



University of Hohenheim
Institute of Agricultural Sciences in the Tropics
Management of Crop Water Stress in the Tropics and Subtropics

Assessment of the transferability of a regional calibrated model for Ecosystem Services from South-East China to Northern Thailand

Master Thesis

Submitted by

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Abstract

Ecologically important forests and traditionally managed agriculture in South-East Asia are disappearing at a rapid pace. Smallholder farmers rely increasingly on cash crops like rubber to improve their standard of living. However, the abrupt shift in land-use results in a great loss of ecosystem services which are heavily underestimated because they don't have an explicit value. This study considered changes in the land use pattern of a mountainous watershed in Nan Province, northern Thailand, for the time period 2001 to 2016 applying the Intensity Analysis framework. To further analyze the impact of land-use change, four ecosystem services have been assessed by using the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model: annual water yield; carbon storage and sequestration; sediment delivery ratio; habitat quality. The models ran with two different input datasets, to test if the transfer of (1) regional calibrated data from south-east China or (2) globally averaged parameters can produce reasonable results. It was found that forest area decreased by 24.4%, whereas corn, rubber and succession areas increased substantially. Both datasets generated similar trends for carbon storage, habitat quality and annual water yield. Each ecosystem service decreased in response to a decline in forest area. However, sediment export declined using the calibrated data but increased with globally averaged parameters. The validation through literature showed that calibrated input parameters produce similar results. The transfer of calibrated data can serve as a cost and time efficient tool to support policy guidance if local input data is not available.

Key Words: land-use change; ecosystem services; deforestation; rubber; InVEST; northern Thailand

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List of Abbreviations

ES	Ecosystem Service
InVEST	Integrated Valuation of Ecosystem Services and Trade-offs
LULC	Land-Use and Land-Cover
LULCC	Land-Use and Land-Cover-Change
MSA	Mean Species Abundance

Declaration

I,

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Born on 01.07.1993

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declare that I have followed the Principles of Good Scientific Practice while writing the present Master's thesis.

I have written the paper/thesis independently and have used no other sources or aids than those given and have marked the passages taken from other works word-for- word or paraphrased.

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Thesis topic Assessment of the transferability of a regional calibrated model for Ecosystem Services from South-East China to Northern Thailand

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“No one yet knows how to engineer systems that provide humans with the life-supporting services that natural ecosystems produce for free.”
(Cohen & Tilman, 1996)

1. Introduction

Currently, our global land surface consists of 30.6% forest area. Between 1990 and 2015, its proportion decreased by 1%, which amounts to 1.291.360 km² of loss (FAO, 2018). Even though deforestation slowed down and global efforts were taken in large-scale afforestation programs, forest areas are majorly affected by Land-Use and Land-Cover Change (LULCC). They are converted into urban or agricultural land to match the needs of a growing population on our limited surface (FAO, 2018). The importance of forest ecosystems is widely investigated and proven. This critical resource provides humanity with services that have an impact locally and globally and play a significant role in balancing global change, which are called services Ecosystem Services (ES). The Millenium Ecosystem Assessment (2005) defines ES as “the benefits people obtain from ecosystems”. They are further classified into four categories: provisioning, regulating, supporting and cultural services. For example, forest ecosystems provide food and fresh water, regulate global climate, support nutrient cycling and soil formation and they can have a recreational or spiritual benefit. Overall human well-being is directly related to and depends on ES. But still, their benefits are often neglected and underestimated in policies because they don’t have an explicit value. According to Costanza et al. (2014), total global ES have a value of \$124.8 trillion/yr in 2011 and the loss of forest area in consequence of LULCC amounts to \$3.3 trillion/yr. An inadequate valuation leads to a loss of ES. This has negative consequences in the long term, such as ecosystem degradation and, eventually, a decline in human well-being (FAO, 2019). The Mekong Region experiences vast LULCC in terms of ongoing deforestation of natural forest cover and the shift from traditional, subsistence production to plantation monocultures of cash crops. The spread of rubber plantations accelerated land-use transformations and affected socio-economic conditions and livelihood of smallholder farmers (Xu et al., 2014). Rubber cultivation increases household income and enables a higher standard of living (Fox & Castella, 2013). However, farmers are now dependent on rubber prices and become more vulnerable. Diversification into other crops to buffer fluctuations on the world market is necessary, but it is unattractive during rubber boom years and local conditions might not allow other crops (Andriesse & Tanwattana, 2018).

Climate change might even promote further expansion of rubber production as new areas with a high cultivation suitability will emerge (Golbon et al., 2018). But this expansion also includes marginal environments, which become more and more attractive for transition leading to wider ecosystem problems. Eventually, this will only cause a loss-loss scenario. The depletion of high-biodiversity value land for a poorly adapted crop that won't produce sustainable yields in the long-term will threaten livelihoods even more (Ahrends et al., 2015). Land-use transformation comes along with a severe alteration in ecosystem functions and services and hence, is negatively impacting carbon stocks and sequestration, water cycles and soil erosion (Häuser et al., 2015). Hu et al. (2008) estimated a loss of ES valuing \$11.427 million in Xishuangbanna, Southwest China, as rubber plantations increased by 33.53% and forest areas decreased by 21.16%. Nevertheless, as long as the global price for rubber remains high, farmers will continue its cultivation.

1.1 Literature Review

“*Land cover* is defined by the attributes of the earth’s land surface and immediate subsurface, including biota, soil, topography, surface and groundwater, and human structures.” Lambin et al., (2003)

“*Land use* is defined by the purposes for which humans exploit the land cover.” Lambin et al., (2003)

Land-use change typically implies *Land-cover conversion* through a complete shift from one land cover type to another (e.g. deforestation, agricultural expansion, urbanization).

However, another aspect which is rather neglected are *Land-cover modifications*. Without altering its overall classification, they only impact the character of a certain land cover (e.g. agricultural intensification).

LULCC has multiple, interacting causes led by resource scarcity. Driving forces can have long (e.g. spread of salinity on irrigated land) or short turnover times (e.g. climatic variability linked to El Nino oscillation). Also trigger events, whether biophysical (e.g. drought) or socioeconomic (e.g. war), can impact land-use change. Lambin et al. (2003) identified five fundamental high-level causes of LULCC:

- “1. resource scarcity leading to an increase in the pressure of production on resources,
2. changing opportunities created by markets,
3. outside policy intervention,
4. loss of adaptive capacity and increased vulnerability, and
5. changes in social organization, in resource access, and in attitudes.”

Modelling land use change is an important tool for understanding key processes of land use systems. Their projection on alternative scenarios into the future can support land use planning and policy. Additionally, they provide information on “the sensitivity of land use patterns to changes in selected variables [...] and allow testing of the stability of linked social and ecological systems, through scenario building” (Veldkamp & Lambin, 2001).

Initially LULCC got into focus for its influence on climate change and the reduction in biotic diversity, in general deforestation, desertification and other changes in natural vegetation.

More recent concerns emphasize sustainability and vulnerability of ecosystems underlining the dynamic relationship of human societies and their ecosystems at a local scale. Land-use change impacts and alters ES. Eventually, these alterations will feed back on the drivers of

land-use change in the long term (Lambin et al., 2003). Hence, identifying and assessing ES of a certain landscape is crucial for land use planning promoting nature conservation. Within the last two decades, the ES concept became increasingly popular and various mapping approaches, models and tools have been developed. The assessment and mapping of ES is essential for their quantification and valuation in order to guide policy and decision making and to ensure a more sustainable allocation of resources. Land-cover data used in Geographic Information Systems (GIS) can provide the necessary input for such analysis and three general approaches can be differentiated: GIS software packages; disciplinary biophysical models and integrated modelling tools (Burkhard & Maes, 2017). Which approach to be used depends on the type of ES to be assessed. Land use planning is majorly performed at the scale of fields to village. Therefore, mapping at municipal and provincial level and the use of a fine resolution (1 ha or less) is important (Malinga et al., 2015). Ideally, ES research should (1) validate ecosystem data and models social-ecologically, (2) recognize trade-offs between ES, (3) consider off-site effects, (4) involve stakeholders and (5) provide relevant results with a high usability for their implication in practice (Lautenbach et al., 2019). Since 2007 publications on ES have increased significantly. Major research interest is driven by policy application in green accounting, land use policy, resource allocation and payments for ES. But many studies are lacking interdisciplinarity and assess single or few ES only. Furthermore, the inclusion of future scenarios to provide guidance on future policy assessments is still limited in many studies (Häuser, 2015; Schägner et al., 2013).

Also, the existing mismatch between demand and consumption of ES and their actual supply should receive more attention (Burkhard et al., 2012; Geijzendorffer et al., 2015). Finally, nature conservation is no longer only recognized by the discrepancy between environment and development. The awareness of its social and economic benefits is increasing (de Groot et al., 2010).

Various previous studies assessed the impact of land-use change on ES in rubber cultivating regions (Arunyawat & Shrestha, 2016; Chanhda et al., 2009; Hu et al., 2008; Yang et al., 2016; Yoshida et al., 2010) and developed future land-use scenarios (Cotter et al., 2017; Thellmann et al., 2017, 2019). Nevertheless, results cannot be generalized, and location-specific assessment is important and necessary for policy guidance.

1.2 Study Area

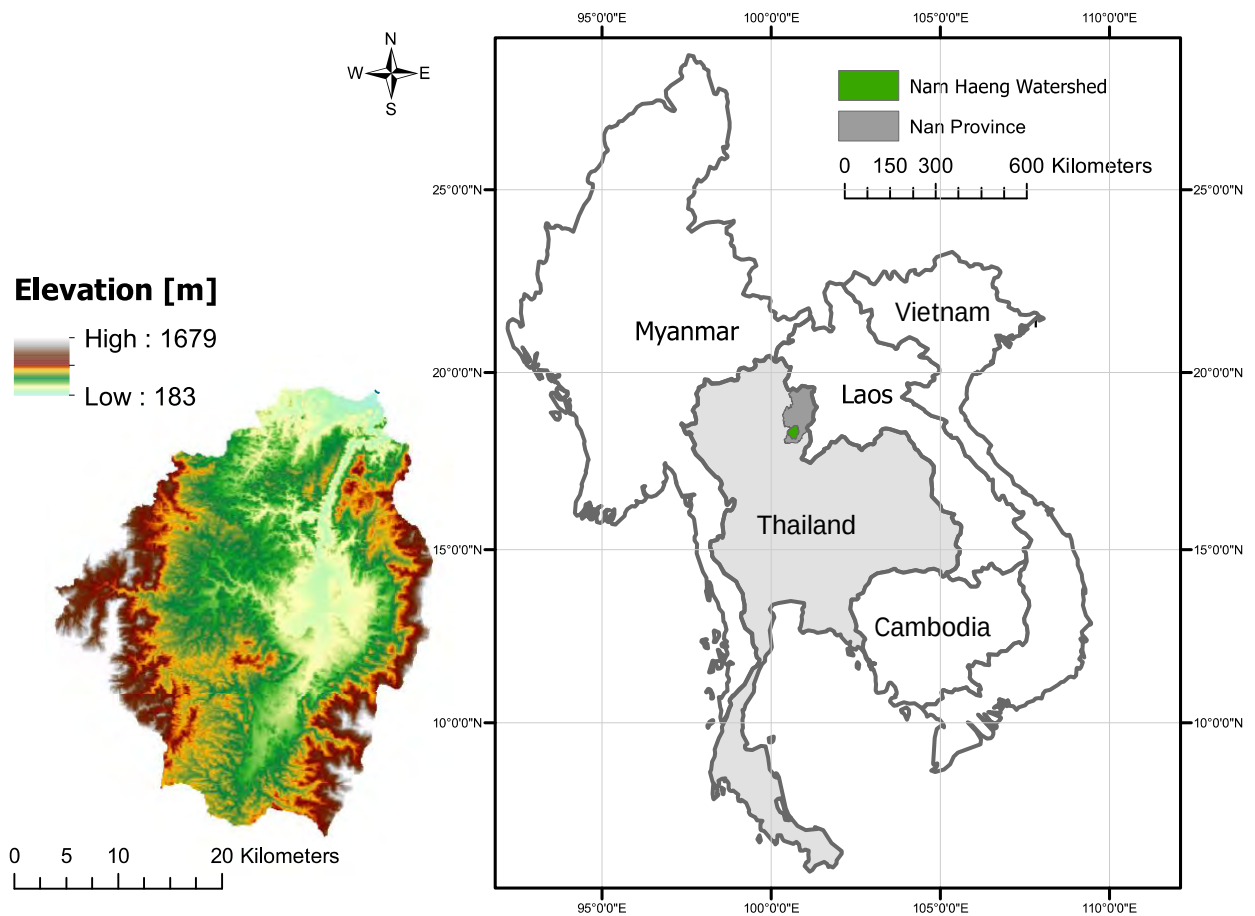


Figure 1: Geographic Location and Digital Elevation Model of the Nam Haeng Watershed, adapted from Data Basin (2020).

The Nam Haeng watershed is located in Na Noi district, in the east of Northern Thailand in Nan province at the border to Laos. It covers an area of 1,003 km² and drains into the Nan river. Hence, it is one of nine sub-catchments of the Upper Nan Basin which comprises 13,000 km². Nan province has a population of 478,227 (Office of Registration Administration, 2020). The area is rich in forests and cultural attraction, but it is deficient in fertile soil and investment capital. Additionally, unsustainable land use practices threaten the ecological condition of the watershed. The landscape can be generalized as mixed agroforestry (Thomas et al., 2004). Conservation forests cover 20% of the watershed area. Corn, rubber and paddy rice are dominant production systems. Further cultivated crops comprise cabbage, upland rice, banana, jack fruit, tamarind, pineapple, longan, truck crop, peanut, papaya, mango and santol. Perennials include oil palm, teak, rain tree, eagle wood, eucalyptus. The region is mountainous with elevations from 1679 to 183 meters above mean

sea level and an average slope of 24.52. The study area has a tropical monsoon climate with winter, summer and rainy seasons and an average annual precipitation of 1,675 mm, with more than 80% occurring during the wet season from mid-May until the end of October. The maximum and minimum values for monthly average rainfall are 262 mm in August and 6 mm in December. Temperatures range between 20 to 30 degree Celsius, highest in April decreasing to a minimum in December. (Krishna Bahadur, 2009; Pheerawat & Babel, 2015)

1.3 Thesis Objectives

The purpose of this study is to analyze land use change of the Nam Haeng watershed throughout the period 2001 to 2016 and by using the results, answer the following research questions:

- How has the land-use change of recent years affected ES?

Furthermore, as data availability for ES mapping and modelling might be scarce and incomplete:

- Can a regionally calibrated model from China be transferred to a similar situation in Thailand?
- Do globally averaged biophysical input parameters produce reasonable results?
- Does either one of the above provide a cost and time efficient tool of communicating research results in a sufficiently correct manner to help inform decision makers?

2. Material & methods

2.1 Data

This study uses five maps of land-use categories for the years 2001, 2007, 2009, 2012 and 2016. All maps are the same spatial extent (18°19' N 100°40' E). Each map has a resolution of 5 m x 5 m containing 40.144.104 pixels, with each pixel representing one of ten land-use categories. Initially, 105 different land-uses were grouped into: annual crops, corn, forest, orchards/horticulture, paddy rice, perennial crops, rubber, succession, urban and water.

2.2 Intensity Analysis

To understand the patterns and processes of LULCC in the Nam Haeng watershed, the intensity analysis framework from Aldwaik & Pontius (2012) was applied. This quantitative method uses cross-tabulation matrices to analyze land use changes within multiple time intervals as well as the intensity of transitions. It is a three-level approach examining, if the pattern of change is stationary, meaning that the reason for a particular transition is the same within multiple time intervals. This study considers four time intervals: 2001–2007, 2007–2009, 2009–2012, 2012–2016.

The first step to perform intensity analysis is to generate transition matrices from time intervals in terms of percentage share of study area. These matrices compare the proportional change in the number of pixels representing each land use category and show stocks and flows of categories. The stocks represent the size of each category at the interval's initial and final time (total column at the right and total row at the bottom). Stocks also include the numbers on the diagonal, which represent persisting land, whereas flows are the numbers off the diagonal indicating change of land. Additionally, flows are computed to gross losses (initial total minus persistence) and gross gains (final totals minus persistence).

The intensity analysis approach runs through three levels: interval, category and transition level.

The interval level considers the rate of annual overall change (Eq. (2)) and computes the annual percentage of change for each interval (Eq. (1)).

At category level, the approach analyses the annual intensity of gross gain (Eq. (3)) and gross loss (Eq. (4)) for each category proportionally to the size of the category at the end of the time interval. The intensity of change within each time interval and category is considered relative to the rate of overall change.

The transition level analysis evaluates if a systematic relationship exists between two transitioning categories in proportion to the sizes of all categories. It considers the annual intensity of transition from one category to another. For a gaining category n , Equations (5), (6) reveal which categories are intensively affected versus ignored for takeover by category n in time interval t . Equations (7), (8) detect for a losing category m , which categories are intensively affected versus ignored for takeover by category m in time interval t . (Aldwaik & Pontius, 2012)

$$S_t = \frac{\frac{\text{area of change during interval}[Y_t, Y_{t+1}]}{\text{area of study region}}}{\text{duration of interval}[Y_t, Y_{t+1}]} \times 100\% = \frac{\left\{ \sum_{j=1}^J \left[\left(\sum_{i=1}^J C_{tij} \right) - C_{tjj} \right] \right\} / \left[\sum_{j=1}^J \left(\sum_{i=1}^J C_{tij} \right) \right]}{Y_{t+1} - Y_t} \times 100\% \quad (1)$$

$$U = \frac{\frac{\text{area of change during all intervals}}{\text{area of study region}}}{\text{duration of all intervals}} \times 100\% = \frac{\sum_{t=1}^{T-1} \left\{ \sum_{j=1}^J \left[\left(\sum_{i=1}^J C_{tij} \right) - C_{tjj} \right] \right\} / \left[\sum_{j=1}^J \left(\sum_{i=1}^J C_{tij} \right) \right]}{Y_T - Y_1} \times 100\% \quad (2)$$

$$G_{tj} = \frac{\frac{\text{area of gross gain of category } j \text{ during } [Y_t, Y_{t+1}]}{\text{duration of } [Y_t, Y_{t+1}]}}{\text{area of category } j \text{ at time } Y_{t+1}} \times 100\% = \frac{\left[\left(\sum_{i=1}^J C_{tij} \right) - C_{tjj} \right] / (Y_{t+1} - Y_t)}{\sum_{i=1}^J C_{tij}} \times 100\% \quad (3)$$

$$L_{ti} = \frac{\frac{\text{area of gross loss of category } i \text{ during } [Y_t, Y_{t+1}]}{\text{duration of } [Y_t, Y_{t+1}]}}{\text{area of category } i \text{ at time } Y_t} \times 100\% = \frac{\left[\left(\sum_{j=1}^J C_{tij} \right) - C_{tii} \right] / (Y_{t+1} - Y_t)}{\sum_{j=1}^J C_{tij}} \times 100\% \quad (4)$$

$$R_{tin} = \frac{\frac{\text{area of transition from } i \text{ to } n \text{ during } [Y_t, Y_{t+1}]}{\text{duration of } [Y_t, Y_{t+1}]}}{\text{area of category } i \text{ at time } Y_t} \times 100\% = \frac{C_{tin} / (Y_{t+1} - Y_t)}{\sum_{j=1}^J C_{tij}} \times 100\% \quad (5)$$

$$W_{tn} = \frac{\frac{\text{area of gross gain of category } n \text{ during } [Y_t, Y_{t+1}]}{\text{duration of } [Y_t, Y_{t+1}]}}{\text{area that is not category } n \text{ at time } Y_t} \times 100\% = \frac{\left[\left(\sum_{i=1}^J C_{tin} \right) - C_{tnn} \right] / (Y_{t+1} - Y_t)}{\sum_{j=1}^J \left[\left(\sum_{i=1}^J C_{tij} \right) - C_{tnj} \right]} \times 100\% \quad (6)$$

$$Q_{tmj} = \frac{\frac{\text{area of transition from } m \text{ to } j \text{ during } [Y_t, Y_{t+1}]}{\text{duration of } [Y_t, Y_{t+1}]}}{\text{area of category } j \text{ at time } Y_{t+1}} \times 100\% = \frac{C_{tmj} / (Y_{t+1} - Y_t)}{\sum_{i=1}^J C_{tij}} \times 100\% \quad (7)$$

$$V_{tm} = \frac{\frac{\text{area of gross loss of category } m \text{ during } [Y_t, Y_{t+1}]}{\text{duration of } [Y_t, Y_{t+1}]}}{\text{area that is not category } m \text{ at time } Y_{t+1}} \times 100\% = \frac{\left[\left(\sum_{j=1}^J C_{tmj} \right) - C_{tmm} \right] / (Y_{t+1} - Y_t)}{\sum_{i=1}^J \left[\left(\sum_{j=1}^J C_{tij} \right) - C_{tim} \right]} \times 100\% \quad (8)$$

Where:

- J number of categories;
- i index for a category at the initial time point for a particular time interval;
- j index for a category at the final time point for a particular time interval;
- m index for the losing category in the transition of interest;
- n index for the gaining category in the transition of interest;
- T number of time points;
- t index for the initial time point of interval $[Y_t, Y_{t+1}]$, where t ranges from 1 to $T-1$;
- Y_t year at time point t ;
- C_{tij} number of pixels that transition from category i at time Y_t to category j at time Y_{t+1} ;
- S_t annual intensity of change for time interval $[Y_t, Y_{t+1}]$;
- U value of uniform line for time intensity analysis;
- G_{tj} annual intensity of gross gain of category j for time interval $[Y_t, Y_{t+1}]$;
- L_{ti} annual intensity of gross loss of category i for time interval $[Y_t, Y_{t+1}]$;
- R_{tin} annual intensity of transition from category i to category n during time interval $[Y_t, Y_{t+1}]$ where $i \neq n$;
- W_{tn} value of uniform intensity of transition to category n from all non- n categories at time Y_t during time interval $[Y_t, Y_{t+1}]$;
- Q_{tmj} annual intensity of transition from category m to category j during time interval $[Y_t, Y_{t+1}]$ where $j \neq m$;
- V_{tm} value of uniform intensity of transition from category m to all non- m categories at time Y_{t+1} during time interval $[Y_t, Y_{t+1}]$.

2.3 Ecosystem Service Assessment

The purpose of this analysis is to assess the impact of LULCC on ES in northern Thailand. Simultaneously, the study evaluates the transferability of a regionally calibrated model from China to a similar situation in Thailand.

The Natural Capital Project developed a tool to quantify and map the values of ES: the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST). Its version 3.7.0/3.8.0. was used to assess ES as well as ArcGIS, to prepare data inputs and evaluate results generated by the software. Four InVEST models were applied: annual water yield, carbon storage and sequestration, sediment delivery ratio and habitat quality. Using the InVEST model results, a ES z-score from was computed. The output values of each ES were normalized and calculated in relation to the initial year, which was set to 1. The arithmetic mean of the normalized ES values give the ES z-score.

To test for transferability, biophysical input parameters were adopted from two different sources. Thellmann et al. (2017) applied the InVEST framework to the Naban River Watershed National Nature Reserve, which is located in Yunnan Province of south-western China. The study area is similar to the Nam Haeng watershed in terms of climate, topography and production systems.

The second data source was the sample data set which comes with the InVEST software package, in the following referred to as Sharp et al. (2020). It is aimed as a guide for formatting data and testing the models. The input values are “globally-averaged [...] from a variety of literature sources” (Sharp et al., 2020). Table 1 shows the assignment of landcover types, as not all landcover types from both data sources are equal to the Nam Haeng watershed.

The results of both datasets were then compared to literature data. Particular literature assessing the Nam Haeng watershed was not available, therefore the scope was put on Nan Province, Northern Thailand and Laos.

The following pages introduce each InVEST model and provide the input parameter and spatial data used to run the models.

Table 1: Assignment of landcover types for the InVEST model parameterization.

LULC Nam Haeng	Thellmann et al. (2017)	Sharp et al. (2020)	
		Habitat Quality/Carbon Storage	Sediment Delivery Ratio/Water Yield
Orchards/Horticulture	Perennial Crops	General Agriculture	Orchard
Corn	Annual Crops	General Agriculture	Grains
Annual	Annual Crops	General Agriculture	Field Crop
Paddy Rice	Rice	General Agriculture	Irrigated Perennial
Perennials	Perennial Crops	Forest Plantation	Horticulture
Rubber	Lowland Rubber/ Upland Rubber	Forest Plantation	Horticulture
Water	Water	Water	Permanent Lentic Water
Forest	Lowland Forest/ Upland Forest	Forest	Upland Forest open/ Forest Closed mixed
Succession	Bushland/Tea	Natural Shrub	Grass
Urban	Urban	Residential & Commercial	Urban and paved roads

Annual Water Yield

The water yield model computes the quantity of water available in the area of interest. From a gridded map, it calculates the amount of water running off each pixel by subtracting evapotranspiration from total precipitation. The following equations used to run the model are adopted from Sharp et al. (2020).

The annual water yield $Y(x)$ for each pixel on the landscape x is determined using the following equation:

$$Y(x) = \left(1 - \frac{AET(x)}{P(x)}\right) \cdot P(x)$$

$AET(x)$ is calculated using two different equations for vegetated LULC types and for other types such as water or urban areas.

1. Vegetating LULC types

$$\frac{AET(x)}{P(x)} = 1 + \frac{PET(x)}{P(x)} - \left[1 + \left(\frac{PET(x)}{P(x)}\right)^\omega\right]^{\frac{1}{\omega}}$$

Where $PET(x) = K_c(\ell_x) \cdot ET_0(x)$

and $\omega(x) = Z \frac{AWC(x)}{P(x)} + 1.25$

Where $AWC(x) = \text{Min}(\text{Rest. layer. depth}, \text{root. depth}) \cdot PAWC$

2. Other LULC types (open water, urban)

$$AET(x) = \text{Min}(K_c(\ell_x) \cdot ET_0(x), P(x))$$

Where:

$Y(x)$	annual water yield for each pixel on the landscape x
$AET(x)$	annual actual evapotranspiration for pixel x
$P(x)$	annual precipitation on pixel x
$PET(x)$	potential evapotranspiration
$ET_0(x)$	reference evapotranspiration from pixel x
$K_c(\ell_x)$	plant evapotranspiration coefficient associated with the LULC ℓ_x on pixel x
$\omega(x)$	non-physical parameter characterizing natural climatic soil properties
$AWC(x)$	volumetric (mm) plant available water content
Z	empirical constant covering the local precipitation pattern.

Table 2: Input parameters for the InVEST water yield model.

	Range	Source
Average Annual Reference Evapotranspiration	1647 – 1712 [mm]	(Trabucco & Zomer, 2018)
Root Restricting layer depth	1000 [mm]	(Shangguan et al., 2014)
Plant available water content	0.05 – 0.15	(Shangguan et al., 2014)
Precipitation	1034 – 1230 [mm]	(Fick & Hijmans, 2017)

Table 3: Biophysical input parameters (rooting depth, Kc coefficients, Z parameter) for the InVEST water yield model according to Thellmann et al. (2017).

LULC	Rooting depth [mm]	Kc coefficient
Orchards/Horticulture	400	1.1
Corn	2100	1.2
Annual	2100	1.05
Paddy Rice	300	1.2
Perennials	400	1.2
Rubber	5000	1
Water	0	1.05
Forest	7000	1
Succession	3500	1
Urban	200	0.3
Z parameter	23	

Table 4: Biophysical input parameters (rooting depth, Kc coefficients, Z parameter) for the InVEST water yield model according to Sharp et al. (2020).

LULC	Rooting depth [mm]	Kc coefficient
Orchards/Horticulture	1000	1.1
Corn	1000	1.1
Annual	1000	1.1
Paddy Rice	1000	1.1
Perennials	3500	1.008
Rubber	3500	1.008
Water	10	1.05
Forest	3500	1.008
Succession	2000	0.865
Urban	0	0.2
Z parameter	5	

Carbon Storage and Sequestration

The carbon model is based on the carbon pools of aboveground biomass, belowground biomass, soil and dead organic matter. These pools are simply aggregated to provide the amount of carbon stored within each pixel of a land use category.

Table 5: Input parameters for the InVEST carbon storage model according to Thellmann et al. (2017).

LULC	c_above	c_below	c_soil	c_dead
Orchards/Horticulture	15	3	56	1
Corn	6	1.67	50	0.5
Annual	6	1.67	50	0.5
Paddy Rice	5	1	39	1
Perennials	15	3	56	1
Lowland Rubber	58	10	56	2.11
Upland Rubber	24	5	62	1.76
Water	0	0	0	0
Lowland Forest	189	41	79	6
Upland Forest	145	29	82	5
Succession	6	10	73	0.5
Urban	2	1	50	0

Table 6: Input parameters for the InVEST carbon storage model according to Sharp et al. (2020).

LULC	c_above	c_below	c_soil	c_dead
Orchards/Horticulture	125	5	115	1
Corn	3	2	10	0
Annual	3	2	8	1
Paddy Rice	5	5	15	0
Perennials	125	5	115	1
Lowland Rubber	125	5	115	1
Upland Rubber	125	5	115	1
Water	0	0	0	0
Lowland Forest	200	130	130	65
Upland Forest	75	45	85	20
Succession	8	8	25	3
Urban	0	0	0	0

Sediment Delivery Ratio

The sediment delivery ratio model estimates sediment export across the watershed. The model uses a digital elevation model (DEM) raster and determines the amount of soil loss or soil retention per pixel.

Sediment Export E_i is the amount of sediment eroded from a given pixel i that reaches the stream. InVEST uses the following equation:

$$E_i = usle_i \cdot SDR_i$$

The first step is to calculate the annual soil loss from each pixel using the revised universal soil loss equation (RUSLE1).

$$usle_i = R_i \cdot K_i \cdot LS_i \cdot C_i \cdot P_i,$$

Where:

- R_i rainfall erosivity
- K_i soil erodibility
- LS_i slope length-gradient factor
- C_i crop-management factor
- P_i support practice factor.

Then, the model computes the Sediment Delivery Ratio (SDR) for a pixel i using the following equation:

$$SDR_i = \frac{SDR_{max}}{1 + \exp\left(\frac{IC_0 - IC_i}{k}\right)}$$

Where:

- SDR_{max} maximum theoretical SDR (set to an average value of 0.8)
- IC_i connectivity index for pixel i
- IC_0 and k calibration parameters.

The connectivity index (IC) is calculated as follows:

$$IC = \log_{10}\left(\frac{D_{up}}{D_{dn}}\right)$$

It relates the sources of sediment and sinks. Higher values of IC imply a higher probability that eroded material reaches a sink. Whereas lower values describe lower slopes and a more vegetated landscape.

D_{up} and D_{dn} are calculated as follows:

$$D_{up} = \overline{CS}\sqrt{A}$$

Where:

C = average C factor of the upslope contributing area

S = average slope gradient of the upslope contributing area

A = upslope contributing area

(Sharp et al., 2020)

$$D_{dn} = \sum_i \frac{d_i}{C_i S_i}$$

Where:

d_i = length of the flow path along the cell according to the steepest downslope direction

C_i = C factor

S_i = slope gradient of the cell

Table 7: Input parameters for the InVEST Sediment Delivery Ratio model.

	Range	Source
DEM	183 – 1679 [m]	(Jarvis et al., 2008)
Rainfall Erosivity	3616.01 – 6559.51 [MJ*mm*(ha*hr) ⁻¹]	(Panagos et al., 2017)
Soil Erodibility	0.0214 [t*ha*hr*(MJ*ha*mm) ⁻¹]	(Shangguan et al., 2014)/ calculated according to (Liu et al., 2016)

Table 8: C-factor, Borselli k parameter, max SDR value, IC0 parameter and threshold flow accumulation for the InVEST Sediment Delivery Ratio model according to Thellmann et al. (2017).

LULC	usle c
Orchards/Horticulture	0.13
Corn	0.31
Annual	0.31
Paddy Rice	0.18
Perennials	0.13
Rubber	0.029
Water	0
Forest	0.001
Succession	0.18
Urban	0.2
Borselli k	1.096
SDR max	0.8
IC0	0.5
Threshold Flow Accumulation	500

Table 9: P-factor for the InVEST Sediment Delivery Ratio according to Thellmann et al. (2017). P values are set in relation to the slope of the landscape and the management measures for each pixel. The calculation procedure is adopted from Sheikh et al. (2011).

LULC	USLE P Measures	Slope				
		0 - 7	7.0 - 11.3	11.3 - 17.6	17.6 - 26.8	> 26.8
Orch./Hort.	no measures	0.27	0.3	0.4	0.45	0.5
Corn	no measures	0.27	0.3	0.4	0.45	0.5
Annual	strip cropping	0.27	0.3	0.4	0.45	0.5
Paddy Rice	terracing	0.1	0.12	0.16	0.18	0.2
Perennials	strip cropping	0.27	0.3	0.4	0.45	0.5
Rubber	terracing	0.1	0.12	0.16	0.18	0.2
Water	no measures	0	0	0	0	0
Forest	no measures	0	0	0	0	0
Succession	contouring	0.55	0.6	0.8	0.9	1
Urban	no measures	0	0	0	0	0

Table 10: C- and P-factor, Borselli k parameter, max SDR value, IC0 parameter and threshold flow accumulation for the InVEST Sediment Delivery Ratio model according to Sharp et al. (2020).

LULC	usle_c	usle_p
Orchards/Horticulture	0.412	1
Corn	0.412	1
Annual	0.412	1
Paddy Rice	0.412	1
Perennials	0.121	1
Rubber	0.121	1
Water	0	1
Forest	0.025	1
Succession	0.034	1
Urban	0.99	1

Borselli k	2
SDR max	0.8
IC0	0.5
Threshold Flow Accumulation	1000

Habitat Quality

Habitat Quality is defined as “the resources and conditions present in an area that produce occupancy – including survival and reproduction - by a given organism” (Hall et al., 1997). This model uses a map that relates LULCC to habitat suitability as well as data on habitat threat density and its impact on habitat quality. Information on habitat suitability is realized by assigning a relative habitat suitability score to each category on a land use raster. This score ranges from 0 to 1, with 1 representing highest habitat suitability. Values less than 1 may indicate a decreased survivability for species.

Threats are LULC types that are leading to habitat fragmentation and degradation in a neighboring habitat by human intervention. E.g. roads present a major threat to forest habitat quality because they provide access to timber and non-timber forest harvesters. Threat data are provided on a gridded raster with each pixel indicating presence (1) or absence (0) of threat. Four factors define the impact of threats on habitat:

1. Relative impact of each threat
2. Distance between habitat, the threat source and the impact of the threat across space
3. Level of legal/ institutional/ social/ physical protection from disturbance
4. Relative sensitivity of each habitat type to each threat on the landscape

The total threat level in grid cell x with LULC type j is defined as

$$D_{xj} = \sum_{r=1}^R \sum_{y=1}^{Y_r} \left(\frac{w_r}{\sum_{r=1}^R w_r} \right) r_y i_{rxy} \beta_x S_{jr}$$

Where

- w_r weight of degradation source
 R index of all modeled degradation sources
 i_{rxy} impact of threat r , that originates in grid cell y , r_y , on habitat in grid cell x
 β_x level of accessibility in grid cell x
 S_{jr} sensitivity of LULC j to threat r
 Y_r set of grid cells on r 's raster map.

The quality of habitat in parcel x that is in LULC j is defined as

$$Q_{xj} = H_j \left(1 - \left(\frac{D_{xj}^z}{D_{xj}^z + k^z} \right) \right),$$

where z and k are scaling parameters with k as the half-saturation constant. (Sharp et al., 2020)

Table 11: Habitat Quality threats according to Thellmann et al. (2017), based on Cotter et al. (2017).

Threat	Maximum Distance	Weight	Decay
Rubber	0.1	0.27	exponential
Agri	0.1	0.3	exponential
Urban	1	1	exponential
Roads	0.1	0.5	exponential

Table 12: Habitat Scores and Sensitivity of each land use category to each threat according to Thellmann et al. (2017), based on Cotter et al. (2017).

LULC	Habitat Score	Rubber	Agriculture	Urban	Roads
Orchards/Horticulture	0.32	0.13	0.07	0.2	0.2
Corn	0.33	0.1	0	0.5	0.33
Annual	0.33	0.1	0	0.5	0.33
Paddy Rice	0.26	0	0.07	0.47	0.33
Perennials	0.32	0.13	0.07	0.2	0.2
Rubber	0.57	0	0.1	0.87	0.63
Water	0.73	0.82	0.82	0.97	0.75
Forest	1	0.7	0.6	1	0.8
Succession	0.33	0.12	0.17	0.39	0.29
Urban	0.1	0	0	0	0

Half-Saturation Constant 0.5

Table 13: Habitat Quality threats according to Sharp et al. (2020).

Threat	Maximum Distance	Weight	Decay
Rubber	6	0.5	exponential
Agri	8	0.7	linear
Urban	10	1	exponential
Roads	3	1	linear

Table 14: Habitat Scores and Sensitivity of each land use category to each threat according to Sharp et al. (2020).

LULC	Habitat Score	Rubber	Agriculture	Urban	Roads
Orchards/Horticulture	1	0.1	0.3	0.5	0.3
Corn	1	0.1	0.3	0.5	0.3
Annual	1	0.1	0.3	0.5	0.3
Paddy Rice	1	0.1	0.3	0.5	0.3
Perennials	1	0.1	0.3	0.5	0.3
Rubber	1	0.1	0.3	0.5	0.3
Water	1	0.5	0.7	0.89999998	0.7
Forest	1	0.4	0.6	0.80000001	0.6
Succession	1	0.2	0.4	0.60000002	4.5
Urban	0	0	0	0	0

Half-Saturation Constant	0.5
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3. Results

The land cover of the Nam Haeng watershed is shown in Fig. 1 for the five different time points: 2001, 2007, 2009, 2012 and 2016. Throughout the whole period, the largest category is forest covering 46.56 – 66.53% between 2001 and 2016. Other dominant land-cover types are succession (4.16 – 28.92%) and corn (0.3% - 21.55%). Rubber plantations started in 2007 only and their share in land cover increased from 0.36% to 8% in 2016.

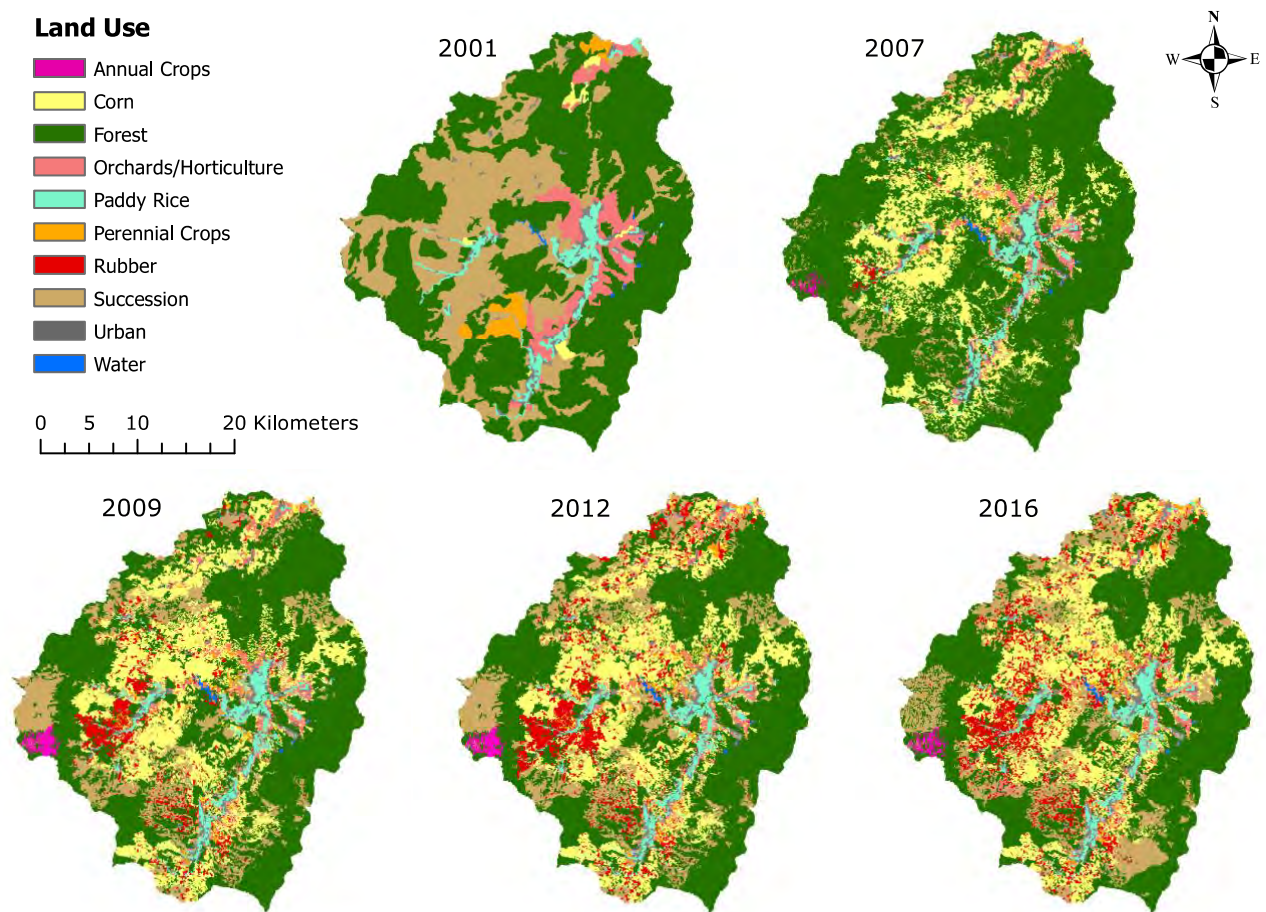


Figure 2: Land cover maps of the Nam Haeng watershed 2001, 2007, 2009, 2012 and 2016.

3.1 Intensity Analysis

Transition Matrices

Tables 16, 17, 18 and 19 on the following two pages present the transition matrices for the four time periods in percentage change of land area. The total column at the right and the total row at the bottom represent the size of each category at the interval's initial and final time. These are basically the values that draw the land-use map. The values on the diagonal, which are shaded grey, represent persisting land. The values off the diagonal present flows and show how the land transitioned. The very last column at the right and the last row at the bottom show gross gain and gross loss. Considering gross loss and gross gain, most change in area can be observed for the largest categories forest, succession and corn. In the first time period, forest lost 9.81% of area but gained almost double (18.97%). The largest decline in forest area was between 2007 and 2009 (16.24%), two thirds of its total net loss.

Table 15 presents the Net Gain/Net Loss of area in km² for each land-use category. Between 2001 and 2016, except for forest and orchards/horticulture, all land-cover types gained area. Total Net Gain in rubber area was 1.920 km², almost double the Net Gain for Corn.

Corn has a Net Loss 2009-2012 of 103 km², whereas rubber continuously gained area.

Between 2007 and 2009, basically all land-cover types, except for orchards/horticulture, benefitted from deforestation and were also experiencing the largest net gains, compared to the other periods.

Table 15: Net Gain/ Net Loss of area in km² for each land-use category. Net Gain/ Net Loss are given for each time interval and as a total.

	2001-2007	2007-2009	2009-2012	2012-2016	Total
Orchards/Horticulture	-17	-125	-77	-32	-251
Corn	175	773	-103	168	1.012
Annual	2	92	0	-41	53
Paddy Rice	2	8	0	-5	5
Perennials	-11	158	94	-56	185
Rubber	4	917	644	355	1.920
Water	1	6	0	3	10
Forest	92	-4.075	-935	-807	-5.724
Succession	-248	2.238	377	375	2.741
Urban	0	9	1	39	49

Table 16: Transition Matrices for the time intervals 2001-2007 in percentage change of land area.

	Category	2007										Total 2001	Gross Loss
		Orch./Hort.	Corn	Annual	Paddy Rice	Perennial	Rubber	Water	Forest	Succession	Urban		
2001	Orch./Hort.	1.36	1.14	0.00	0.64	0.19	0.02	0.03	2.04	0.21	0.35	5.99	4.63
	Corn	0.23	0.30	0.00	0.05	0.03	0.00	0.00	0.13	0.01	0.04	0.79	0.49
	Annual	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Paddy Rice	0.41	0.41	0.00	1.24	0.05	0.04	0.01	0.61	0.10	0.41	3.27	2.03
	Perennial	0.07	0.55	0.00	0.01	0.02	0.00	0.00	0.98	0.07	0.04	1.75	1.73
	Rubber	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Water	0.02	0.01	0.00	0.00	0.00	0.00	0.03	0.10	0.00	0.00	0.16	0.13
	Forest	0.71	5.67	0.09	0.31	0.11	0.07	0.07	47.55	2.47	0.31	57.37	9.81
	Succession	1.28	9.84	0.11	0.75	0.25	0.21	0.07	14.76	1.23	0.42	28.92	27.69
	Urban	0.27	0.29	0.00	0.51	0.02	0.00	0.00	0.36	0.06	0.23	1.76	1.53
Total 2007		4.34	18.21	0.21	3.51	0.66	0.36	0.22	66.53	4.16	1.79	100.00	
Gross gain		2.98	17.91	0.21	2.27	0.65	0.36	0.19	18.97	2.93	1.57		

Table 17: Transition matrix for the time interval 2007-2009 in percentage change of land area.

	Category	2009										Total 2007	Gross Loss
		Orch./Hort.	Corn	Annual	Paddy Rice	Perennial	Rubber	Water	Forest	Succession	Urban		
2007	Orch./Hort.	3.71	0.26	0.01	0.00	0.22	0.12	0.00	0.00	0.02	0.01	4.34	0.63
	Corn	0.11	15.55	0.00	0.01	0.33	2.14	0.00	0.00	0.07	0.00	18.21	2.66
	Annual	0.00	0.00	0.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.00
	Paddy Rice	0.00	0.00	0.00	3.51	0.00	0.00	0.00	0.00	0.00	0.00	3.51	0.00
	Perennial	0.00	0.00	0.00	0.00	0.65	0.01	0.00	0.00	0.00	0.00	0.66	0.01
	Rubber	0.00	0.00	0.00	0.00	0.00	0.36	0.00	0.00	0.00	0.00	0.36	0.00
	Water	0.00	0.00	0.00	0.00	0.00	0.00	0.22	0.00	0.00	0.00	0.22	0.00
	Forest	0.02	5.47	0.36	0.01	0.08	1.17	0.01	50.29	9.11	0.01	66.53	16.24
	Succession	0.00	0.01	0.00	0.01	0.01	0.21	0.01	0.00	3.88	0.01	4.16	0.27
	Urban	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.79	1.79	0.00
Total 2009		3.85	21.29	0.57	3.54	1.30	4.01	0.25	50.29	13.08	1.83	100.00	
Gross gain		0.14	5.75	0.37	0.03	0.64	3.66	0.02	0.00	9.19	0.03		

Table 18: Transition Matrices for the time intervals 2009-2012 and 2012-2016 in percentage change of land area.

	Category	2012										Total 2009	Gross Loss
		Orch./Hort.	Corn	Annual	Paddy Rice	Perennial	Rubber	Water	Forest	Succession	Urban		
2009	Orch./Hort.	3.53	0.07	0.00	0.00	0.06	0.16	0.00	0.00	0.01	0.00	3.85	0.31
	Corn	0.00	19.63	0.00	0.00	0.15	1.29	0.00	0.00	0.22	0.00	21.29	1.67
	Annual	0.00	0.00	0.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.57	0.00
	Paddy Rice	0.00	0.00	0.00	3.54	0.00	0.00	0.00	0.00	0.00	0.00	3.54	0.00
	Perennial	0.00	0.01	0.00	0.00	1.29	0.00	0.00	0.00	0.00	0.00	1.30	0.01
	Rubber	0.00	0.00	0.00	0.00	0.00	4.01	0.00	0.00	0.00	0.00	4.01	0.00
	Water	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.00	0.00	0.00	0.25	0.00
	Forest	0.00	1.16	0.00	0.00	0.17	0.80	0.00	46.56	1.60	0.00	50.29	3.73
	Succession	0.00	0.01	0.00	0.00	0.00	0.32	0.00	0.01	12.74	0.00	13.08	0.34
	Urban	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.83	1.83	0.00
Total 2012		3.54	20.88	0.57	3.54	1.67	6.58	0.25	46.56	14.58	1.83	100.00	
Gross gain		0.00	1.25	0.00	0.00	0.38	2.57	0.00	0.01	1.84	0.00		

Table 19: Transition matrix for the time interval 2012-2016 in percentage change of land area.

	Category	2016										Total 2012	Gross Loss
		Orch./Hort.	Corn	Annual	Paddy Rice	Perennial	Rubber	Water	Forest	Succession	Urban		
2012	Orch./Hort.	3.01	0.22	0.00	0.01	0.04	0.20	0.00	0.01	0.02	0.04	3.54	0.53
	Corn	0.12	17.97	0.00	0.01	0.07	1.83	0.00	0.32	0.55	0.02	20.88	2.91
	Annual	0.00	0.00	0.39	0.00	0.00	0.00	0.00	0.18	0.00	0.00	0.57	0.18
	Paddy Rice	0.00	0.00	0.00	3.46	0.00	0.01	0.00	0.00	0.01	0.06	3.54	0.08
	Perennial	0.04	0.22	0.00	0.00	1.29	0.10	0.00	0.00	0.01	0.00	1.67	0.37
	Rubber	0.05	1.10	0.00	0.01	0.02	4.84	0.00	0.13	0.43	0.00	6.58	1.74
	Water	0.00	0.00	0.00	0.00	0.00	0.00	0.24	0.00	0.00	0.00	0.25	0.00
	Forest	0.03	1.32	0.02	0.02	0.02	0.29	0.00	41.56	3.26	0.03	46.56	5.00
	Succession	0.15	0.70	0.00	0.02	0.01	0.73	0.01	1.14	11.80	0.01	14.58	2.77
	Urban	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.83	1.83	0.00
Total 2016		3.41	21.55	0.41	3.52	1.45	8.00	0.26	43.35	16.07	1.99	100.00	
Gross gain		0.40	3.58	0.02	0.07	0.15	3.16	0.02	1.79	4.27	0.16		

Interval Level

The result of the interval level intensity analysis is presented in Figure 2. The horizontal bars show the percentage change of landscape, either as the size of total or annual change in one time interval. The first time interval experienced the greatest transition in total, 48.04% of the landscape changed. For the next two intervals there is a decline in total change. The last interval experiences an increase by 13.61% total change in area.

By also taking into account, that each time interval has a different duration, the interval level analysis computes the annual change of interval. Figure 2 shows, that the second interval has the largest annual change of 9.92% if a constant annual change is assumed. The least change happened 2009 -2012, regarding both, total change and annual intensity of change. The uniform annual change (5.84%) indicates that change was relatively slow for the last two time intervals because the bars end to the left of the uniform line. It also depicts that land change was accelerating in the first two intervals.

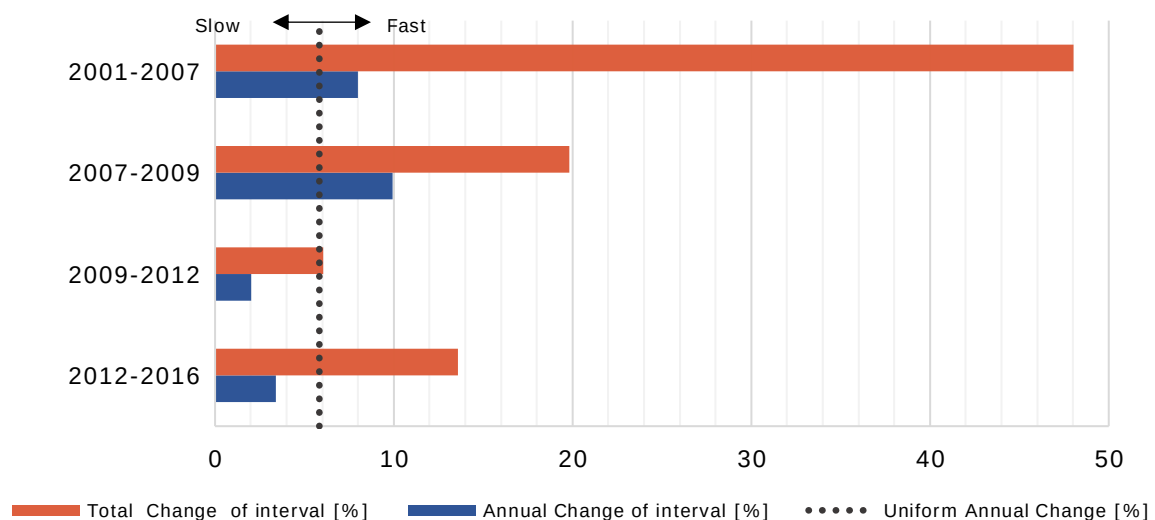


Figure 2: Intensity analysis at the interval level for four time intervals: 2001-2007, 2007-2009, 2009-2012 and 2012-2016. Total and annual change of interval in percentage change of area and uniform annual change.

Category Level

Figures 3, 4, 5 and 6 present the results of the category level analysis. For each category pairs of horizontal bars show either the gross loss and gross gain in area in terms of pixels as well as their loss intensity or the gain intensity. The intensity shows if the annual transition happened only due to the large size of the category or due to the intensity of activity within the categories. A category is considered dormant, if the bar ends before the uniform line and active, if it extends to the right of the uniform line.

In the first time interval, succession has the largest size in terms of losses and forest in terms of gains. This switches for the last three time intervals because now forest accounts for the largest annual losses and succession, corn and rubber are involved in the largest annual gains. In the second time interval (Fig. 4), the forest category loses 162 million pixels and succession gains 92 million pixels.

The right side of Fig. 3-6 gives an understanding if the large size of annual transition is explained by their large size in general or if it's related to the intensity of activity within the categories. For succession, corn and rubber, the bars show in every interval that the gain intensity extends to the right of the uniform line. This implies these categories experience gains more intensively than the landscape in general. Rubber experiences gains more intensively than corn. But the size of gains in rubber is smaller than for corn (except 2009-2012) and this is explained by the fact that rubber accounts for a smaller percentage of the landscape. For the second time interval, gain intensity for rubber reaches 45.54%, which is also the largest for all categories and all time periods.

The loss intensity for forest is active in the second and third time interval because the bars extend the uniform line. Also, the loss intensity almost equal (2.47% - 2.85%) in all time intervals except for 2007-2009. Most categories experience loss more intensively than forest (except 2007-2009), because they account for a smaller share of the landscape.

The results are not consistent for all four time intervals because none of the bars match the uniform line, meaning that the pattern of change is not stationary at the category intensity level of analysis.

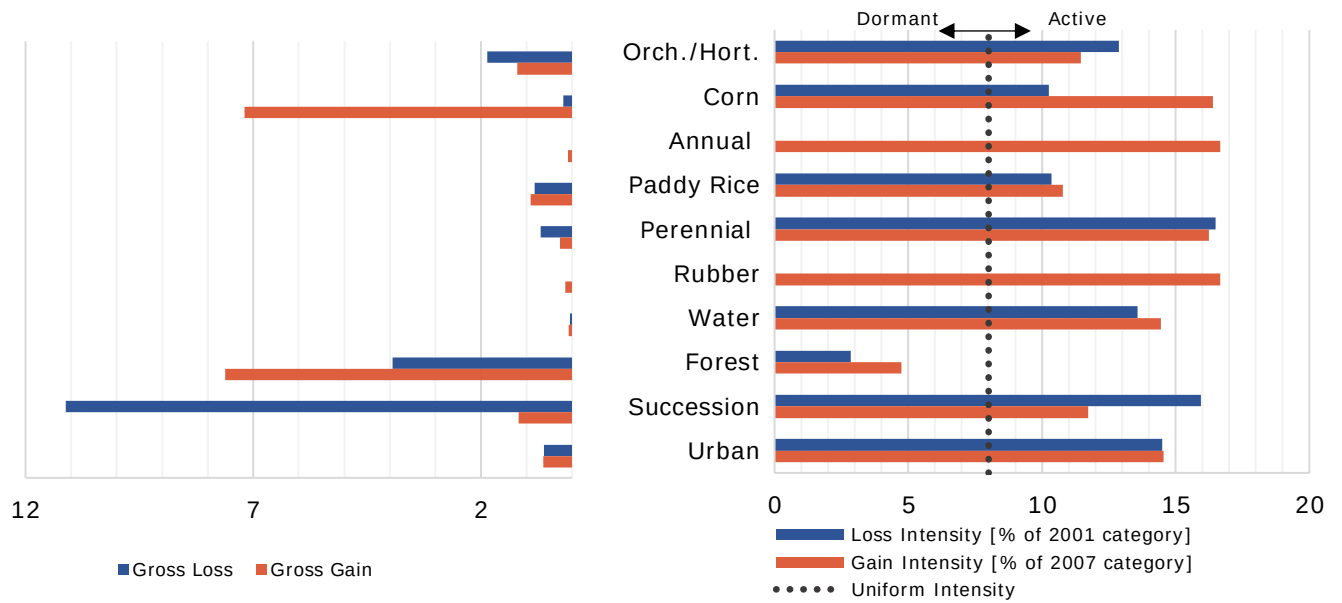


Figure 3: Category intensity analysis for the time interval 2001 – 2007. Bars that extend to the left of zero show annual gross loss and gross gain of area in numbers of pixels (10^6). Bars that extend to the right of zero show annual intensity of gains and losses within each category

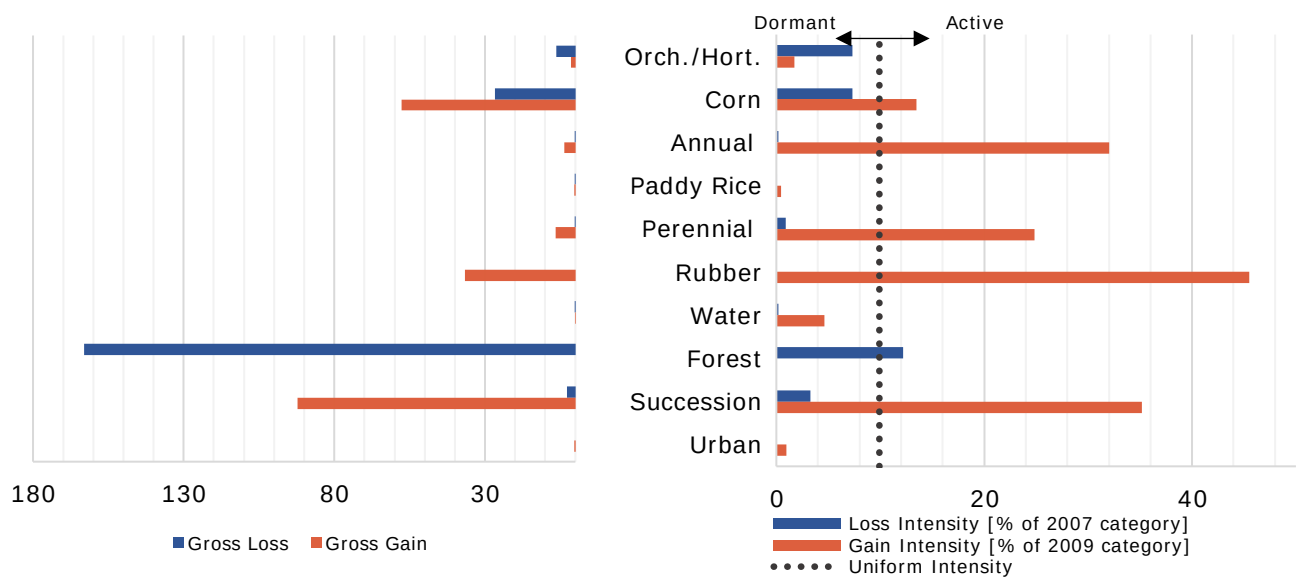


Figure 4: Category intensity analysis for the time interval 2007-2009. Bars that extend to the left of zero show annual gross loss and gross gain of area in numbers of pixels (10^6). Bars that extend to the right of zero show annual intensity of gains and losses within each category.

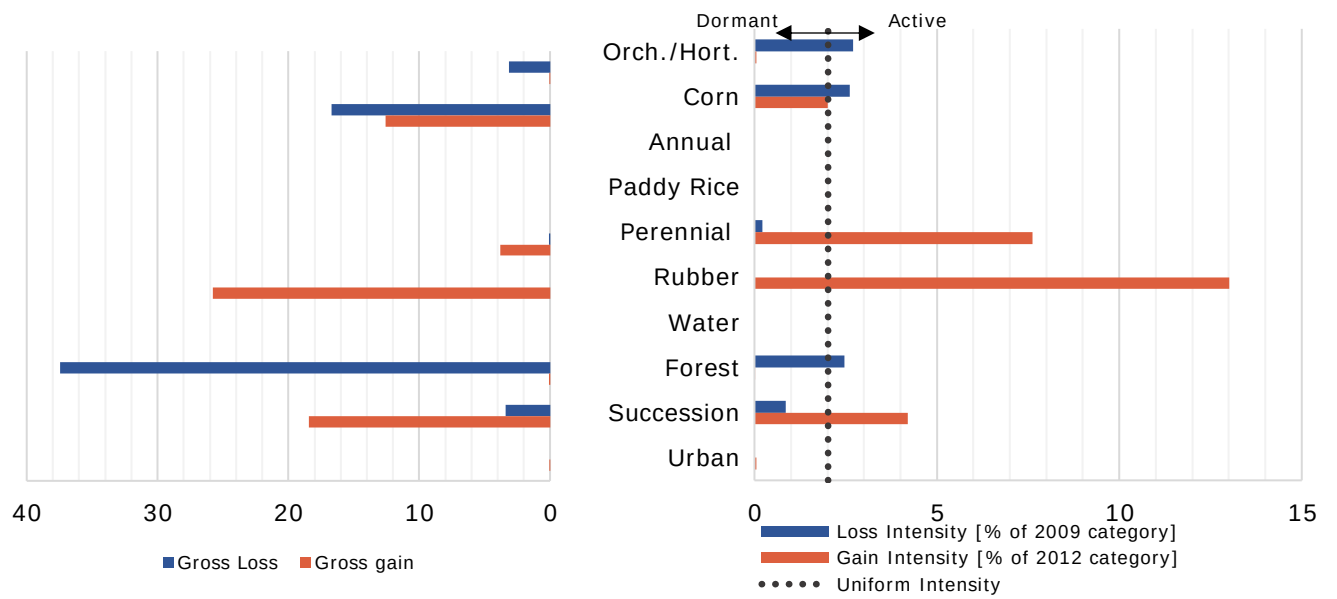


Figure 5: Category intensity analysis for the time interval 2009 – 2012. Bars that extend to the left of zero show annual gross loss and gross gain of area in numbers of pixels (10^6). Bars that extend to the right of zero show annual intensity of gains and losses within each category.

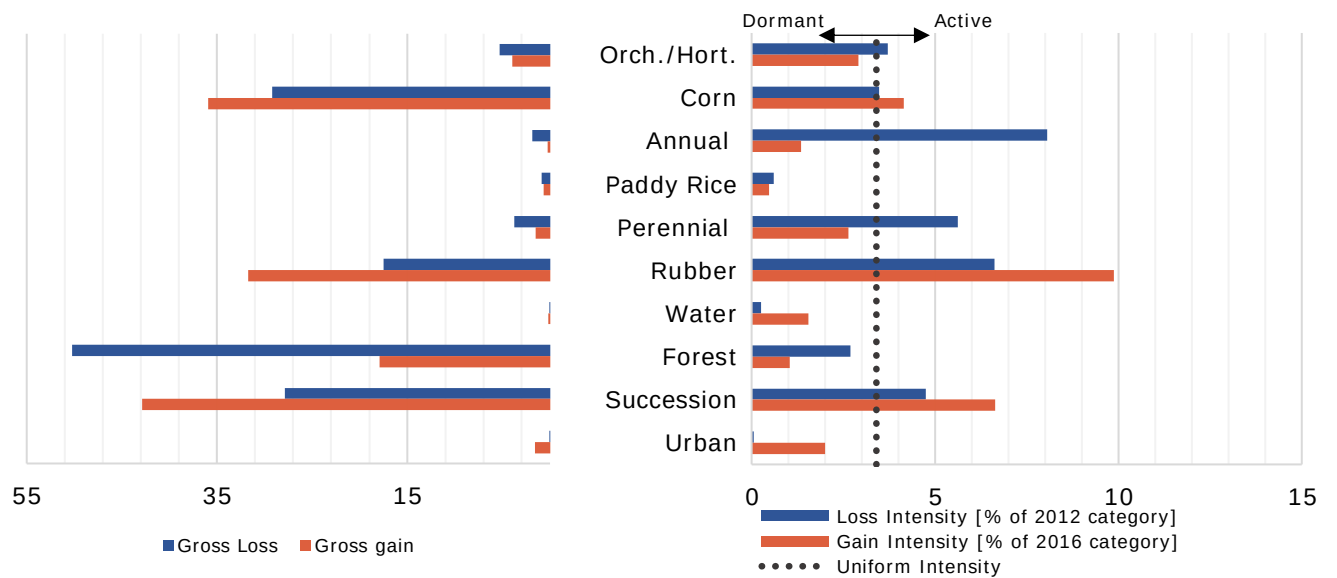


Figure 6: Category intensity analysis for the time interval 2016 – 2012. Bars that extend to the left of zero show annual gross loss and gross gain of area in numbers of pixels (10^6). Bars that extend to the right of zero show annual intensity of gains and losses within each category.

Transition Level

The transition level analysis gives the sizes of transition relative to the stock of the other categories. A category is being avoided, if the bar ends on the left side of the uniform line and it is being targeted, if it extends to the right of the uniform line.

Figures 7, 8, 9 and 10 present the results for the transition from any category to rubber in each time interval. The left side shows that in general, rubber gains from corn, forest and succession in terms of size of annual transition. In the first time interval (Fig. 7) majorly succession is affected, 9,697 pixels transitioned to rubber. This might be explained by the fact that during this interval, succession accounts for a large percentage of the landscape. The last three intervals (Fig. 8, 9, 10) behave similarly and foremost corn and forest lose to rubber. In the last interval (Fig. 10), corn loses 183 Million pixels and forest 29 Million pixels.

The right side shows the intensities of transition. In the first time interval rubber actually gains more intensively from paddy rice and water than from succession.

In the last time interval (Fig. 10), perennial crops are more intensively affected than forest.

The bar for forest ends on the left side of the uniform line in every time interval, which indicates that forest is being avoided by rubber. Regarding the last three time intervals, rubber targets corn most.

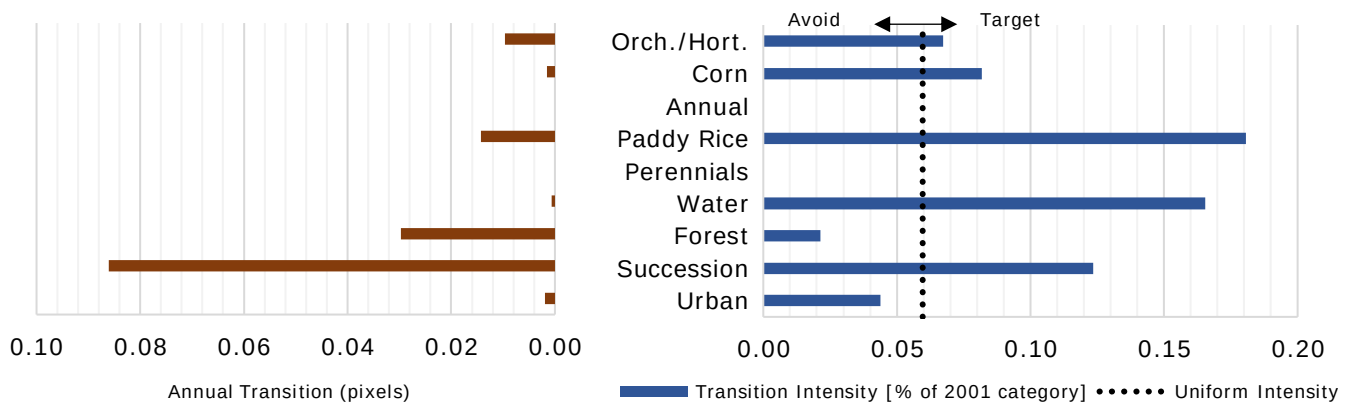


Figure 7: Transition intensity analysis to rubber for the time interval 2001 – 2007. Bars that extend to the left of zero show the annual transition area in number of pixels (10^6). Bars that extend to the right of zero show annual transition intensity to rubber from each non-rubber category.

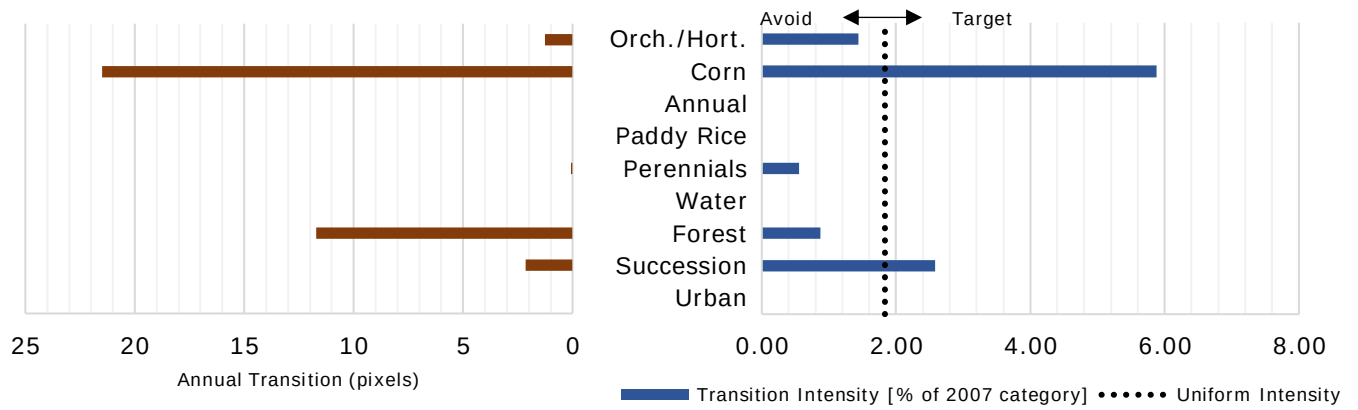


Figure 8: Transition intensity analysis to rubber for the time interval 2007 – 2009. Bars that extend to the left of zero show the annual transition area in number of pixels (10^6). Bars that extend to the right of zero show annual transition intensity to rubber from each non-rubber category.

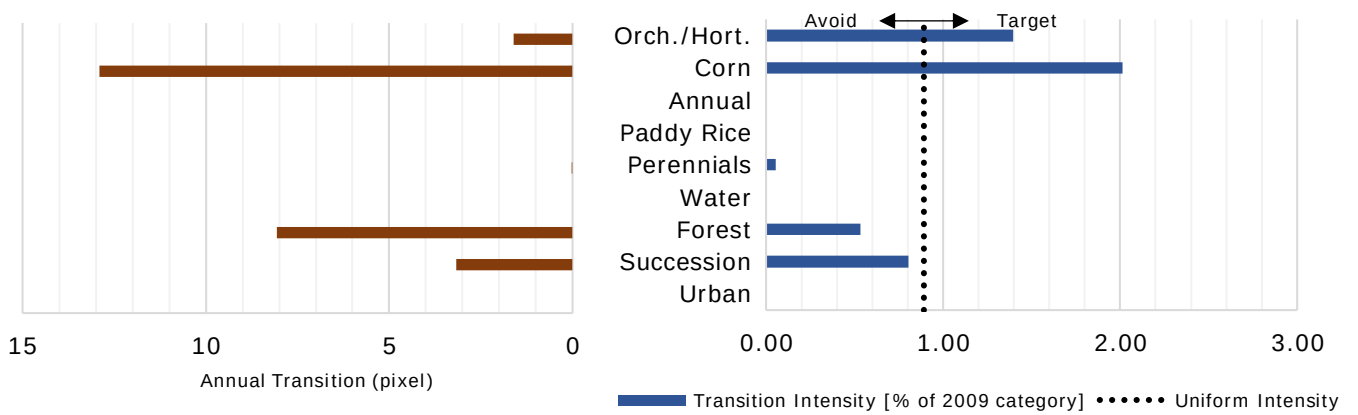


Figure 9: Transition intensity analysis to rubber for the time interval 2009 – 2012. Bars that extend to the left of zero show the annual transition area in number of pixels (10^6). Bars that extend to the right of zero show annual transition intensity to rubber from each non-rubber category.

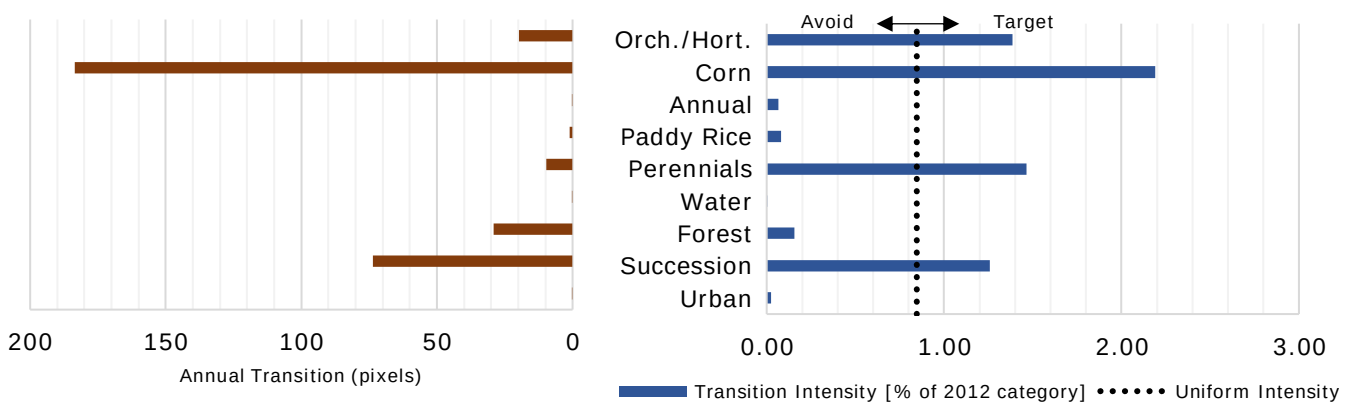


Figure 10: Transition intensity analysis to rubber for the time interval 2012 – 2016. Bars that extend to the left of zero show the annual transition area in number of pixels (10^6). Bars that extend to the right of zero show annual transition intensity to rubber from each non-rubber category.

3.2 Ecosystem Service Assessment

Table 20 presents the total provision each ES from the calibrated and the sample dataset.

Figures 12, 13, 14 and 15 at the end of this chapter show their spatial distribution.

Water yield decreases in both datasets. The results using parameters from Thellmann et al. (2017) show a decrease from 2001 to 2016 by 5.6% and the highest yield in 2001 with 251 million m³. The results produced by the sample dataset is more than double with 543 million m³ in 2001. But it decreased from 2001 to 2016 by only 1.47%.

Regarding sediment export, the sample dataset has significant higher values than the dataset from Thellmann et al. (2017). In 2012, an amount of 3,838 million kg was exported, which is almost 10 times larger than the result from the calibrated dataset. This difference does apply for all years if not to the same extent. The calibrated dataset shows a significant drop in the year 2007 by 73% and overall the amount exported between 2001 and 2016 decreases by 24%.

Carbon storage decreased for both datasets between 2001 and 2016. By 16.5% for the calibrated dataset and 19.7% for the sample dataset.

Habitat quality also decreases for both datasets. The calibrated data from China produce a drop by 10.6%, the InVEST sample dataset only by 0.22%. Overall, habitat quality is scored higher in the InVEST dataset.

Table 20: InVEST result for ES provision in the Nam Haeng watershed. First column applying parameters from Thellmann et al. (2017), second column with values shaded grey applying parameters from Sharp et al. (2020).

Year	Water Yield (10 ⁶ m ³)		Sediment Export (10 ⁶ kg)		Carbon Storage (kg)		Habitat Quality Score (10 ⁶)	
2001	251	543	488	1204	21.29	31.89	28.40	39.31
2007	239	531	132	2925	22.83	35.11	30.90	39.36
2009	237	534	380	3756	19.63	30.90	26.88	39.30
2012	238	535	384	3838	18.47	27.00	26.13	39.29
2016	237	535	370	3724	17.78	25.60	25.39	39.22

Figure 11 shows the normalized ES and the ES z-score, as well as the proportion of forest and rubber area in the watershed from 2001 to 2016. Values from the sample data set range from 0 to 3.12, the calibrated data set from 0 to 1.07. Habitat quality and carbon storage decrease in both datasets as response to a decline in forest area. Water yield remains close to 1. Major

difference can be observed for sediment export, the data from (Thellmann et al., 2017) drop to a minimum in 2007. Sediment export from the sample data set increases to a maximum in 2009. The ES z-score behaves accordingly, for the calibrated dataset it decreases below one, for the sample dataset it increases to 1.5.

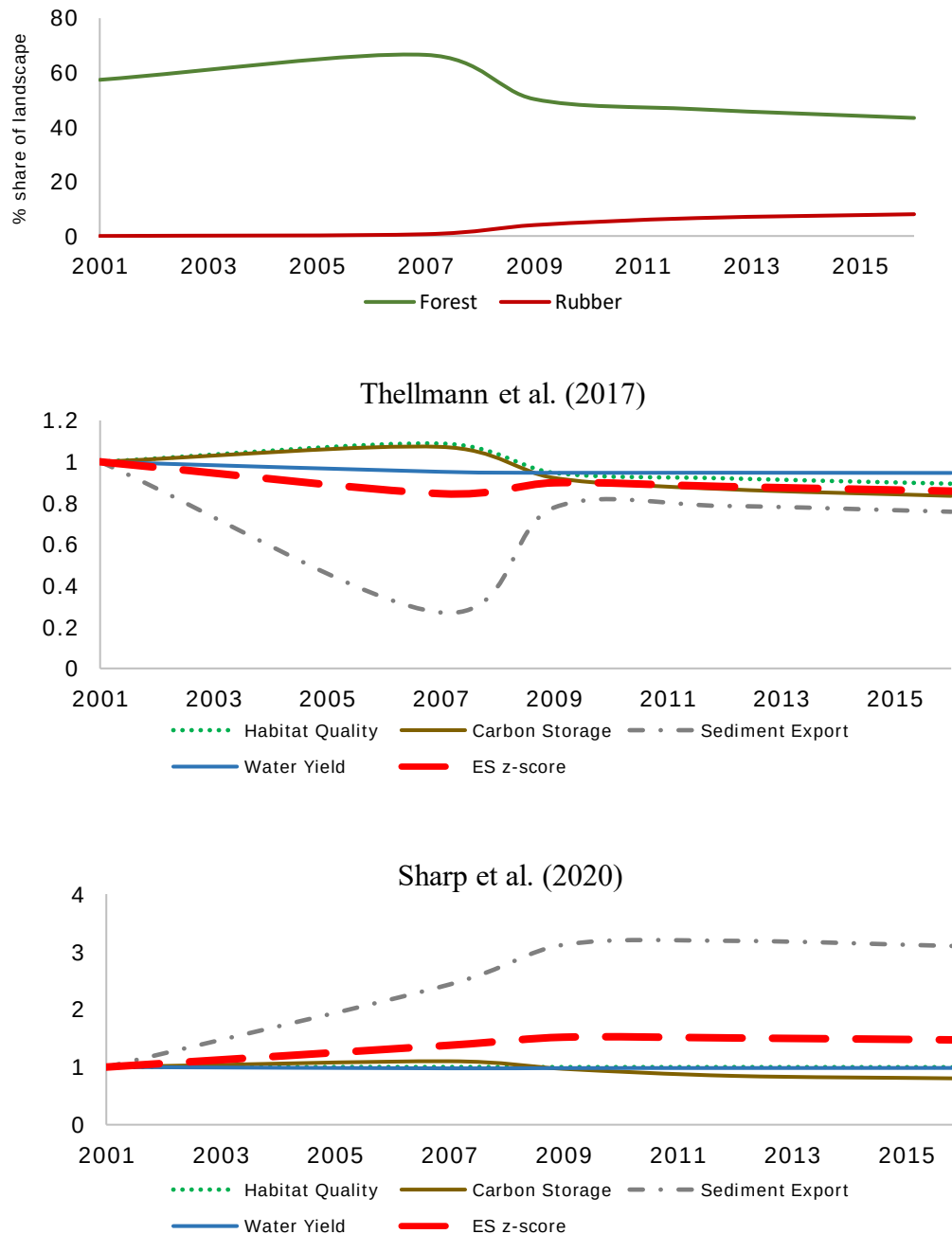


Figure 11: Normalized ES indices for habitat quality, carbon storage, sediment export, water yield and their annual arithmetic mean value (z-score) for the dataset according to Thellmann et al. (2017) and Sharp et al. (2020).

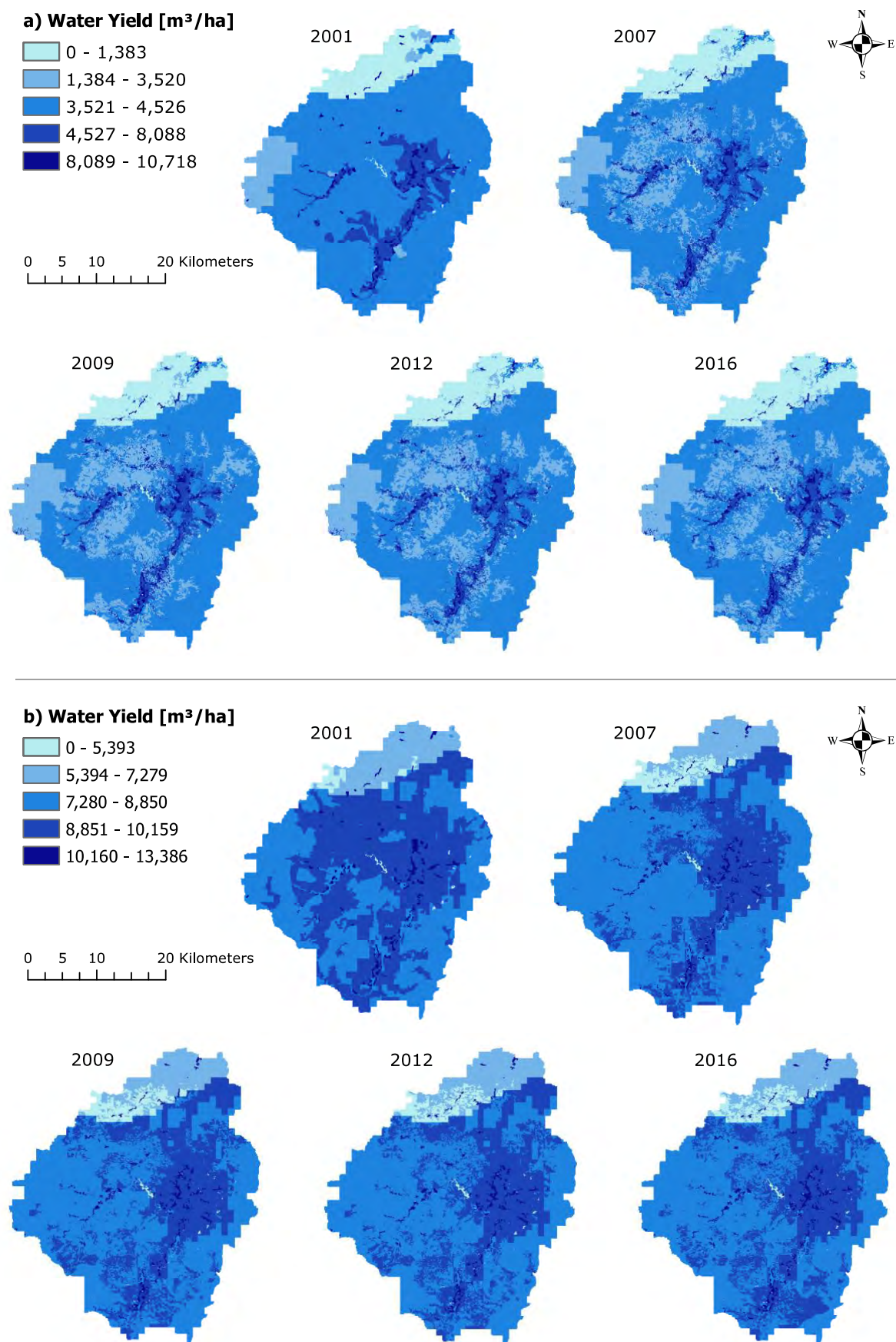


Figure 12: Water Yield results applying parameters from a) Thellmann et al. (2017) and b) Sharp et al. (2020).

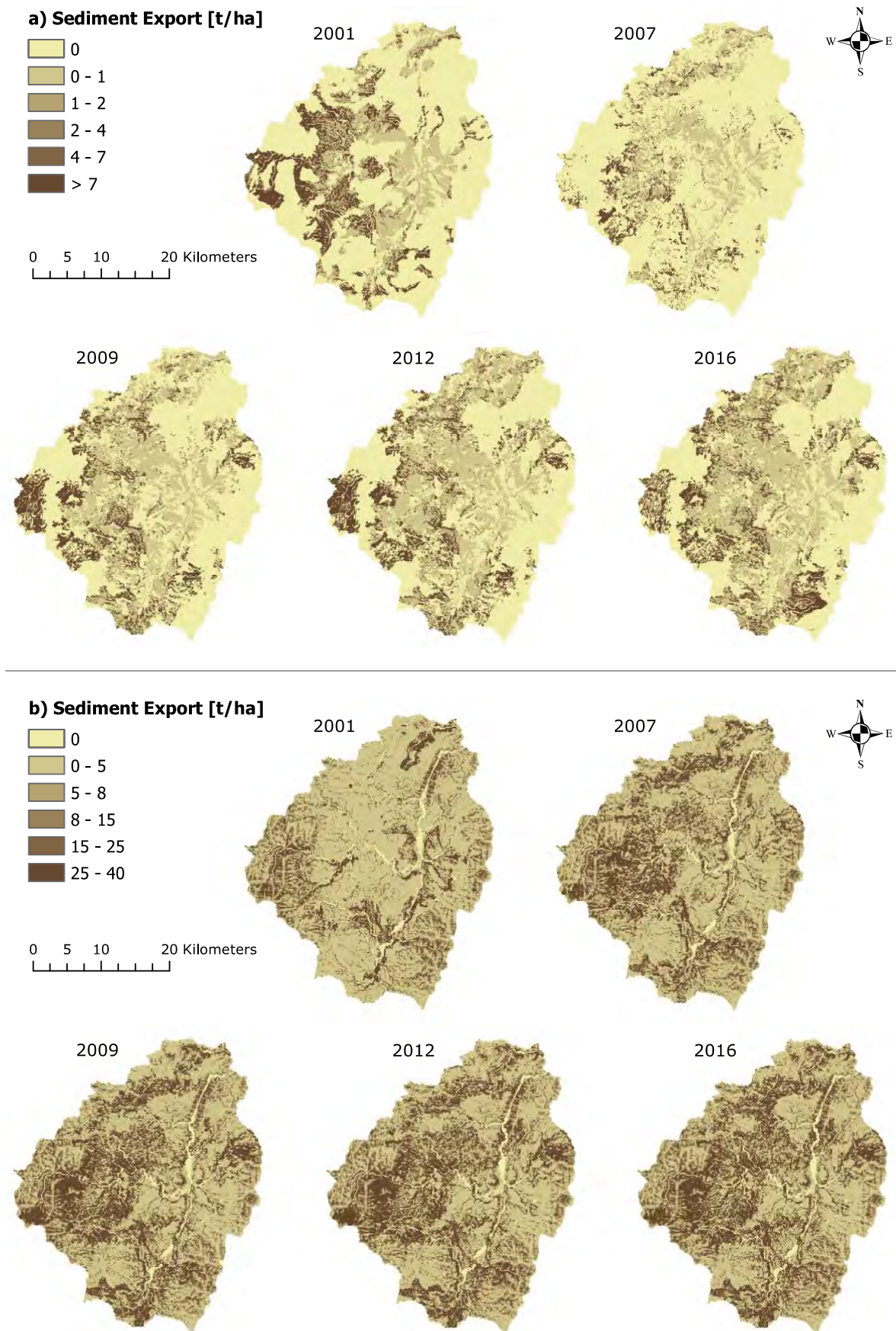


Figure 13: Sediment Export results applying parameters from a) Thellmann et al. (2017) and b) Sharp et al. (2020).

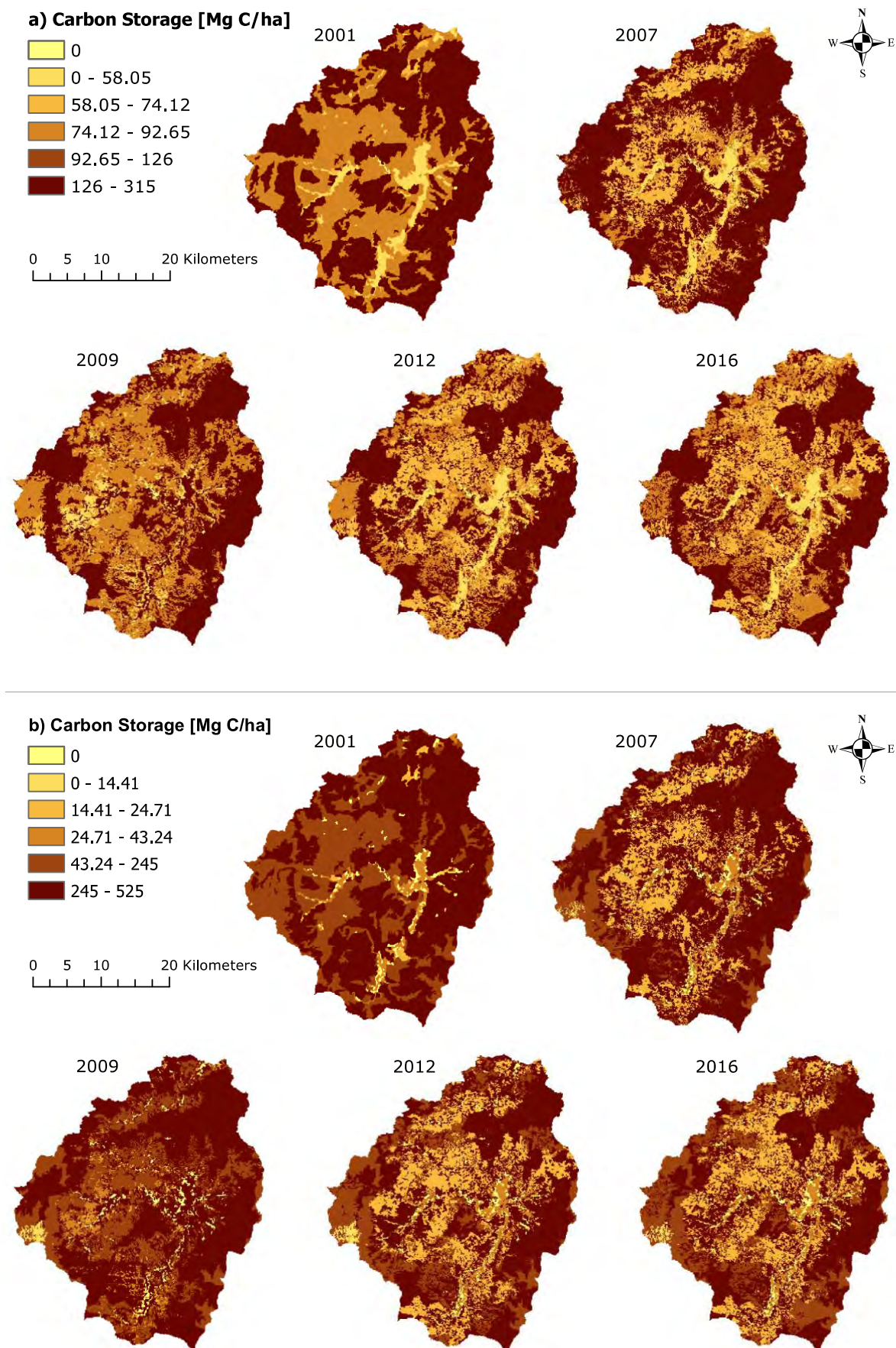


Figure 14: Carbon Storage and Sequestration results applying parameters from a) Thellmann et al. (2017) and b) Sharp et al. (2020).

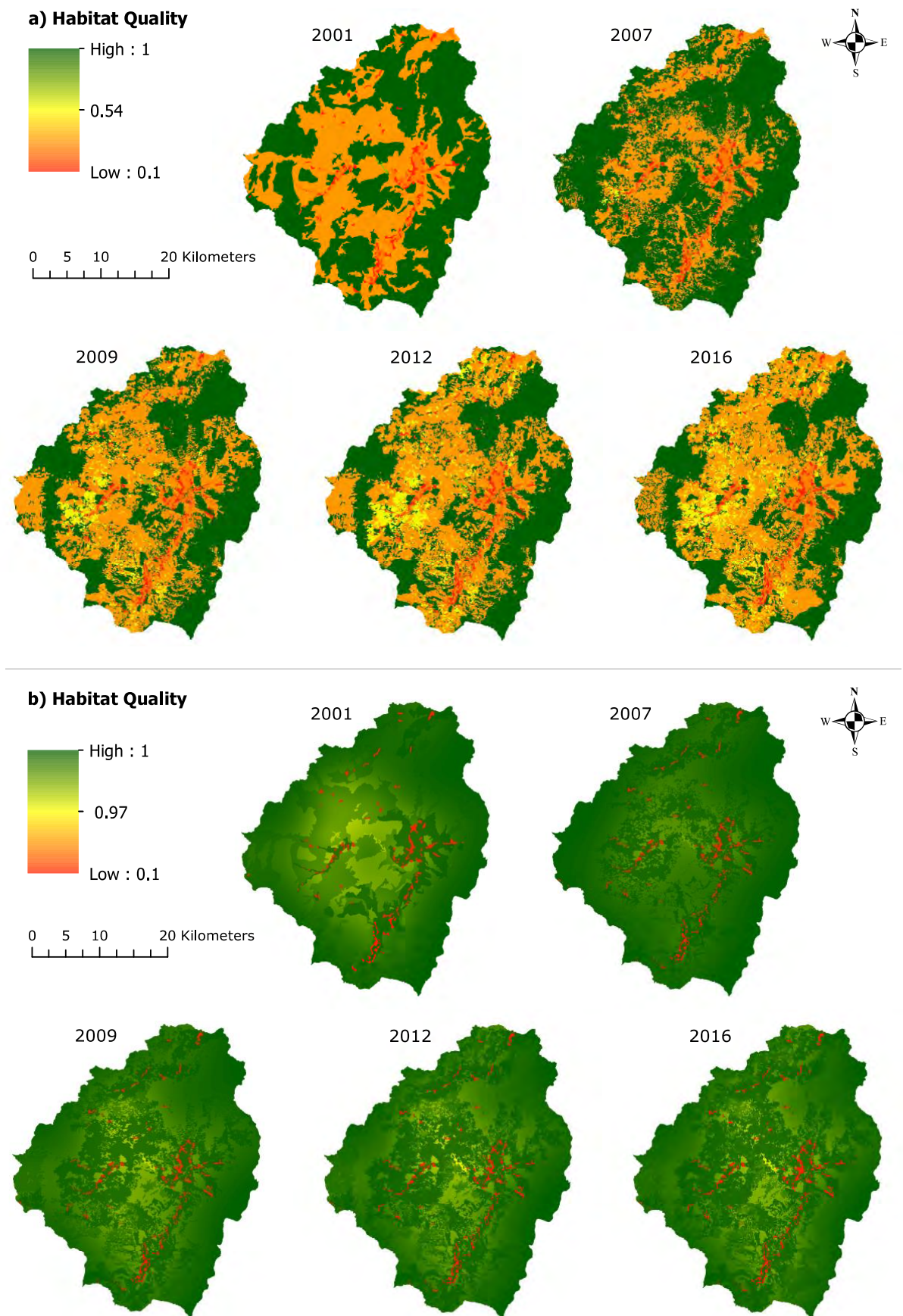


Figure 15: Habitat Quality results applying parameters from a) Thellmann et al. (2017) and b) Sharp et al. (2020).

4. Discussion

4.1 Land-use Change in Nam Haeng

Since 1960, Thailand's economy started to grow rapidly but at the same time natural forest resources have suffered substantially under this achievement. Between 1950 and 1980, commercial agriculture was established and became the backbone of the country's economy. The promotion of the agricultural sector, also by adopting the technologies of the Green Revolution, enabled economic growth from the mid-1980s that was built upon export-oriented manufacturing (Buch-Hansen et al., 2006). Thomas et al. (2004) identified three major forces of deforestation in northern Thailand: Conversion of forest, logging of natural forest and farmers in the forest. Conversion of forest was initially associated with agricultural expansion to ensure food and fuel for a growing population and economy. As population growth and migration from the lowlands decelerated, structural adjustments in the industrial and service sectors promoted expansion of urban areas. Established road networks and markets made the purchase of agricultural inputs and the sale of crops easier for farmers. The second force of deforestation, logging, supported economic growth in the beginning, but concessions were abolished in 1989 because of the sector's unsustainability. However, up until now logging is still practiced illegally and a known problem in reserved forests and protected areas. Farmers in the forest is associated with diverse ethnic minority groups that populate the mountainous regions of northern Thailand and the impact of their land use practices on the environment. According to the Asian Development Bank (2001) these minorities make up 12.2 – 20.2% of the population in Nan province and the different groups are distributed within key altitude zones. In the Highlands (1,000 -1,800 m.a.s.l.), the minorities of Hmong, Lisu and Akha have shifted from opium to intensive vegetable crops. The Midlands (600 – 1,000 m.a.s.l.) are populated by Karen, Lua and Khmu which practice short cropping cycles and long rotational forest fallow. Finally, the Khon Muang (Northern Thai) cultivate paddy rice, vegetables and increasingly field crops in the Lowlands (300 – 600 m.a.s.l.) (Thomas et al., 2004). Given these circumstance, land-use conflicts arose through policies, that enabled private and governmental companies to acquire forest concessions, and the classification of watersheds and national reserve forests. Open access to natural resources became restricted and illegal land occupation followed (Dontree, 2003). In Nan province land-use change was driven by lack in forest monitoring, diffuse boundaries between rural and protected areas as well as the presence of markets for illegally produced crops (maize) (Baicha, 2016).

This study assessed land-use change in the Nam Haeng watershed between 2001 and 2016. forest area decreased by almost 24.2% and the cultivation of corn and rubber expanded, especially between 2007 - 2009. Various studies made similar observations in the decrease of forests and the increase of field crop areas in northern Thailand and Nan Province (Arunyawat & Shrestha, 2016; Baicha, 2016; Paiboonvorachat & Oyana, 2011; Prachwanee Pibumrung, 2007; Trisurat et al., 2019).

During the study period (2001-2016) the population in Nan province declined by 1.4%. Therefore, land-use change in the Nam Haeng watershed can't be clearly attributed to population growth. However, from 1993 to 2001, population figures increased by 5.6% and maybe influenced agricultural transition sustainably (Office of Registration Administration, 2020). An even more important role played the cultivated agricultural commodities corn and especially rubber.

The introduction of rubber and corn aimed to improve the economic situation and standard of living for local farmers. Valentin et al. (2008) indicates that a consistently shorter summer monsoon in Thailand promoted crops with shorter cultivation cycles such as corn.

Additionally, with the change from subsistence to more market-oriented farming, producers benefitted from improved market access and increasing prices (Cramb, 2005). Between 2008 and 2010 the Thai government introduced mortgage and price guarantee schemes to provide economic incentives to farmers for corn production (Kitchaicharoen et al., 2015).

Rubber was first introduced to southern Thailand in 1899. In 2004, government policies encouraged the expansion to the northern part of the country. Various food crops, such as garlic and longan were replaced, because of surplus and decreased revenues due to the China-Thai Free Trade Agreement (Wangpakapattananawong et al., 2014). Also, rubber was used in government-sponsored substitution programs to eliminate opium cultivation (Fox et al., 2014) and since 2005, local farmers and landholders receive subsidies by the Rubber Plantation Supporting Fund (Kitchaicharoen et al., 2015). Finally, rubber prices boomed with beginning of the new millennium, promoted its expansion even more and impacted land-use change in the Nam Haeng watershed substantially (UNCTAD, 2020).

The interval level analysis showed that the first (2001-2007) and second (2007-2009) time interval experienced the greatest transition overall and transition even accelerated. This was likely driven by the Free Trade Agreement of 2004 and increasing rubber prices starting from 2000. The least change happened during the third interval, 2009-2012. Also the time of global recession after the economic crisis in 2008, after which the prices for most agricultural commodities dropped, including rubber (Wiggins et al., 2010). The willingness to do

investments and incentives for land conversion were rather low. The transition level analysis revealed the areas that have been converted to rubber. In general, rubber gains from corn, forest and succession. After 2007, especially corn areas are targeted and converted to rubber even though corn also has the largest annual gains besides rubber and succession. At the same time, forests are being converted to corn. One likely reason could be that rubber has been intercropped with corn in the early stages of development and satellite images were not classified accordingly. After three years, corn yields are substantially influenced by rubber tree growth (Pansak, 2015) and areas are being identified as rubber. Further expansion of rubber in the Nam Haeng watershed might continue even though limited by Forest conservation and elevation, as plantations above 900m are not sustainable (Yi et al., 2014).

4.2 Impact on Ecosystem Services

Land-use change had an impact on ES in the Nam Haeng watershed. Water yield in Nam Haeng decreases by 5.6% between 2001 and 2016 using the calibrated data from Thellmann et al. (2017). The results from the sample dataset produce more than double the amount of water collected within the watershed (543 Million m³ in 2001) and an overall decrease by 1.47%. Considering the spatial distribution, water yield is highest on urban areas, followed by paddy fields and forests.

According to Homdee et al., (2011), a conversion of forest to farmland with a decrease in forest area by 10% results in a change of annual water yield by +2.1% because the rate of evapotranspiration is lower on farmland than on forest areas. Using the calibrated dataset, forest area in Nam Haeng decreased by 14.02% but change of annual water yield is -5.6%. Important to note is that the decline of forest area in Nam Haeng does not only account for conversion to farmland but also to urban and rubber areas. The evapotranspiration rate of rubber is actually higher than of forests and therefore water yield decreases (Tan et al., 2011). Also, the total amount of water produced in the watershed using the calibrated dataset, ranging 234 - 239 million m³, might be too high. The regional irrigation office measured an inflow volume of 97.9 and 98.1 million m³ into the Nam Haeng reservoir in 2012 and 2016 (*Water Situation Analysis*, 2016). To validate water yield using literature data is difficult if it is not from the very same area. Most of all, precipitation and topography generate the result but can vary strongly from one location to another. Also, the sizes of watersheds differ, and downscaling is necessary to make comparisons. However, rather than providing a high degree of accuracy and precision, the goal is to give a useful impression of how land use

change may affected the annual delivery of water. Thanapakpawin et al. (2007) observed an annual yield of 987 million m³ in a watershed in Chiang Mai province, northern Thailand, four times as large as Nam Haeng but with very similar biophysical conditions. After downscaling, the result of 256 million m³ is comparable to the study area. Also from northern Thailand, with similar precipitation but in less steep terrain, Arunyawat & Shrestha (2016) and Graiprab et al. (2010) computed water yields at subwatershed level amounting 50 – 284 Million m³ and 268.9 million m³, respectively.

The largest impact and difference in datasets can be observed for sediment export. The calibrated dataset produced a decrease in the overall amount of sediment exported by 24%. With only 132 million kg in 2007, the result is significantly smaller than for the other years. This might be explained by the share of forest and succession areas. Forest areas with an average soil loss of 0.22 tons ha⁻¹year⁻¹ protect soils and their share is highest in 2007. But also, most prone to soil erosion are succession areas (4.06 tons ha⁻¹year⁻¹) and their share is lowest in this year. The sample dataset produced overall significantly higher values, in 2012 by a factor of 10. Also, it follows a different trend as compared to the calibrated dataset because sediment export increases between 2001 and 2016. The reason for the huge gap in results can be explained by the input data because USLE P and C values are higher in the sample dataset. In general, the Nan watershed has a high risk of soil erosion in consequence of land-use change (Paiboonvorachat & Oyana, 2011). Furthermore, rapid conversion rates intensified slope processes such as landslides and solifluction, increased overland runoff and the risk of heavy floods during the wet season (Baicha, 2016).

After reviewing the literature, various studies provide data for validation. Changnoi & Nontananandh (2012) obtained an average soil loss of 4.94 tons ha⁻¹year⁻¹ in 2006 and 3.59 tons ha⁻¹year⁻¹ in 2010 in Songkhram Watershed, Northeastern Thailand. This is similar to the Nam Haeng watershed with values ranging 1.32 - 4.88 tons ha⁻¹year⁻¹. However, Semmahasak (2014) predicted total average soil loss of 31.11 tons ha⁻¹year⁻¹ for a watershed in Northwestern Thailand and Bahadur (2009) 21.27 tons ha⁻¹year⁻¹ for the Upper Nam Wa Watershed in Nan Province. These values reflect the results from the sample dataset which produced 12.04 – 38.38 tons ha⁻¹year⁻¹ sediment export in Nam Haeng.

Regarding single land use categories, Bahadur (2009) estimated soil loss of 0.67 tons ha⁻¹year⁻¹ from paddy rice and 3.91 tons ha⁻¹year⁻¹ from forest. Liu et al. (2016) measured 0.5 - 4.25 tons ha⁻¹year⁻¹ under rubber plantations in Xishuangbanna, China. For Corn in Northeast Thailand, Pansak et al. (2008) reported soil loss of 1.6-2.5 tons/ha in and Valentin et al.

(2008) predicted 11.7 tons ha⁻¹year⁻¹. Results from the Nam Haeng watershed in 2016 with the calibrated dataset are very similar for paddy rice (0.68 tons ha⁻¹year⁻¹). Losses are comparable for rubber (1.49 tons ha⁻¹year⁻¹) and corn (4.08 tons ha⁻¹year⁻¹) but were lower for forest areas (0.38 tons ha⁻¹year⁻¹).

Carbon storage decreased for both datasets between 2001 and 2016. By 16.5% for the calibrated dataset and 19.7% for the sample dataset. Results are higher produced by the sample dataset, but the trend is very similar.

The calibrated data produced 56.96 Mg C ha⁻¹year⁻¹ in Paddy rice in 2016. This is similar to Gnanavelrajah et al. (2008) with 71 Mg C ha⁻¹year⁻¹ in eastern Thailand but higher than reported from Arunyawat & Shrestha (2016) with only 19 Mg C ha⁻¹year⁻¹ in northern Thailand. Forests store 294.02 Mg C ha⁻¹year⁻¹ in the Nam Haeng watershed, which is lower than compared to Pibumrung et al. (2008) in Nan Province and Arunyawat & Shrestha (2016) with 358 and 304 - 427 Mg C ha⁻¹year⁻¹, respectively. With 122.46 Mg C ha⁻¹year⁻¹ in rubber areas, results are very similar to Petsri et al. (2013) with 128 Mg C ha⁻¹year⁻¹ but lower than compared to Gnanavelrajah et al. (2008) with 254 Mg C ha⁻¹year⁻¹. Finally, 83.49 Mg C ha⁻¹year⁻¹ in Orchards is slightly lower than the result from Gnanavelrajah et al. (2008) with 120 Mg C ha⁻¹year⁻¹.

Habitat quality in the Nam Haeng watershed decreased between 2001 and 2016. The calibrated dataset produced a drop by 10.6%, with highest habitat quality in 2007. Forest areas and water bodies are assigned the highest quality and urban areas the lowest.

Agricultural land is scored rather low, especially paddy rice, and rubber is intermediate. In 2007, we find the largest share in forest area and therefore, the overall highest score in this year is reasonable. Hence, the model depicts reality in an appropriate way.

The sample dataset produced a rather uniform output and only urban areas are assigned a low habitat quality. This is insufficient and doesn't represent the variations in impact from different agricultural production systems. It almost equates natural forests with cultivated, human modified land, implying to provide similar habitats to local flora and fauna. The simplicity of the spatial pattern can be traced back to the input dataset. All land use classes have a habitat score of 1, except for urban areas which has a score of 0. Therefore, it's recommendable to at least select a habitat score that sets land use classes in relation to each other in a reasonable way.

Only few publications for validation were available. (Trisurat et al., 2010) quantified biodiversity in north-western Thailand using Mean Species Abundance (MSA) as an

indicator, which accounted 0.52 in 2002. Between 2009 and 2016 MSA declined by 12% from 0.41 to 0.36 (Trisurat et al., 2019). This does correspond with the trend of the habitat quality score from the calibrated dataset, which declined between 2001-2009 by 5% and between 2009-2016 by 5.5%. (Akber & Shrestha, 2015) estimated MSA of 0.45% in 2009 in Chiang Rai province, also located in northern Thailand.

The spatial pattern of MSA in 2002 does correspond with the results from the calibrated dataset. Areas with a low habitat quality are reflected with low MSA. This is similar to 2016, where habitat quality and MSA decreased as compared to 2002.

Trisurat et al. (2010) predict a continuation of forest and biodiversity loss in northern Thailand and promotes to concentrate protection measures especially on forest areas with a high biodiversity. Another factor that causes biodiversity loss is the spread of monocultural rubber plantations. The adoption of agroforestry systems within existing rubber plantations can help improving the biodiversity, as there is no difference in yield compared to monocultures (Warren-Thomas et al., 2020).

5. Conclusion

This study assessed land-use change in a mountainous watershed in northern Thailand and its impact on ES. Additionally, it has been analyzed whether calibrated data from China or even globally averaged input parameters can be transferred to produce reasonable results.

Between 2001 and 2016 forest area decreased by 24.4% and has been mainly converted to corn and rubber. This development is rooted in the economic circumstances of local, smallholder farmers. The cultivation of corn and rubber is promising because of increasing market prices. Also, mortgage and price guarantee schemes promoted by the Thai government or subsidies by the Rubber Plantation Supporting Fund provide further incentives for farmers to convert forests into agricultural land.

The impact on ES is crucial. Carbon storage and habitat quality decreased accordingly to a decline in forest area. Regarding annual water yield the impact was minimal, but it was also declining. Most significant was the impact on sediment export with contrary trends from the different datasets. Using the calibrated data from China, sediment export decreased and produced a drop in 2007 which can be attributed to the largest share in forest area compared to other years. With globally averaged data, the amount exported tripled within the study period 2001 to 2016. In general, the sample dataset generated overall higher results for all ES than the calibrated data.

The validation through literature proofed that calibrated data from China could be transferred to a watershed in northern Thailand with similar topographic and climatic conditions. The application of globally averaged biophysical input parameters provided a general idea on how ES would be impacted over the years, but modeled outputs could not match the results from scientific literature. However, only few publications from the study region directly were available and made validation, especially of habitat quality, difficult. After all, a more accurate comparison can only be achieved through further assessment by running the model with onsite data. As rubber and corn majorly transitioned the landscape, policies should further focus on the enhancement of ES through sustainable production systems. Finally, the transfer of calibrated parameters in data-scarce environments can provide a cost and time efficient tool of communicating research results in a sufficiently correct manner to help inform decision makers.

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