Mapping threatened dry deciduous dipterocarp forest in South-east Asia for conservation management

Authors: Wohlfart, Christian, Wegmann, Martin, and Leimgruber, Peter

Source: Tropical Conservation Science, 7(4) : 597-613

Published By: SAGE Publishing

URL: https://doi.org/10.1177/194008291400700402

Research Article

Mapping threatened dry deciduous dipterocarp forest in South-east Asia for conservation management

Christian Wohlfart[1,2]*, Martin Wegmann[3] and Peter Leimgruber[4]
[1] Global Change Ecology, University of Bayreuth, Wuerzburg & Augsburg, D-95447 Bayreuth, Germany
[2] Company for Remote Sensing and Environmental Research (SLU), D-81243 Munich, Germany
[3] Department of Remote Sensing, University of Wuerzburg, D- 97074 Wuerzburg, Germany
[4] Smithsonian Conservation Biology Institute, Smithsonian National Zoological Park, Front Royal, VA 22630, USA
*Corresponding author: e-mail: christian.wohlfart@remote-sensing-biodiversity.org

Abstract
Habitat loss is the primary reason for species extinction, making habitat conservation a critical strategy for maintaining global biodiversity. Major habitat types, such as lowland tropical evergreen forests or mangrove forests, are already well represented in many conservation priorities, while others are underrepresented. This is particularly true for dry deciduous dipterocarp forests (DDF), a key forest type in Asia that extends from the tropical to the subtropical regions in South-east Asia (SE Asia), where high temperatures and pronounced seasonal precipitation patterns are predominant. DDF are a unique forest ecosystem type harboring a wide range of important and endemic species and need to be adequately represented in global biodiversity conservation strategies. One of the greatest challenges in DDF conservation is the lack of detailed and accurate maps of their distribution due to inaccurate open-canopy seasonal forest mapping methods. Conventional land cover maps therefore tend to perform inadequately with DDF. Our study accurately delineates DDF on a continental scale based on remote sensing approaches by integrating the strong, characteristic seasonality of DDF. We also determine the current conservation status of DDF throughout SE Asia. We chose SE Asia for our research because its remaining DDF are extensive in some areas but are currently degrading and under increasing pressure from significant socio-economic changes throughout the region. Phenological indices, derived from MODIS vegetation index time series, served as input variables for a Random Forest classifier and were used to predict the spatial distribution of DDF. The resulting continuous fields maps of DDF had accuracies ranging from R^2 = 0.56 to 0.78. We identified three hotspots in SE Asia with a total area of 156,000 km^2, and found Myanmar to have more remaining DDF than the countries in SE Asia. Our approach proved to be a reliable method for mapping DDF and other seasonally influenced ecosystems on continental and regional scales, and is very valuable for conservation management in this region.

Keywords: Tropical dry forest conservation; Remote sensing; Vegetation phenology; MODIS NDVI; Time series analysis; Fractional cover

Received: 11 April 2014; Accepted 14 September 2014; Published: 15 December 2014

Cite this paper as: Wohlfart, C., Wegmann, M. and Leimgruber, P. 2014. Mapping threatened dry deciduous dipterocarp forest in South-east Asia for conservation management. *Tropical Conservation Science* Vol.7 (4): 597-613. Available online: www.tropicalconservationscience.org

Introduction

Habitat conservation is critical for maintaining healthy ecosystems and their associated biodiversity [1–3]. Rapidly accelerating land cover changes caused by human expansion increase the need to conserve remaining pristine habitats. There has been much scientific focus on conserving tropical forest habitats, especially tropical moist forests, cloud forests, and mangroves [4-8]. However, little attention has been paid to less well-known ecosystems and habitats such as tropical dry forests [9-12]. These forests remain understudied, although they are the most extensive forest types within the tropics, are greatly endangered, and are the least protected [13-15]. In addition, the geographical distribution of studies of tropical dry forests is biased: South-east Asia (SE Asia) itself as a study region has been neglected by scientific research in comparison to other tropical regions, such as the Neotropics [11, 16-19]. This scientific lack is even more worrisome as the region is exposed to the highest relative deforestation and logging rates globally [22-23] due to rapidly expanding human populations and recent dramatic socio-economic changes throughout its range (Fig.1) [20-21].

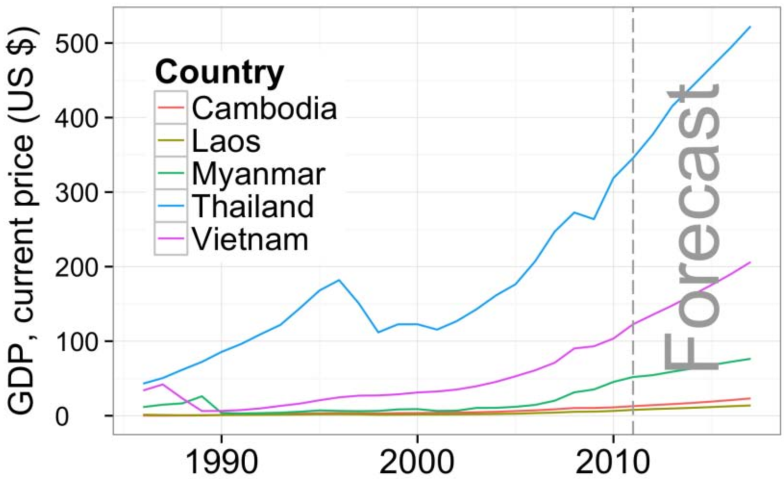

Fig. 1. Development of the Gross Domestic Product (GDP, in billion US $) from 1986 to 2017 (predicted) in Cambodia, Lao People´s Democratic (Laos), Myanmar, Thailand, and Vietnam in US Dollar. As of 2011, the GDP observation is an IMF forecast [42].

Dry forests in continental SE Asia differ considerably in structure and composition from the characteristics of dry forests in the Neotropics [25]. In Asia a wide range of different seasonal forest types occurs in mosaics, mainly determined by local elevation and moisture gradients [24-25]. The main dry forest types in the study region are deciduous dipterocarp forests (DDF), mixed deciduous forests (MDF), and dry evergreen forests (EF). DDF, a key dry forest type in SE Asia, are restricted to areas with a total annual rainfall of 1,000 -1,500 mm and a pronounced dry season, and thus are characterized by great seasonal changes in tree phenology [24-25]. In addition to their adaptation to strongly seasonal tropical and subtropical environments, DDF are set apart from other tropical forest types by their characteristic open canopy and abundant grassland, supporting high mammalian biomass, including important herbivores and grazers such as rhinos, elephants, gaur, banteng and Eld´s deer [26-28]. High abundance in grazers and browsers in turn allows for the development of a significant predator community including highly endangered species such as tigers [29]. In addition to their importance to biodiversity, DDF also provide a variety of ecosystem services: they are important carbon sinks, they regulate regional to local climate, and they help maintain water levels [24-25, 30-31]. DDF are a unique and valuable forest type in need of better representation in global, regional and local strategies for biodiversity conservation.

One of the great challenges in the conservation of DDF is the lack of detailed and accurate maps of their geographical distribution, which are essential for the development of effective conservation strategies and prioritized areas for conservation. Efforts to delineate dry dipterocarp forest extent and distribution on regional scales have been made with various remote sensing techniques [12, 32-36], but accurate and reliable maps for SE Asia on continental scales are scarce. Global coarse-scale resolution products tend to inaccurately delineate dry forest ecosystems [37-39]. Current coarse resolution remote sensing applications usually perform poorly in mapping open-canopy forest structures, and a clear classification of these open-canopy forest types from other forests or other open areas is difficult [40]. The extreme seasonality causes problems in separating DDF from agricultural or other human-made areas in the dry season, whereas in the wet season the dense cloud cover makes it difficult to delineate the prevailing land cover [37, 39, 41]. Further, remaining DDF occur in small and fragmented patches, requiring high spatial resolution imagery. However, high spatial resolution data cannot deal with dense cloud cover.

Our study delineates DDF gradients throughout Indo-Burma and provides a new and accurate continuous DDF map for conservation decisions at 250 m resolution. We also determined the current protection status of DDF and compared our outcome to existing land cover products. We developed and tested a way to accurately map DDF, taking advantage of the very factors that have limited previous mapping approaches, such as the strong seasonality, small-scale structure, and the open canopy structure of DDF. This fractional approach is based on phenological information to better separate seasonal DDF, and we provide a continuous representation of DDF cover throughout SE Asia.

Methods

Study Area

This study was conducted in the continental SE Asian countries of Myanmar, Thailand, Lao P.D.R. (hereafter referred to Laos), Cambodia, and Vietnam to develop a reliable distribution map for DDF at a continental scale (Fig. 2, upper left 92.18°, 28.52°; lower right 109.44°, 5.63°). We refined our mapping by focusing on three geographical subregions where extensive DDF areas were expected, including upper Myanmar (ul: 94.30°, 22.45°; lr 96.30°, 24.13°), western Thailand (ul: 98.50°, 16.27°; lr: 100.40°, 17.95°), and eastern Cambodia (ul: 105.62°, 11.78°; lr 107.52°, 13.46°). The entire area is also known as the Indo-Burma biodiversity hotspot, a crucial part of the Indo-Malayan ecoregion that is a priority region for nature conservation [5, 43]. The climate is dominated by a strongly seasonal monsoon, which occurs between April and October, separated by an extended dry season [44]. Annual precipitation varies significantly within the region, with up to 5,000 mm in coastal and mountainous areas and 700-1,500 mm in the drier central areas, depending on the prevailing microclimate [45]. Annual mean temperature averages around 27° Celsius in lowlands, but ranges between 11-20° Celsius in mountainous mainland areas. Historically, forests make up a significant portion of the natural vegetation cover, where DDF used to be a common forest type throughout mainland SE Asia [46]. The region has been transformed and degraded by human activities for centuries [47]. Recent socio-economic changes have led to severe increases in forest loss from agricultural conversion for crops and livestock, large-scale commercial plantations, and expanding urban areas [48-50].

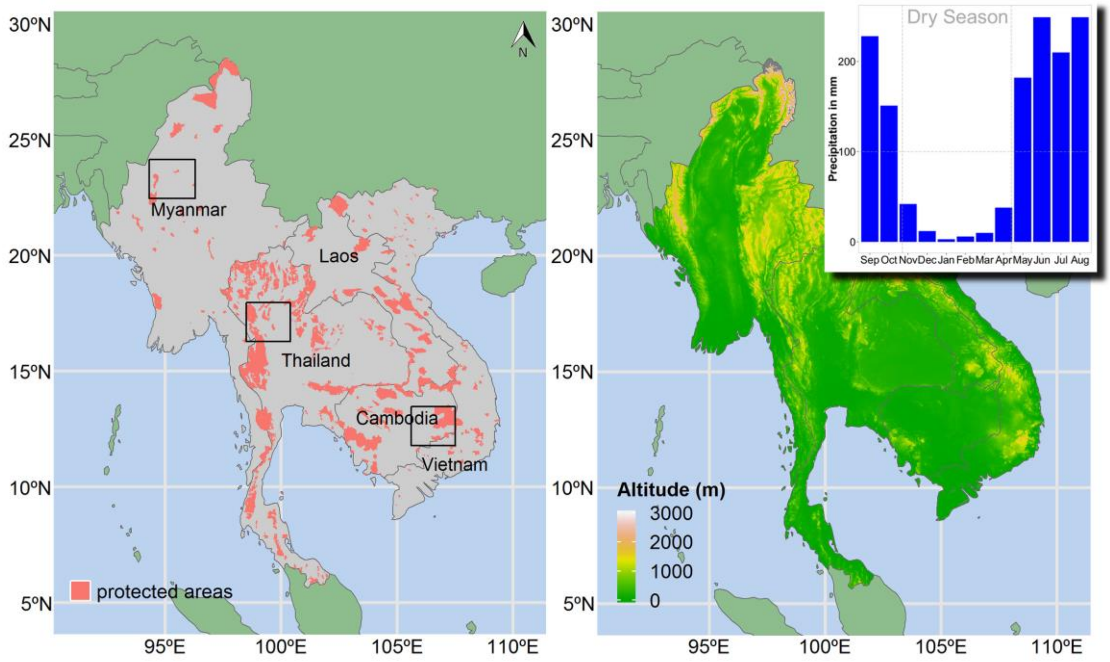

Fig 2. Left figure: the study site (continental South-east Asia: Myanmar, Laos, Thailand, Cambodia, and Vietnam) and the three selected subregions: Upper Myanmar (Chatthin), Western Thailand (Mae Ping), and Eastern Cambodia (Phnom Prich). Protected areas highlighted in the study region are red. The right figure provides a physiographic overview of South-east Asia and the mean annual precipitation distribution (Data from [45]).

Remote sensing data

In this study, we used the MODIS NDVI vegetation index 16-day 250 m composite (MOD13Q1) acquired by the Terra satellite [51-52]. For our analysis we downloaded all MODIS data acquired from 2001 to 2011 [53] and provided in total eight MODIS tiles (h26v06, h27v06, h28v06, h26v07, h27v07, h28v07, h27v08, and h28v08) covering continental SE Asia. Each scene was re-projected from the native Sinusoidal projection to the geographical latitude/longitude projection (WGS84 datum).

Protected areas and land cover data

To determine the degree of protection for DDF, we acquired protected area data for Myanmar, Thailand, Laos, Cambodia, and Vietnam supplied from the World Database on Protected Areas (WDPA) (http://www.unep-wcmc.org/). We used all areas within the IUCN categories I-IV and superimposed these polygons on our study area to determine the protection status of the remaining DDF.

We selected four global land cover classification products, which are often used in conservation studies, in order to compare our findings with existing land cover data. These products contain no clear DDF class, so we had to choose classes that best represent DDF (Fig. 3): (1) classes *"Tree cover broadleaf"* and *"Deciduous, mainly open"* in the 1,000 m Global Land Cover 2000 Product (GLC2000) [54]; (2) class *"Open (15-40 %) broadleaved deciduous"* in the GlobCover product with a medium resolution of 300 m [55]; (3) classes *"Deciduous broadleaf forest"*, *"open and closed shrubland savanna"*, and *"woody savanna"* in the 500 m IGBP MODIS land cover product (MCD12Q1) [56]; and (4) the outcome dry forest map from the study of Miles et al. [57]. The latter product, the Global Distribution of Tropical Dry Forest (GDTDF) was developed specifically for DDF. All global land cover data were derived from medium (300 m) to coarse (1,000 m) resolution satellite data and used discrete land cover classes.

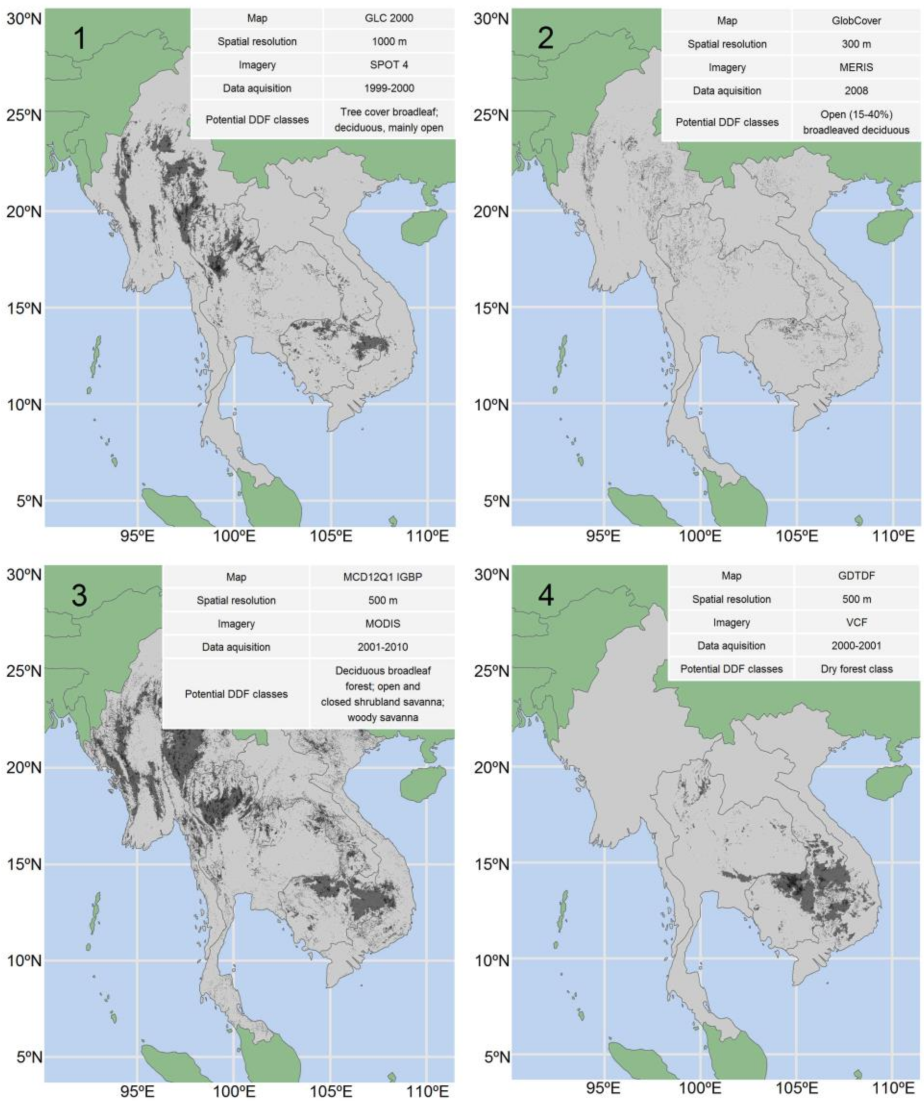

Fig 3. Overview of the used land cover products and their spatial distribution of potential dry deciduous dipterocarp forest (DDF) classes in existing land cover products.

Google earth data sampling

We used very high spatial resolution remote sensing data via Google Earth (GE, Version 6.2.2) to collect training data for model development as well as an independent data set for accuracy assessments. The availability of very high-resolution imagery (VHR, less than 1 m) allowed a clear visual interpretation of the prevailing land cover. GE provides images of different acquisition dates, which allow the user to compare images from different time periods in a given area to differentiate the land cover types.

To ensure a representative distribution of sampling points, we selected 4,500 random MODIS 250m pixels for further analysis using VHR data. As clear interpretation of the prevailing land cover is only possible from high quality and high resolution data, we deleted all sample points where no VHR imagery was available, or where cloud cover, shadows, or steep slopes made interpretation difficult.

Within the selected MODIS pixels, all DDF were mapped. We separated the small-scale mosaic structure of DDF and other land cover types within one pixel using temporally different images. The first sampling yielded 3,078 locations, with a low frequency of high DDF fractions (n=456). Therefore, we implemented a stratified random sampling approach, specifically in areas where we expected large DDF areas. Three sampling areas were identified: (I) upper Myanmar (around Chatthin area), (II) western Thailand (Mae Ping), and (III) eastern Cambodia (Phnom Prich). This resulted in 333 additional high fractional DDF samples. We collected and processed 3,695 reference areas in total. The resulting DDF proportions within each pixel were scaled to range between 0 and 100 % of DDF.

Data preparation

To analyze the pronounced seasonality of DDF for differentiation from other land cover classes, we used phenological metrics as predictor variables. We used the software TIMESAT to process the NDVI time series to reduce the influence of noise found in original MODIS data [58]. We used the Savitzky-Golay filter with a three point window over two fitting steps, an adaptation strength of 2.0 and amplitude cutoff of 0.0. The minimum season was set to the first of January. The following phenological variables were derived from 2001 to 2011 [59]: (1) start of the season (StartSeason); (2) end of the season (EndSeason); (3) length of the season (LengthSeason); (4) base level calculated as the average of the left and right minimum values (BaseLevel); (5) middle of the season (MidSeason); (6) largest data value during the season (PeakValue); (7) seasonal amplitude (Amplitude); (8) rate of increase at the beginning of the season (LeftDerivative); (9) rate of decrease at the end of the season (RightDerivative); (10) large seasonal integral (LargeIntegral); (11) small seasonal integral (SmallIntegral). We extracted the TIMESAT phenological data for the year corresponding to the acquisition date of the VHR imagery from 2001 to 2011 to account for the GE image samples having been acquired in different years. Selecting 70% for training and 30% for testing the model, we split the dataset containing the continuous DDF values. Presence and absence samples of DDF were split independently. This procedure was executed for the entire data set and for each geographic subregion. The training data sets served as input for the respective model.

Dry deciduous dipterocarp forest classification

Decision tree based classifiers, such as Random Forests (RF), have often been successfully applied to land cover studies [60-62] as well as modelling of species distribution from presence data. We used the Random Forest approach with the number of trees set to 500 [63]. We generated four separate models, one for entire SE Asia and for each geographical subregion, and conducted a variable importance analysis. Using the TIMESAT variables from the year 2011 computed from three consecutive years (2009 to 2011) and the result from the selected models, we made a spatial prediction of the continuous DDF data. To assess the accuracy of our DDF map, we compared the generated test data set to the predicted values via linear regression analysis. Additionally we used the internal RF accuracy assessment measure, the so called out-of-bag (OOB) accuracy [64]. We resampled the final DDF map to the respective resolution of each land cover product to conduct the comparative analysis. All analyses, maps and graphics were prepared solely with open source software using the statistical programming language R (Version 2.15) [65] with the packages rgdal(v0.7-22) [66], randomForest (v.6-6) [63] and ggplot2 [67], Quantum GIS (Version 1.8.0) [68], and GRASS GIS (Version 6.4) [69]. The entire workflow is depicted in Fig. 4.

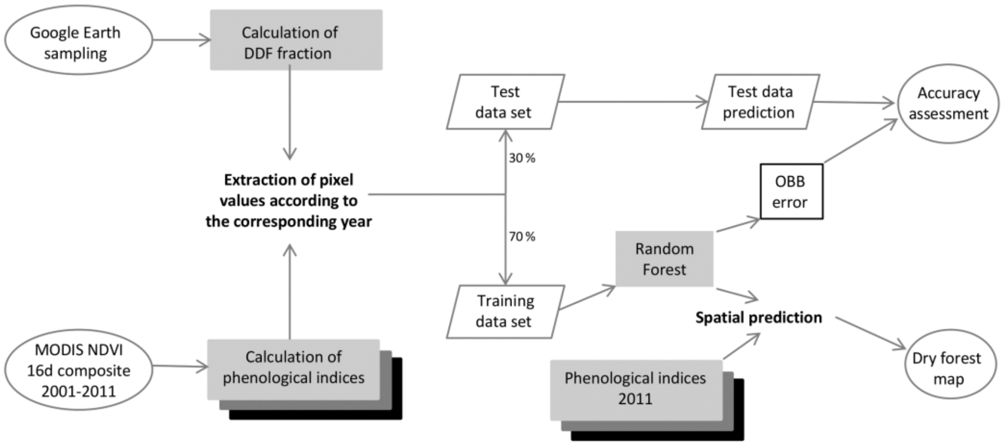

Fig. 4. Flow chart illustrating how we applied the fractional cover approach for delineating dry deciduous dipterocarp forest (DDF).

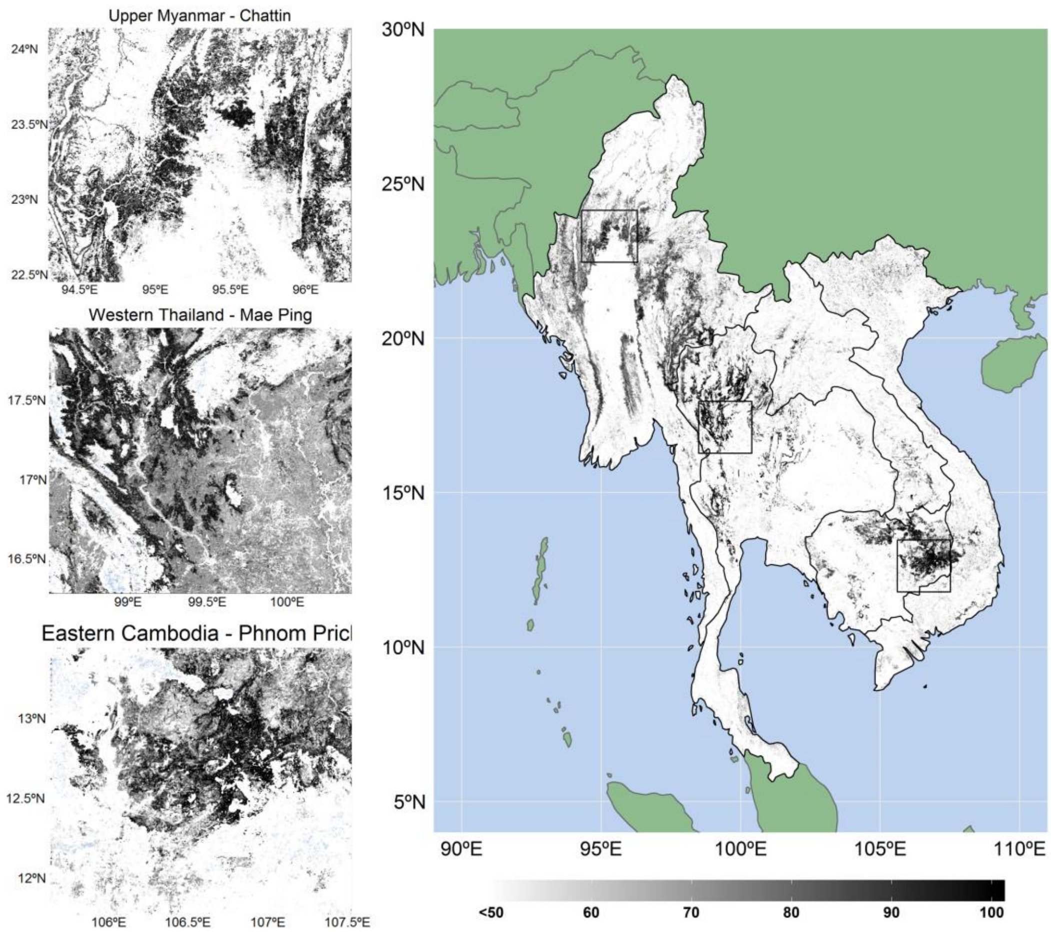

Fig 5. Spatial distribution of dry deciduous dipterocarp forest coverage (in %) in South-east Asia and the three geographical subregions in upper Myanmar, western Thailand, and eastern Cambodia in 2011.

Results

Spatial prediction of remaining DDF and protection status

Approximately 156,000 km² of DDF, defined as pixel with a fractional DDF cover of larger than 50 %, remain in SE Asia in the year 2011, making up about one-sixth of the total remaining forest cover for the region [70]. As can be seen in Fig. 5, the highest DDF coverage is in Myanmar (79 000 km²), Thailand (37 000 km²) and Cambodia (23 000 km²), whereas little DDF is left in Laos and Vietnam. At the country level, in Myanmar DDF is still present in the northern part of the central dry zone (Sagaing and Shan State) as well as in small patches along the foothills of the Rakhine Yoma. In Thailand, DDF only remains in the northeastern part of the country at the Thanon Thong Chai Range (below 1,000 m). In Cambodia, the DDF hotspots extend from the Dângrêk Mountains in the northern part of the country to the southeastern part of the Mondulkiri Province. As we can see in Fig. 5, high DDF fractions tend to be fragmented and interspersed across landscape and scale. The comparison of the protected DDF among the countries (Fig. 6) shows enormous discrepancies, with Thailand and Cambodia providing a high protection percentage (~35 %), while DDF within protected areas is minimal in Myanmar (~2 %), where the largest DDF areas are still present.

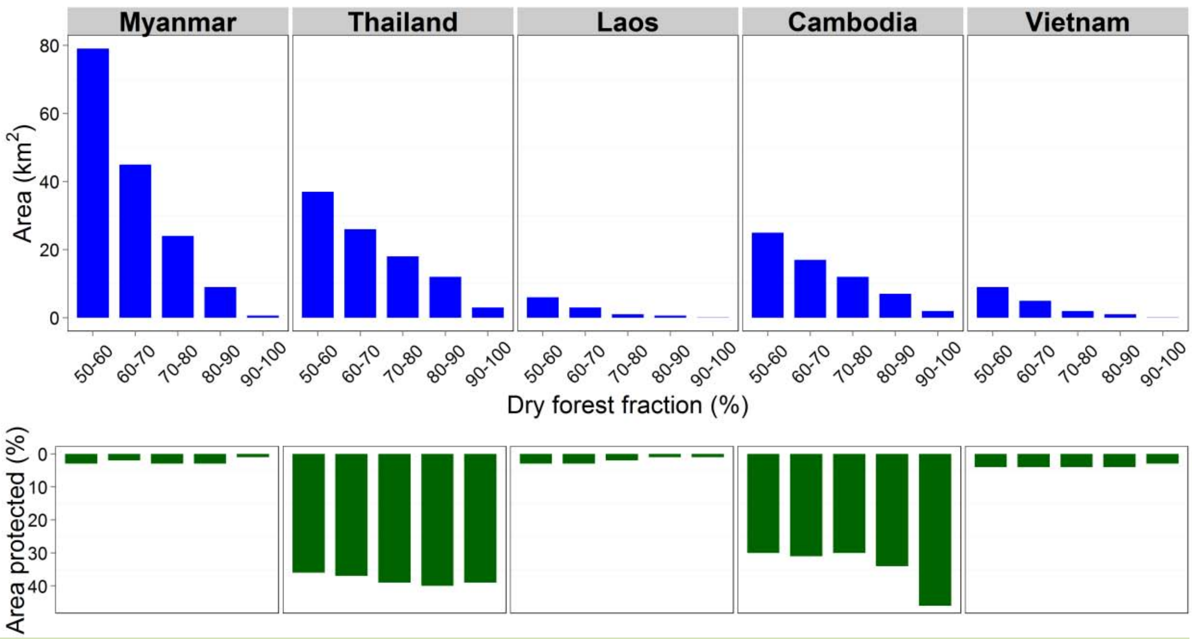

Fig 6. The upper diagram depicts the remaining dry deciduous dipterocarp forest (DDF) areas (km²) for each country, the lower the protection status of DDF (in %).

Modelling performance

Using this approach, the model performances ranged between R^2 = 0.55 and 0.78 for both types of accuracy assessments (OOB and the independent test) (Tab. 1). Three models yielded similar performance, with R^2 of 0.55 ± 0.01. Only the model of the Eastern Cambodian region produced a distinctly higher accuracy with an R^2 = 0.78. OOB and the independent test accuracies only differed slightly, with OOB providing marginally more pessimistic estimates. The mean squared error (MSE) of the RF model varied between 0.05 - 0.09. The error rate of the test data set was quite similar, ranging between 0.04 - 0.09. Amongst the TIMESAT variables, BaseLevel, Amplitude, PeakValue, and

SmallInegral were most important, with some variations among the four models. BaseLevel was the most important variable in all models, while RightDerivative, LeftDerivative, and Midseason were considered less important.

Table. 1. Accuracy assessment per region for the separate Random Forest models using the RF's OOB (out-of-bag) accuracy and an independent test set.

Geographic region	OOB		Test set	
	R^2	MSE	R^2	MSE
South-east Asia	0.55	0.06	0.56	0.06
Upper Myanmar (Chatthin)	0.66	0.05	0.57	0.08
Western Thailand (Mae Ping)	0.55	0.09	0.56	0.06
Eastern Cambodia (Phnom Prich)	0.76	0.03	0.78	0.04

Comparison to existing land cover maps

It appears that the four selected land cover maps GLC 2000, GlobCover, MODIS IGBP, and GDTDF have pronounced discrepancies among each other in the spatial distribution and extent of DDF in continental SE Asia (Fig. 3). The estimated areas for DDF range between 76,627 km^2 (Globcover) and 299,874 km^2 (MODIS IGBP), a more than fourfold difference. Beside the differences between the land cover maps themselves, these also differ from the dry forest coverage analyzed in this study. Globcover and GDTDF tend to underestimate DDF, whereas GLC 2000 and MODIS IGBP show a larger DDF distribution compared to our map (Tab. 2 and Fig. 7). Considering the spatial overlap of DDF, GLC and Globcover agreed best with the DDF outcome of this study with a mean value of around 60% (Tab. 2). The land cover product GDTDF showed the least agreement (only 27%) with this study. Also, the range of DDF is larger compared to the other land cover maps.

Table. 2. Calculated dry forest areas for all existing land cover products and the spatial overlap with our dry deciduous dipterocarp forest map.

Land cover product	Dry forest area (km^2)	Spatial overlap (%)
GLC 2000	201,370	59
Globcover	76,627	57
MODIS IGBP	299,874	51
GDTDF	88,520	37
Reference DDF map from this study	**156,000**	**100**

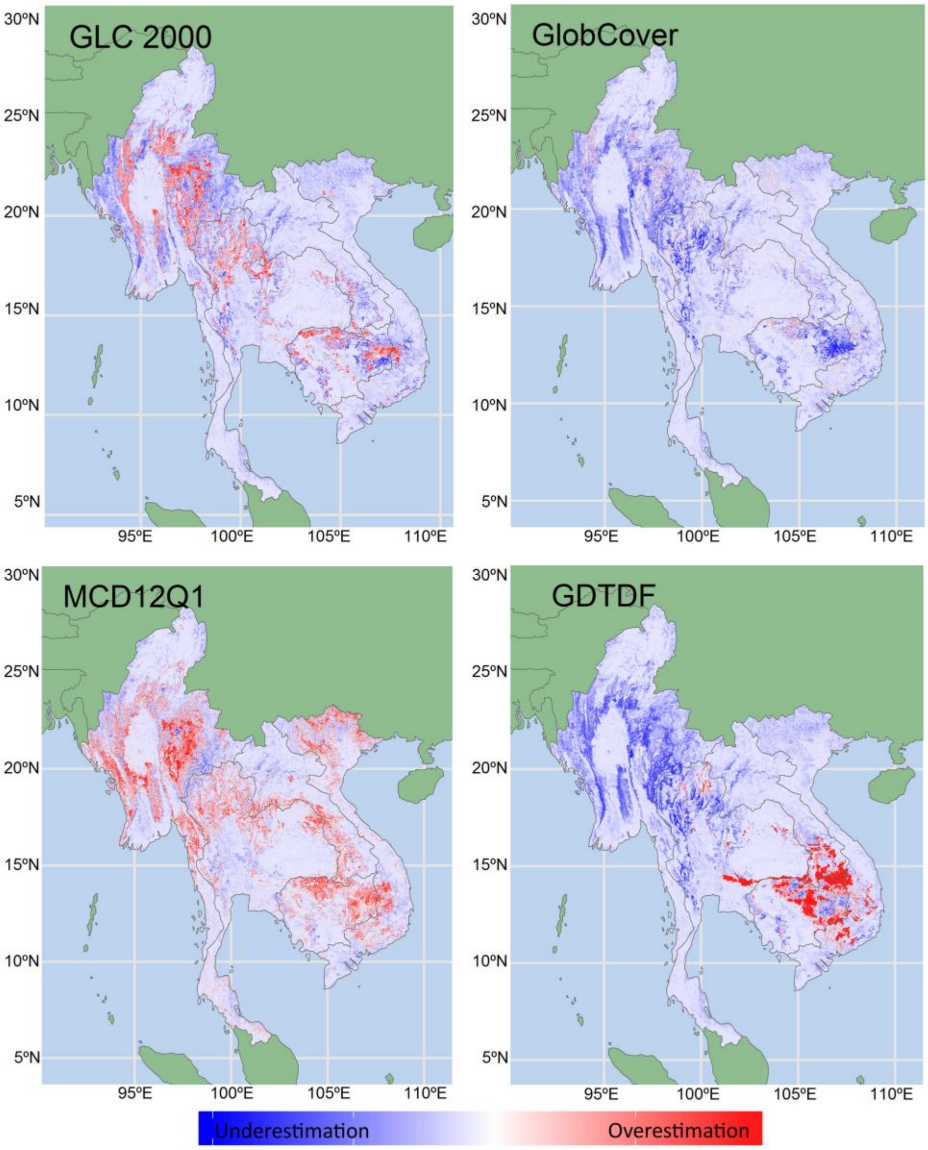

Fig 7. Spatial variation among the four selected land cover maps and the dry forest map derived in this study.

Discussion

Most remote sensing work in the tropics focuses on tropical wet forest, whereas tropical dry forest ecosystems have been neglected in the scientific community, despite their ecological importance and the increasing socio-economic pressure [9-12]. The reasons why DDF specifically in Asia is understudied are not entirely clear. The most likely explanation is that relatively few DDF areas remain and are often fragmented and degraded, and many of the megafauna species that used to occur within DDF have been exterminated, such as the rhino, tiger, banteng, gaur, and elephants. In addition, DDF has less plant species diversity than wet forests, possibly making them less interesting [24].

To our knowledge, there is no reliable map showing the extent and distribution of DDF for SE Asia on larger spatial scales. In the present study, DDF is delineated as fractional cover for SE Asia at 250 m spatial resolution on regional and continental scales, using phenological information to separate DDF from other land cover types. In general, the delineation of spatially and compositionally complex vegetation, such as DDF with mixed and heterogeneous vegetation from medium and coarse remote sensing data, is difficult due to mixed pixels [79-81]. To overcome this problem, we combined high spatial and temporal remote sensing data. We proved an alternative way to overcome all obstacles (small-scale and open canopy structure; high seasonality; cloud cover in wet season) related to DDF mapping by combining a sub pixel analysis with continuous data instead of using discrete "hard" per pixel classes.

We took advantage of DDF´s strong seasonality and computed several phenological variables based on a MODIS NDVI time series. Since the high temporal resolution of MODIS allows for depicting great seasonal variability, it also increases the chances of acquiring cloud-free imagery in the wet season. The calculated variables are straightforward to interpret, as this forest type is mainly determined by great seasonal change in phenology during the year. In this study, the key variables for delineating DDF were BaseLevel, Amplitude, PeakValue, and LengthSeason, which make sense from a biological perspective. The BaseLevel is the most important variable to identify DDF and helps to discriminate it from other surrounding land cover types during the dry season, where MDF and EF are still leafy and agricultural fields are bare [32, 37, 39, 41]. During the wet season EF and MDF have higher NDVI maximum values than DDF, resulting in a higher PeakValue. The Amplitude was considered equally important, which separates agriculture with a very distinct amplitude from DDF, whilst the seasonal difference of MDF and EF remains smaller.

Using the methodology described above, it is possible to delineate DDF on regional and continental scales, and our map can be used as a reliable basis for conservation decisions in SE Asia. A recent study by Portillo-Quintero and Sánchez-Azofeifa [38] delineated dry forest ecosystems in the Neotropics at 500 m spatial resolution, also using also multi-temporal information. The advances of continuous representation of a specific land cover class within a heterogeneous landscape have been demonstrated in many studies [33, 80-84]. Sub-pixel analysis has the ability to identify transitions in space and time better and provides a more realistic view of surface reflectance to the prevailing land cover than traditional "hard" discrete classes. Discrete classes do not allow an accurate delineation of spatially complex areas [84, 86-87].

The findings in this study also indicate the low performance of existing land cover products delineating DDF, and we demonstrate the shortcomings of global products based on coarse resolution data in delineating strong seasonal and small-scale vegetation types. Current land cover maps are conventionally developed using discrete "hard" per pixel classes or clusters, where a single land cover class is represented by a satellite pixel [54-55, 85]. DDF, as a transitional ecosystem, cannot be deduced well by per pixel classification algorithms on which these conventional maps are based. Also the medium to coarse spatial resolution (300-1,000 m) hampers an accurate delineation.

Previous studies have demonstrated the inconsistency of these land cover products, when comparing dry forest ecosystems [37, 39]. DDF is not represented as a specific land cover class in these products, so we had to choose alternative categories representing DDF best, such as "*Deciduous broadleaf forest*" or "*Open and closed shrubland*" or "*woody savanna*". Many comparative studies confirmed the low thematic accuracy and spatial overlap among different land cover classifications [88-90]. Surprisingly, the attempt of Miles et al. [57] showed the highest divergence in DDF distribution compared to our findings. The malfunction stems from defining wrongly the canopy cover threshold (>40 %) and the implementation of coarse-scaled WWF-ecoregions [37]. The majority of these global products do not integrate seasonality pattern in their classification algorithm. This often leads to misclassification of DDF either as open/agricultural areas in the dry season, or as other forest types during the wet season [37, 39].

Given the freely available remote sensing data, including MODIS and the reference data retrieved by very high resolution Google Earth imagery, as well as free open source software, we have developed a cost efficient way to monitor ecosystems influenced by strong seasonal change on different scales. This inexpensive method supports remote sensing and conservation communities with limited monetary resources. Further, this approach reduces the need for field campaigns, which are time and money consuming in areas with access constraints. Our classification method can be easily reproduced and transferred to other regions with prevailing heterogeneous and complex land cover.

Implications for Conservation

Current and future socio-economic trends in continental SE Asia result from population and economic growth, which are major drivers of forest destruction and the subsequent loss of suitable habitats for different mammalian species [21]. Indeed, this region has one of the highest deforestation rates in the tropics, and DDF seem to be especially affected by current deforestation and degradation trends, which may result in the total loss of this ecosystem in SE Asia [34, 48, 71]. Activities such as logging, settlement, conversion, and mining contribute to the loss and degradation of the remaining DDF fragments. In contrast to the dense and closed EF, DDF's abundant ground biomass during the wet season offers suitable habitat and forage conditions for herbivores such as the Asian elephant (*Elephas maximus*), and several wild cattle and ungulate species. These medium to large DDF specialists require large forage areas to satisfy their food demand. Higher encounter rates between herbivores and their natural predators through the open, less dense structure of DDF foster the abundance of large carnivores such as tiger (*Panthera tigris*), lion (*Panthera lion*), and dhole (*Cuon alpinus*) [27, 73]. Gray and Phan [27] found that the highest abundance of large mammals is found in mosaic landscapes of DDF and MDF entities. DDF provide sufficient resources during the wet season, whereas MDF offer shelter and water specifically in the hot and dry season. Hence conservation efforts should target large continuous areas of DDF and MDF, as well as small patches and fragments that maintain connectivity within the landscape [72-73].

Currently, mammals in SE Asia have the highest proportion of endangered species among all taxa in the Tropics [48, 74]. The main reason for the decline is the rapid loss of suitable habitats, including DDF, due to destruction and degradation, which is crucial for mammals as they are more sensitive than other taxa [20]. According to the latest IUCN Red List assessment, more than 35 mammalian species are categorized as either *Critically Endangered* or *Endangered* in SE Asia, and predictions reveal extinction rates between 21-48 % by the end of this century [75-76]. Therefore, precise information about the current extent of DDF is crucial for global mammal conservation.

Our results indicate a lack of conservation priority, particularly in Myanmar, which has large DDF but the fewest protected areas. Countries like Myanmar and Cambodia have recently become more engaged within the international community, and large portions of the physical environment, as well as many social, political, and economic institutions, are experiencing profound and widespread changes that will dramatically increase pressure on nature [77]. These countries still hold vast tracts of intact forests, but increasing domestic and international demand for valuable timber has already resulted in accelerated logging activities, and DDF are strongly affected by these trends [78]. Therefore, SE Asian countries really need strong regulations and law enforcement that promote sustainable resource use. In addition, illegal poaching and wildlife trafficking needs to be controlled. The enforcement and management of conservation areas and strong policies are crucial for successful protection of the native habitats and biodiversity of SE Asia. It is important to integrate multinational and multidisciplinary strategies, where all involved stakeholders must partake.

Acknowledgements

We would like to thank the study program Global Change Ecology and the Elite Network Bavaria for their support. Further, the authors would like to thank the anonymous reviewer for their valuable comments and suggestions to improve the quality of this study.

References

[1] Thirgood, S., Mosser, A., Tham, S., Hopcraft, G., Mwangomo, E., Mlengeya, T., Kilewo, M., Fryxell, J., Sinclair, A. R. E. and Borner, M. 2004. Can parks protect migratory ungulates? The case of the Serengeti wildebeest. *Animal Conservation* 7:113-120.

[2] Nagendra, H., Lucas, R., Honrado, J. P., Jongman, R. H. G., Tarantino, C., Adamo, M. and Mairota, P. 2013. Remote sensing for conservation monitoring: Assessing protected areas, habitat extent, habitat condition, species diversity, and threats. *Ecological Indicators* 33:45-59.

[3] Brooks, T. M., Mittermeier, R. A., Da Fonseca, G. A. B., Gerlach, J., Hoffmann, M., Lamoreux, J. F., Mittermeier, C. G., Pilgrim, J. D. and Rodrigues, A. S. L. 2006. Global Biodiversity Conservation Priorities. *Science* 313:58-61.

[4] Gentry, A. H. 1992 .Tropical forest biodiversity - Distributional patterns and their conservational significance. *Oikos* 63:19-28.

[5] Myers, N., Mittermeier, R. A., Mittermeier, C. G., Da Fonseca, G. A. B. and Kent, J. 2000. Biodiversity hotspots for conservation priorities. *Nature* 403:853-858.

[6] Alongi, D. M. 2002. Present state and future of the world's mangrove forests. *Environmental Conservation* 29:331-349.

[7] Laurance, W. F., Albernaz, A. K. M., Schroth, G., Fearnside, P. M., Bergen, S., Venticinque, E. M. and Da Costa, C. 2002. Predictors of deforestation in the Brazilian Amazon. *Journal of Biogeography* 29:737-748.

[8] Sodhi, N. S., Brook, B. W. and Bradshaw, C. J. A. 2007. *Tropical conservation biology*. Oxford: Blackwell.

[9] Sánchez-Azofeifa, G. A., Quesada, M., Rodríguez, J. P., Nassar, J. M., Stoner, K. E., Castillo, A., Garvin, T., Zent, E. L., Calvo-Alvarado, J., Kalacska, M., Fajardo, L., Gamon, J. A. and Cuevas-Reyes, P. 2005. Research priorities for Neotropical dry forests. *Biotropica* 37:477-485.

[10] Gillespie, T. W., Grijalva, A. and Farris, C. N. 2000. Diversity, composition, and structure of tropical dry forests in Central America. *Plant Ecology* 147:37-47.

[11] Trejo, I. and Dirzo, R. 2000. Deforestation of seasonally dry tropical forest: a national and local analysis in Mexico. *Biological Conservation* 94:133-142.

[12] Songer, M., Aung, M., Senior, B., DeFries, R. and Leimgruber, P. 2009. Spatial and temporal deforestation dynamics in protected and unprotected dry forests: a case study from Myanmar (Burma). *Biodiversity and Conservation* 18:1001-1018.

[13] Murphy, P. G. and Lugo, A. E. 1986. Ecology of tropical dry forest. *Annual Review of Ecology and Systematics* 17:67-88.

[14] Janzen, D. 1998. *Tropical dry forests: The most endangered tropical ecosystem*. Wilson, E. O., (Ed). Washington, DC: National Academy of Sciences/Smithsonian Institution.

[15] Hoekstra, J., Boucher, T., Ricketts, T. and Roberts, C. 2005. Confronting a biome crisis: global disparities of habitat loss and protection. *Ecology Letters* 8:23-29.

[16] Kalacska, M., Sánchez-Azofeifa, G. A., Calvo-Alvarado, J. C., Quesada, M., Rivard, B. and Janzen, D. 2004. Species composition, similarity and diversity in three successional stages of a seasonally dry tropical forest. *Forest Ecology and Management* 200:227-247.

[17] Arroyo-Mora, J. P., Sánchez-Azofeifa, G. A., Rivard, B., Calvo, J. and Janzen, D. 2005. Dynamics in landscape structure and composition for the Chorotega region, Costa Rica from 1960 to 2000. *Agriculture, Ecosystems & Environment* 30:27-39.

[18] Stoner, K. and Sánchez-Azofeifa, G. 2009. Ecology and regeneration of tropical dry forests in the Americas: Implications for management. *Forest Ecology and Management* 258:903-906.

[19] Portillo-Quintero, C. A. and Sánchez-Azofeifa G. A. 2010. Extent and conservation of tropical dry forests in the Americas. *Biological Conservation* 143:144-155.

[20] Sodhi, N. S., Koh, L. P., Brook, B. W. and Ng, P. K. L. 2004. Southeast Asian biodiversity: an impending disaster. *Trends in Ecology & Evolution* 19:654-660.

[21] Bawa, K. S. and Dayanandan, S. 1997. Socioeconomic factors and tropical deforestation. *Nature* 386, 562–563.

[22] Laurance, W. F. 1999. Reflections on the tropical deforestation crisis. *Biological Conservation* 91:109-117.

[23] Bradshaw, C., Sodhi, N. S. and Brook, B. 2009. Tropical turmoil: a biodiversity tragedy in progress. *Frontiers in Ecology and the Environment* 7:79-87.

[24] Bunyavejchewin, S. C., Baker, P. and Davis, S. J. 2011. Seasonally dry tropical forests in continental Southeast Asia - Structure, composition, and dynamics. In: *The ecology and conservation of seasonally dry forests in Asia*. McShea, W. J., Davis, S. J. and Bhumpakphan, N. (Eds), pp. 9-35. Washington DC: Smithsonian Institution Scholarly Press.

[25] Rundel, W. and Boonpragob, K. 1995. Dry forest ecosystems of Thailand. In: *Seasonally Dry Tropical Forests*. Bullock, S. H., Mooney, H. A. and Medina, E. (Eds), pp.93-123. University Press, Cambridge.

[26] Koy, K., McShea, W. J., Leimgruber, P., Haack, B. N. and Aung, M. 2005. Percentage canopy cover - using Landsat imagery to delineate habitat for Myanmar's endangered Eld's deer (Cervus eldi). *Animal Conservation* 8:289-296.

[27] Gray, T. N. E. and Phan, C. 2011. Habitat preferences and activity patterns of the larger mammal community in Phnom Prich wildlife sanctuary, Cambodia. *The Raffles Bulletin of Zoology* 59:311-318.

[28] McShea, W. J. and Baker, M. C. 2011 Tropical deer in the seasonally dry forests of Asia: Ecology, concerns, and potential for conservation. In: *The ecology and conservation of seasonally dry forests in Asia*. McShea, W. J., Davis, S. J. and

[29] Karanth, K. U., Chundawat, R. S., Nichols, J. D. and Kumar, N. S. 2004. Estimation of tiger densities in the tropical dry forests of Panna, Central India, using photographic capture - recapture sampling. *Animal Conservation* 7:285-290.

[30] Terakunpisut, J., Gajaseni, N. and Ruankawe, N. 2007. Carbon sequestration potential in aboveground biomass of Thong Pha Phum National Forest, Thailand. *Applied Ecology and Environmental Research* 5:93-102.

[31] Chaiyo, U., Garivait, S. and Wanthongchai, K. 2011. Carbon storage in above-ground biomass of tropical deciduous forest in Ratchaburi Province, Thailand. *World Academy of Science, Engineering & Technology* 58:539-544.

[32] Arroyo-Mora, J. P., Sánchez-Azofeifa, G. A., Kalacska, M., Rivard, B. , Calvo-Alvarado, J. and Janzen, D. H. 2005. Secondary forest detection in a Neotropical dry forest landscape using Landsat 7 ETM+ and IKONOS Imagery. *Biotropica* 37:497-507.

[33] Koy, K., McShea, W. J., Leimgruber, P., Haack, B. N. and Aung, M. 2005. Percentage canopy cover - using Landsat imagery to delineate habitat for Myanmar's endangered Eld's deer (*Cervus eldi*). *Animal Conservation* 8:289-296.

[34] Leimgruber, P., Kelly, D. S., Steininger, M. K., Brunner, J., Müller, T. and Songer, M. 2005. Forest cover change patterns in Myanmar (Burma) 1990-2000. *Environmental Conservation* 32:356-364.

[35] Kalacska, M., Sánchez-Azofeifa, G. A., Rivard, B., Caelli, T., White, H. P. and Calvo-Alvarado, J. C. 2007. Ecological fingerprinting of ecosystem succession: Estimating secondary tropical dry forest structure and diversity using imaging spectroscopy. *Remote Sensing of Environment* 108:82-96.

[36] Castillo, M., Rivard, B., Sánchez-Azofeifa, G.A., Calvo-Alvarado, J. and Dubayah, R. 2012. LIDAR remote sensing for secondary Tropical Dry Forest identification. *Remote Sensing of Environment* 121:132-143.

[37] Leimgruber, P., Delion, M. and Songer, M. 2011. The uncertainty in mapping seasonally dry tropical forests in Asia. In: *The ecology and conservation of seasonally dry forests in Asia*. McShea, W. J., Davis, S. J. and Bhumpakphan, N. (Eds), pp. 59-74. Washington DC: Smithsonian Institution Scholarly Press.

[38] Portillo-Quintero, C. A. and Sánchez-Azofeifa, G. A. 2010. Extent and conservation of tropical dry forests in the Americas. *Biological Conservation* 143:144-155.

[39] Kalacska, M., Sánchez-Azofeifa, G. A., Rivard, B., Calvo-Alvarado, J. C. and Quesada, M. 2008. Baseline assessment for environmental services payments from satellite imagery: A case study from Coasta Rica and Mexico. *Journal of Environmental Management* 88:348-359.

[40] Grainger, A. 1999. Constraints on modelling the deforestation and degradation of tropical open woodlands. *Global Ecology and Biogeography* 8:179-190.

[41] Sánchez-Azofeifa, G. A., Castra, K. L., Rivard, B., Kalascka, M. R. and Harriss, R. C. 2003. Remote sensing research priorities in tropical dry forest environments. *Biotropica* 35:134-142.

[42] IMF. 2012. World Economic Outlook Database. https://www.imf.org/external/data.htm

[43] Olson, D. M., Dinerstein, E., Wikramanayake, E. D., Burgess, N. D., Powell, G. V. N., Underwood, E. C., D'amico, J. A., Itoua, I., Strand, H. E., Morrison, J. C., Loucks, C. J., Allnutt, T. F., Ricketts, T. H., Kura, Y., Lamoreux, J. F., Wettengel, W. W., Hedao, P. and Kassem, K. R. 2001. Terrestrial ecoregions of the world: A new map of life on earth. *BioScience* 51:933-938.

[44] Lau, K. M. and Yang, S. 1997. Climatology and interannual variability of the southeast asian summer monsoon. *Advances in Atmospheric Sciences* 14:141-162.

[45] Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P. G. & Jarvis, A. 2005. Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology* 25:1965-1978.

[46] McShea, W. J., Koy, K., Clements, T., Johnson, A., Vongkhamheng, C. and Aung, M. 2005. Finding a needle in the haystack: Regional analysis of suitable Eld´s deer (*Cervus eldi*) forest in Southeast Asia. *Biological Conservation* 125:101-111.

[47] Sodhi, N. S. and Brook, B. W. 2008. Fragile Southeast Asian biotas. *Biological Conservation* 141:883-884.

[48] Sodhi, N., Posa, M., Lee, T., Bickford, D., Koh, L. and Brook, B. 2010. The state and conservation of Southeast Asian biodiversity. *Biodiversity and Conservation* 19:317-328.

[49] Taubenböck, H., Esch, T., Felbier, A., Wiesner, M., Roth, A. and Dech, S. 2012. Monitoring urbanization in mega cities from space. *Remote Sensing of Environment* 117:162-176.

[50] Koh, L. P., Kettle, C. J., Sheil, D., Lee, T. M., Giam, X., Gibson, L. and Clements, G. R. 2013. Biodiversity state and trends in Southeast Asia. In: *Encyclopedia of biodiversity*. Levin, S. A. (Ed), pp. 509-527. Amsterdam: Elsevier Academic Press.

[51] Huete, A., Didan, K., Miura, T., Rodriguez, E. P., Gao, X. and Ferreira, L. G. 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment* 83:195-213.

[52] Pettorelli, N., Ryan, S., Mueller, T., Bunnefeld, N., Jedrzejewska, B., Lima, M. and Kausrud, K. 2011. The Normalized Difference Vegetation Index (NDVI): unforeseen successes in animal ecology. *Climate Research* 46:15-27.

[53] Carroll, M. L., DiMiceli, C. M., Sohlberg, R. A. and Townshend, J. R. G. 2004. MODIS Normalized Difference Vegetation Index, 250ndvi28920033435, Collection 4.

[54] Bartholomé, E. and Belward, A. S. 2005. GLC2000: a new approach to global land cover mapping from Earth observation data. *International Journal of Remote Sensing* 26:1959-1977.
[55] Bicheron, P., Defourney, P., Brockmann, C., Schouten, L., Vancutsem, C., Huc, M., Bontemps, S., Leroy, M., Achard, F., Herold, M., Ranera, F. and Arino, O. 2010. GLOBCOVER - Products Description and Validation Report.
[56] Friedl, M. A., Sulla-Menashe, D., Tan, B., Schneider, A., Ramankutty, N., Sibley, A. and Huang, X. 2010. MODIS Collection 5 global land cover: Algorithm refinements and characterization of new datasets. *Remote Sensing of Environment* 114:168-182.
[57] Miles, L., Newton, A. C., DeFries, R. S., Ravilious, C., May, I., Blyth, S., Kapos, V. and Gordon, J. E. 2006. A global overview of the conservation status of tropical dry forests. *Journal of Biogeography* 33:491-505.
[58] Jönsson, P. and Eklundh, L. 2002. Seasonality extraction by function fitting to time-series of satellite sensor data. *IEEE Transactions on Geoscience and Remote Sensing* 40:1824-1832.
[59] Jönsson, P. and Eklundh, L. 2004. TIMESAT – a program for analyzing time-series of satellite sensor data. *Computers & Geosciences* 40:1824-1832.
[60] Gislason, P. O., Benediktsson, J. A. and Sveinsson, J. R. 2006. Random Forests for land cover classification. *Pattern Recognition Letters* 27:294-300.
[61] Chan, J. C.-W. and Paelinckx, D. 2008. Evaluation of Random Forest and Adaboost tree-based ensemble classification and spectral band selection for ecotope mapping using airborne hyperspectral imagery. *Remote Sensing of Environment* 112:2999-3011.
[62] Clark, M. L., Aide, T. M., Grau, H. R. and Riner, G. 2010. A scalable approach to mapping annual land cover at 250 m using MODIS time series data: A case study in the Dry Chaco ecoregion of South America. *Remote Sensing of Environment* 114:2816-2832.
[63] Liaw, A. and Wiener, M. 2002. Classification and regression by randomForest. R News 2, 18–22.
[64] Breiman, L. 2001. Random Forests. *Machine Learning* 45:5-32.
[65] R Development Core Team 2012. A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna.
[66] Bivand, R., Keitt, T. and Rowlingson, B. 2012. rgdal: Bindings for the geospatial data abstraction library. R package version 0.7-22.
[67] Wickham, H. 2009. ggplot2: elegant graphics for data analysis.
[68] Quantum GIS Development Team 2009. Quantum GIS Geographic Information System. Open Source Geospatial Foundation.
[69] GRASS Development Team 2011. Geographic Resources Analysis Support System (GRASS GIS) Software. Open Source Geospatial Foundation.
[70] FAO and JRY. 2012. Global forest land-use change 1990-2005. FAO Forestry Paper No. 169.
[71] Laurance, W. F. 2007. Forest destruction in tropical Asia. *Current Science* 93, 1544-1550.
[72] Leimgruber, P., Gagnon, J. B., Wemmer, C., Kelly, D. S., Songer, M. and Selig, E. R. 2003. Fragmentation of Asia´s remaining wildlands: implications for Asian elephant conservation. *Animal Conservation* 6:347-359.
[73] Gray, T. N. E., Phan, C. and Long, B. 2010. Modelling species distribution at multiple spatial scales: gibbon habitat preferences in a fragmented landscape. *Animal Conservation* 13:324-332.
[74] Sodhi, N. S., Lee, T. M., Koh, L. P. and Brook, B. W. 2009. A Meta-Analysis of the Impact of Anthropogenic Forest Disturbance on Southeast Asia's Biotas. *Biotropica* 41:103-109.
[75] IUCN 2013. 2013 IUCN Red List of Threatened Species. Version 2013.2.
[76] Brook, B. W., Sodhi, N. S. and Ng, P. K. L. 2003. Catastrophic extinctions follow deforestation in Singapore. *Nature* 424:420-426.
[77] Rao, M., Htun, S., Platt, S., Tizard, R., Poole, C., Myint, T. and Watson, J. M. 2013. Biodiversity Conservation in a Changing Climate: A Review of Threats and Implications for Conservation Planning in Myanmar. *AMBIO* 42:789-804.

[78] FAO and JRC 2012. Global forest land-use change 1990-2005, by Lindquist, E. J., D'Annunzio, R., Gerrand, A., MacDicken, K., Archard, F., Beuchle, R., Brink, A., Mayaux, P., San-Miguel-Ayanz, J. and Stibig, H-J. FAO Forestry Paper No. 169. Food and Agricultural Organization of the United Nations and European Commission Joint Research Cenre. Rome: FAO

[79] Yan, G. Mu, X. and Liu, Y. 2012. Fractional vegetation cover. In: *Advanced Remote Sensing*. Liang, S., Li, X. and Wang, J. (Eds.), pp.415-466. Academic Press.

[80] Gaughan, A. E., Holdo, R. M. and Anderson, T. M. 2013. Using short-term MODIS time-series to quantify tree cover in a highly heterogeneous African savanna. *International Journal of Remote Sensing* 34:6865-6882.

[81] Gessner, U., Machwitz, M., Conrad, C. and Dech, S. 2013. Estimating the fractional cover of growth forms and bare surface in savannas. A multi-resolution approach based on regression tree ensembles. *Remote Sensing of Environment* 129:90-102.

[82] Heiskanen, J. and Kivinen, S. 2008. Assessment of multispectral, -temporal and –angular MODIS data for tree cover mapping in the tundra-taiga transition zone. *Remote Sensing of Environment* 112:2367-2380.

[83] Clark, M. L., Aide, T. M., Grau, H. R. and Riner, G. 2010. A scalable approach to mapping annual land cover at 250 m using MODIS time series data: A case study in the Dry Chaco ecoregion of South America. *Remote Sensing of Environment* 114:2816-2832.

[84] Fernandes, R., Fraser, R., Latifovic, R., Cihlar, J., Beaubien, J. and Du, Y. 2004. Approaches to fractional land cover and continuous field mapping: A comparative assessment over the BOREAS study region. *Remote Sensing of Environment* 89:234-251.

[85] DeFries, R. S., Hansen, M. C. and Townshend, J. R. G. 2000. Global continuous fields of vegetation characteristics: A linear mixture model applied to multi-year 8 km AVHRR data. *International Journal of Remote Sensing* 21:1389-1414.

[86] Hansen, M. C., DeFries, R. S., Townshend, J. R. G., Sohlberg, R., Dimicelli, C. and Carroll, M. 2002. Towards an operational MODIS continuous field of percent tree cover algorithm: examples using AVHRR and MODIS data. *Remote Sensing of Environment* 83:303-319.

[87] Hansen, M. C. and DeFries, R. S. 2004. Detecting long-term global forest change using continuous fields of tree-cover maps from 8-km Advanced Very High Resolution Radiometer (AVHRR) data for the years 1982-99. *Ecosystems* 7:695-716.

[88] Fritz, S., See, L., McCallum, I., Schill, C., Obersteiner, M., Van der Velde, M., Boettcher, H., Havlik, P. and Achard, F. 2011. Highlighting continued uncertainty in global land cover maps for the user community. *Environmental Research Letters* 6, 44005.

[89] Giri, C., Zhu, Z. and Reed, B. 2005. A comparative analysis of the Global Land Cover 2000 and MODIS land cover data sets. *Remote Sensing of Environment* 94:123-132.

[90] McCallum, I., Obersteiner, M., Nilsson, S. and Shvidenko, A. 2006. A spatial comparison of four satellite derived 1km global land cover datasets. *International Journal of Applied Earth Observation and Geoinformation* 8:246-255.