF), 2x The Center for People and Forests (RECOFTC), Wildlife Conservation Society (WCS), Flora & Fauna International (FFI), 3 research institutions: 2x Onemap Myanmar (OMM), Dawei Research Association (DRA), Environmental Care and Community Security Institute (ECCSi)
Tanintharyi Region knowledge	11 interviewees based in Dawei 1 interviewee based in Yebyu 1 interviewee based in Myeik 2 interviewees based in Yangon with working experience in Tanintharyi
Position with good institutional overview and close to communities	5 heads or assistant heads of (local) institution 7 project leaders 3 field assistants
Cultural knowledge	13 Burmese 1 Foreign national with > 5 years working experience in Myanmar 1 Foreign national with < 2 years working experience in Myanmar

nodes were assessed according to the authors' confidence in them and they were subjected to a first sensitivity analysis in Netica. Nodes with a high sensitivity to ES outcome (mutual information ≥ 0.01) and a low authors' confidence were selected for calibration to improve the soundness of the CPTs and, consequently, the predictive accuracy of the models. Calibration was done through a household survey (n = 40) with a standardized questionnaire to ask about the most probable states for the respective nodes. An example question was 'Do you trust in herbal medicine?' A total of 40 household heads from seven different villages in three townships participated in the survey. The distribution of responses (in the example 93% yes and 7% no) was set as conditional probability for the respective node. For the nine end nodes ('ES outcome'), rules were compiled to populate the CPTs based on triangulation between existing ES concepts and a standardized survey with 12 additional scientific ES experts. The experts were asked 'What is the most likely ES outcome on a scale from 1 (lowest) to 5 (highest) if ES supply has state X, ES flow state Y and ES demand state Z?' The updated 'outcome' rules, valid for all ES, are:

- Range of outcome = Range of the values of 'supply', 'flow', 'demand' (min – max)
- ES outcome = mean of 'supply', 'demand' and 'flow'
- Accounting for uncertainty: 25% higher (if.00 or.75) and 25% lower (if.00 or.25)
- Accounting for 'no' values: 10% lower if no 'supply', 'demand' or 'flow'
- Accounting for expert estimations: 10% lower (all)

Figure A1 describes the process of populating CPTs for different types of nodes.

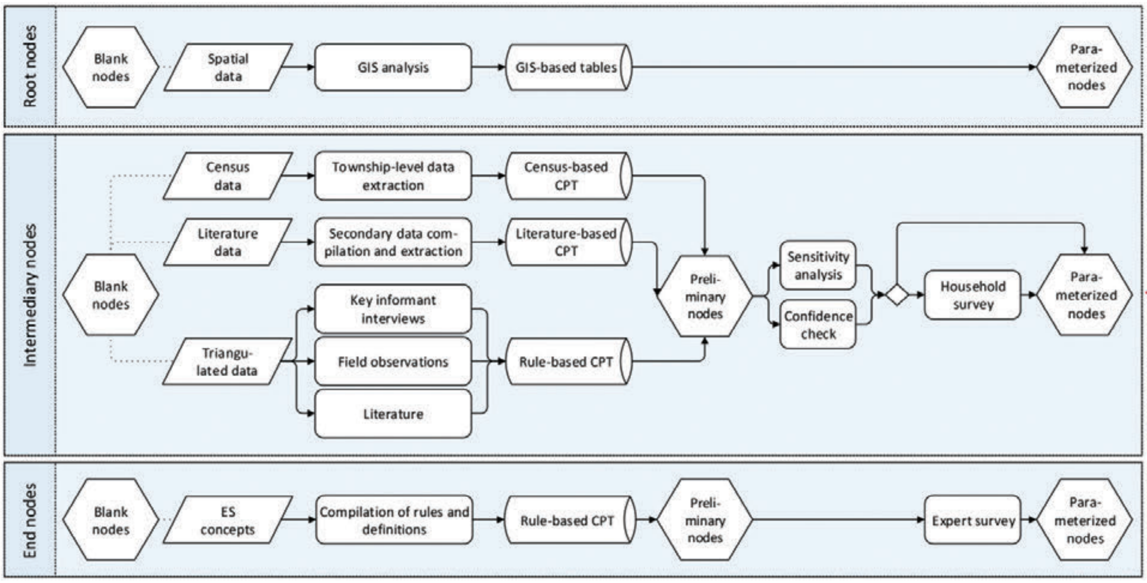

Figure A1. Flow chart of processes involved in populating probability tables for root nodes and CPTs for intermediary and end nodes

CPT = Conditional probability table; ES = Ecosystem services; GIS = Geographic information systems

Phase (c) Validating final models

As a final step, we used two validation approaches. As suggested and described by Kleemann et al. (2018), we applied the extreme-condition test checking model outputs given most extreme inputs to confirm the operational validity of each parameterized model. Then the models underwent a face validity test (Kleemann et al., 2018) with the 12 ES experts who are also familiar with natural resource use in the Southeast Asian context. Based on a standardized survey including pictures of the model structures, the experts had to rate the supply, demand and flow for each ES based on the direct parent nodes or, where needed for contextual reasons, the parent nodes to those. Combining all expert responses, probabilities and means for the states of supply, demand and flow were calculated for each ES and compared to the probabilities and weighted averages calculated from the models. Results are depicted in Appendix V.

Appendix II. Model structures

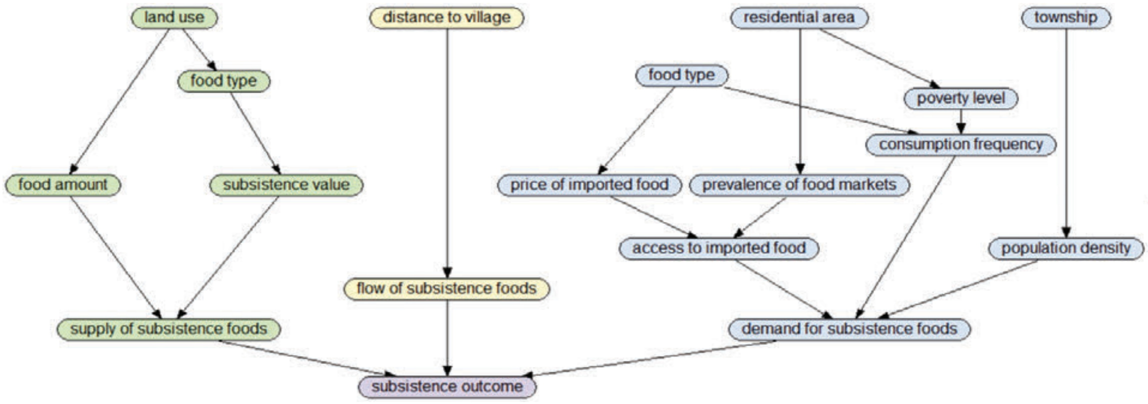

Figure A2. Model structure for ES 'subsistence foods' (green = supply nodes, yellow = flow nodes, blue = demand nodes; prepared in Netica).

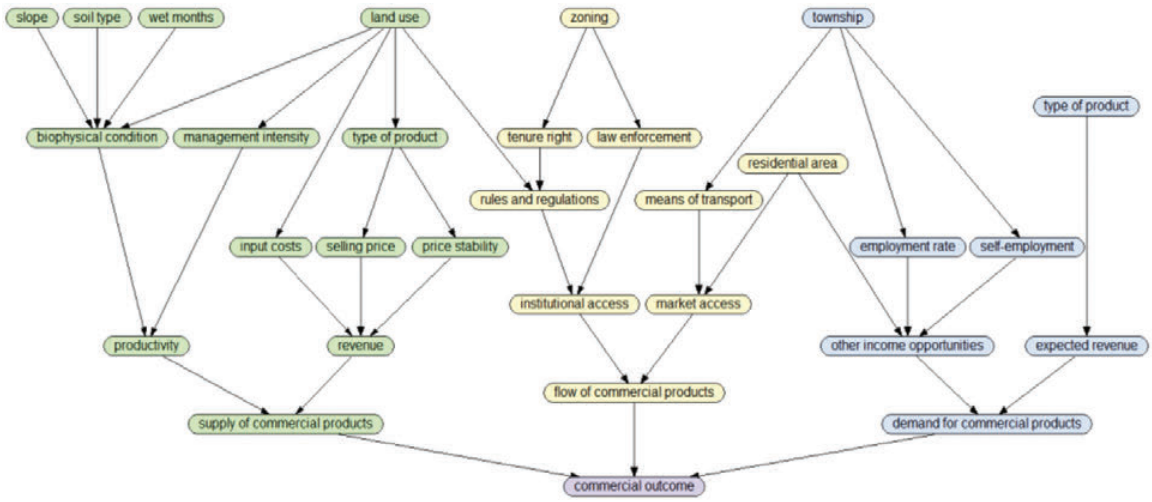

Figure A3. Model structure for ES 'commercial products' (green = supply nodes, yellow = flow nodes, blue = demand nodes; prepared in Netica).

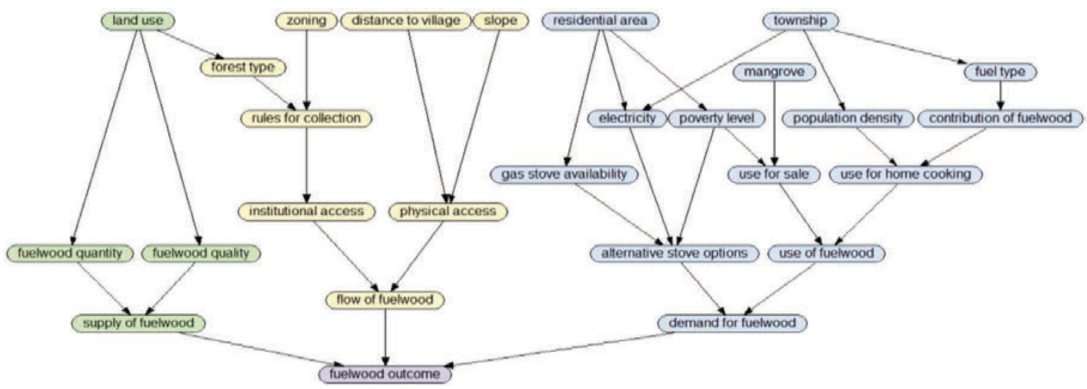

Figure A4. Model structure for ES 'fuelwood' (green = supply nodes, yellow = flow nodes, blue = demand nodes; prepared in Netica).

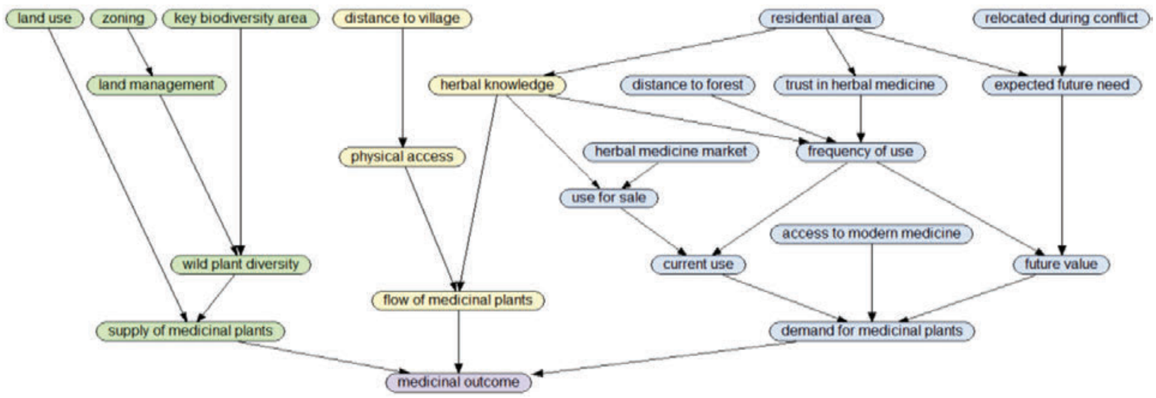

Figure A5. Model structure for ES 'medicinal plants' (green = supply nodes, yellow = flow nodes, blue = demand nodes; prepared in Netica).

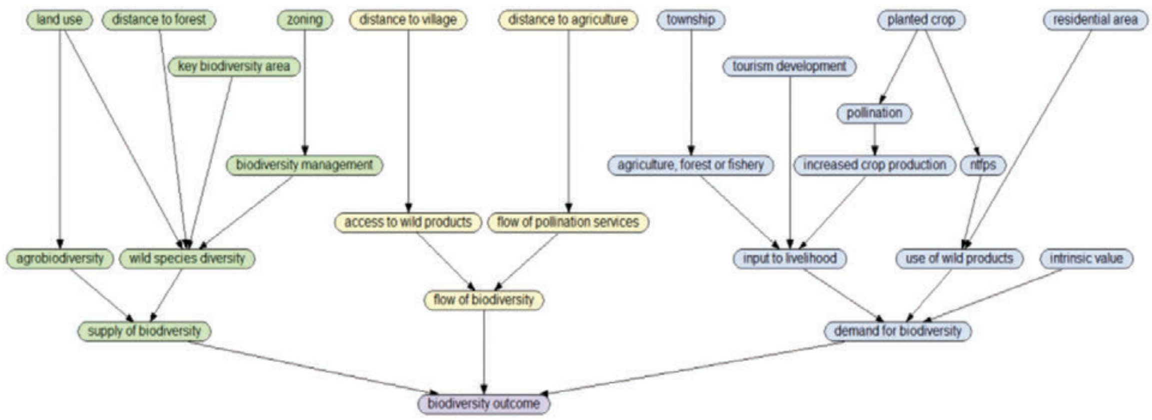

Figure A6. Model structure for ES 'biodiversity' (green = supply nodes, yellow = flow nodes, blue = demand nodes; prepared in Netica).

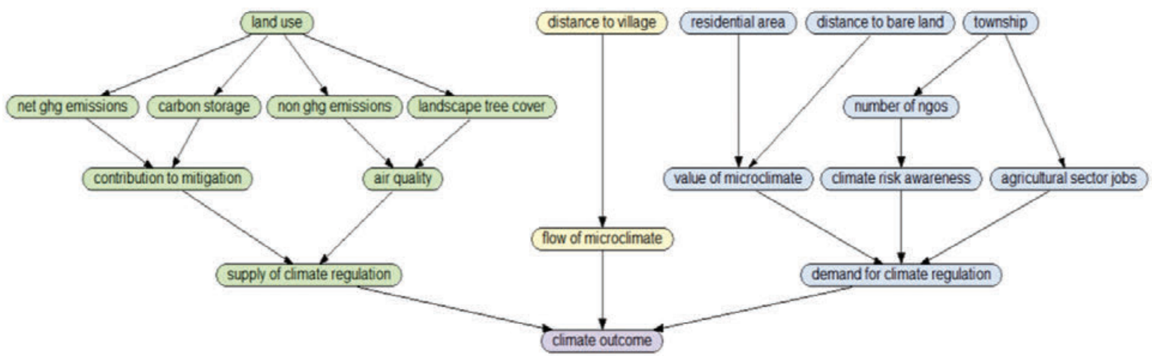

Figure A7. Model structure for ES 'climate regulation' (green = supply nodes, yellow = flow nodes, blue = demand nodes; prepared in Netica).

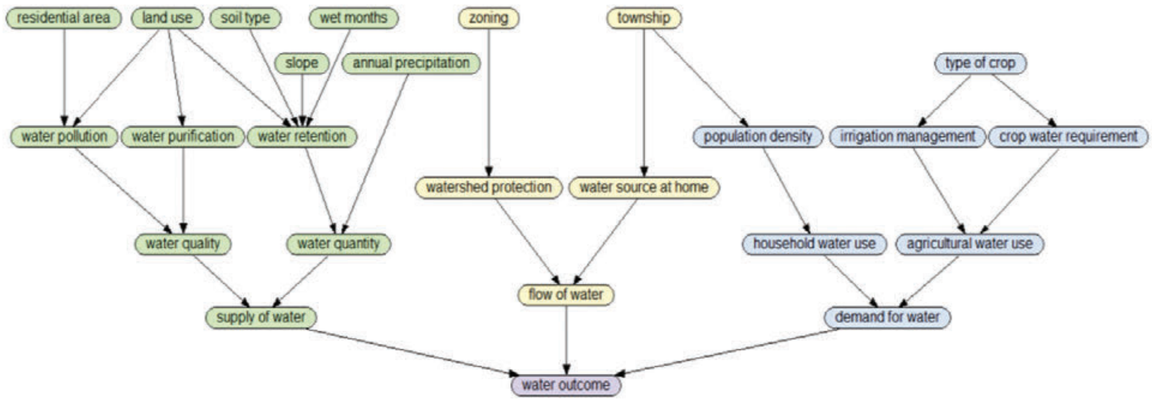

Figure A8. Model structure for ES 'water regulation' (green = supply nodes, yellow = flow nodes, blue = demand nodes; prepared in Netica).

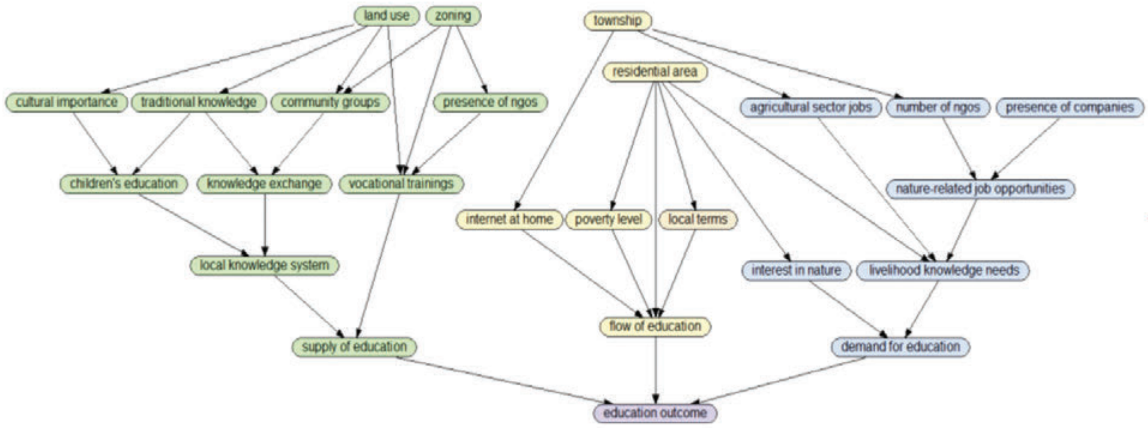

Figure A9. Model structure for ES 'environmental education' (green = supply nodes, yellow = flow nodes, blue = demand nodes; prepared in Netica).

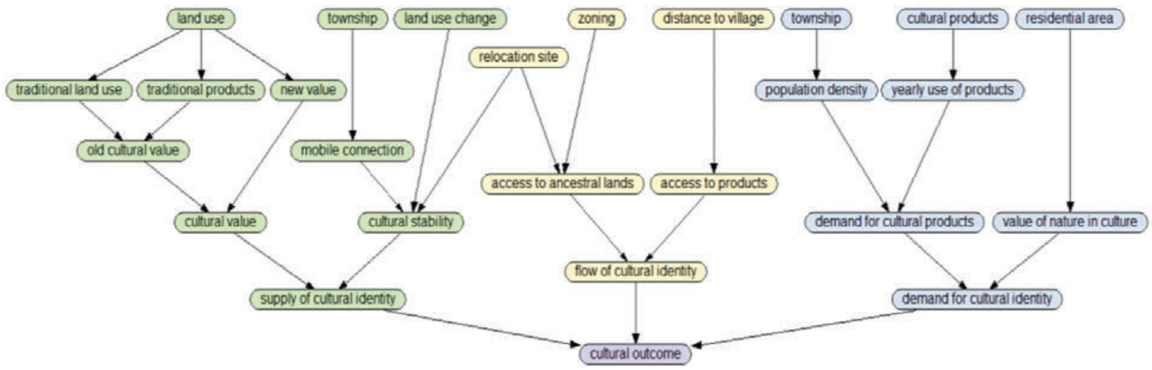

Figure A10. Model structure for ES 'cultural identity' (green = supply nodes, yellow = flow nodes, blue = demand nodes; prepared in Netica).

Appendix III. Nodes, data types and CPT rules

Table A2. Data types and rules for populating conditional probability tables for nine ecosystem service models using Bayesian networks (S = supply, F = flow, D = demand, O = outcome).

ES model	Node type	S/F/D/O	Code	Node	Type of data (spatial, census, literature, primary)	Additional information (rules or references) for filling conditional probability tables (CPT)
Subsistence foods	Root node	S	1a	land use	spatial	
		F	1b	distance to village	spatial	
		D	1 c	residential area	spatial	
			1d	township	spatial	
	Inter-mediary node	S	1e	food amount	household survey	based on 1a
			1 f	food type	triangulated	based on 1a
			1 g	subsistence value	triangulated	based on 1 f
			1 h	supply of subsistence foods	mixed	- based on 1e - 1 g: if very important +*50*, if important +*25*, if not important −*25*
		F	1i	flow of subsistence foods	mixed	*equals* 1b
		D	1 j	price of imported food	household survey	based on 1 f
			1 k	prevalence of food markets	triangulated	based on 1 c
			1 l	access to imported food	primary (mixed)	– 1 k: if always *yes*, if sometimes *75 yes* - 1 j: if high −*25*, if medium −*10*, if low +*10*
			1 m	poverty level	census	
			1 n	consumption frequency	household survey	based on 1 f
			1o	population density	census	
			1p	demand for subsistence foods	triangulated	- based on 1 n - 1 l: if yes −*50*, if no -*all*
	End node	O	1q	subsistence outcome	expert survey	- range of values supply, flow, demand - *mean*, (if.00 or.75 then +*25*, if.00 or 0.25 then −*25*) - −*10%* if no suppy, demand or flow - all: −*10%*

(*Continued*)

Table A2. (Continued).

ES model	Node type	S/F/D/O	Code	Node	Type of data (spatial, census, literature, primary)	Additional information (rules or references) for filling conditional probability tables (CPT)
Commercial products	Root node	S	2a	land use	spatial	
			2b	slope	spatial	
			2 c	soil type	spatial	
			2d	wet months	spatial	
		F	2e	zoning	spatial	
			2 f	residential area	spatial	
		D	2 g	township	spatial	
	Inter-mediary node	S	2 h	biophysical condition	triangulated	based on 2a – 2d
			2i	management intensity	triangulated	based on 2a
			2 j	productivity	mixed	- *equals* 2 h - 2i: if intensive *+25*, if extensive *−25*
			2 k	type of product	triangulated	based on 2a
			2 l	input costs	triangulated	based on 2a
			2 m	selling price	household survey	based on 2 k
			2 n	price stability	household survey	based on 2 k
			2o	revenue	mixed	- *equals* 2 m (if no sale *no change* later) - 2 l: if high *−50*, if low *+50* - 2 n: if fluctuating *+5* and *−20*
			2p	supply of commercial products	mixed	- *mean* of 2 j and 2o - for high *+50*, for low *−50*, for medium *+25* and *−25*
		F	2q	tenure right	triangulated	based on 2e
			2 r	rules and regulations	triangulated	based on 2a and 2q
			2s	law enforcement	triangulated	based on 2e
			2 t	institutional access	triangulated	based on 2 r and 2s
			2 u	means of transport	census	
			2 v	market access	triangulated	– 2 f: if urban *good*, if rural see below - 2 u: if car/tractor or boat *75 good*, if cart *50 good*, if motorbike *25 good*, if no *50 low*, rest *medium*
			2 w	flow of commercial products	mixed	- *equals* 2 v - 2 t: if no *75 low*
		D	2x	employment rate	census	
			2y	self-employment	census	
			2z	other income opportunities	mixed	– 2x and 2y: if 2x yes *high*, if 1x yes *medium*, if 2x no *low* - 2 f: if urban *+25*, if rural *−25*
			2aa	expected revenue	triangulated	equals 2o
			2ab	demand for commercial products	triangulated	- based on 2aa - 2z: if high *−25*, if low *+25*
	End node	O	2ac	commercial outcome	expert survey	see 1q

(*Continued*)

Table A2. (Continued).

ES model	Node type	S/F/D/O	Code	Node	Type of data (spatial, census, literature, primary)	Additional information (rules or references) for filling conditional probability tables (CPT)
Fuelwood	Root node	S	3a	land use	spatial	
		F	3b	zoning	spatial	
			3 c	distance to village	spatial	
			3d	slope	spatial	
		D	3e	residential area	spatial	
			3 f	township	spatial	
			3 g	mangrove	spatial	
	Inter-mediary node	S	3 h	fuelwood quantity	triangulated	based on 3a
			3i	fuelwood quality	triangulated	based on 3a
			3 j	supply of fuelwood	triangulated	- equals 3 h (if no then *no change* later) - 3i: if high *+50*, if low *−50*
		F	3 k	forest type	literature	based on 3a
			3 l	rules for collection	triangulated	based on 3b and 3 k
			3 m	institutional access	triangulated	based on 3 l (if restricted *50/50*)
			3 n	physical access	triangulated	– 3 c: if low *100 good*, if medium *75/25*, if low *50/50* - 3d: if yes *−25*
			3o	flow of fuelwood	mixed	based on 3 m and 3 n
		D	3p	gas stove availability	triangulated	based on 3e
			3q	electricity	census	
			3 r	poverty level	census	
			3s	alternative stove options	triangulated	– 3 r: if non-poor *100 yes*, if poor *20 yes* - if no electricity and no gas then *100 no*
			3 t	use for sale	triangulated	based on 3 g and 3 r
			3 u	fuel type	census	
			3 v	population density	census	
			3 w	contribution of fuelwood	triangulated	based on 3 u
			3x	use for home cooking	triangulated	- *equals* 3 v - 3 w: if daily *+50*, if occasionally *−50*
			3y	use of fuelwood	mixed	- based on 3x - 3 t: if yes *25 to very high*, if no *−25*
			3z	demand for fuelwood	mixed	- *equals* 3y - 3s: if yes *−50*
	End node	O	3ab	fuelwood outcome	expert survey	see 1q

(*Continued*)

Table A2. (Continued).

ES model	Node type	S/F/D/O	Code	Node	Type of data (spatial, census, literature, primary)	Additional information (rules or references) for filling conditional probability tables (CPT)
Medicinal plants	Root node	S	4a	land use	spatial	
			4b	zoning	spatial	
			4 c	key biodiversity area	spatial	
		F	4d	distance to village	spatial	
		D	4e	residential area	spatial	
			4 f	distance to forest	spatial	
			4 g	relocated during conflict	literature	fixed CPT (UNHCR, 2015)
			4 h	herbal medicine market	primary	fixed CPT
			4i	access to modern medicine	primary	fixed CPT
	Inter-mediary node	S	4 j	land management	triangulated	based on 4b
			4 k	wild plant diversity	mixed	– 4 c: if yes *high*, if no *medium* - 4 j: if intensive *−25*, if extensive *+25*
			4 l	supply of medicinal plants	triangulated	- based on 4a - 4 k: if high *+50*, if medium *−25*
		F	4 m	physical access	household survey	
			4 n	herbal knowledge	household survey	
			4o	flow of medicinal plants	triangulated	– 4 n: if many *high*, if few *high/medium*, if no *low* and *no change* later - 4 m: if good *+25*, if low *−25*
		D	4p	use for sale	triangulated	based on 4 h and 4 n
			4q	trust in herbal medicine	household survey	
			4 r	frequency of use	household survey	
			4s	current use	mixed	- *equals* 4 r - 4p: if yes *+50*, if no *−25*
			4 t	expected future need	triangulated	based on 4e and 4 g
			4 u	future value	mixed	- *equals* 4 r - 4 t: if more *+50*, if less *−50*
			4 v	demand for medicinal plants	mixed	- *equals* 4s (if high *+50*) - 4 u: if high *+50*, if low *−25* - 4i: if yes *−25*, if no *+25*
	End node	O	4 w	medicinal outcome	expert survey	see 1q

(*Continued*)

Table A2. (Continued).

ES model	Node type	S/F/D/O	Code	Node	Type of data (spatial, census, literature, primary)	Additional information (rules or references) for filling conditional probability tables (CPT)
Biodiversity	Root node	S	5a	land use	spatial	
			5b	distance to forest	spatial	
			5 c	key biodiversity area	spatial	
			5d	zoning	spatial	
		F	5e	distance to village	spatial	
			5 f	distance to agriculture	spatial	
		D	5 g	township	spatial	
			5 h	tourism development	primary	fixed CPT
			5i	planted crop	spatial	
			5 j	residential area	spatial	
			5 k	intrinsic value	primary	fixed CPT
	Inter-mediary node	S	5 l	biodiversity management	triangulated	based on 5d
			5 m	wild species diversity	triangulated	- based on 5a - 5 l: if yes *+50*, if no *−50* - 5 c: if yes *+25*, if no *−25* - 5b: if low *100 very high*, if medium *+25*
			5 n	agrobiodiversity	triangulated	based on 5a
			5o	supply of biodiversity	mixed	- *equals* 5 m - 5 n: if >5 + 50, if 2–5 + *25*
		F	5p	access to wild products	household survey	
			5q	flow of pollination services	literature	FAO (1995)
			5 r	flow of biodiversity	mixed	- *equals* 5p - 5q: if good *+25*, if limited *−25*
		D	5s	agriculture, forest or fishery	census	
			5 t	pollination	literature	FAO (1995)
			5 u	increased crop production	literature	FAO (1995)
			5 v	input to livelihood	mixed	– 5 h, 5s, 5 u: if 3x yes *100 high*, if 2x *75*, if 1x *25*, if 3x *no*
			5 w	ntfps	triangulated	based on 5i
			5x	use of wild products	triangulated	- based on 5 w - 5 j: if rural *+25*, if urban *−25*
			5y	demand for biodiversity	mixed	- based on 5x - 5 v: if high *+50*, if low *−25* - 5 k: if high *+25*, if low *−25*
	End node	O	5z	biodiversity outcome	expert survey	see 1q

(*Continued*)

Table A2. (Continued).

ES model	Node type	S/F/D/O	Code	Node	Type of data (spatial, census, literature, primary)	Additional information (rules or references) for filling conditional probability tables (CPT)
Climate regulation	Root node	S	6a	land use	spatial	
		F	6b	distance to village	spatial	
		D	6 c	residential area	spatial	
			6d	distance to bare land	spatial	
			6e	township	spatial	
	Inter-mediary node	S	6 f	net ghg emissions	triangulated	based on 6a
			6 g	carbon storage	literature	Bhat et al. (2003), Donato et al. (2011), Kongsager et al. (2013)
			6 h	non ghg emissions	triangulated	based on 6a
			6i	landscape tree cover	literature	
			6 j	contribution to mitigation	triangulated	- *mean* of 6 f and 6 g
			6 k	air quality	triangulated	
			6 l	supply of climate regulation	mixed	– 6 k: if good *very high*, if medium *high/medium*, if low *low* - 6 j: if very high *+50*, if high *+25*, if low *−25*, if no *−50*
		F	6 m	flow of microclimate	mixed	based on 6b
		D	6 n	value of microclimate	triangulated	- *equals* 6d - 6 c: if urban *+50*, if rural *−50*
			6o	number of ngos	census	
			6p	climate risk awareness	mixed	based on 6o
			6q	agricultural sector jobs	census	
			6 r	demand for climate regulation	mixed	- based on 6 n - 6p: if aware *+50* - 6q: if yes *+50*, if no *−25*
	End node	O	6s	climate outcome	expert survey	see 1q

(*Continued*)

Table A2. (Continued).

ES model	Node type	S/F/D/O	Code	Node	Type of data (spatial, census, literature, primary)	Additional information (rules or references) for filling conditional probability tables (CPT)
Water regulation	Root node	S	7a	residential area	spatial	
			7b	land use	spatial	
			7 c	soil type	spatial	
			7d	slope	spatial	
			7e	wet months	spatial	
			7 f	annual precipitation	spatial	
		F	7 g	zoning	spatial	
			7 h	township	spatial	
		D	7i	type of crop	spatial	
	Inter-mediary node	S	7 j	water pollution	triangulated	- based on 7b (mining, built-up > oil palm > rubber, paddy, bare > rest) - 7a: if urban *+25*
			7 k	water purification	literature	Saad et al. (2013)
			7 l	water retention	triangulated	- based on 7b - 7e: if 1–3 *– 50*, if 4–6 *– 25* –7d: if slope *–25* - 7 c: if fluvisol/nitisol *+25*, if acrisol/gleysol *–25*
			7 m	water quality	mixed	– 7 j: if yes *polluted*, if no *good* - 7 k: if high *+50*, if medium *+25*
			7 n	water quantity	mixed	- based on 7 f - 7 l: if high *+50*, if low *–50*
			7o	supply of water	mixed	- *equals* 7 n - 7 m: if good *+25*, if polluted *–50*
		F	7p	watershed protection	triangulated	based on 7 g
			7q	water source at home	census	
			7 r	flow of water	mixed	- based on 7q - 7p: if yes *+25*, if no *–25*
		D	7s	population density	census	
			7 t	household water use	mixed	based on 7s
			7 u	irrigation management	triangulated	based on 7i
			7 v	crop water requirement	literature	calculated with Cropwat (FAO)
			7 w	agricultural water use	mixed	- *equals* 7 v - 7 u: if yes *+50* and *++50*
			7x	demand for water	triangulated	- *equals* 7 t - 7 w: if high *+all*, if medium *+50*, if low *+25* - potential additional demand (all): *+25*
	End node	O	7y	water outcome	expert survey	see 1q

(*Continued*)

Table A2. (Continued).

ES model	Node type	S/F/D/O	Code	Node	Type of data (spatial, census, literature, primary)	Additional information (rules or references) for filling conditional probability tables (CPT)
Environ-mental education	Root node	S	8a	land use	spatial	
			8b	zoning	spatial	
		F	8 c	township	spatial	
			8d	residential area	spatial	
		D	8e	presence of companies	primary	fixed CPT
	Inter-mediary node	S	8 f	cultural importance	household survey	
			8 g	traditional knowledge	triangulated	
			8 h	community groups	triangulated	based on 8a and 8b
			8i	presence of ngos	mixed	based on 8b
			8 j	children's education	triangulated	– 8 f: if high *yes*, if medium *50/50*, if low *no* - 8 g: if high *+25*, if low *−25*
			8 k	knowledge exchange	triangulated	– 8 h: if formal *regularly*, if informal *50/50*, if no *never* - 8 g: if high *+25*, if low *−25*
			8 l	local knowledge system	triangulated	- *equals* 8 k - 8 j: if part *+50*, if not part *−50*
			8 m	vocational trainings	triangulated	- based on 8a and 8b - 8i: if yes *+25*, if no *−25*
			8 n	supply of education	mixed	– 8 m: if yes *very high/high*, if no *no* - 8 l: if strong *+25* and *++25*, if medium *+25*
		F	8o	internet at home	census	
			8p	poverty level	census	
			8q	local terms	triangulated	based on 8d
			8 r	flow of education	triangulated	– 8d: urban *50/25/25*, rural *25/50/25* - 8p: if poor *−25*, if non-poor *+25* - 8q: if different *−25*
		D	8s	agricultural sector jobs	census	
			8 t	number of ngos	census	
			8 u	nature-related job opportunities	mixed	- based on 8 t and 8e
			8 v	livelihood knowledge needs	mixed	– 8s: if yes *yes*, if no change accordingly: - 8 u: if many *75 yes*, if some *50 yes*, if limited *25 yes* - 8d: if rural *+25*
			8 w	interest in nature	triangulated	based on 8d
			8x	demand for education	mixed	– 8 v: if yes *very high/high*, if no *low/no* - 8 w: if high *+50*, if medium *+25*
	End node	O	8y	education outcome	expert survey	see 1q

(*Continued*)

Table A2. (Continued).

ES model	Node type	S/F/D/O	Code	Node	Type of data (spatial, census, literature, primary)	Additional information (rules or references) for filling conditional probability tables (CPT)
Cultural identity	Root node	S	9a	land use	spatial	
			9b	township	spatial	
			9 c	land use change	spatial	
		F	9d	relocation site	literature	fixed CPT (UNHCR, 2015)
			9e	zoning	spatial	
			9 f	distance to village	spatial	
		D	9 g	township	spatial	
			9 h	cultural products	primary	based on land use
			9i	residential area	spatial	
	Inter-mediary node	S	9 j	traditional land use	triangulated	based on 9a
			9 k	traditional products	triangulated	based on 9a
			9 l	old cultural value	mixed	based on 9 j and 9 k
			9 m	new value	triangulated	based on 9a
			9 n	cultural value	mixed	- *equals* 9 l - 9 m: if yes *+50*
			9o	mobile connection	census	
			9p	cultural stability	triangulated	– 9 c: if yes *low*, if no *high* - 9d: if yes *−100*, if no *+50* - 9o: if yes *−50*, if no *+100*
			9q	supply of cultural identity	mixed	- *equals* 9 n - 9p: if high *+25*, if low *−25*, if very low *−50*
		F	9 r	access to ancestral lands	triangulated	based on 9e and 9d
			9s	access to products	household survey	
			9 t	flow of cultural identity	mixed	- if 2x yes *high*, if 1x yes *medium*, if 2x no *low* - 9s: if yes *+25* - 9 r: if no *−25*
		D	9 u	population density	census	
			9 v	yearly use of products	household survey	based on 9 h
			9 w	demand for cultural products	triangulated	- *equals* 9 v - 9 u: if > 100 + *25*, if < 50 − *25*
			9x	value of nature in culture	triangulated	based on 9i
			9y	demand for cultural identity	mixed	- *equals* 9 w - 9x: if high *++25*, if low – *25*
	End node	O	9z	cultural outcome	expert survey	see 1q

Appendix IV. Questionnaire for household survey

Mélanie Feurer, 17/01/2020

ES-Survey Tanintharyi

Date: ____________ Location: ____________ No: ____________

Name: ____________ Ethnic: ____________ Gender: ____________

1. Which of the following types of lands do you have / use?

	land use	tenure			distance	comments
		no	yes	area (ac)		
	Intact forest					
	Degraded forest					
	Mangrove					
	Betelnut					
	Cashew					
	Lime					
	Mixed plantation					
	Rubber					
	Oil palm					
	Paddy rice					
	Upland rice					

2. How do the following lands contribute to the food you consume in your household?

land use	a) contribution			b) seasonal		comments
	enough	additional	no food	yes	no	
Intact forest						
Degraded forest						
Mangrove						
Mixed plantation						
Rubber						
Oil palm						
Paddy rice						
Upland rice						

3. How is the price of the following foods to buy on the market?

i) Rice ▫ high ▫ medium ▫ low
ii) Vegetables ▫ high ▫ medium ▫ low
iii) Fruit ▫ high ▫ medium ▫ low
iv) Spices ▫ high ▫ medium ▫ low
v) Fish ▫ high ▫ medium ▫ low
vi) Meat ▫ high ▫ medium ▫ low

4. a) Which price do you currently get for selling the following products?

b) Compared to other products, do you think this price is high / medium / low?

c) Is the price stable or fluctuating?

product	a) current selling price	b) price range			c) stability	
		high	medium	low	yes	no
Timber						
NTFPs						
Rice						
Rubber						
Palm fruit						
Betelnut						
Cashew						
Lime						
Pepper						
Fruit						
Vegetables						
Fish						
Crab						

5. In your culture, how often do you use the following products?

i) NTFPs ▫ 1/w ▫ 1/m ▫ 3-4/y ▫ never
ii) Rice ▫ 1/w ▫ 1/m ▫ 3-4/y ▫ never
iii) Betelnut ▫ 1/w ▫ 1/m ▫ 3-4/y ▫ never
iv) Cashew ▫ 1/w ▫ 1/m ▫ 3-4/y ▫ never
v) Coconut ▫ 1/w ▫ 1/m ▫ 3-4/y ▫ never
vi) Toddy ▫ 1/w ▫ 1/m ▫ 3-4/y ▫ never
vii) Fruits ▫ 1/w ▫ 1/m ▫ 3-4/y ▫ never
viii) Snails ▫ 1/w ▫ 1/m ▫ 3-4/y ▫ never
other: ______________________________ ▫ 1/w ▫ 1/m ▫ 3-4/y ▫ never

6. How much fuelwood can you get from the following lands and how would you rate the quality?

land use	a) quantity (1=no, 5=very high)					b) quality		
	5	4	3	2	1	high	medium	low
Intact forest								
Degraded forest								
Mangrove								
Mixed plantation								
Rubber								
Oil palm								

7. a) How many medicinal plants do you know? ▫ > 10 ▫ 5 - 10 ▫ less than 5 ▫ none

b) Do you trust in herbal medicine? ▫ yes ▫ no

c) How often do you use herbal medicine? ▫ often ▫ sometimes ▫ never

d) How far is the closest forest? ▫ < 2 miles ▫ 2 miles or more

e) If you lived closer to a forest, would you use more medicinal plants? ▫ yes ▫ no

8. a) Do you participate in farmer / forest / environment groups within the community? □ yes □ no

b) group	c) formal	d) How often do you meet and exchange information?
	□ yes □ no	
	□ yes □ no	
	□ yes □ no	

9. a) Are there NGOs present in your village / village tract? □ yes □ no
   b) Are there companies present in your village / village tract? □ yes □ no
   c) Did you ever have contact with staff from the FD or AD? □ yes □ no
   d) Did you ever have the opportunity to participate in a training on farming or forests? □ yes □ no
   If yes, please fill in this table:

a) trainer	b) institution			c) topic
	NGO	Company	FD/AD	

10. a) Are you interested in nature? □ yes □ no
    b) How do you rate the value of nature in your culture? □ very high □ high □ medium □ low

11. a) Do you get the following products from your lands or from the market?
    b) What is the maximum distance from your house that you would walk to collect them?

Rice	a) □ own land □ market	b)________________
Betelnut	a) □ own land □ market	b)________________
Fruit	a) □ own land □ market	b)________________
Fuelwood	a) □ own land □ market	b)________________
Vegetables	a) □ own land □ market	b)________________
Cashew	a) □ own land □ market	b)________________
NTFPs	a) □ own land □ market	b)________________
Medicine	a) □ own land □ market	b)________________

Appendix V. Validation process

Based on a standardized survey including pictures of the model structures, the twelve experts had to rate, on a scale from 1 to 5, the supply and demand and, on a scale from 2 to 4, the flow of each ES based on the direct parent nodes or, where needed for contextual reasons, the nodes above. Table A3 below is a summary of the differences (in %) found between the models and the expert responses. We calculated the differences by comparing the mean ratings of the experts with the weighted average of model output probabilities.

Appendix VI. Input variables and data sources

Table A3. Summary of validation results including the calculated differences in % between modelled supply, flow and demand values and expert estimations.

	Supply		Demand		Flow		
	mean	sd	mean	sd	mean	sd	Total (mean)
Subsistence foods	−0.7	16.0	−13.0	13.0	−0.7	4.1	**−4.8**
Commercial products	14.9	29.9	−9.7	26.7	8.4	12.1	**4.5**
Fuelwood	−4.4	27.4	−8.6	5.9	3.8	12.7	**−3.1**
Medicinal plants	−39.4	27.8	−2.4	21.2	−2.3	9.1	**−14.7**
Biodiversity	−19.0	10.8	−15.0	10.8	15.0	9.8	**−6.3**
Climate	−17.8	20.9	−17.0	18.3	1.7	1.7	**−11.0**
Water	−14.2	32.0	−12.4	16.5	−4.5	15.9	**−10.4**
Environmental education	17.0	42.1	−7.8	26.1	−2.2	12.2	**2.3**
Cultural identity	−15.2	26.5	7.4	43.1	−2.5	8.6	**−3.4**
Total (mean)	**−8.8**		**−8.7**		**1.9**		**−5.2**

Sd = standard deviation

Table A4. List of input variables (root nodes), states and data sources.

Variable (node)	Classes (states)	% in Tanintharyi (calculated in ArcGIS)	Integration in ES models	Sources	Processing (in ArcGIS)
Land use	Intact forest Degraded forest Mangrove Mixed plantation Rubber Oil palm Paddy Bare Mining Built-up	49.6 27.6 6.1 2.3 2.0 2.5 3.8 4.6 0.1 1.4	Subsistence foods (SF), Commercial products (CP), Fuelwood (FW), Medicinal plants (MP), Biodiversity (BD), Climate regulation (CR), Water regulation (WR), Environmental education (EE), Cultural identity (CI)	Connette et al. (2016) (16 land cover classes), Nomura et al. (2019) (oil palm), LaJeunesse Connette et al. (2016) (mining)	a) reclassify 16 land use classes into 9 by combining forest types (lowland, broadleaf, upland) and mangrove (intact, degraded) b) add updated oil palm data (multiply and reclassify) c) add mining data as additional class (multiply and reclassify)
Zoning	Protected area Oil palm concession Mining concession Special Economic Zone Community forestry Other	4.5 7.5 0.1 0.5 0.3 87.1	CP, FW, MP, BD, WR, EE, CI	WCS (Protected areas), Nomura et al. (2019) (oil palm concessions), OneMap Myanmar (2018) (CF) DOM (2015) (mining concessions), MIMU (2020) (SEZ)	- delete planned protected areas - merge all into a raster - no data = other
Key bio-diversity area	Yes No	48.7 51.3	MP, BD	BirdLife International (2010)	
Land use change	Yes No	52.5 47.5	CI	Schmid (2018)	
Slope	Flat Slope	57.0 43.0	CP, FW, WR	NASA (2001)	- classify flat/slope if < 30% >
Soil type	Acrisols Gleysols Fluvisols Nitisols	56.7 8.5 0.2 34.5	CP, WR	FAO (2007)	

(*Continued*)

Table A4. (Continued).

Variable (node)	Classes (states)	% in Tanintharyi (calculated in ArcGIS)	Integration in ES models	Sources	Processing (in ArcGIS)
Wet months	1–3 4 – 6 > 6	1.4 84.7 13.9	CP, WR	WorldClim (2012)	- count months with rainfall - classify
Annual precipitation	> 4000 mm 3000–3999 mm 2000–2999 mm 1000–1999 mm < 1000 mm	14.8 48.9 28.9 7.2 0.2	WR	WorldClim (2012)	- classify
Township	Bokpyin Dawei Kawthoung Kyunsu Launglon Myeik Palaw Tanintharyi Thayetchaung Yebyu	14.0 16.8 6.1 9.7 1.9 2.9 5.9 27.5 5.1 10.1	SF, CP, FW, BD, CR, WR, EE, CI	MIMU (2020) (townships) DOP (2014) (census)	
Residential area	Rural Urban	96.8 3.2	SF, CP, FW, MP, BD, CR, WR, EE, CI	Worldpop (2013)	- classify rural/urban if < 4 pph >
Distance to village/forest/agriculture/bare land	low medium high		SF, FW, MP, BD, CR, CI	Connette et al. (2016)	- Euclidean distance - classify according to ecosystem service

Paper V: Ecosystem services for local stakeholders: Mapping supply, demand, and flow – and identifying mismatches – at regional scale in Myanmar

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Ecosystem services for local stakeholders: Mapping supply, demand, and flow – and identifying mismatches – at regional scale in Myanmar

Abstract

Mapping ecosystem service (ES) supply, demand, and flow – and identifying supply/demand mismatches – has become a focus of ES research and has benefitted from recent advances in modelling techniques and their combination with Geographic Information Systems. But few studies have been done in data-scarce tropical forest frontiers and these were limited in terms of area, land uses, and number and types of ES. Aiming to evolve contemporary approaches, we used Bayesian networks to model and map nine ES across Myanmar's Tanintharyi Region for local stakeholders. We found that while there is a high supply of multiple ES at regional level, demand for ES in urban and rapidly developing agricultural areas is not fully covered. Further, we identified a clear connection between land tenure and ES outcomes for rural communities. Agricultural concessions and protected areas with restricted access for the local population were related to lower ES flows and more supply/demand mismatches than community forests or untenured land. For future research on local ES outcomes in tropical forest frontiers, we recommend combined mismatch and flow analyses under consideration of tenurial rights.

Keywords

Ecosystem services, balance, access, Bayesian networks, frontier landscape, Tanintharyi

Highlights

- Combining Bayesian networks with GIS, we modelled nine ecosystem services (ES)
- We mapped ES supply, demand, and flow in a tropical forest frontier landscape in Myanmar
- Supply/demand are mismatched in urban and rapidly developing agricultural areas
- Land tenure and zoning affect ES flows and final ES outcomes for local stakeholders
- Mosaic landscapes are important for providing multiple ES and human well-being

1 Introduction

Human–nature interrelations are becoming ever more apparent in the joint search for solutions to global goals of biodiversity conservation, climate change mitigation, economic development, and human well-being (UN, 2015). In forest frontier landscapes, trade-offs almost always occur in efforts to achieve both ecological and social goals, especially if policies fail to take a holistic approach. Within such landscapes, the concept of ecosystem services (ES) (Costanza et al., 2017) is highly useful for assessing the multiple benefits people obtain from different landscapes. First popularized in 1997 (Costanza et al., 1997), the concept was applied at a larger scale in the Millennium Ecosystem Assessment (MEA, 2005) and has since seen various adaptations. It has also evolved into further concepts, such as that of nature's contribution to people by the Intergovernmental Science–Policy Platform on Biodiversity and Ecosystem Services (Díaz et al., 2018). The ES concept nevertheless remains the most suitable way to assess local relations between humans and nature in an integrative way (Braat, 2018; Pandeya et al., 2016). Meanwhile, research on ES has made much progress on different valuation methods (Gómez-Baggethun et al., 2016) and on modelling and mapping (Willemen et al., 2015). Mapping is an important tool for policymakers to better understand the links between ecosystems, society, and human well-being (Burkhard and Maes, 2017). In the last decade, spatial assessments of ES have thus become increasingly relevant and have evolved by including demand (Schröter et al., 2012; Wolff et al., 2015) as well as flows (Bagstad et al., 2013; Baró et al., 2016; Schirpke et al., 2019).

While simple mapping methods showing ES provision scores by land cover type are particularly useful in data-scarce regions, they do not usually reflect the dynamics of supply and demand. More complex mapping has been done by Burkhard et al. (2012) including supply and demand for a variety of ES and land cover types based on expert valuation. Santos-Martín et al. (2019) mapped synergies and trade-offs for eight ES in Spain based on different indicators for each service. Other studies added the notion of ES flows, conceptualized as the access that leads to final ES outcomes [Anonymous, 2021]. Mapping ES supply, demand, and flow can inform policymakers of a potential mismatch in a certain area, through unsatisfied demand or overuse (Geijzendorffer et al., 2015). Several studies have mapped such mismatches between supply and demand (Baró et al., 2016; Burkhard et al., 2012; Chen et al., 2020). One of the most comprehensive studies so far mapped supply and flow of, and demand for, eight ES in the European Alps, and assessed the respective ES bundles (Schirpke et al., 2019). In tropical regions, recent notable mapping studies presented trade-offs between three services in Ecuador (Forio et al., 2020), (mis)matches and trade-offs in Brazil (Pinillos et al., 2020), and spatial equity in accessing services in ES hotspots in forested landscapes of Suriname (Ramirez-Gomez et al., 2020).

However, due to the inherent complexity of socio-ecological systems and data scarcity in many tropical regions, ES assessments in the tropics remain limited in terms of area, land uses, and number and types of services investigated. Furthermore, mapping studies have considered mostly ES that are important from a public perspective such as carbon sequestration, water regulation, food production, or recreation and tourism (Malinga et al., 2015). There is an inherent need to better include the perspective of local stakeholders such as smallholder farmers and forest-dependent people into the modelling and mapping process (Willemen et al., 2015), particularly in contested frontier regions.

In tropical forest frontier landscapes such as Myanmar's Tanintharyi Region, where overlapping land claims cause conflicts and hinder sustainable development planning (Schneider et al., 2020), spatial ES assessments can provide opportunities to identify local stakeholder needs and plan landscape development accordingly. In Tanintharyi, the remaining large, intact, and mostly undisturbed natural forest landscapes are under increasing pressure from infrastructure development, agricultural expansion, mining, and overuse (Alban et al., 2019; Lim et al., 2017). The situation is further aggravated by conflicting interests between local communities, the private sector, and government institutions. A global biodiversity hotspot

(Myers et al., 2000), Tanintharyi is increasingly characterized by large-scale oil palm concessions (Woods, 2016), private rubber plantations (Vagneron et al., 2017), and mining (LaJeunesse-Connette et al., 2016); it is also the location of a Special Economic Zone, with plans for development (Walsh, 2015). Priority issues at the global level include biodiversity and climate change mitigation, but local stakeholders may require different ES from land systems. In northern Tanintharyi, where rural communities use the land for shifting cultivation, mixed betelnut and cashew plantations, rubber plantations, and to gather non-wood forest products (NWFP), ES associated with these land uses were found to be essential for the well-being of the inhabitants (Feurer et al., 2019). Unfortunately, local communities have little say when it comes to the use of land and are thus limited in their access to ES, especially in zones allocated to government entities or concessionaires (Feurer et al., 2019). Understanding spatial ES outcomes for local stakeholders by analysing supply, demand, and flow – and to what extent they are matched or mismatched – is a crucial step towards formulating adequate policies for more sustainable landscapes and human well-being.

Until now, few studies have attempted to map both ES supply and demand in tropical forest frontiers, and none have provided details on actual ES outcomes for local stakeholders under consideration of spatial supply/demand (mis)matches and access to provisioning areas, which is a particularly sensitive issue in forest frontiers (Ramirez-Gomez et al., 2020).

Recognizing this gap, the objective of this study is to map the supply, demand, and flow of nine (provisioning, regulating, and cultural) ES and to identify spatial supply/demand (mis)matches in a tropical frontier landscape. By using previously developed ES supply, demand, and flow models [Anonymous, 2021] and incorporating a variety of ecological and socio-economic data sets from Tanintharyi Region, qualitative data from local communities, and field observations, this study aims to assess ES outcomes and mismatches with a focus on local stakeholders across the region.

The study was guided by the following research questions:

a) What is the regional extent and spatial distribution of the supply, demand, and flow of nine ES for local stakeholders?
b) What are the supply and demand balances for nine ES across Tanintharyi Region?
c) How many ES mismatches are found across the region and how intense are they? How can they be contextualized considering land use and zoning?

2 Material and Methods

2.1 Study area

Tanintharyi Region in Myanmar's South is situated between Mon State in the North, Thailand in the East and South, and the Andaman Sea in the West. It encompasses 4.3 million ha of land including a large number of islands. Land cover is mostly forest along the hilly areas near the Thai border, with degraded forest patches and both large-scale (oil palm, rubber) and small-scale (rubber, mixed) plantations near the roads (Figure 1). Oil palm plantations are found mainly in the southern part near Kawthoung, while rubber plantations are concentrated around Dawei in the northern part. Mangrove forests are most prevalent near Myeik and in the archipelago. Paddy rice production is common in the flat areas near villages and roads. Most villages are located near the main roads, with most of Tanintharyi's 1.4 million-strong population (DOP, 2014) living in these areas.

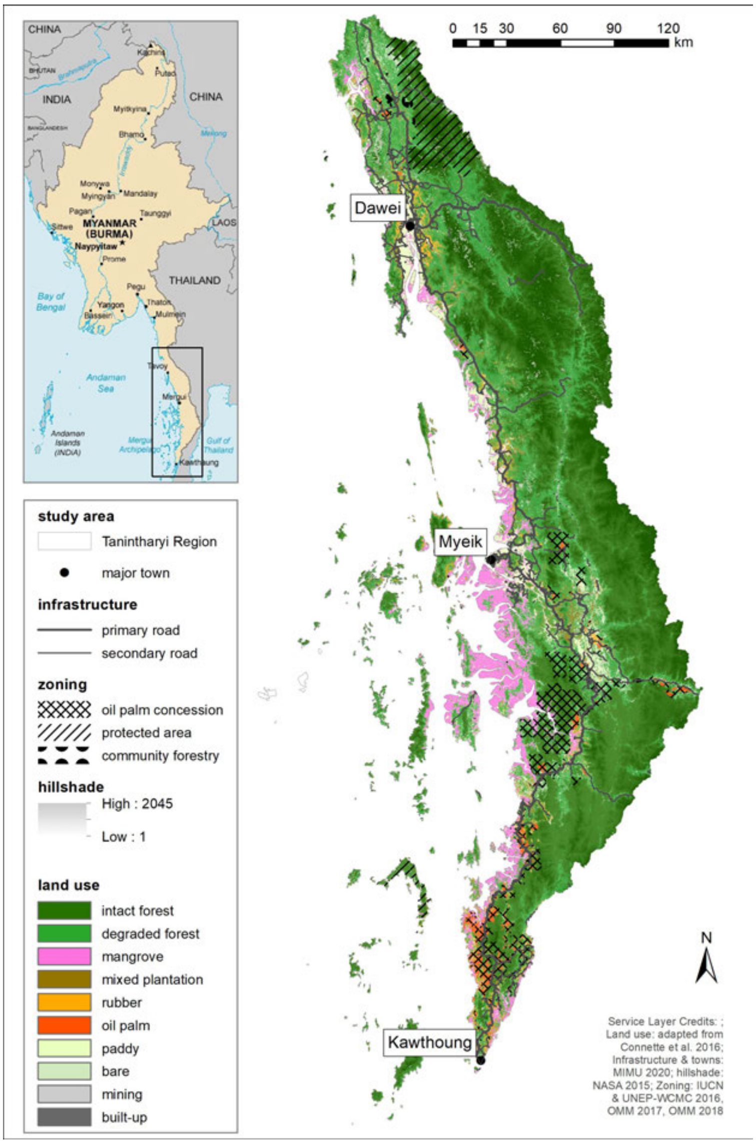


Figure 1 Map of the study area (land use adapted from Connette et al. [2016])

Tanintharyi Region is one of the focal areas of the OneMap Myanmar initiative, which aims to improve country-wide accuracy and availability of data on land use, land cover, and land tenure by combining official sources with participatory mapping and public contributions. Thus, Tanintharyi has a relatively good availability of land use data compared to other regions of Myanmar. There are currently two protected areas (PA) (Tanintharyi Nature Reserve and Lampi National Park [NP]); a further two were proposed in 2002 but are contested due to the top-down approach of the proposals (Lenya NP and Tanintharyi NP). In addition, there are a total of 69 formal community forests (CF) (OMM, 2018) as well as several informal community protected areas. In another development, concession lands have been granted to various companies since the early nineties, with 7.5% and 0.1% of Tanintharyi's land area under oil palm and mining concessions, respectively [Anonymous, 2021]. The remaining land is under the relevant government departments, where local land users can apply for formal user rights. However, much of the cultivated land, including shifting cultivation areas, is managed through customary rights.

2.2 Theoretical framework

This research builds on current understandings of the ES concept (Costanza et al., 2017) and recent advances in ES mapping (Burkhard and Maes, 2017; Willemen et al., 2015). The underlying idea is that final ES outcomes are influenced by the supply and flow of, and demand for, such services ([Anonymous, 2021];

Geijzendorffer et al., 2015; Schirpke et al., 2019). While *ES supply* encompasses the goods and services provided by nature, *ES demand* refers to the use and perceived value of these goods and services. Finally, *ES flow* refers to people's access to the goods and services they require. We consider ES supply to be the result of biophysical factors such as vegetation, climate, soil type or slope, and land management aspects including land use, agricultural practices, or chemical inputs. ES demand, on the other hand, is the result of the perceived benefits, including non-material and intrinsic values, and actual use by the local people based on population density and the local availability of substitutes, e.g. modern medicine instead of traditional herbal remedies. We consider ES flow to represent people's access to service providing areas, consisting of physical accessibility based on distance, institutional accessibility based on zoning (PA, CF, concession), and tenurial rights.

Nine ES were selected based on the Common International Classification of Ecosystem Services classes (Haines-Young and Potschin, 2018), with adaptations to the local context. The main selection criteria were: coverage of at least one provisioning, regulating, and cultural service, a link to dominant land uses in the study area, relevance for local stakeholders (based on a ranking exercise in three villages), secondary data availability, suitability for modelling, and relevance for policymakers (based on a literature review). The selected ES are: subsistence foods, commercial products, fuelwood, medicinal plants, biodiversity, climate regulation, water regulation, environmental education, and cultural identity.

2.3 ES models

Bayesian networks (BN), which have gained attention in ES modelling and mapping (Burkhard and Maes, 2017), are probabilistic models resting on causal dependencies (Kjærulff and Madsen, 2008). They include one or several root nodes (input variables), structuring intermediary nodes, and end or target nodes (output variables). BN are particularly useful in data-scarce regions; advantages include their ability to integrate different types of data and knowledge sources as well as their handling of uncertainties by operating with probabilities. These features contribute to the qualities recommended by Willemen et al. (2015) for mapping ES: robustness, transparency, and stakeholder relevance. We adopted previously developed BN [Anonymous, 2021] and updated them with secondary data on Tanintharyi Region (see section 2.4.1) using Netica commercial software (version 6.05). The models had been developed in a comprehensive iterative process of several steps and three main phases: defining model structures, construing conditional probabilities, and calibrating and validating final models. The process was grounded on a comprehensive literature review and three months of field research between 2017 and 2020 by the first author. The field research included transect walks; field observations and focus group discussions in eight villages in three townships; a household survey (n=40); and 15 in-depth interviews with local experts from non-governmental organizations, civil society, and research institutions active in the study area. More details are found in [Anonymous, 2021]. The final BN thus incorporate various data types including available geodata, a population census, and qualitative data. Each of the nine BN had the end nodes 'supply' and 'demand' with five values on a scale of 1 (very low) to 5 (very high), as well as 'flow' with three respective values from 1 (low) to 3 (high). The main input variables included in the models are listed in Table 1. The complete BNs are displayed in the Annex.

Table 1 Main model variables considered as determinants for supply, demand, and flow in relation to nine ecosystem services

Ecosystem service	Supply variables	Demand variables	Flow variables
Subsistence foods	land use	land use (food type) population density residential area	distance to village
Commercial	land use	land use (type of product)	township (means of transport)

products	slope soil type wet months	population density residential area township (employment rate)	zoning
Fuelwood	land use	population density residential area township (fuel type)	distance to village slope zoning
Medicinal plants	key biodiversity area land use zoning (land management)	access to modern medicine distance to forest herbal medicine market population density relocation during conflict residential area	distance to village herbal knowledge
Biodiversity	distance to forest key biodiversity area land use zoning (land management)	land use population density residential area township (employment sector)	distance to agriculture distance to village
Climate regulation	land use	distance to bare land population density residential area township (employment sector)	distance to village
Water regulation	annual precipitation land use residential area (pollution) slope soil type wet months	land use (type of product) population density township (water source)	township (water source) zoning (watershed protection)
Environmental education	land use zoning (vocational trainings)	population density residential area presence of companies township (employment sector) township (number of NGOs)	residential area township (internet)
Cultural identity	land use land use change relocation during conflict township (mobiles phones)	land use (cultural products) population density residential area	distance to village zoning

Certain limitations of the models relating to representativeness across the region must be acknowledged. Reasons for these limitations include the vastness of the area investigated, the limited availability of data, the low accessibility of some areas of the region, and the high diversity in both land use and culture. While the models take the perspective of local stakeholders, notably rural communities, the perception of certain minority groups are not fully accounted for. These include, among others, internally displaced people living in the Tanintharyi hills, the Moken living on the sea, and migrant workers staying in concession areas.

2.4 Mapping process

2.4.1 Data sources and processing

The ES maps produced are based on currently available secondary data for the study region as well as primary data collected for this research and included in the BN. For the selection of the most accurate and recent data for this study, the following criteria were used: Availability (published or made available by the OneMap Myanmar project), scope (covering the entire Tanintharyi Region), date (most recent), and accuracy (according to the authors' knowledge on the situation on the ground).

All data sets were pre-processed in ArcGIS (V 10.6.1) to fit the same extent, include only relevant classes, and show consistency with the categories used in the ES models. All vector data were first converted to raster data. At the end, all raster files were stored in .tif format and clipped to the extent of the land use raster with the same resolution as the original raster (31m x 31m). Table 2 lists all data sets underlying the ES models, the original sources, and the relevant pre-processing that was done.

Table 2 List of spatial data sets, sources, and pre-processing steps carried out in ArcGIS (V 10.6.1)

Data set	Subset	Source(s)	Pre-processing
Land use	All land use classes	Connette et al. (2016)	• Reclassify 16 land cover classes into 9 land use classes → *landuse9*
	Oil palm (planted)	Nomura et al. (2019)	• Reclassify to oil palm and built-up • Multiply with *landuse9* and reclassify (rubber where no oil palm planted in second data set) → *landuse9_op*
	Mining areas	LaJeunesse-Connette et al. (2016)	• Reclassify (yes, no) • Multiply with *landuse9_op* and reclassify → *landuse10*
Zoning	Protected areas	IUCN and UNEP-WCMC (2016)	• Delete features (proposed protected areas) • Reclassify (yes, no)
	Community forests	OMM (2018)	• Reclassify (yes, no)
	Mining concessions	DOM (2015)	• Delete feature (large overlapping concession area) • Reclassify (yes, no)
	Oil palm concessions	OMM (2017)	• Reclassify (yes, no)
	SEZ	MIMU (2020)	• Combine all and reclassify
Key biodiversity area		BirdLife International (2010)	• Delete features (marine protected areas) • Reclassify (yes, no)
Slope		NASA (2015)	• Classify (flat if < 30%, slope if ≥ 30%)
Soil type		FAO (2007)	• Dissolve according to main soil types (acrisols, gleysols, fluvisols, nitrosols)
Precipitation		WorldClim (2012)	• Combine rasters (PPET 1 – 12) • Add field and calculate annual precipitation • Reclassify into 5 classes according to model
Wet months		WorldClim (2012)	• Calculate number of wet months • Add field and classify (1-3, 4-6, > 6)
Residential area		Worldpop (2016)	• Classify (rural if < 4 pph, urban if ≥ 4 pph)
Township		MIMU (2020)	
Population density	Village tracts	MIMU (2020)	• Add field in attribute table (pp/ha) • Classify (high if, medium if, low if)
Land use change		Schmid et al. (2021)	• Reclassify (yes, no)
Distance to agriculture		based on *landuse10* (see above)	• Agriculture = mixed plantation, oil palm, paddy, rubber • Calculate Euclidean distance for maximum of 10 km
Distance to forest		based on *landuse10* (see above)	• Forest = intact forest • Calculate Euclidean distance
Distance to bare land		based on *landuse10* (see above)	• Bare land = bare, mining, built-up, paddy • Calculate Euclidean distance for maximum of 3 km
Distance to village	Villages	MIMU (2020)	• Calculate Euclidean distance

2.4.2 Generating spatial model outputs

We used an online tool, gBay, (Stritih et al., 2020) to link the BN with the respective spatial data. BN models were uploaded to the tool in .dne format and spatial data were uploaded in .tif format. The gBay tool then connected the spatial data (raster cells) with the BN provided. In the spatial data sets (e.g. on land use or soil type), each pixel has a specific value (e.g. oil palm or nitisol), which provide the evidence for the BN's root nodes. We then calculated the rest of the nodes with the underlying conditional probabilities of the BN and produced as output the posterior probability of each possible value for the determined target nodes (ibid.). In our case, the target nodes were 'supply', 'demand', and 'flow' for all nine ES models. The supply and demand nodes had five values on a scale of 1 to 5, with 1 representing a very low outcome and 5 representing a very high outcome. Flow nodes had three respective values on a scale of 1 to 3. After updating the BN with spatial data (i.e. hard evidence), gBay produced outputs in the form of a multi-band raster (in .tif format) for each determined target node. The multi-band raster consisted of one band per value showing their respective probability and an additional band with the most likely state number of a target node. Further, gBay provided an additional multi-band raster including some basic statistics (Shannon's evenness index, mean, median, standard deviation). The Shannon's evenness index reflects a measure of uncertainty and ranges between 1 (uniform distribution and maximum uncertainty) and 0 (complete certainty) (ibid.).

2.5 Data analysis (outputs)

All outputs including nine ES supply, demand, and flow maps were closely examined for plausibility in ArcGIS by comparing them with the land use map and by zooming in on different areas. The analysis was supported by field observations by the first author of this paper from a total of three months spent in Tanintharyi Region between 2017 and 2020. To examine the supply, demand, and flow outputs, we operated with the most likely values (1 to 5 and 1 to 3, respectively) and additionally displayed evenness indices representing map uncertainties. Spatial statistics were calculated in ArcGIS. In addition to supply, demand, and flows, we calculated spatial supply/demand balances by subtracting the most likely demand value (between 1 and 5) from the most likely supply value (between 1 and 5). This led to ES balances in the range from -4 (demand > supply) to 4 (supply > demand). The resulting ES balance maps show positive values where potential supply outweighs local demand and negative values where demand exceeds supply. All negative balances were termed mismatches. Two sets of spatial analyses were done (frequency and intensity of mismatches) combining the nine ES balances. The frequency analysis consisted of summing up the number of ES presenting mismatches (balance < 0) per pixel, resulting in a theoretical range from 0–9. For the intensity analysis, we first inverted all negative balance values (balance < 0) into positive mismatch values (-4 to 4, -3 to 3, etc) to simplify further analyses. We then added the mismatch values of all nine ES, resulting in a theoretical range from 0–36. In a final step, these mismatches were contextualized in more detail for two case study sites where extensive combined field experience by several of the authors provided reliable insight. We selected the two sites based on the following criteria: representativeness of land uses, occurrence of mismatches, and contextual information from field research. Study site A is located in Yebyu township and represents a typical frontier landscape with high development and various zoning arrangements such as a PA, CFs, and an oil palm concession. Study site B encompasses the coastal town of Myeik and some surrounding areas including paddy fields and mangroves. Both study sites were analysed in terms of mismatch frequency and intensity. In order to contextualize them more accurately, the prevalence of mismatches for each ES was additionally calculated as the percentage of pixels (% per area) presenting a mismatch for the respective ES in each study site.

3 Results

3.1 Ecosystem services distribution in Tanintharyi Region

3.1.1 ES supply

We found that six of the ES investigated are in high supply in Tanintharyi, with values of ≥ 4 in most parts of the region (Figure 2). Forest-related ES including fuelwood, medicinal plants, biodiversity, climate regulation, and cultural identity are provided throughout Tanintharyi, with mean values of 4.5 and above and only a few low-supply areas near roads and towns. Our results reflect the strong link between land use and ES provision, even though the models included other variables. Interestingly, although PAs are often established with the goal of safeguarding regulating services, our findings indicate that ES supply for local stakeholders is just as high outside of PAs where forests remain intact. While the importance of forests and mangroves for providing regulating ES is evident, regulating ES are also to some extent provided in areas dominated by agricultural plantations. Subsistence foods are provided largely in agricultural areas but also in forested uplands, where shifting cultivation and gathering of NWFPs still play an important role. The lowest supply by far was found for commercial products (mean = 1.3), and they are confined to agricultural and coastal lands. In coastal areas, mangroves provide commercial products mainly in the form of fisheries. Although forests theoretically also provide timber and valuable NWFPs, rural communities make little commercial use of those due to legal restrictions and limited marketing opportunities. Another noteworthy result is shown for environmental education. Even though the provision of educational services is limited overall (mean = 1.4), opportunities for environmental or agricultural training exist both in sites with agricultural development and in PAs. The low supply of water regulation in the highly forested area to the east may be surprising. However, this can be explained by the comparatively low annual rainfall in the area covered in the model and does not appear to reflect land use or soil properties.

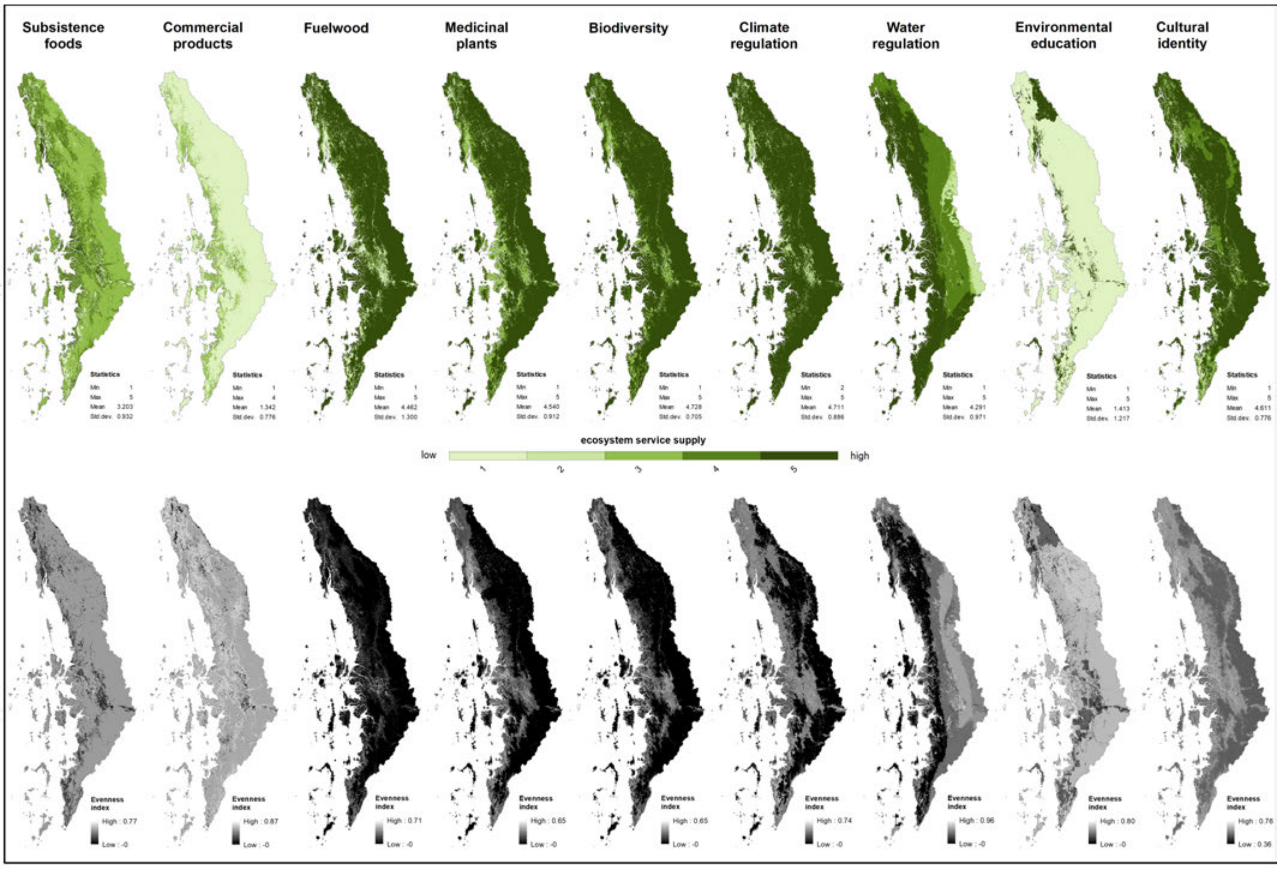


Figure 2 Above: Most likely ES supply values; below: corresponding evenness index (representing uncertainty of those values)

Across all ES, we found a relatively low mean evenness index of 0.37, indicating little variation in the probability distribution, hence the displayed values are relatively distinct from the other possible values. ES with high supply values such as fuelwood, medicinal plants, or biodiversity have few variations in their probability distributions and express more certainty. Similarly, for all ES, areas with higher supply values correspond to lower uncertainties. Accordingly, lower supply values are associated with higher uncertainties. The low supply values of commercial products and environmental education displayed are thus subject to high uncertainties with mean evenness indexes of 0.68 and 0.64, respectively. Due to these high variations in the distribution of probable values, it can thus be assumed that the maps of most likely values for commercial products and environmental education supply depict a rather conservative picture.

3.1.2 ES demand

We found that demand varies more than supply across the nine ES, particularly in remote areas (Figure 3). Higher population densities in urban and peri-urban areas prompt a higher demand for ecosystem goods such as subsistence foods, commercial products, fuelwood, and medicinal plants. Commercial products have a higher importance for the more market-oriented communities living near roads and towns. On the contrary, biodiversity is valued more by rural communities, which depend largely on agriculture and natural forests for their livelihoods. The overall high value of biodiversity (mean = 4.8) hinges on several variables included in the model: direct use of NWFPs, indirect benefits through pollination, and intrinsic value. After biodiversity, local communities also have a strong demand for environmental education (4.1), subsistence foods (3.9), water regulation (3.2), and fuelwood (3.1). The results for subsistence foods and fuelwood shows that although population density is low in remote areas, demand for ES remains high, as these communities have limited access to markets and are dependent on subsistence products with few alternatives. What may be surprising is the low result for both medicinal plants (1.1) and cultural identity (1.7). This reflects the increasingly available and attractive alternatives, including modern medicine but also cultural attractions that are unrelated to nature. On the other hand, interpretation of the results in very remote areas should take into account that internally displaced people and other remote communities were not involved in developing the model. This is underscored by the high uncertainty in demand values for cultural identity throughout the region, but particularly in remote areas.

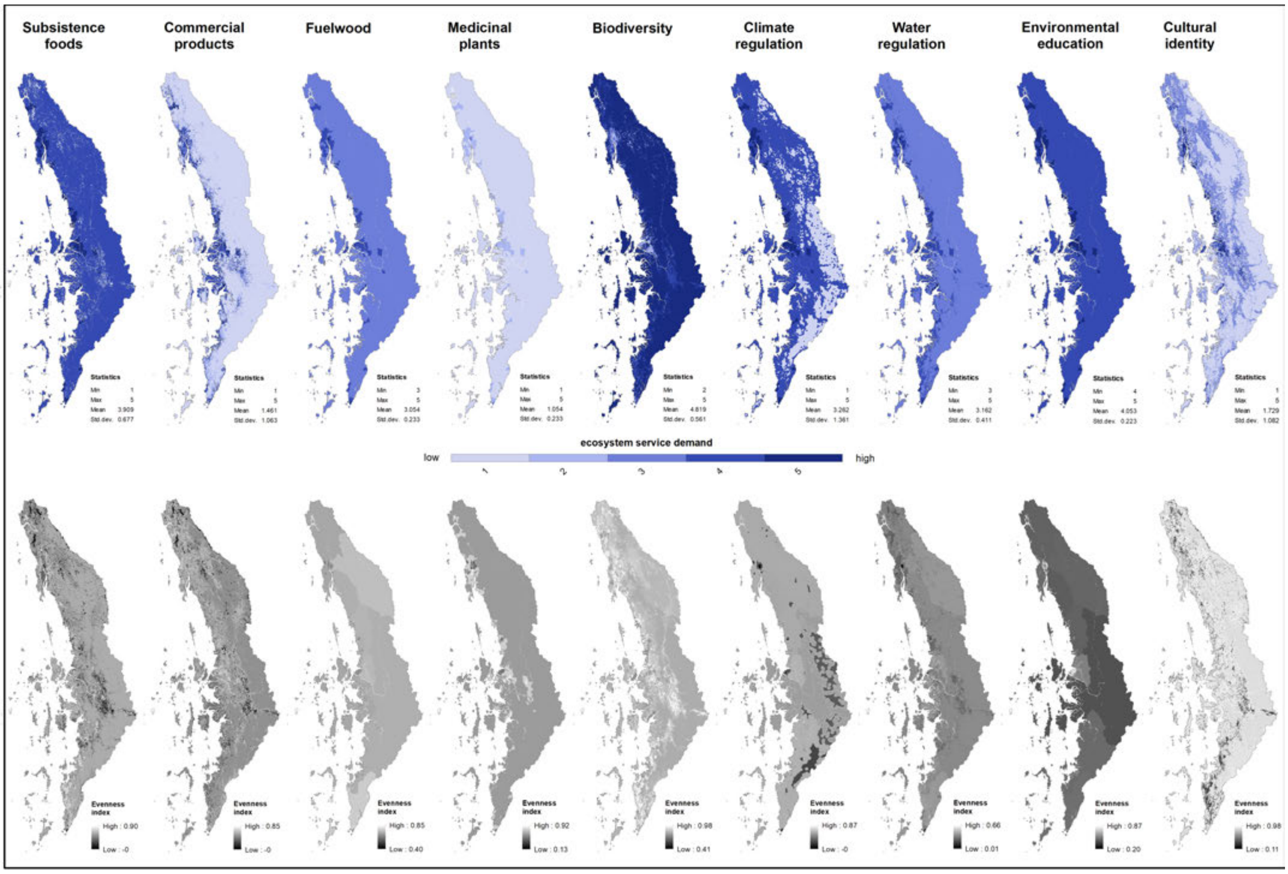


Figure 3 Above: Most likely values of demand for ES; below: corresponding evenness index (representing uncertainty of those values)

Compared with supply, we also found a higher overall evenness index across ES (mean = 0.63) and thus increased uncertainties related to the displayed demand values. A combination of high values and high certainty was found for environmental education, confirming the widespread demand also experienced during our field visits.

3.1.3 ES flow

Our results illustrate two clear patterns of ES flow. First, flow is higher near roads and settlements (Figure 4). Naturally, these areas are more accessible due to physical proximity, largely flat terrain, and existing infrastructure. Second, rural communities can readily make use of some ES including water, medicinal plants, and fuelwood, whereas access to other ES is considerably more restricted. Our results further illustrate the impact of zoning (PA, CF, concessions) on local ES flows. We found that local communities are often prohibited from entering PAs or concession lands, which limits their access to ES provided by these lands. The access limitations of concession lands located in the South are well visible for provisioning services including commercial products and fuelwood and even cultural identity. We found that PAs, while not restricting cultural identity, have a similar effect on provisioning services. Limited access to conserved forest lands can thus reduce local ES outcomes from these areas, at least temporarily.

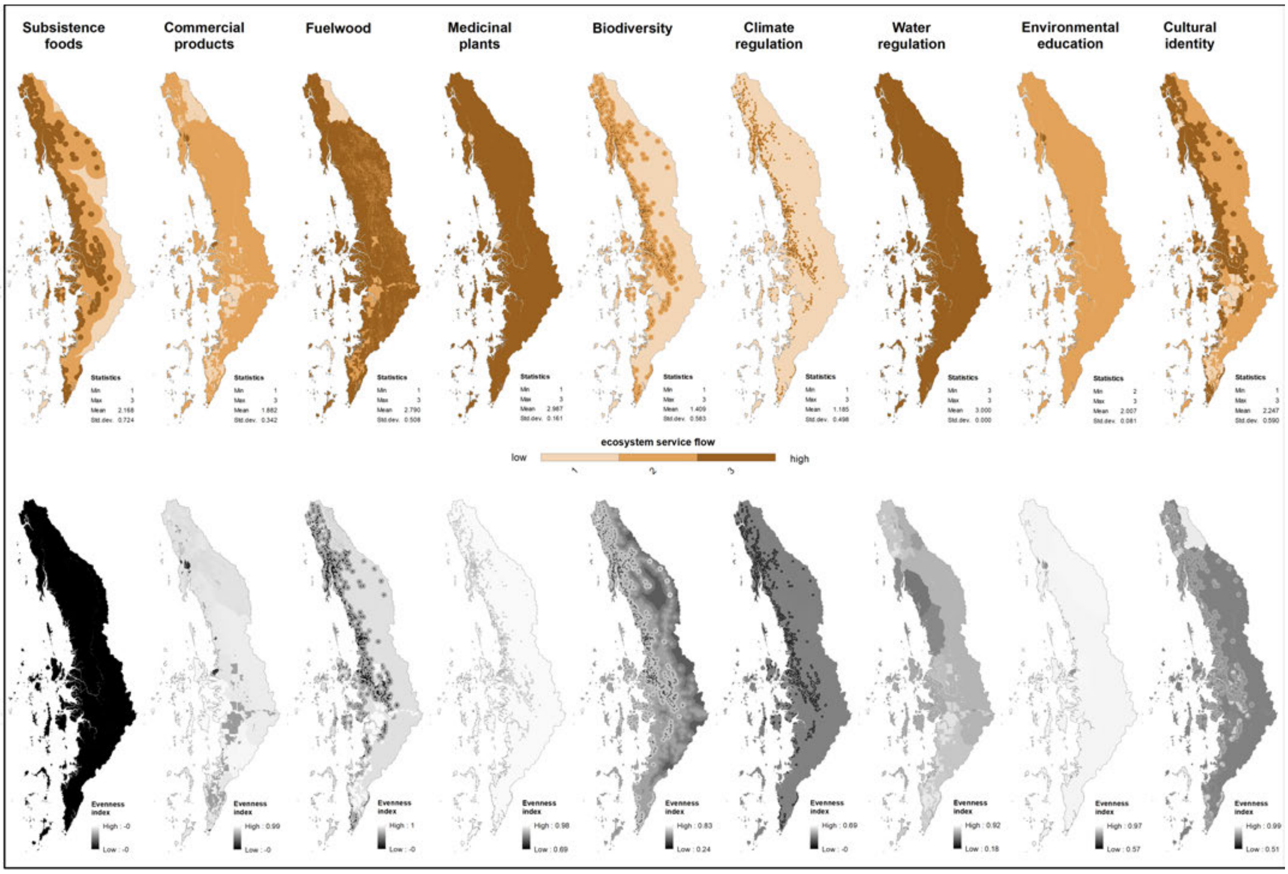


Figure 4 Above: Most likely ES flow values; below: corresponding evenness index (representing uncertainty of those values)

The evenness index differs strongly across the nine ES. Displayed flow values of subsistence foods and climate regulation are relatively distinct with a mean evenness index below 0.5. But flow values of medicinal plants, environmental education, and commercial products show more variation in their probability distributions. The displayed values are highly uncertain with respective mean indices of 0.9 and above. In contrast to ES supply, high certainties do not correspond to high values for ES flows.

3.2 Supply and demand balances

Comparing the nine ES, we found that only biodiversity and commercial products, at least in rural areas, are balanced, where supply approximately covers local demand (Figure 5). Medicinal plants and cultural identity are oversupplied or underutilized. For all other ES we identified larger mismatch areas (supply < demand). Critical mismatches were found for environmental education, which the communities interviewed often described as a major limitation, as well as subsistence foods in large areas of Tanintharyi. Although these ES are in high demand by local stakeholders, supply is limited throughout the region. Geographically, the most adversely affected areas are found along roads, in urban and peri-urban areas, and in sites facing agricultural expansion. In contrast, large landscapes along the forested eastern border provide a local surplus in fuelwood, medicinal plants, climate regulation, and cultural identity.

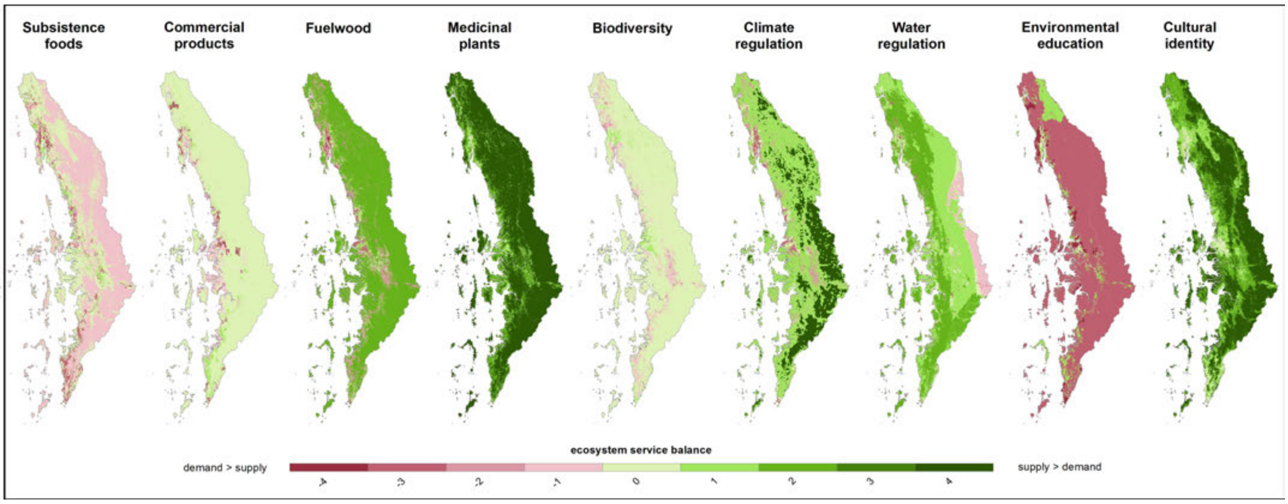


Figure 5 Ecosystem service balances (supply–demand) in Tanintharyi Region, with red areas illustrating mismatches

While large forest complexes in rural upland areas contribute to climate regulation, this is not the case in large settlements, rice producing areas, and other bare lands, where the microclimate is often problematic during the summer. Towns and coastal sites with many fish factories experience reduced air quality. In addition, coastal regions are more directly affected by climate change through sea level rise and increased frequency and intensity of cyclones, and therefore people living there may be more sensitized to climate issues. Thus, demand for more trees in the landscape is highest in these areas, leading to strongly negative ES balances (-3). Water regulation, on the other hand, seems to be balanced regionally. The only mismatch (-1) is found where annual rainfall is comparatively low. But we also detected small patches with stronger mismatches (-4) in some of the more developed zones. With the high seasonality of rainfall in Tanintharyi, it is possible that certain coastal areas face water scarcity particularly during the summer. According to our results, environmental education is the ES that is by far the most affected by negative supply/demand balances. Demand for environmental education, which is heavily linked to agricultural and environmental capacity building, is extremely high in both rural and urban areas and is driven by people's dependence on agriculture and natural resources for their livelihoods, a genuine interest and cultural connection to the environment, and a generally strong desire to learn new things. But with no functioning extension services there are very few opportunities for smallholders to attend formal training. Notable exceptions with positive supply/demand balances are found in the two PAs (+1). This is linked to the fact that establishing a PA often involves capacity building activities on environmental management and conservation. This is sometimes coupled with livelihood projects and agricultural training. On the other hand, there are few communities living within the PAs, which leads to an overproportioned supply. For subsistence foods, there is a distinct divide between balanced areas and those where local demand cannot be met with local supply. Balanced areas are coastal and other low-lying areas with adequate road networks where smallholder agriculture and paddy fields are common. Proximity to roads and access to foods from markets further reduces the need for these communities to produce their own food. This is different in the hilly areas where forest landscapes dominate. The few communities living there rely on shifting cultivation and on the wild foods they can gather from forest and fallows. This is represented in only a slightly negative balance (-1). More severe mismatches are admittedly found in oil palm concessions in Tanintharyi's southern part (-3) and in some urban and peri-urban areas, especially around Dawei (-4). Our results indicate that demand for subsistence foods cannot be covered in these highly populated areas, even with the surrounding paddy fields. For fuelwood, another important subsistence product for many, there is either a high surplus or a distinct lack thereof. Considering that both fuelwood and charcoal are by far the most common types of fuel used by households in Tanintharyi, such distinct positive or negative balances can be explained largely by the respective population densities. The high surplus in rural areas and unsatisfied demand in towns could increase trade in fuelwood and charcoal.

3.3 Regional and local supply/demand mismatches

3.3.1 Frequency and intensity of mismatches at regional scale

Combining all models, we identified on average four ES across Tanintharyi for which mismatches (supply < demand) were present (Figure 6, left). No mismatches were detected in some areas within the PAs. Only one ES was undersupplied in most other areas in and around PAs as well as in regions dominated by villages and smallholder agriculture. However, overall, there are only few areas in Tanintharyi Region with such a negligible number of mismatches (≤ 1). Areas with a high number of mismatches (7–8) are just as rare. They are distinctly found in urban settings, e.g. in Dawei or Myeik, as well as along roads and in recently emerging development areas, as visible e.g. on the road to Thailand in the eastern part of the region. For the areas in between, characterized as mosaic landscapes with remaining natural forest patches interspersed with small-scale agriculture, we found a limited number of mismatches ranging between 1 and 3. Similarly, we found a rather low mismatch intensity in these mosaic landscapes (Figure 6, right), indicating that while there may be an undersupply of some services, it is not severe.

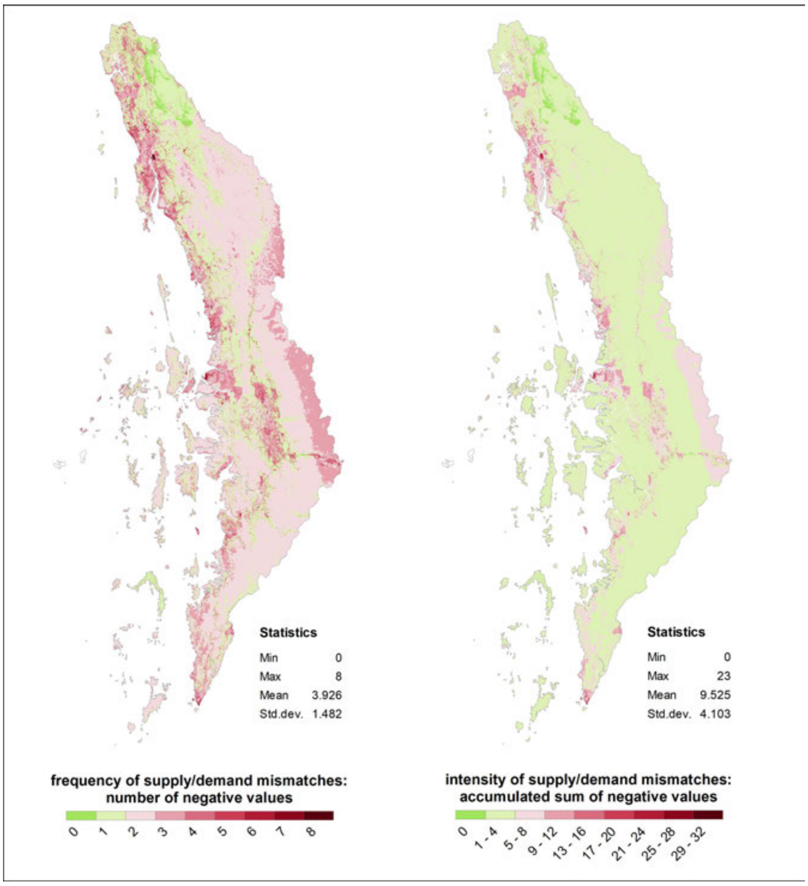
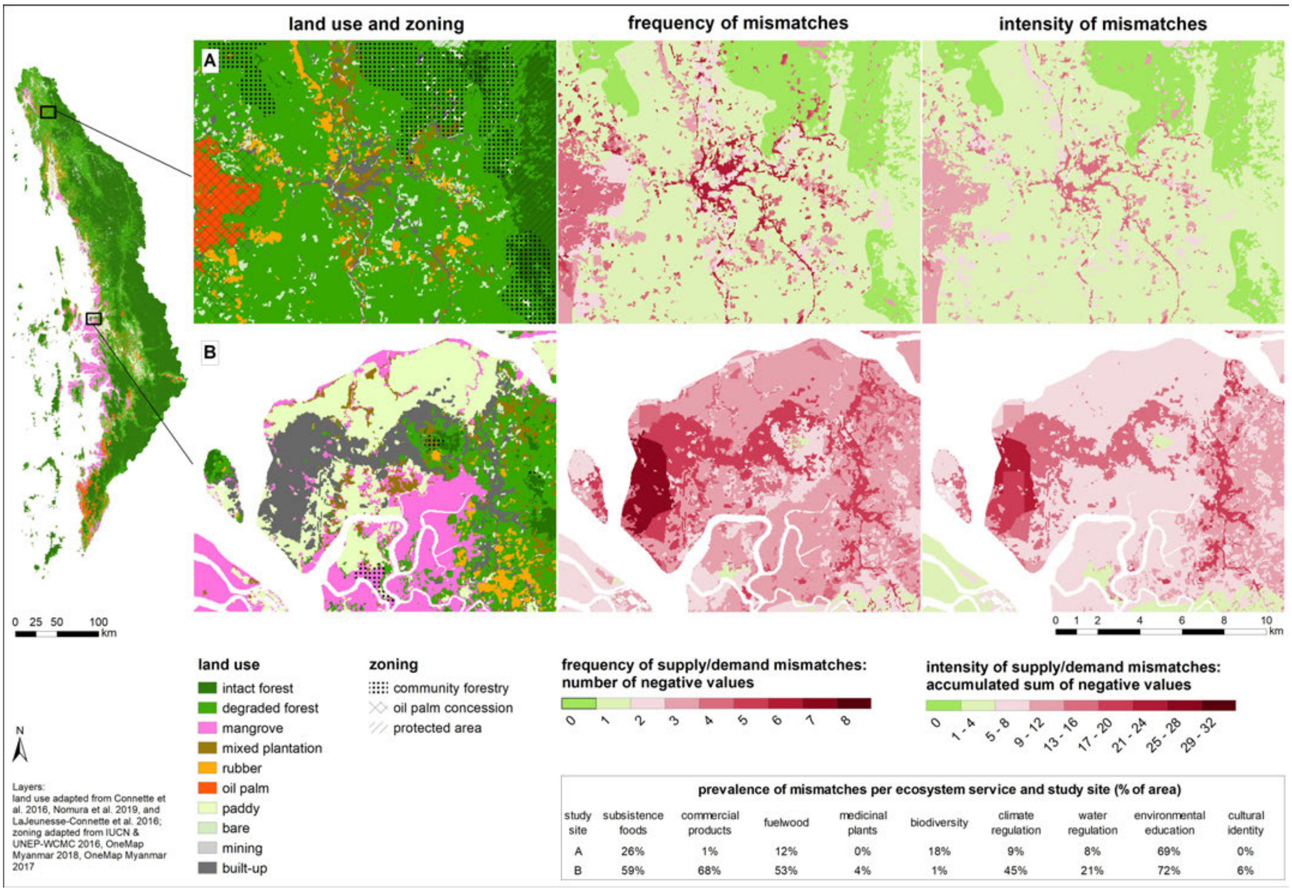


Figure 6 Frequency and intensity of mismatches in Tanintharyi Region (*left*: frequency of supply/demand mismatches calculated as the number of negative ES balance values per raster cell; *right*: intensity of supply/demand mismatches calculated as the accumulated sum of negative ES balance values per raster cell)

Although both frequency and intensity of mismatches exhibit similar patterns across the region, they are higher in urban and peri-urban areas and in areas with infrastructure. They are lower in PAs and smallholder agricultural lands, but the mismatches are less pronounced in intensity than in frequency (i.e. in number). Combining all nine ES, we found up to 8 mismatches (mean = 3.9) in the study area, but with intensities of a maximum of 23 out of a potential 32 (if all mismatches had the highest possible inversed value of 4) and a mean of 9.5. So, while we identified several mismatches in large parts of Tanintharyi Region, the overall low intensity of those relativizes the impact on local stakeholders to a certain extent.

3.3.2 Exploring mismatches in the context of two study sites

Although differences exist between the nine ES, there are some areas within Tanintharyi Region that are affected more by supply/demand mismatches. These include urban and other developed areas along roadsides with agricultural and/or mining concessions. In this section, we contextualize mismatches by zooming in on two study sites and inspecting ES mismatches in relation to land use and zoning. Figure 7 shows the distribution of mismatches in these sites in terms of frequency and intensity.



study site	subsistence foods	commercial products	fuelwood	medicinal plants	biodiversity	climate regulation	water regulation	environmental education	cultural identity
A	26%	1%	12%	0%	18%	9%	8%	69%	0%
B	59%	68%	53%	4%	1%	45%	21%	72%	6%

Figure 7 Ecosystem service supply/demand mismatches in terms of frequency (number of negative ES balance values per raster cell) and intensity (accumulated sum of negative ES balance values per raster cell) in two study sites of Tanintharyi Region (A: rural area in Yebyu township, B: Myeik town and surrounding area)

Study site A in Yebyu township is characterized by several different zoning arrangements and related land uses. It includes not only part of the Tanintharyi Nature Reserve and adjacent CF, but also an oil palm concession amid smallholder rubber and mixed plantations. Our results highlight first of all the importance of forest landscapes in providing multiple and balanced ES, also at local scale. We found that the number and intensity of mismatches is generally small in forest lands: in CF areas, there are no mismatches; in PAs and other forested lands, there is one or more mismatches ranging in intensity from 1–4. Oil palm plantations, by contrast, are linked to several and intense ES mismatches. Since these plantations are under concession management, it is not evident whether local small-scale oil palm plantations would have fewer or less intense negative effects on ES. What can be seen, though, is that concession areas not planted with oil palm still limit the number of ES provided to local communities. For comparison, the scattered small-scale plantations in the area, mostly planted with rubber but also mixed with cashew and betelnut, are linked to 2–3 low-intensity mismatches. Thus, although they provide fewer regulating ES than the surrounding forests, these small-scale plantations are important for providing local communities with commercial products, fuelwood, and even some NWFPs such as foods or medicine. Overall, in study site A with its mosaic of land uses and zoning arrangements, the most frequent mismatches were found for environmental education (69% of the area – similar to regional level findings), followed by subsistence foods (26%) and biodiversity (18%).

Comparatively strong ES mismatches in urban areas are evident in study site B, which encompasses the town of Myeik and its surroundings, which include paddy fields, mangroves, and some lowland forests and tree crop plantations. In all built-up areas we identified severe mismatches, both in terms of frequency and intensity. In contrast to site A, even forested lands do not provide enough ES to compensate for this and satisfy local demand. Considering that the large demand for ES in more populated areas can hardly be covered with nearby supply areas, local communities therefore depend more on alternatives to ES. As an example, with limited land availability and thus few options to generate income from commercial crops, more urban people depend on non-agricultural jobs or businesses. Notable exceptions to the overall large mismatch areas are the two relatively small CFs, one covering intact lowland forest and the other covering mangroves. Most areas of both CFs present only one mismatch. According to Figure 7, mangroves are related to fewer and particularly less intense mismatches compared to other land uses. Based on previous findings (see Figure 2 in section 3.1.1), mangroves are important providers of regulating services including biodiversity and climate mitigation as well as cultural identity and diverse subsistence and commercial products based on fisheries. Overall, a lower mismatch prevalence was found for biodiversity (1%) compared to study site A (18%). Apart from commercial crops, which are undersupplied on 68% of the land area, study site B also faces a lack of environmental education (72%), subsistence foods (59%), fuelwood (53%), and climate regulation (45%). The undersupply of climate regulation can be attributed to the large greenhouse gas emissions from towns and abundant paddy fields, as well as the naturally high demand for a good microclimate in a city with low air quality. This is particularly true for Myeik, which has several fish factories, and while there are climate-regulating mangrove areas south of Myeik, these provide only partial compensation.

4 Discussion

4.1 The role of forest frontier landscapes in providing local and global ecosystem services

Debates on tropical forest frontier landscapes have long revolved around land use trade-offs between agricultural production and environmental conservation (Mastrangelo and Laterra, 2015; Verburg et al., 2014) or between customary and elite rights that benefit some stakeholders while harming others (German et al., 2014; Schoneveld, 2014). Land sparing versus land sharing policies are a critical point of debate in many developing countries (Mertz and Mertens, 2017), but the picture is more nuanced. Stakeholder-driven and holistic ES assessments can contribute to the discussion by looking beyond biodiversity and agricultural productivity (Grau et al., 2013). In fact, mosaic landscapes that are common in forest frontiers have been found to offer vast opportunities for sustainable development and the delivery of multiple ES (Muhamad et al., 2014; Pinillos et al., 2020; Tscharntke et al., 2005). Similarly, shifting cultivation, a traditional land use in Southeast Asian mosaic landscapes including in Tanintharyi (Schmid et al., 2021), also supports local livelihoods and ES outcomes where long fallow periods are upheld (Dressler et al., 2017). Our findings confirm the important role that these frontier landscapes can play in providing various ES, especially for local stakeholders. Across Tanintharyi's mosaic landscape we found not only high local outcomes for agricultural subsistence and commercial products, but also many NWFPs and regulating services from remaining natural forests. Ahammad et al. (2019) found that rural and poor communities in

Bangladesh use forest products mainly for subsistence rather than for income generation. This is also the case in Tanintharyi, where households consider the main benefits from forests to be fuelwood for household use, medicinal plants, and subsistence foods. This is partly due to regulatory barriers that limit commercial use of forests by communities (Gritten et al., 2015). Still, these products contribute to the health and well-being of rural communities. While forest and shifting cultivation lands are most closely linked to the lives and cultural identity of remote communities, community members perceive that all lands contribute in some way to their culture, including new land use types such as rubber plantations (Feurer et al., 2019). Environmental education, also a cultural ES, is less directly linked to land uses. In the models we used, traditional land uses are associated with informal knowledge exchanges, while newer land uses or management forms such as CF are linked to formal agricultural or silvicultural training. In tropical forest frontiers, both types of knowledge make important contributions to the sustainable development of landscapes. Traditional and indigenous knowledge contributes to the conservation and sustainable management of remaining natural forest and shifting cultivation areas (Siahaya et al., 2016), whereas formal education can enable the sustainable intensification of existing agricultural lands (Tscharntke et al., 2005), including agroforestry. Overall, it is evident that local ES benefits go beyond biodiversity, climate regulation, and agricultural production, and that they are key for all aspects of human well-being in forest frontier landscapes.

From a global perspective, larger forest complexes are critical for non-material services. We found a high supply of biodiversity and climate regulation, both of which are in severe decline across the globe (IPBES, 2019). While such regulating ES are also highly sought after by local stakeholders, the benefits perceived by local stakeholders differ from those required at the global level. In terms of climate regulation, for example, rural communities perceive fewer direct benefits from carbon sequestration but appreciate a regulated microclimate and better air quality (Feurer et al., 2019). They perceive climate services as regulating temperature and humidity at micro or regional scale (Haines-Young and Potschin, 2018). In coastal areas, we found a higher local demand for climate regulation, which confirms the findings of Bennett et al., (2014) that coastal communities are more sensitive to the impacts of climate change. For rural communities, biodiversity is represented through a variety of NWFPs, pollination services that support their agricultural livelihoods, and a safety net that gives them a sense of security. Related to this, Feurer et al. (2019) found in Northern Tanintharyi that medicinal plants are valued for potential future benefits or in times of need, rather than for current use, and should therefore be conserved.

However, biodiversity conservation should go beyond implementing large PAs, as such areas often contain customary lands and could negatively affect the livelihoods of people living there (Schleicher et al., 2019). Conservation must be coupled with adequate land management in surrounding areas, including buffer zones to ensure the long-term availability of multiple ES and connecting elements to safeguard biodiversity at landscape scale (Kremen and Merenlender, 2018). Acknowledging both that local communities are important actors in frontier landscapes and that they highly value the various ES provided (Muhamad et al., 2014), sustainable development planning and policy must be participatory, include relevant customary land rights and practices (Dressler et al., 2017), and enable tenure security (Robinson et al., 2014).

4.2 Options for reducing mismatches in affected areas

In this regard, there are existing options to improve ES flows within forest frontier landscapes. This is critical in areas affected by high supply/demand mismatches, where the inability of local stakeholders to access service-providing areas reduces welfare (Kmoch et al., 2021) and, in the long term, their adaptive capacities (Ensor et al., 2015), eventually inducing conflicts. Sustainable solutions to landscape planning must take into account different stakeholder perspectives. Establishing PAs may reduce forest loss and conserve biodiversity, but their effectiveness strongly depends on their design, governance, restrictions

(Schleicher et al., 2019), and other factors such as road networks, accessibility, and human pressure (Leberger et al., 2020). In highly populated areas, rights-based approaches to forest conservation can improve environmental and livelihood outcomes simultaneously (Porter-Bolland et al., 2012). Conservation should thus not be totally separated from sustainable use. The example of CF in our study confirms that rights-based approaches can achieve multiple goals. CF areas were linked to fewer supply/demand mismatches than other land uses, including PAs. Several other studies have also shown the valuable contribution of CF to rural livelihoods, poverty alleviation, erosion control, climate change mitigation and adaptation, and biodiversity (Birch et al., 2014; Feurer et al., 2018; Pandit and Bevilacqua, 2011). In addition to forest-based land uses, Kremen and Merenlender (2018) suggest a holistic approach by enhancing biodiversity in working agricultural lands, while Reith et al. (2020) found that including large shares of agroforestry in landscapes enhances the variety of ES provided. Pinillos et al. (2020) suggest that the simultaneous delivery of multiple ES requires a combination of both land sharing and land sparing strategies. More precisely, Law et al. (2017) modelled different policy scenarios in a frontier landscape in Indonesia and found that mixed strategies were most effective in supporting several provisioning and regulating ES, provided that approximately one-third of the landscape was conserved for biodiversity. While our research did not provide insights on potential scenarios, it did indicate that areas with a mosaic of land uses including smallholder plantations and natural forests are linked to fewer mismatches. Further, our results provide evidence that land sparing, a concept founded on ecological principles, can have strongly adverse social outcomes. In oil palm concessions, we found low supply (and, consequently, more mismatches) and limited flows of ES for local stakeholders. Where supply is high, Boesing et al. (2020) suggest that enhancing flows should be a main goal in land sparing policies. In land sharing regions, efforts need to focus more on increasing supply or lowering demand (Boesing et al., 2020). To achieve the highest local ES outcomes, we propose a holistic approach to landscape planning that consists of some PAs with well-defined, community-managed buffer zones and a mosaic of optimized smallholder agricultural systems.

As expected, we found a higher number and intensity of mismatches in urban and peri-urban areas, which is consistent with other studies (Baró et al., 2016; Burkhard et al., 2012). Even though low urbanization rates have been observed in Tanintharyi in the past, this could change once the Special Economic Zone in Dawei has been completed (Walsh, 2015), further enhancing demand for ES. But towns generally provide more options on ES substitutes such as electric or gas stoves to replace fuelwood, or jobs to reduce dependency on agricultural incomes, and so high mismatches in urban areas may therefore not have as high an impact on local stakeholders as we estimated. Globally, most efforts to enhance provision of ES in cities are related to green infrastructure including tree planting (Geneletti et al., 2020). Additionally, small gardens and trees within housing compounds can play a considerable role in securing some ES at local scale. In all three towns of Tanintharyi, we observed numerous home gardens, which provide the owners with subsistence foods, fruit for religious ceremonies, as well as shade and thus a regulated microclimate. However, due to their small scale, these ES are not visible in our results and may have led to slightly overestimated mismatches in towns. The area surrounding towns also needs to be considered when evaluating mismatches (Baró et al., 2016). Our findings indicate, however, that it is nearly impossible for a large population in urban areas to cover their multiple ES demands through the surrounding lands. As all towns in our study site are coastal, the value of mangroves is evident with very few mismatches across the nine ES. Mangrove forests have a portfolio of diverse ES such as storm protection (Richards and Friess, 2016), a crucial service that was however not considered in our assessment. We therefore stress the importance of actively including mangrove areas in coastal urban planning. In sum, while urban and peri-urban areas may not be able to reach balanced ES outcomes, there are options to reduce mismatches to a certain extent, either by increasing supply (tree planting, home gardens, high-provisioning land uses surrounding urban spaces) or by reducing demand through improved access to man-made alternatives and more sustainable technologies.

4.3 Limitations, lessons learnt from mapping mismatches, and moving forward

Using comprehensive BN for nine ES in this study, we were able to model and map their supply, demand, flow, and mismatches at a scale unprecedented for tropical regions. Data scarcity was addressed by combining secondary data with qualitative data collected with different stakeholders across Tanintharyi Region. Our research aimed to adhere to the recommendations for ES mapping provided by Willemen et al. (2015), including robustness, stakeholder relevance, and transparency. We found that the latter implies a modest trade-off with the former two, as the inclusion of a wide range of variables and stakeholders inherently obscures ES models and reduces clarity for map users. For smaller-scale studies and projects aiming to implement findings from ES assessments, a more holistic co-production of knowledge is recommended (Gritten et al., 2015; Pandeya et al., 2016). Regional-level mapping still comes with some limitations on stakeholder involvement. Although our results give a good overview of ES outcomes for the majority of Tanintharyi's highly diverse population (smallholder farmers, forest-dependent communities, and residents of coastal towns), some groups may be underrepresented. Regional assessments, particularly those in ecologically and culturally diverse tropical frontier landscapes, inherently face this challenge of representativeness, but we argue that they are nonetheless important baselines for landscape planning and policy, provided that limitations are clearly communicated. Given the sensitivity of the results in respect to model design and input data, the outputs should be regarded as approximations of the actual situation and not as final values. The evenness index is useful here as it discloses variations in the results. An advantage of BNs is that they can be easily updated once new data becomes available, and that temporal dynamics could be included, e.g. with the gBay tool (Stritih et al., 2020). The inclusion of temporal dynamics to assess ES extirpation over time (Boesing et al., 2020) would be a relevant next step but is hampered in regions suffering from data scarcity. Monitoring information on land use distributions is particularly important in forest frontier landscapes where land use changes occur rapidly. Further, limited land tenure data reduces the reliability of mapped ES flows. It is therefore crucial to update tenure data and monitor progress made in customary land rights. Future use of these ES models could include policy scenario analysis, similar to recent work in Indonesia (Law et al., 2017). We believe that mapping supply/demand mismatches is a useful tool for identifying sustainable development pathways that closely involve local stakeholders. Finally, integrating considerations of flow into these mismatch analyses is key to enhancing the well-being of local communities.

5 Conclusions

Combining comprehensive BN models with GIS, we mapped the supply, demand, and flow of nine ES for local stakeholders in a forest frontier landscape in Tanintharyi Region, Myanmar, using values between 1 (very low) and 5 (very high). Across the region, we found a high supply of biodiversity (mean = 4.7), climate regulation (4.7), cultural identity (4.6), fuelwood (4.5), medicinal plants (4.5), and water regulation (4.3) – with particularly high supply in forest areas. Flat lands and shifting cultivation areas provide high amounts of subsistence foods, but few areas provide commercial products (1.3) and environmental education (1.4) for local communities. Local demand is particularly high for biodiversity (4.8), environmental education (4.1), and subsistence foods (3.9), and for all ES, it increases with population density. Urban and other rapidly developing areas face the strongest supply deficits. Mapping such supply/demand mismatches for all nine ES, we found that most occur in urban areas or degraded forest lands with up to eight and three mismatches, respectively. In contrast, mosaic landscapes consisting of remaining patterns of natural forests and smallholder agricultural plantations presented very few mismatches (≤ 1). However, the degree to which the respective ES are undersupplied is generally low, especially in rural areas. Zooming in on two study sites – in Yebyu township and in and around the town of Myeik – we found that mismatches are not only related to land use but also to zoning and land tenure arrangements such as concession lands, protected areas, or community forests. Our results show that local stakeholder access to ES is restricted in oil palm concessions and protected forests. This is also reflected in high mismatches. On the other hand, community forests perform much better both in terms of limited mismatches and secure ES flow.

This study gives a comprehensive overview of ES outcomes for local stakeholders in a tropical forest frontier landscape. In addition to globally important ES such as biodiversity or climate regulation, we found that local communities value subsistence products such as food, fuelwood, or medicinal plants – as well as educational services provided by nature and related institutions. We contributed to ongoing ES research by developing and applying complex models for a data-scarce region. Our findings highlight the importance of mapping mismatches, as they particularly affect local stakeholders and influence effective ES outcomes. Regional-scale assessments that consider spatial mismatches can inform potential policies or management interventions in a more targeted way. With zoning and land tenure having an impact on both supply/demand mismatches and flow, we recommend that future research in tropical forest frontiers integrate these two aspects of ES. In future scenarios for Tanintharyi Region, local access and rights to land and natural resources are key to assessing and ensuring effective ES outcomes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work of this paper.

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Annex: Bayesian network models for nine ecosystem services

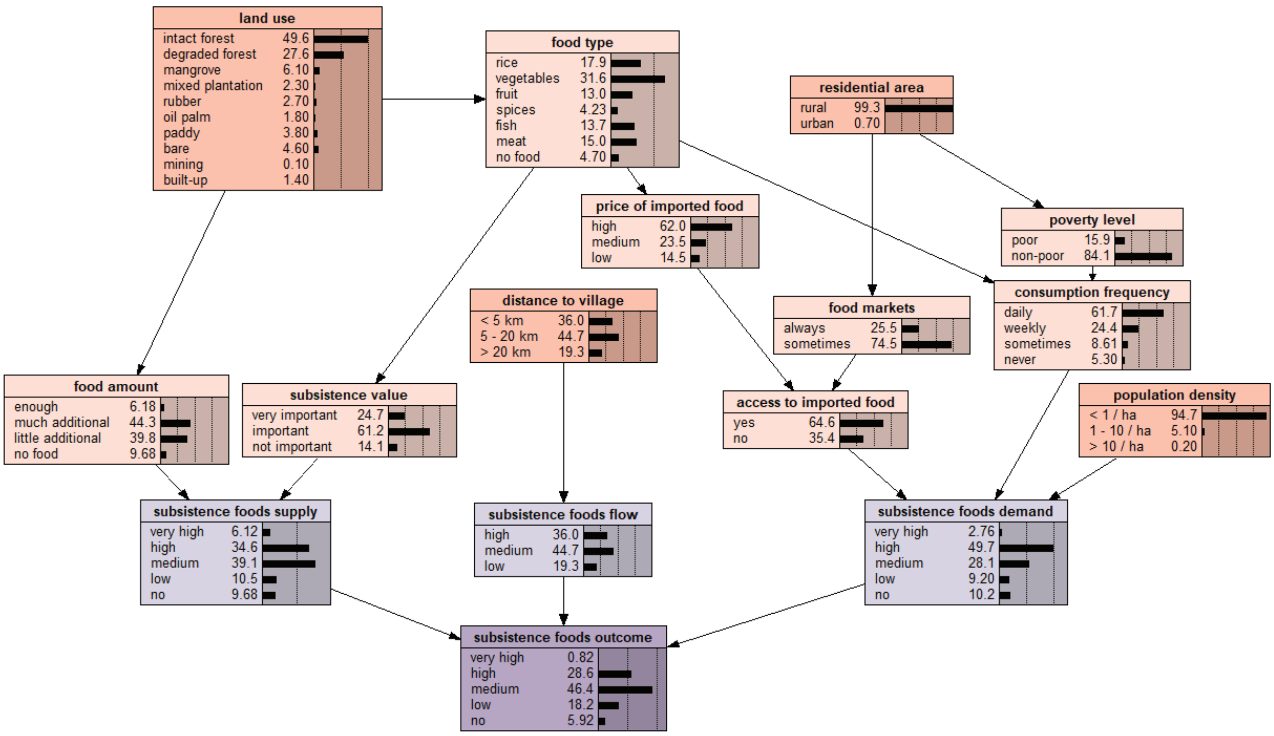

Figure A.1 'Subsistence foods' model

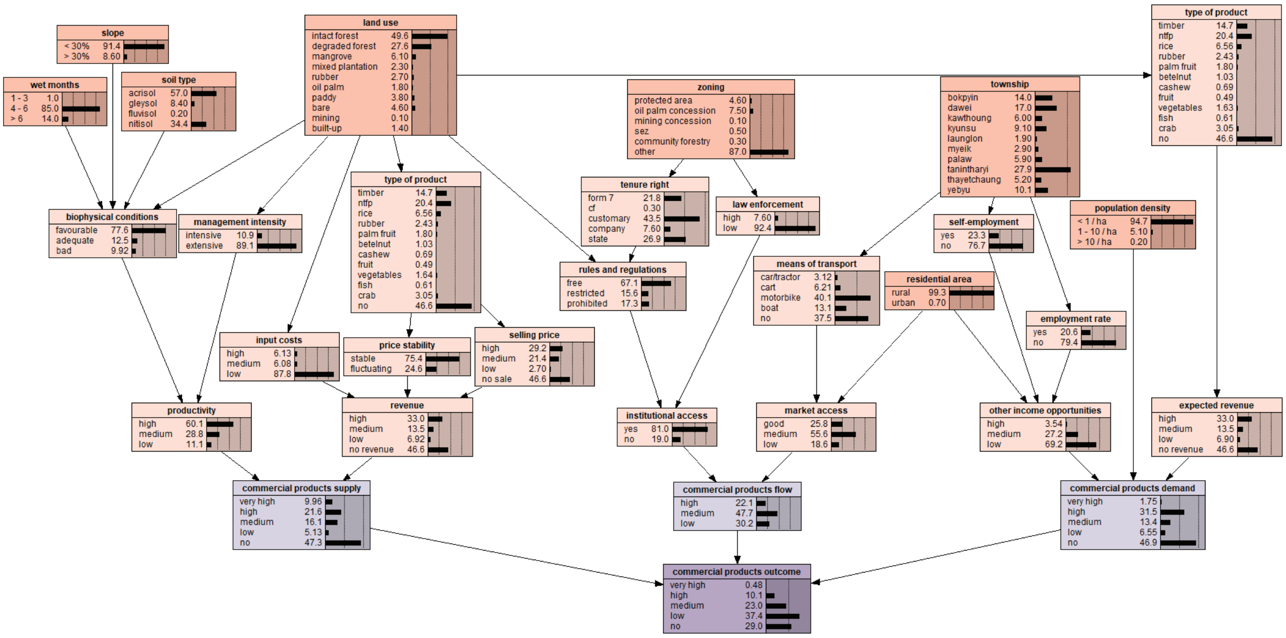

Figure A.2 'Commercial products' model

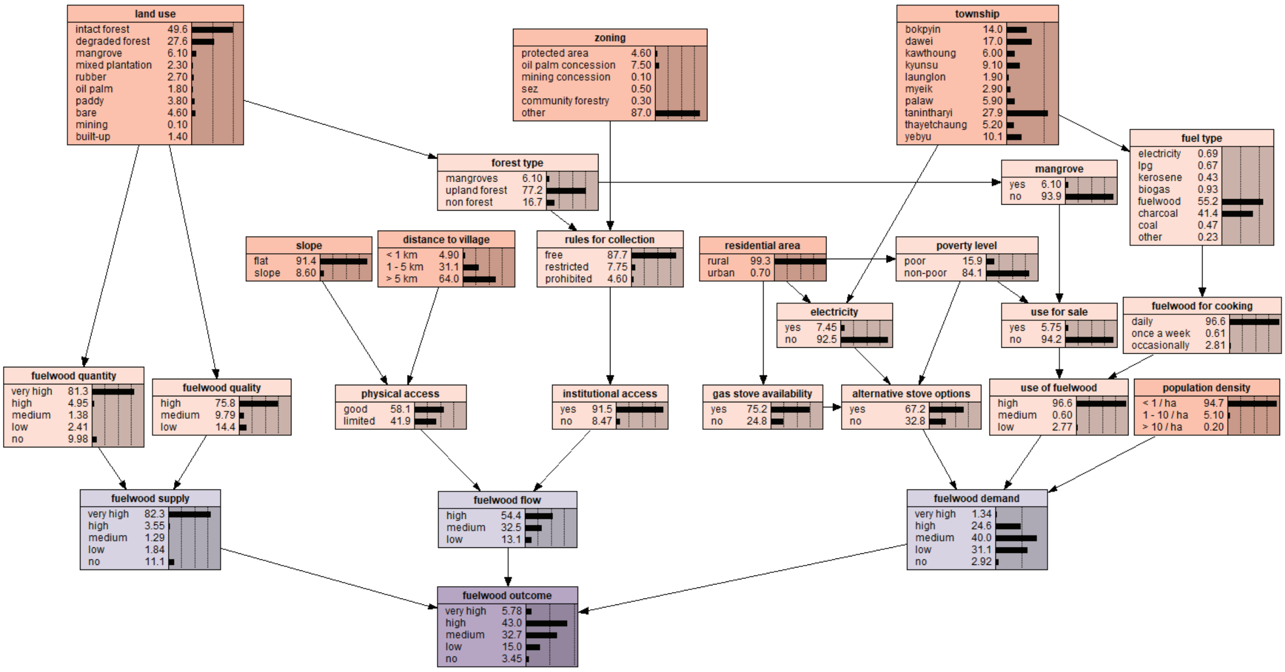

Figure A.3 'Fuelwood' model

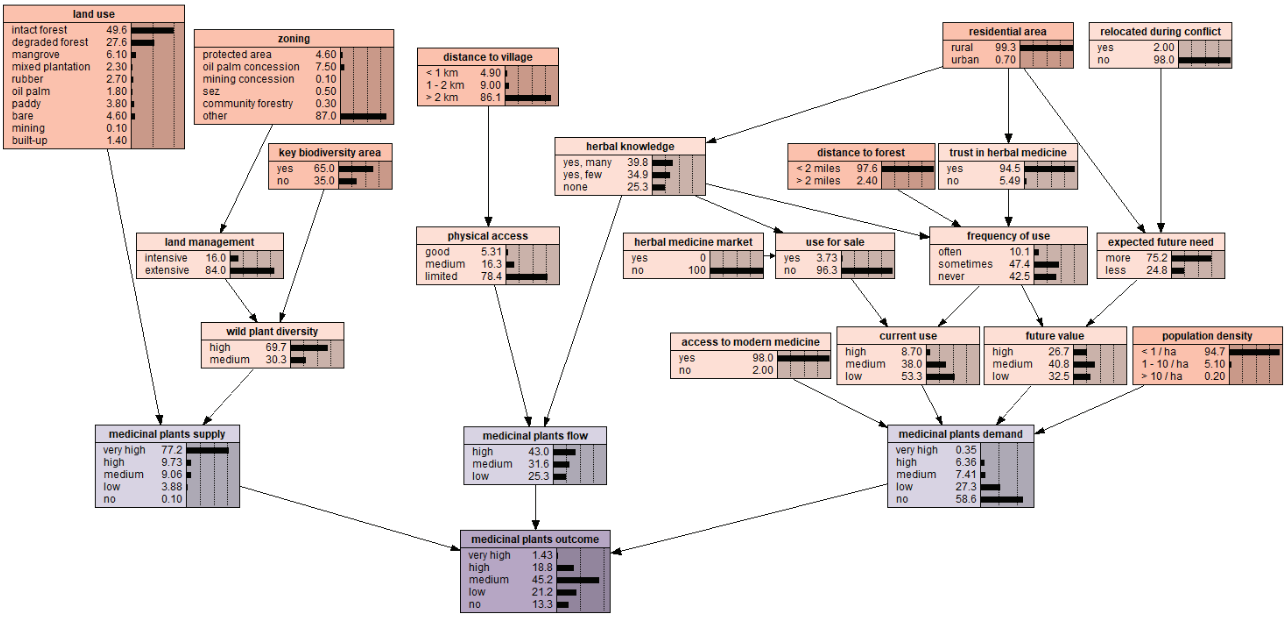

Figure A.4 'Medicinal plants' model

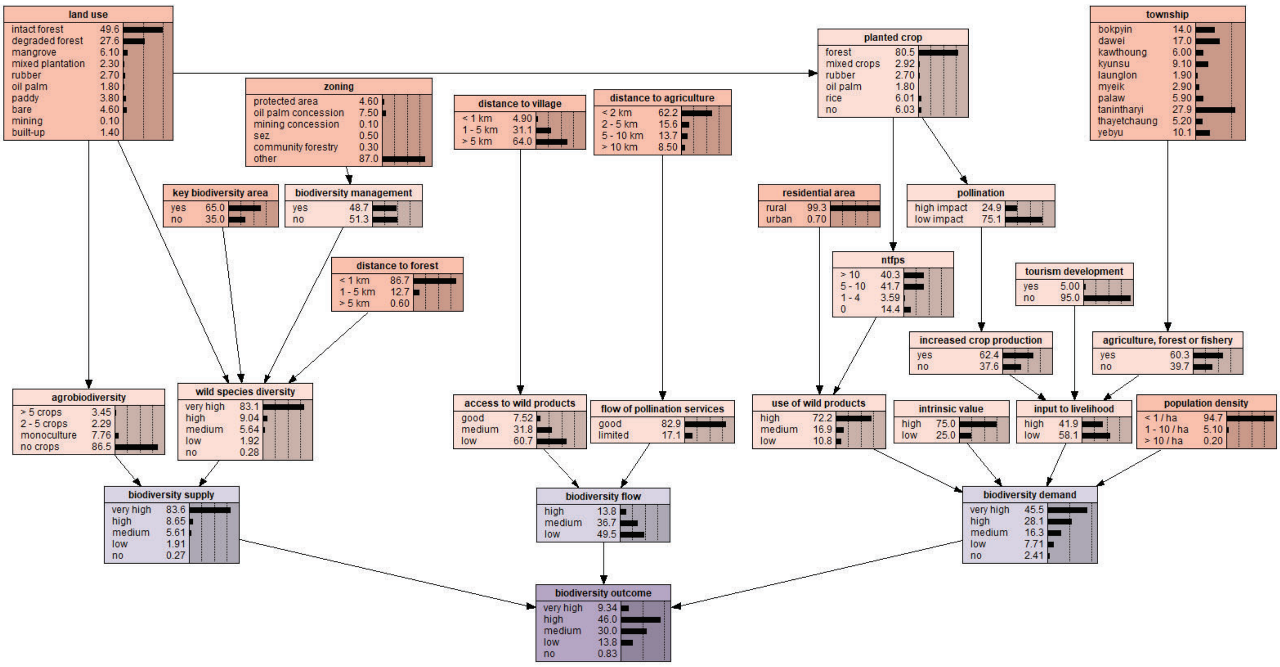

Figure A.5 'Biodiversity' model

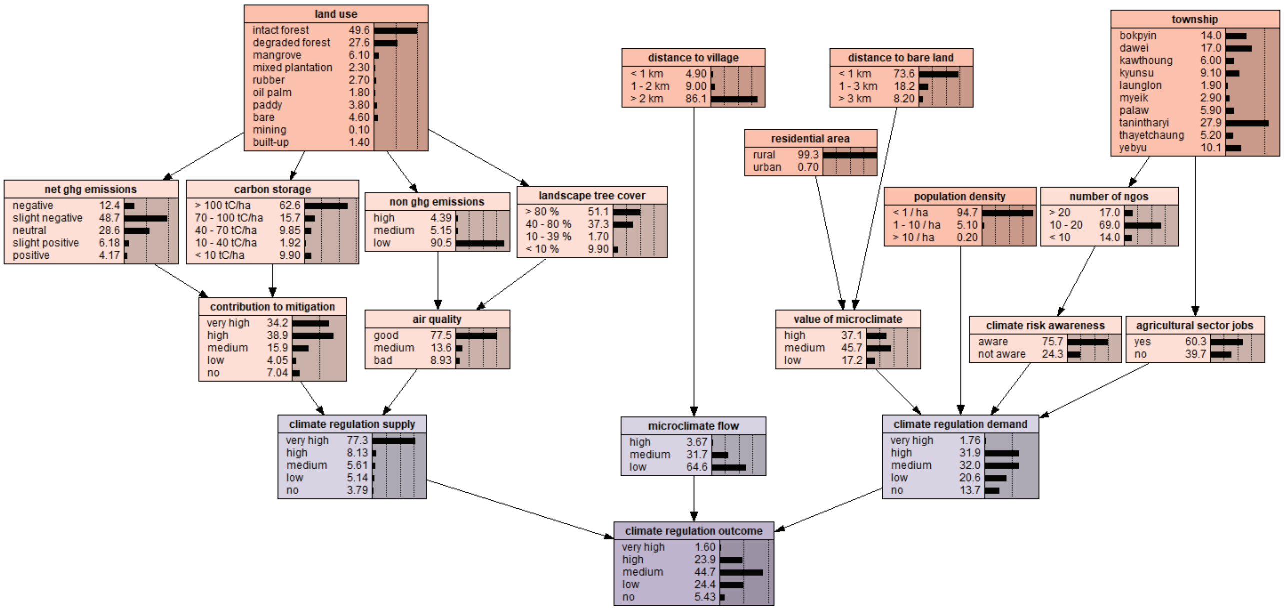

Figure A.6 'Climate regulation' model

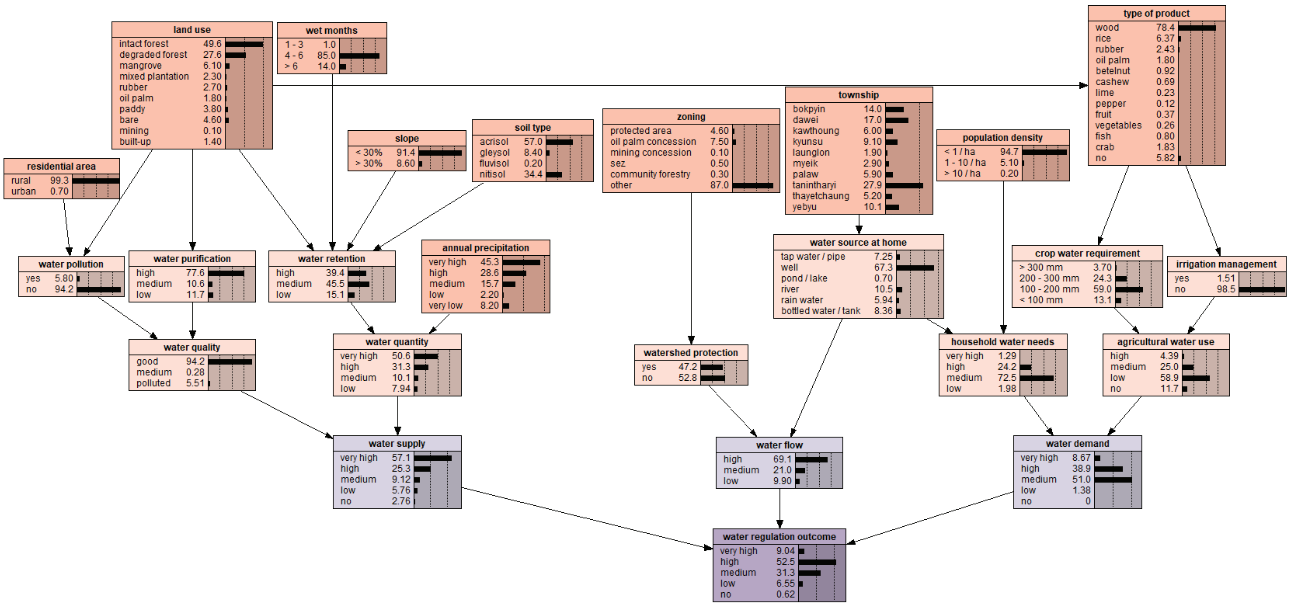

Figure A.7 'Water regulation' model

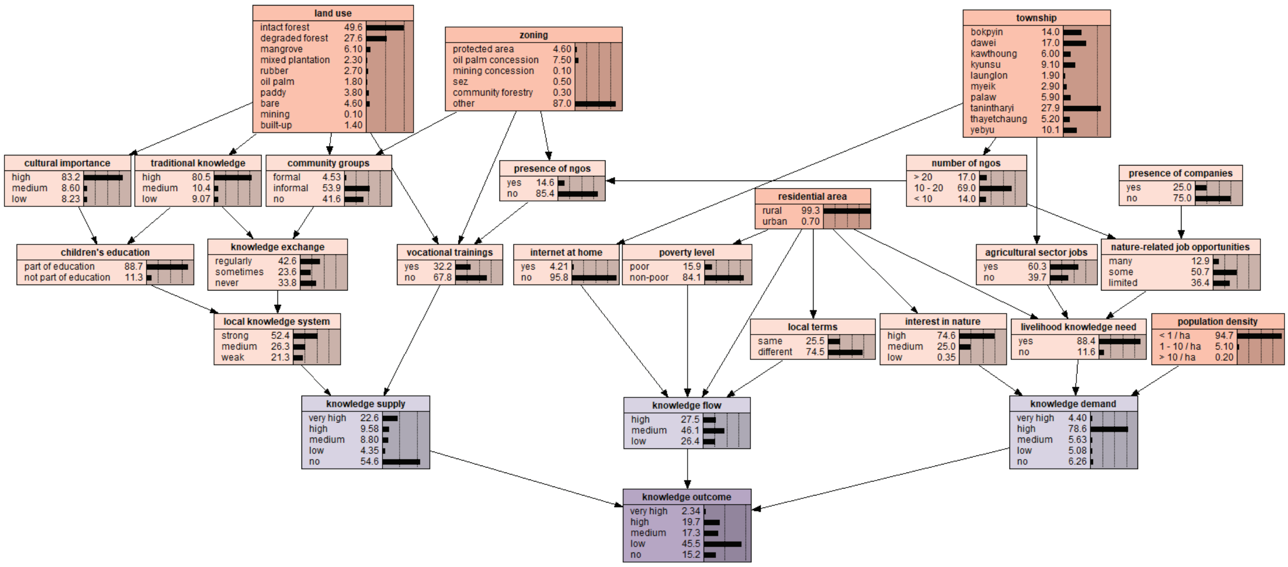

Figure A.8 'Environmental education' model

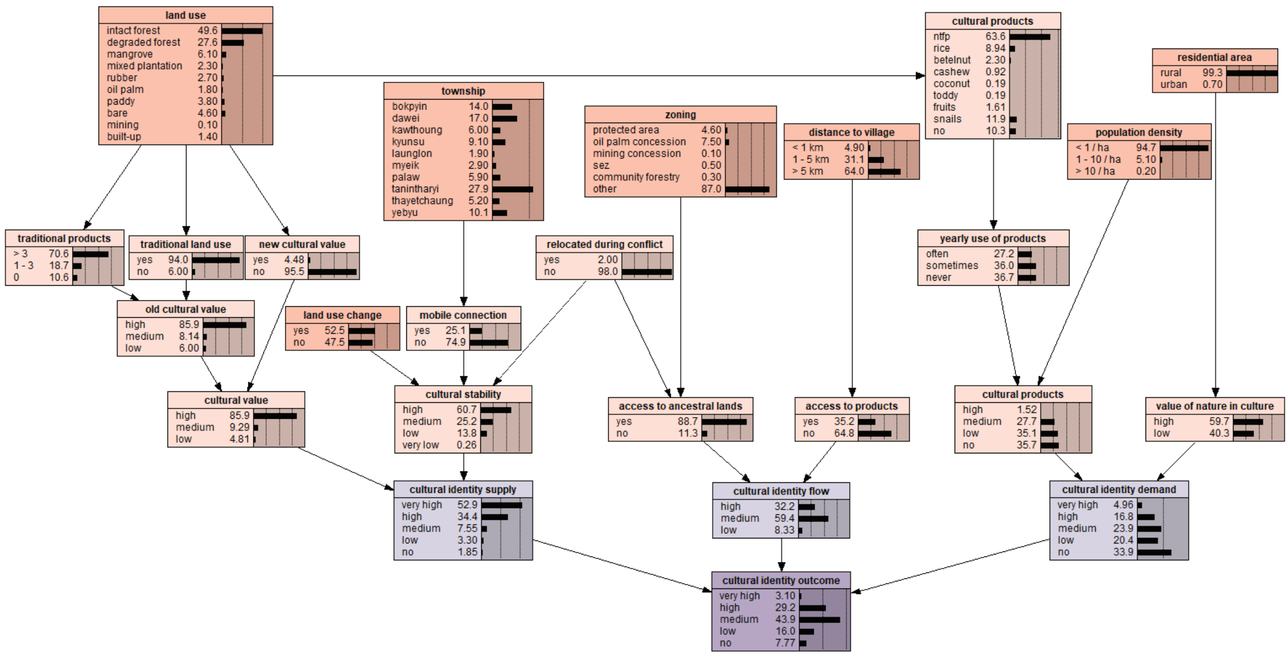

Figure A.9 'Cultural identity' model

Declaration of consent

on the basis of Article 18 of the PromR Phil.-nat. 19

Name/First Name: Feurer Mélanie

Registration Number: 10-582-252

Study program: Geography and Sustainable Development

Bachelor ☐ Master ☐ Dissertation ☑

Title of the thesis: Ecosystem services for communities in forest frontiers: An assessment of nature's benefits to local stakeholders under different land use and tenure systems in a tropical frontier landscape in Myanmar

Supervisor: PD Dr. Andreas Heinimann,
Dr. Julie G. Zähringer, Dr. Enrico Celio, Dr. Jürgen Blaser

I declare herewith that this thesis is my own work and that I have not used any sources other than those stated. I have indicated the adoption of quotations as well as thoughts taken from other authors as such in the thesis. I am aware that the Senate pursuant to Article 36 paragraph 1 litera r of the University Act of September 5th, 1996 and Article 69 of the University Statute of June 7th, 2011 is authorized to revoke the doctoral degree awarded on the basis of this thesis.
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