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Patterns of land system change in a Southeast Asian biodiversity hotspot

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ABSTRACT

Growing demand for agricultural commodities like rubber or oil palm is causing rapid change in Southeast Asia's biodiversity-rich forested landscapes. This change is particularly pronounced in Myanmar, whose economy is developing at great speed after the end of decades-long economic and political isolation and armed conflicts. Interventions are needed to ensure that development is sustainable. Designing successful interventions requires spatially explicit knowledge of recent landscape changes. To provide such knowledge, we applied a landscape mosaic approach and analysed land system change in Tanintharyi Region in southern Myanmar between 2002 and 2016. Our findings show that nearly half of the study region experienced degradation of the vegetation cover, intensification of agricultural use, or a combination of both. Although intact forest was still the prevailing vegetation cover of land systems in Tanintharyi Region in 2016, it had suffered from degradation in wide parts of the region. Land systems without or with only extensive agricultural use in 2002 had become dominated by smallholders' shifting cultivation systems and permanent betel nut gardens and paddy rice fields by 2016. Elsewhere, smallholder dominated land systems were intensified through the expansion of oil palm and rubber plantations, pointing to potential displacement effects. The land system maps offer a sound basis for planning interventions to slow the degradation of biodiversity-rich forests and support smallholder farmers in coping with the fast-paced expansion of commercial cash crop plantations and its social and environmental impacts. Sustainable development in this global biodiversity hotspot requires careful land use planning to support nature and people, along with continued efforts for peace-building.

1. Introduction

Southeast Asia's biodiversity-rich forested landscapes are undergoing large-scale changes due to global influences on land (Fox & Vogler, 2005; Hurni & Fox, 2018; Sodhi et al., 2010). Farmers practicing shifting cultivation have long been receiving the blame for deforestation (Devendra & Thomas, 2002; e.g.; Rasul & Thapa, 2003). More recently, however, large-scale commercial permanent crop plantations have replaced shifting cultivation as the direct driver of deforestation in many areas of Southeast Asia (Curtis et al., 2018; Heinimann et al., 2017; van Vliet et al., 2012). This is the case in Laos, for example, where rubber plantations, often with investments from China, have replaced shifting cultivation systems and are expanding into forests (Hurni & Fox, 2018; Lu, 2017). Land cover and land use changes (LCLUC) from forest or shifting cultivation to monoculture crop plantations may lead to a decrease in the provision of biodiversity as well as key ecosystem services such as hydrological cycles or carbon storage (e.g. Barnes et al., 2014; Bruun et al., 2009; Koh & Wilcove, 2008; Ziegler et al., 2009). LCLUC are therefore among the key challenges to be addressed in order to attain the 2030 Agenda's sustainable development goals (UN, 2015).

Myanmar, which still harbours one of Southeast Asia's last intact high conservation value forests (Donald et al., 2015; Woods, 2015), is quite a unique case with regard to sustainable development. After decades of economic and political isolation and armed conflicts in several parts of the country, it is now embracing economic development and transforming at a rapid pace (Schneider et al., 2020). In 2018, the Government of Myanmar defined a number of goals and strategies for sustainable development (GoM, 2018). However, different actors' claims on land often favour one of these goals over the others, leading to complex land use related trade-offs (Zaehringer et al., 2019). These LCLUC need to be monitored as a basis for the design of adequate political, social, and economic interventions to put Myanmar on a sustainable development trajectory.

Myanmar's forested landscapes have already experienced

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widespread modifications. Deforestation and forest degradation occurred, for example, through timber exploitation (Dasgupta, 2015; Woods, 2015), oil palm and rubber expansion (Baskett, 2016; Leimgruber et al., 2005; Saxon & Sheppard, 2014; Woods, 2012), and investments in infrastructure such as roads and pipelines (Burnley et al., 2017). The country's economic opening and subsequent policy reforms, such as the reformulation of the Farmland Law and the Vacant, Fallow, and Virgin Land Management Law in 2012 (Oberndorf, 2012; The Republic Union of Myanmar, 2012), are continuing to attract further investments in commercial agriculture, which might increase pressure on the remaining forests. This is particularly relevant in the southern Tanintharyi Region, as it hosts some of the large continuous forest areas that provide a habitat for tigers and other rare species (Aung et al., 2017). At the same time, it is Myanmar's most suitable area for growing oil palms (Baskett, 2016; Saxon & Sheppard, 2014). Although several studies have been published recently on LCLUC in Myanmar and, more specifically, in Tanintharyi Region, they do not consider changes between shifting cultivation and commercial agriculture and thus do not sufficiently account for general landscape change. Bhagwat et al. (2017) mapped changes in vegetation cover, including oil palm and rubber plantations, between 2002 and 2014 at the national level. They concluded that during this period, forest in Myanmar declined by 0.94% annually, resulting in a total forest loss of more than two million hectares. Logging, expanding plantations, and degradation were identified as major threats to the remaining forests. Torbick et al. (2017) mapped the extent of harvested rice paddies for the whole country in 2015, quantifying it at 6,652,111 ha, which was in line with government census statistics. Their analysis also showed that of all regions, Tanintharyi Region had the highest uncertainties due to the high patchiness and mosaic character of the landscape. Connette et al. (2016) mapped land cover for Tanintharyi Region in 2016, including the agricultural land cover categories of oil palm, rubber, and betel nut plantations, as well as rice. They estimated that natural forest covered around 80% of Tanintharyi Region, of which the most degraded forest types were mangroves (66% degraded) and lowland evergreen forest (47% degraded). For the same area, De Alban et al. (2019) used annual land cover data between 1997 and 2004 combined with a literature review to identify a regime shift from a forest-oriented to an agriculture-oriented region. Zaehringer et al. (2020) described land use regime shifts from small-scale farmers' shifting cultivation to plantations of rubber, betel nut, cashew, and oil palm in two village-level case study areas in northern Tanintharyi. However, little is known to date about how smallholders' agricultural systems across the entire Tanintharyi Region have changed over the past decades.

Land system science offers a suitable framework for understanding LCLUC from a coupled human–environment or social-ecological perspective (Turner et al., 2007). For the empirical analysis of complex social-ecological processes and their impacts on land, remote sensing and pixel-based LCLUC analysis alone are not sufficient, as they fail to adequately incorporate socio-economic aspects (Asselen & Verburg, 2012). Further, retrieving land use information from land cover data or, in other words, linking land cover to human activities, presents a range of difficulties (Verburg et al., 2009). The same land cover may be used in different ways, and may therefore result from different land uses (Coffey, 2013). For example, degraded forest can be used for commercial logging or as a plot to be cleared at a later time as part of a shifting cultivation system. To better understand the interactions between agricultural change processes, such as intensification or extensification, and changes in vegetation cover, such as forest degradation or regeneration, geospatial analysis needs to move beyond land cover change assessment. This is especially important when the aim is to unravel landscape-level land system regime shifts, i.e. shifts from one state to another in a land system, which come along with substantial and often irreversible changes to peoples' livelihoods (Müller et al., 2014). By land systems we refer to the Earth's biophysical resources shaped by humans' strategies and activities of use (Verburg et al., 2013). More specifically, we use the term land systems to describe systems of land use with distinct intensities of use and specific functions, for example shifting cultivation for rice production or large-scale intensively managed oil palm plantations.

For southern Myanmar and Tanintharyi Region, which can be considered one of South-East Asia's hotspot regions of agricultural expansion into biodiversity-rich forest areas, a generalized representation of land system change is lacking. To address this research gap and make the step from pixel-level land cover information to the wider analysis of land system change in Tanintharyi Region, we applied a landscape mosaic approach, as proposed by Messerli et al. (2009). This spatial analysis approach was developed to interpret land cover information taking into account the socio-economic context. It has been applied in the Lao PDR at a national (Messerli et al., 2009) and at a regional scale (Hett et al., 2012). Furthermore, it was adapted to understand changes in shifting cultivation systems over time in north-eastern Madagascar by Zaehringer et al. (2016).

The main goal of our study was to obtain a holistic understanding of the past and present land systems in Tanintharyi Region and to detect whether a land system regime shift has taken place. To attain this goal, we proceeded as follows. As sufficiently detailed land cover and land use (LCLU) information featuring different agricultural LCLU classes did not exist for the past, we first reconstructed 2002 LCLU distributions based on different available data sources. Next, we mapped the land systems, taking into account the socio-economic context in Tanintharyi Region in 2002 and 2016. Finally, we identified how these land systems changed from 2002 to 2016, along two land use gradients of vegetation cover and agricultural use intensity. Our results contribute empirical evidence on the simultaneous intensification of agricultural land use and the degradation of vegetation cover in one of Southeast Asia's remaining prime biodiversity sites. This evidence is an important basis for planning land use and direct development interventions on behalf of more sustainable land governance in conflict-prone Tanintharyi Region.

2. Materials and methods

2.1. Study region

We selected our study region, Tanintharyi Region – the southernmost division of Myanmar – because of its importance for the conservation of biodiversity-rich forests and their ecosystem services (Fig. 1). Tanintharyi Region, on the one hand, has one of the highest forest covers in Myanmar. Among its forests is one of Southeast Asia's last remaining high conservation value forests (Donald et al., 2015). Bordering the Andaman Sea to the west and Thailand to the east, Tanintharyi Region it is divided into the delta region with the Myeik Archipelago, the coastal lowlands, and the coastal uplands (Tenasserim Hills), which rise up to 2000 m a.s.l. The huge differences in precipitation, reaching from an average 500 mm in the driest inland areas up to 5000 mm at the coast, enable a rich variety of microclimates, flora, and fauna (Donald et al., 2015; Woods, 2015). On the other hand, Myanmar has one of the highest deforestation rates worldwide. An annual forest loss of 1.2% between 1990 and 2010 (FAO, 2015) and 16.5% of global forest loss between 2010 and 2015 occurred in Myanmar (FAO, 2016), and Tanintharyi Region is no exception to this trend (Bhagwat et al., 2017).

Tanintharyi Region has a population of around 1.7 million according to the 2014 census (Department of Population, Ministry of Immigration and Population, 2015). Traditionally, the economy was dominated by fishing and agriculture. Agriculture, especially smallholders' cultivation systems, is characterized by low productivity, extreme inequality, and high volatility. Smallholders cultivate paddy rice, betel nuts, and rubber and practice shifting cultivation. It has been suggested that smallholder agriculture, especially shifting cultivation, is undergoing a transition from being subsistence oriented to being commercially oriented (Fox et al., 2014). Oil palms and rubber are mainly grown on large-scale plantations, which are mainly owned by domestic government and

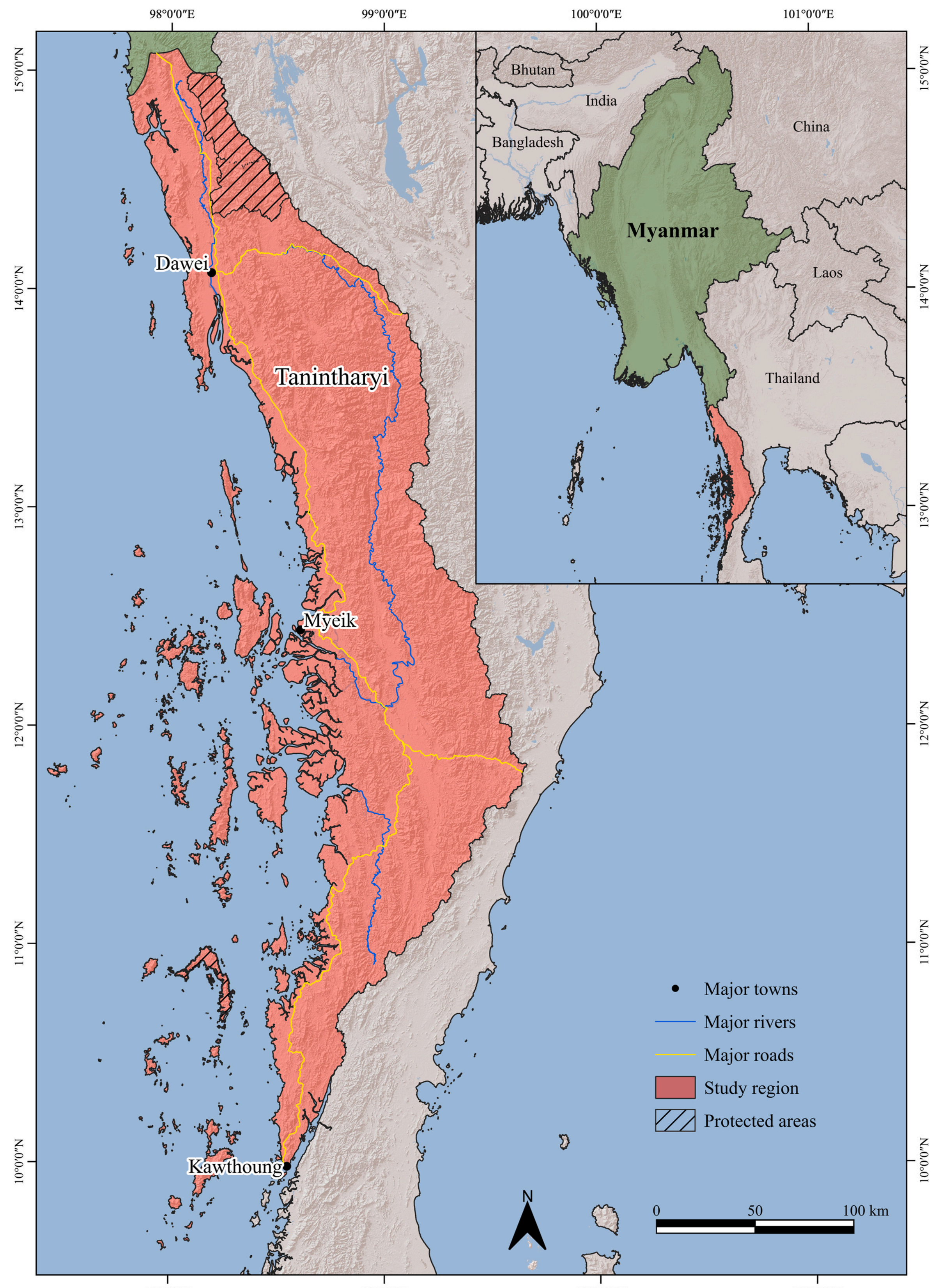

Fig. 1. Overview map of the Tanintharyi study region in southern Myanmar (base map: ESRI; roads and rivers: www.openstreetmap.org; towns: www.themimu.info (Myanmar Information Management Unit); protected areas: https://www.protectedplanet.net/country/MM; borders: https://gadm.org. These sources apply to all other maps showing towns, rivers, roads, and protected areas.

private investors (Baskett, 2016; Lundsgaard-Hansen et al., 2018; Woods, 2012). These large-scale plantations and land under agribusiness contracts have increased rapidly in recent years (Woods, 2015).

2.2. Land cover and land use data availability

The LCLU data required as an input to the landscape mosaic analysis had to reflect the major land cover and land use categories present in Tanintharyi Region, including smallholder agriculture (shifting cultivation, paddy rice, rubber, and betel nuts), large-scale plantations (oil palm), and forest. As no existing LCLU layers included all of the agricultural categories, we aggregated several available LCLU data layers that had originally been derived from Landsat satellite imagery by means of supervised classifications and visual image interpretation (Table 1). The LCLU data layers from Connette et al. (2016) (referred to below as the "Smithsonian" layer) and from Bhagwat et al. (2017) (referred to below as the "EcoDev" layer) cover the extent of Tanintharyi Region. The shifting cultivation probability layer (Würsch, 2017) covers parts of Southeast Asia (Myanmar, Laos, Vietnam and Cambodia). Finally, the Hansen et al. (2013) deforestation and tree cover layer is provided at a global scale.

In view of our study goals, and considering data availability, we selected two time points, 2002 and 2016, for the assessment. These were the only time points in the available datasets that included most of the required LCLU classes (Fig. 2). For the more recent time point (2016) we could simply combine the existing LCLU layers into one that suited our requirements. Because no sufficiently detailed LCLU data reflecting agricultural land use in Tanintharyi Region existed for 2002, the LCLU for that year had to be reconstructed on the basis of the 2016 LCLU data (see Section 2.3). We processed all spatial data in *ArcMap 10.4* (ESRI 2015).

2.3. Reconstruction of LCLU layers

We reconstructed the LCLU data for 2002 based on the Smithsonian LCLU data (see Fig. A1 for the detailed decision tree). In a first step, the different LCLU classes of the Smithsonian layer indicating intact forest were aggregated into a single class named "intact forest", and the classes indicating degraded forest into a class named "degraded forest". In a second step, we used the Hansen global deforestation and tree cover layer to identify areas with intact, degraded, and no forest. To reconstruct the forest cover for the year 2002, we took the Hansen tree cover for 2000 and subtracted the tree cover loss in 2001 to obtain the tree cover in 2002. The LCLU classes from the Smithsonian layer were then adapted according to the Hansen layer, as follows: where the Hansen layer indicated no forest cover, the class from the Smithsonian remained as in 2016, except for degraded and intact forest in the Smithsonian layer, in which case the class "other vegetative cover" was introduced to the 2002 LCLU layer (Fig. 2). In a third step, wherever the EcoDev layer for 2002 showed a presence of plantations (rubber or oil palm), these were added to our reconstructed LCLU layer. In a fourth step, to introduce shifting cultivation to the 2002 LCLU data, we combined information from the Hansen layer with the layer on shifting cultivation probability by Würsch (2017). Wherever the Hansen data showed deforestation between 2002 and 2004 and the probability of shifting cultivation was 90% or higher, we assigned the LCLU class of "shifting cultivation" to the pixels in the 2002 LCLU layer. Excepted from this were pixels in the "plantations" class (see previous step). In the end, for the remaining LCLU classes from the Smithsonian (2016) layer, "paddy rice" and "betel nut garden/plantation" were merged into "other smallholder agriculture", while "mudflat" and "human settlement" were merged into "no vegetation cover". The LCLU class "water" was masked out as it was not required for this study.

The data for 2016 is based on the Smithsonian LCLU data and the shifting cultivation probability data for cleared plots for the years 2014–2016 (see Fig. A2 for the detailed decision tree). The other two data layers were not needed, as the Smithsonian layer included all required classes except shifting cultivation. In the end, the LCLU classes were merged into the same classes used for the 2002 layer (see Fig. 2).

2.4. Land system mosaic maps

In our study, we sought to visualize land systems by analysing LCLU data for Tanintharyi Region and interpreting the presence of spatial patterns of different LCLU classes within a defined spatial window. We took the landscape mosaic approach, first proposed by Messerli et al. (2009) for Laos, and adapted it to the context of Tanintharyi Region in Myanmar.

The landscape mosaic approach was applied separately to both the 2016 LCLU layer and the reconstructed LCLU layer for 2002. First, a moving window technique was used to aggregate the surrounding LCLU information for each pixel. The purpose of this technique is to calculate the percentage occupied by each of the LCLU classes surrounding a pixel within the chosen window size of 5 × 5 km, and to attribute this information to the pixel (Fig. 3). The window size should be selected in accordance with the reach of influence land users have on their surrounding landscapes, i.e. the average distance of the furthest cultivated fields from the households' settlements. Based on in-depth field experience of a group of Myanmar researchers working in Tanintharyi Region (Feurer et al., 2019; Lundsgaard-Hansen et al., 2018), we estimated this distance to range between 2.0 and 2.5 km on average, resulting in a window size of 5 × 5 km. The same window size was used by Messerli et al. (2009) in Lao PDR and by Zaehringer et al. (2016) in northeastern Madagascar, in similar forest frontier contexts.

To interpret the composition of different LCLU classes in the given window, we developed a land system classification scheme that takes into account the Tanintharyi context. It is based on two major spatio-temporal land use gradients that are relevant for sustainable development in Tanintharyi Region (Fig. 4):

1. *Degradation of vegetation cover:* Myanmar has one of the highest deforestation rates in the world (see 2.1). The loss of tree cover is mostly due to illegal and legal logging for high value timber (Dasgupta, 2015; Woods, 2015) and clearing for new large-scale plantations or smallholder farmland (Bhagwat et al., 2017; Woods, 2015).
2. *Intensity of agricultural use:* The context of agricultural use intensity considered in this study includes: (1) Myanmar's national goal of reaching self-sufficient edible oil production (Baskett, 2016); (2) Myanmar's national goal of increasing rubber exports (Woods, 2012); and (3) the 2012 Farmland Law, which allows commercially

Table 1
Overview of LCLU data used in this study.

Name	Year	Geometry	Classes used	Type (LCLU)	Source
Smithsonian	2016	Raster (30 m resolution)	16 land cover classes	Vegetation cover	Connette et al. (2016)
Hansen[a]	2000–2016	Raster (25 m resolution)	0–100% and annual loss	Tree cover	Hansen et al. (2013)
EcoDev	2002–2014	Raster (30 m resolution)	Plantations	Vegetation cover	Bhagwat et al. (2017)
Shifting cultivation[b]	2000–2015	Raster (54 m resolution)	0–100% probability	Shifting cultivation	Würsch (2017)

[a] 10N/90E and 20N/90E.
[b] Data layer was not available for the entire Tanintharyi Region; the southern area around Kawthoung is missing (10N/90E).

LCLU class	Description	Relevance	Photo of LCLU
Intact forest (IF)	Forest (upland, lowland, mangrove, and mixed deciduous) with canopy cover of 80% and more.	Tanintharyi still has one of the largest intact forests in Southeast Asia (Woods 2015; Connette et al. 2016).	
Degraded forest (DF)	Forest (upland, lowland, mangrove, and mixed deciduous) with canopy cover of 10% to 80%.	Tanintharyi has high deforestation rates (Woods 2015; Bhagwat et al. 2017) due to timber extraction and plantations.	
Bare ground/ clearing (BC) (only in 2016/ T1)	Exposed soil and recent clearings with grassy or low herbaceous vegetation cover.	Bare areas result from logging activities and fires and are later used for plantations, grazing, or shifting cultivation.	
Plantations (oil palm and rubber) (OR)	Mature oil palm (large scale) or rubber plantations (mostly smallholders) with coverage over 50%.	Oil palm plantations have greatly expanded in recent years; rubber is traditionally cultivated in plantations as a cash crop (Woods 2012; 2015; Bhagwat et al. 2017).	
Shifting cultivation (SC)	Cleared plots mainly for shifting cultivation.	Belongs to traditional smallholder agriculture in Southeast Asia (Mertz et al. 2009).	
No vegetation cover (mudflats/ settlement) (NO)	Coastal mudflats, estuarine mudflats, and areas with interspersed to complete cover of buildings and man-made structures. Assumed to be vegetation free.	A lack of vegetation can have a huge impact on the surrounding land system, especially human settlements (Ornetsmüller, Heinimann, and Verburg 2018).	
Other smallholder agriculture (paddy rice, betel nuts) (SA)	Rice paddies and mature betel nut gardens, plantations, or plantings in forest.	Paddy rice is important for small-scale agriculture (Torbick et al. 2017), and betel nuts are one of the most important cash crops in Southeast Asia (Ramappa 2013).	
Other vegetative cover (BC) (only in 2002/ T0)	Unknown vegetation for the year 2002. For the land system mosaics it is considered to be at the same level of degradation as bare ground/clearing.	Missing LCLU data are needed to complete the regional LCLU dataset.	

Fig. 2. The eight LCLU classes of the 2002 and 2016 layers, with a description of each and information on its importance for this study.

oriented actors to acquire land if the previous landowners cannot prove that they are cultivating the land (The Republic Union of Myanmar, 2012), and which led to an expansion of smallholder cash crop plantations in Tanintharyi (Fox et al., 2014; Woods, 2015). In this study, we consider agricultural use intensity at the plot level, distinguishing smallholder self-sufficiency (shifting cultivation or paddy rice) from commercial agriculture (rubber, oil palm, betel nuts), whether by smallholders or external governmental or private investors. Accordingly, extensively managed plots cultivated for self-sufficiency have a lower use intensity than commercial agriculture (Asselen & Verburg, 2012). Plantations have the highest use intensity among the different land uses within commercial agriculture.

Each land system type is described by means of a conditional statement, based on defined threshold percentages of each LCLU class in the total window area indicating the pixel's position on each of the two land use gradients. Each gradient was analysed separately, resulting in a map that attributed every single pixel to one of several land system types. Each pixel of the LCLU mosaics was first assigned to one of the four land system types of various vegetation cover degradation, and then to one of the four types of agricultural use intensity.

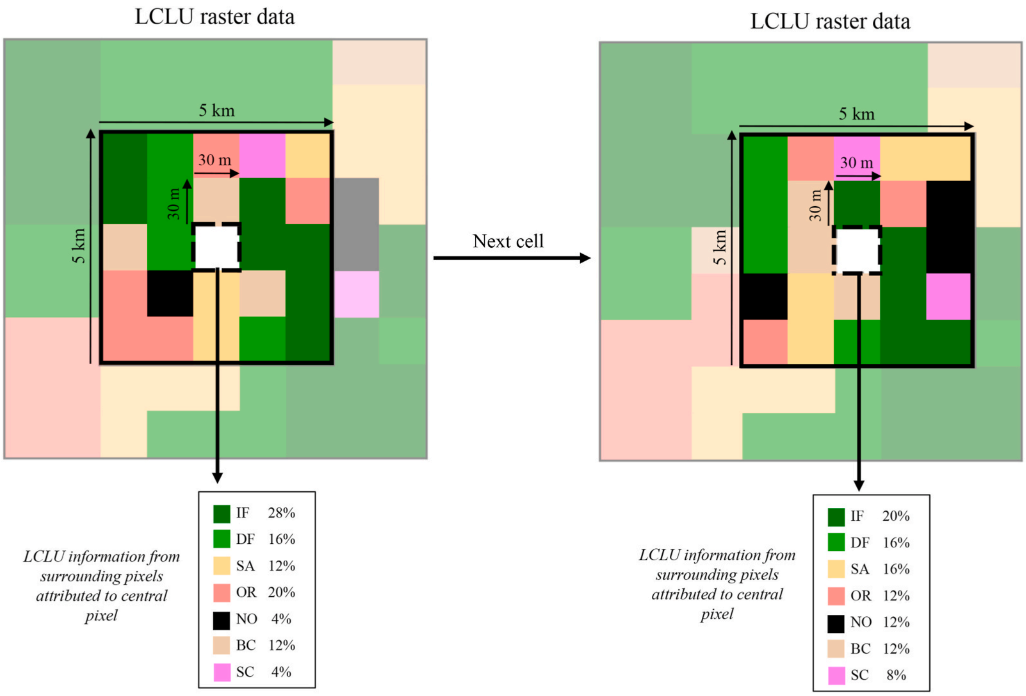

Fig. 3. An illustration of the moving window technique, which is part of the landscape mosaic approach. For the sake of clarity, only a reduced number of pixels are shown; in reality, a 5 × 5 km window would contain many more 30 × 30 m pixels. IF = intact forest, DF = degraded forest, BC = bare ground/clearing (T1), other vegetative cover (T0), NO = no vegetation cover, OR = plantations (oil palm, rubber), SA = other smallholder agriculture (paddy rice, betel nuts), SC = shifting cultivation.

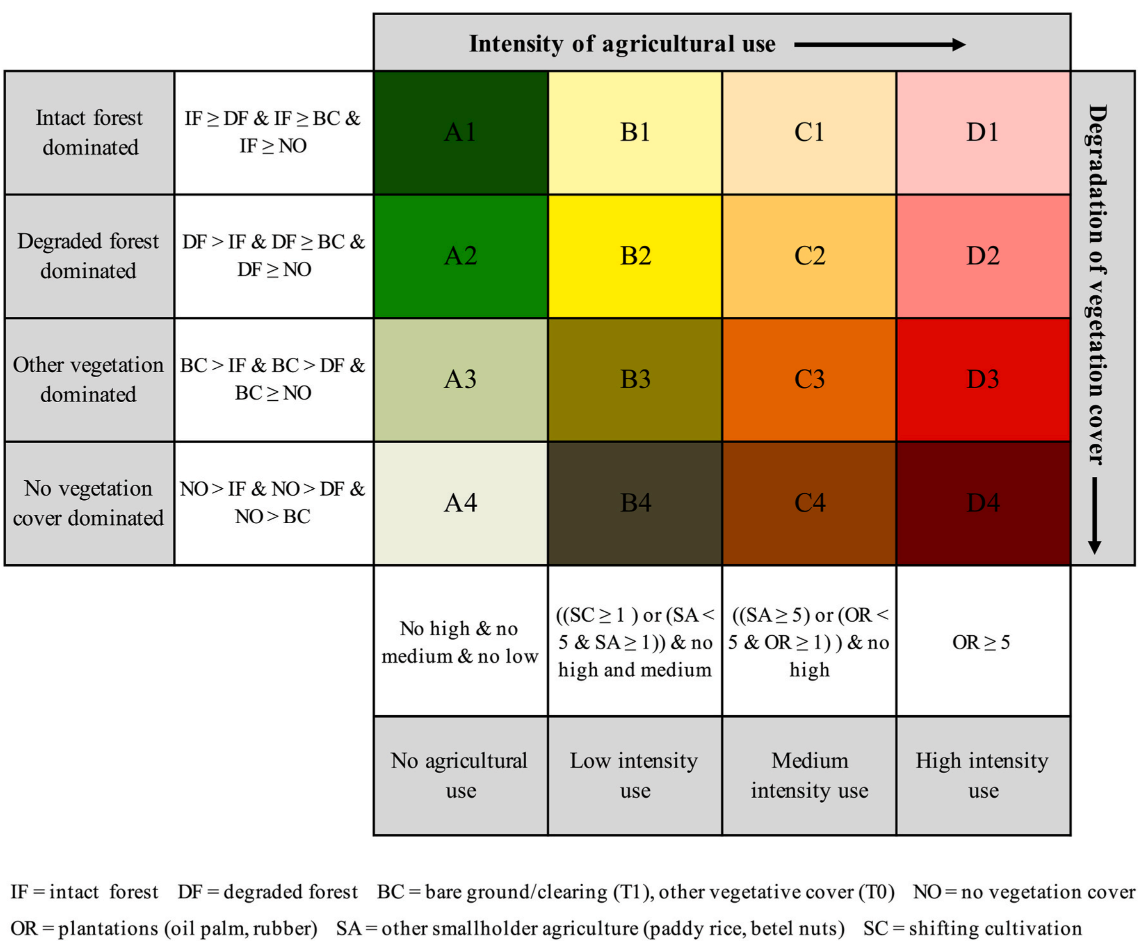

Fig. 4. Land system classification based on the intensity of agricultural use and the degradation of vegetation cover with thresholds (in % of the window) for each land system type presented in the white boxes.

Along the gradient of vegetation cover degradation, the central pixels in the moving window were classified as follows:

Intact forest dominated: The percentage of the "intact forest" LCLU class in the pixel's neighbourhood is larger or equal to the percentage of "degraded forest", "other vegetative cover" (in 2002) or "bare ground/clearing" (in 2016), and "no vegetation cover".

Degraded forest dominated: The percentage of the "degraded forest" LCLU class is greater or equal to the percentage of "other vegetative cover" (in 2002) or "bare ground/clearing" (in 2016) and "no vegetation cover".

Other vegetation dominated: The percentage of the LCLU classes "other vegetative cover" (in 2002) or "bare ground/clearing" (in 2016) is the highest present or equal to that of "no vegetation cover".

No vegetation cover dominated: The percentage of the LCLU class "no vegetative cover" is the highest present.

Along the gradient of agricultural use intensity, the pixels were classified as follows:

High intensity use: A strong presence of "plantations" (oil palm and rubber) (OR $\geq$ 5%) and therefore commercial agriculture.

Medium intensity use: A strong presence of "other smallholder agriculture" (SA $\geq$ 5%), coupled with a weaker presence of oil palm and rubber "plantations" (OR $\geq$1% and <5%) and no high intensity use.

Low intensity use: The LCLU class with the highest percentage present is "Cleared plots for shifting cultivation" (SC $\geq$ 1%).

No agricultural use: no presence of high, medium, or low intensity agricultural use.

2.5. Analysis of land system change

Looking at land system change over time, we differentiated four types of changes resulting in eight different combinations of change trajectories. In terms of changes in vegetation cover, these types included: (1) *degradation of vegetation cover*, i.e. a change from an intact forest dominated land system to one dominated by degraded forest; and (2) *regeneration of vegetation cover*, i.e. the change from a no vegetation cover dominated land system to a vegetation dominated land system. In terms of changes in agricultural use intensity, they included: (1) *agricultural extensification*, i.e. a transition from a land system with a higher intensity of use towards one with a lower intensity of use, and (2) *agricultural intensification*, a transition from a land system with a lower use intensity towards one with a higher use intensity. The possibility of no change at all also exists for both types of changes. The trajectories make it possible to see which land system types experienced change and which remained stable. To illustrate these changes, we used a transition matrix like the one proposed by Zaehringer et al. (2016).

3. Results

3.1. Past and current land systems

In 2002, land systems whose predominant vegetation cover was intact forest were omnipresent in Tanintharyi, covering almost 88% of the study region, which has a total area of 40,283 km. Over half of the study region consisted entirely of intact forest, with no agricultural use whatsoever (A1) (Fig. 5, Fig. 6). This land system was mostly located in the uplands and the central part of Tanintharyi. A total 41% of the study region was under agricultural use, predominantly of medium intensity (22%), which included mostly paddy rice fields and betel nut plantations. Around 12% of the study region were under high intensity use, consisting of oil palm and rubber plantations. Areas of low intensity agricultural use, with land systems consisting of cleared plots and few

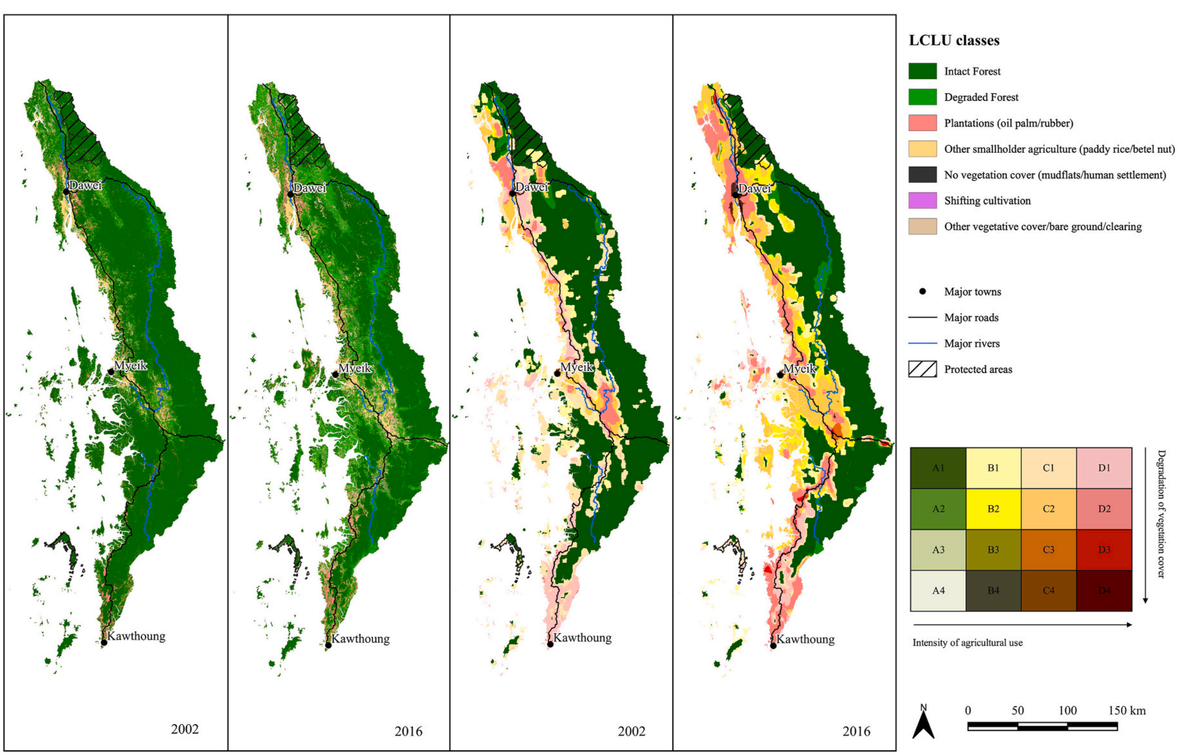

Fig. 5. (a) LCLU in 2002 and 2016 and (b) land system mosaics in 2002 and 2016 in Tanintharyi according to the land system classification. A = no agricultural use, B = low intensity agricultural use, C = medium intensity agricultural use, D = high intensity agricultural use, 1 = intact forest dominated, 2 = degraded forest dominated, 3 = other vegetation dominated, 4 = no vegetation cover dominated.

Degradation of vegetation cover ↓	No agricultural use 2002	No agricultural use 2016	Low intensity use 2002	Low intensity use 2016	Medium intensity use 2002	Medium intensity use 2016	High intensity use 2002	High intensity use 2016	Total 2002	Total 2016
Total	59.0	46.8	6.3	12.8	22.1	22.4	12.6	18.0		
Intact forest dominated	56.7	43.1	6.0	5.2	16.5	4.3	8.7	3.6	87.8	56.2
Degraded forest dominated	2.3	3.5	0.3	7.5	5.4	17.3	3.9	13.6	11.9	41.9
Other vegetation dominated	0.0*	0.2	0.0	0.1	0.0*	0.4	0.0*	0.4	0.1	1.1
No vegetation cover dominated	0.0	0.0*	0.0	0.0*	0.1	0.3	0.0*	0.4	0.2	0.7

Intensity of agricultural use →

Fig. 6. Land system mosaics in 2002 (left columns) and 2016 (right columns), in % of the observed area. * = This land system type exists in patches in Tanintharyi, but they are too small to show up in this figure. All percentages are rounded.

signs of agricultural use, covered about 6% of the study region. The areas under agricultural use were concentrated in the lowlands and along the coast. In terms of vegetation cover, these land systems were mostly dominated by intact forest. The remaining land systems were almost exclusively dominated by degraded forest.

In 2016, intact forest dominated land systems were still the most widespread type of land system, covering 56% of the study region. Looking at the individual land system classes, intact forest without any signs of agricultural use remained the most widespread, covering 43% of the study region. The total area under agricultural use accounted for 53% of the study region. Most of it was characterized by medium intensity agricultural use, covering about 22% of the study region, followed by areas of high intensity agricultural use (18%). Areas with low intensity agricultural use accounted for almost 13% of the study region. In terms of vegetation cover, all of these land systems were mostly dominated by degraded forest. In 2016, almost 2% of the study region was covered by highly degraded land systems, dominated by "other vegetation" or "no vegetation".

3.2. *Land system change from 2002 to 2016*

Although intact forest dominated land systems continued to cover more than half of the study region in 2016, they lost around 32 percentage points compared to 2002, especially in the coastal lowlands. Intact forest dominated land systems decreased across the board, whereas all other land systems expanded, especially the ones dominated by degraded forest. Areas of low and high intensity agricultural use each increased by about 6 percentage points from 2002 to 2016. At the same time, the overall area under medium intensity agricultural use remained almost stable. However, it did experience a shift from being intact forest dominated to being degraded forest dominated – the same as all other land systems that had been dominated by intact forest in 2002. Low intensity agricultural use remained present along the coast and in the lowlands, but, compared to 2002, shifted towards the forest frontier in the uplands, which had previously been characterized by intact forest without agricultural use. Areas of high intensity agricultural use were still mostly located in the coastal lowlands, especially around larger settlements like the cities of Dawei and Kawthoung.

All major land system changes occurred in either intact forest dominated or degraded forest dominated land systems. Most changes were from one level of degradation or intensification to the next higher level, but not across multiple levels. This suggests a gradual transition towards more intensive and more degraded land systems, rather than a direct change from no agricultural use to high intensity use or from intact forest dominated to no vegetation cover dominated land systems.

3.3. *Intensification of agricultural use and degradation of vegetation cover*

The most common change trajectory was degradation of vegetation cover with no change in agricultural intensity (Fig. 7). This occurred mainly in land systems with medium or high intensity agricultural use that were dominated by intact forest in 2002 and became dominated by degraded forest in 2016 (Fig. 8, Fig. 9). This trajectory was concentrated along the coast and in the coastal lowlands, where some level of agricultural use was already present in 2002. The second most common change was agricultural intensification coupled with degradation of vegetation cover. The most prominent examples of this change are land systems that were dominated by intact forest without agricultural use in 2002 and were converted into land systems dominated by degraded forest with low intensity agricultural use in 2016. This occurred mainly north of Dawei and south of Myeik, in the mangrove forests. The third most common change was agricultural intensification with no change in vegetation cover, which occurred north of Dawei and along the road from Dawei to Kawthoung, mostly towards the coastal uplands. Agricultural intensification and degradation of vegetation cover were by far the most common land system change trajectories. Yet, almost half (48%) of the study region experienced no change at all. Overall, land systems dominated by intact forest with no agricultural use account for most of the stable area (84% of the total area with no change). Very few areas (0.2% of the study region) experienced regeneration of vegetation cover coupled with agricultural extensification. This trajectory occurred mainly along the Tanintharyi river. However, this is the area where the LCLU input data from Bhagwat et al. (2017) and Connette et al. (2016) contained significant uncertainty.

4. Discussion

Use of the landscape mosaic approach enabled us to identify different land systems in Tanintharyi Region, southern Myanmar, and to assess how they changed over a time span of 14 years. Most available land cover data do not distinguish different agricultural land cover classes, as this is difficult based on low to medium resolution satellite imagery. As land system assessment necessarily requires information about

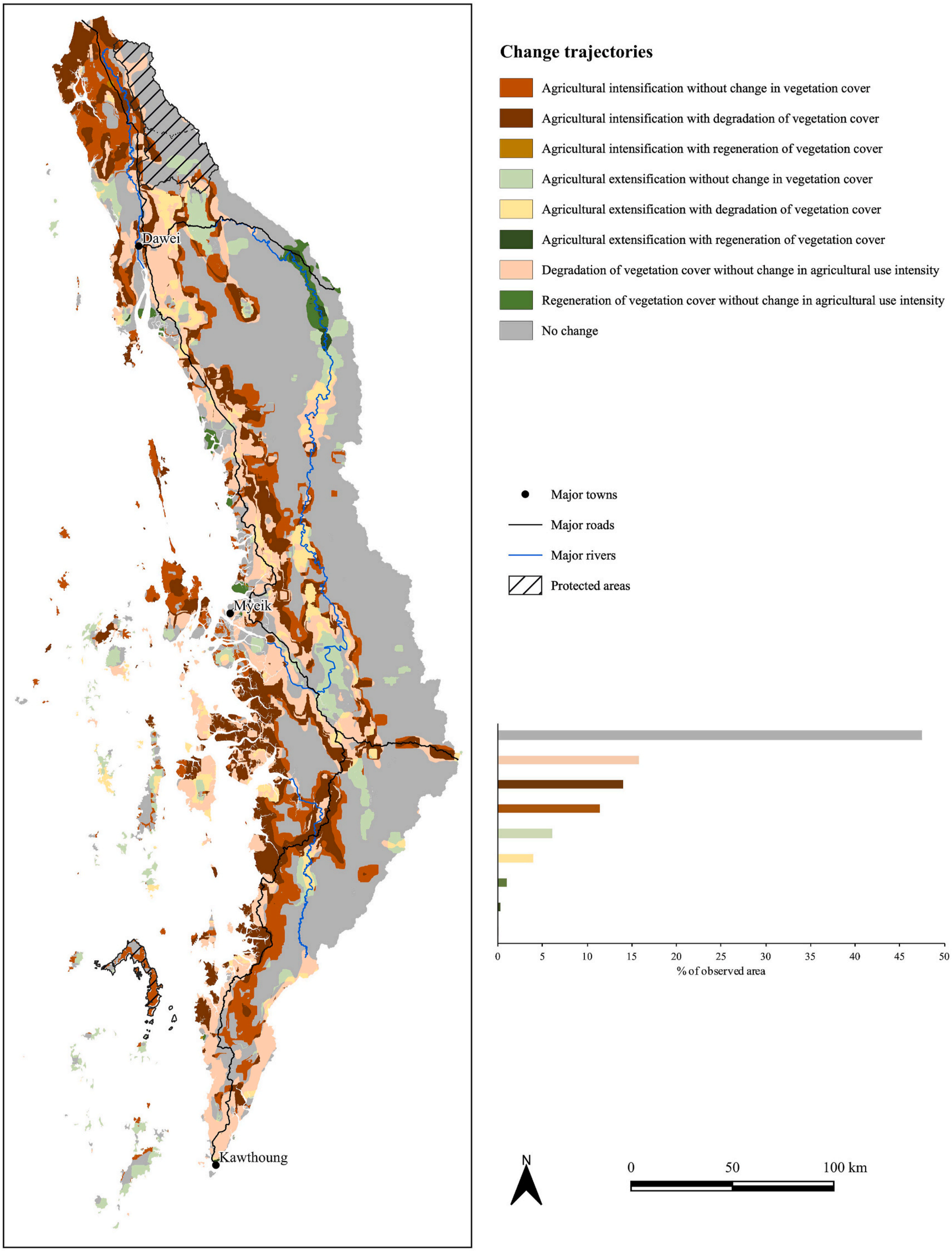

Fig. 7. Land system change trajectories from 2002 to 2016 and percentages of observed area affected by each trajectory.

agricultural land cover types, we reconstructed 2002 land cover by combining different data sources. This constitutes a methodological innovation which, coupled with a landscape mosaic approach, helps to better understand changes in agricultural land systems in other data-scarce tropical regions.

4.1. Landscape changes and implications for the environment and people's livelihoods

Our study showed that land systems dominated by intact forest still covered more than half of Tanintharyi Region in 2016. Land systems dominated by other vegetation types continued to be in the minority. This means that it is not too late to take measures to conserve these forests and the biodiversity and ecosystem services they provide. However, land systems covering more than 30% of the study region that had been dominated by intact forest in 2002 experienced vegetation cover degradation over the 14-year time span observed. This highlights the speed at which vegetation cover is becoming degraded at the landscape level and, consequently, the urgency of action to preserve the remaining intact forest. Our results are in line with the observation of around 16% forest loss in Tanintharyi Region between 1992 and 2015 by De Alban et al. (2019). As the landscape mosaic approach is an approach of

2002			2016															
			No Agricultural use				Low intensity use				Medium intensity use				High intensity use			
			ID	DD	OD	ND	ID	DD	OD	ND	ID	DD	OD	ND	ID	DD	OD	ND
2002	No agricultural use	ID	15,967	899	57	0	1,393	1,540	32	0	933	1,050	20	1	570	365	50	0
		DD	283	100	18	0	0	151	4	0	0	212	4	0	0	145	7	0
		OD	0	0	0	0	0	0	0	0	0	1	0	0	0	8	2	0
		ND	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Low intensity use	ID	178	3	0	0	306	481	0	0	162	987	3	0	130	162	0	0
		DD	0	0	0	0	0	4	0	0	0	43	2	0	0	63	0	0
		OD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		ND	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Medium intensity use	ID	821	345	0	0	335	633	0	0	444	2,374	14	4	302	1,290	58	1
		DD	93	40	0	0	0	167	0	0	98	1,076	87	63	2	500	1	65
		OD	0	0	0	0	0	0	0	0	0	17	0	2	0	1	0	0
		ND	0	0	0	0	0	0	0	0	0	0	0	48	0	0	0	10
	High intensity use	ID	43	12	0	0	51	22	0	1	100	512	9	0	450	2,229	16	33
		DD	0	6	0	0	0	45	0	0	3	680	38	1	5	730	11	62
		OD	0	0	0	0	0	0	0	0	0	3	0	2	0	1	0	0
		ND	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0

Agricultural intensifiaction without change in vegetation cover
Agricultural intensification with degradation of vegetation cover
Agricultural intensification with regeneration of vegetation cover
Agricultural extensification without change in vegetation cover
Agricultural extensification with degradation of vegetation cover
Agricultural extensification with regeneration of vegetation cover
Degradation of vegetation cover without change in agricultural use intensity
Regeneration of vegetation cover without change in agricultural use intensity
No change

ID = Intact forest dominated   DD = Degraded forest dominated   OD = Other vegetation dominated   ND = No vegetation cover dominated

Fig. 8. Land system change trajectories from 2002 to 2016 in km^2.

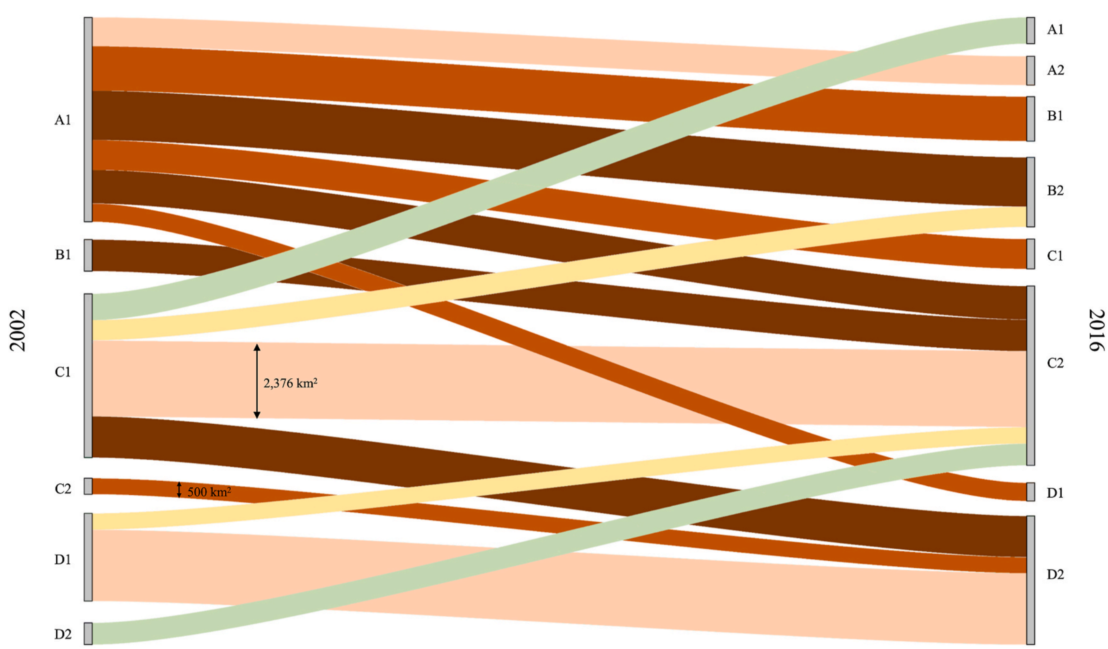

Fig. 9. Major land system changes (affecting a total area of 500 km^2 or more) from 2002 to 2016, using the same trajectories and colours as in Fig. 8. The width of the coloured bands is proportional to the total area affected by each change trajectory. A = no agricultural use, B = low intensity use, C = medium intensity use, D = high intensity use, 1 = intact forest dominated, 2 = degraded forest dominated. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

generalization that assesses each pixel based on the land cover in a surrounding 5 × 5 km window, our results do not show the exact forest loss but rather depict changes at the land system or landscape level. This explains why the area we found to consist of landscapes experiencing vegetation cover degradation is larger than the direct area of deforestation determined by De Alban et al. (2019).

Most of this degradation occurred along the frontiers of land systems characterized by intact forest with no agricultural use, mostly on the coast and towards the uplands. This forest cover degradation threatens to decrease associated biodiversity and ecosystem services (Sodhi et al., 2010), necessitating interventions to reverse this trend. However, the recent history of nature conservation in Tanintharyi Region is highly conflictive, as a large part of Tanintharyi's forested areas are under mixed control by the Karen National Union (KNU), an armed opposition group, and the Myanmar government. People who were internally displaced due to the civil war are now making a living from agriculture in forested areas, for example in the area of the proposed Lenya National Park (Conservation Alliance of Tanawthari, 2018). As the KNU has its own land policy, which conflicts with that of the Myanmar government in many respects, any conservation interventions in this region need to carefully balance these stakeholders' different aims and visions; otherwise, they might risk to upset the 2012 ceasefire agreement between the two parties (Carroll, 2018).

The decrease in land systems dominated by intact forest without agricultural use from 2002 to 2016 is largely related to an increase in land systems with low or medium intensity agricultural use and a degraded vegetation cover. This indicates that the expansion of smallholders' agricultural activities – shifting cultivation, betel nut gardens, and paddy rice fields – was related to these land system's intensification and degradation. Our results show that oil palm and rubber plantations of commercial investors were established in land systems formerly dominated by smallholder farmers and their betel nut plantations and paddy rice fields. Accordingly, a considerable share of the expansion of smallholder systems into land systems with previously intact forest may be related to the displacement of smallholders by large-scale commercial plantations or the described conflicts in the region. However, our results cannot provide any further details on the roles of these displacement processes in the increase of land systems with low to medium intensity agricultural use.

Overall, land systems with agricultural use increased by 12 percentage points in the region. These increases occurred mostly in systems with low or high intensity agricultural use. Although the total area of land systems with medium agricultural use remained stable, this land system replaced land systems with no or low intensity agricultural use. In turn, large areas under medium agricultural use were converted into systems with high intensity use, especially in the lowlands. This agricultural intensification occurred alongside vegetation cover degradation, suggesting a strong association between these two change processes. While the expansion of cash crop plantations is in line with the Myanmar government's plans for sustainable development (GoM, 2018), this land use regime shift (Müller et al., 2014) has implications for smallholders' livelihoods. The private sector commercial actors usually have considerably greater agency than smallholders, who are excluded from decision making and do not benefit from the expansion of palm oil plantations (Lundsgaard-Hansen et al., 2018). Additionally, the replacement of smallholders' land uses with oil palm plantations decreases the perceived provision of different ecosystem services, especially a healthy water flow (Feurer et al., 2019). Further research efforts should be devoted to investigating whether this shift towards high intensity agricultural use also displaced smallholders' crop production (e.g. of rice and betel nuts) towards the forest frontier, thus causing indirect land use changes (Meyfroidt, 2016). If not, this would beg the question of how the reduced self-sufficiency from rice production affects smallholders' food security. To prevent further loss of access to land, smallholders' land rights should be formalized, taking into account the customary approach to land rights (Voices, 2019).

Lastly, vegetation cover degradation within existing agricultural land use systems was especially visible in the mangrove forest along the coast south of Myeik and towards Kawthoung. This transition of the mangroves corresponds to the finding of Richards and Friess (2016), who noted that the mangrove forests in Southeast Asia show very high deforestation rates and suffer more from increasing agricultural use than other forest types. This reduces the provision of important provisioning ecosystem services to local land users – such as wood, non-timber forest products, or mud crabs for selling (Feurer et al., 2018). Furthermore, the loss of regulating services from mangrove ecosystems, such as flood protection, has potentially disastrous consequences in the case of a cyclone (Das & Vincent, 2009).

4.2. *Potential and limitations of the landscape mosaic approach*

The landscape mosaic approach holds an important potential for land use planning, as it goes far beyond the assessment of forest to non-forest land cover change. Although the precise land cover information of a single pixel is lost, the approach offers a better understanding of wider landscapes and their change processes. Unlike pixel-based LCLUC maps, maps of land system changes make it possible to identify areas where land systems' ecological functions are under pressure from agricultural intensification and vegetation cover degradation. Further, they make it possible to distinguish between change processes resulting from to smallholders' agricultural activities and those resulting from large-scale commercial investments. By doing so, they can help to target specific actors with interventions to slow vegetation cover degradation or to support smallholders' land uses where this is needed most. The landscape mosaic approach makes it possible to identify patterns of land system change. To untangle the complex decision-making processes leading to the specific land system change outcomes, however, the approach would have to be combined with in-depth case studies.

With a landscape mosaic approach, the selected window size and land cover classification system and the defined thresholds influence the resulting land system maps. The characteristics of these land system maps depend on the level of detail of the input land cover data. In our study, the assessment of changes in shifting cultivation systems was complicated by the fact that the land cover input contained a land cover class of cleared plots but no fallows. To make up for this, we compared the location of cleared plots with a layer of shifting cultivation probabilities that relied on the specific footprint such shifting cultivation systems leave in time and space. This enabled us to indicate the presence or absence of shifting cultivation in the wider land system. Furthermore, as the landscape mosaic approach consists in generalizing and aggregating information (Messerli et al., 2009), it is only suitable for larger-scale assessments, such as at the regional level.

5. Conclusion

Using the landscape mosaic approach – a spatial analysis approach in which land cover is analysed in light of its surrounding context – we showed that land systems dominated by intact forest in Tanintharyi Region decreased strongly between 2002 and 2016, instead becoming dominated by degraded forest. Nevertheless, intact forest continued to be the prevailing vegetation cover of land systems in Tanintharyi Region in 2016. Nearly half of the study region experienced vegetation cover degradation, intensification of agricultural use, or a combination of both. Land systems without or with only extensive agricultural use in 2002 became dominated by smallholders' shifting cultivation systems and permanent betel nut gardens and paddy rice fields. The expansion of smallholders' agricultural systems might, at least partly, be a consequence of land system intensification. In different areas, smallholder dominated land systems were intensified through the expansion of oil palm and rubber plantations. As these plantations are mostly in the hands of commercial private investors and agribusinesses, this suggests that smallholders lost access to their land, were displaced and forced to establish new plantations elsewhere. The land system maps offer a sound basis for planning interventions to slow the degradation of biodiversity-rich forests and to support smallholder farmers in coping with the fast-paced expansion of commercial cash crop plantations and their social and environmental impacts. Sustainable development in this global biodiversity hotspot requires careful land use planning to support nature and people and to avoid the resurgence of smouldering conflicts.

CRediT authorship contribution statement

Marc Schmid: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Andreas Heinimann:** Conceptualization, Methodology, Supervision, Funding acquisition. **Julie G. Zaehringer:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Supervision, Project administration.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apgeog.2020.102380.

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