CHAPTER THREE

Monitoring tropical forest degradation and restoration with satellite remote sensing: A test using Sabah Biodiversity Experiment

Jinhui Wu^{a,b,*}, Bin Chen^d, Glen Reynolds^e, Jun Xie^f, Shunlin Liang^c, Michael J. O'Brien^{e,g}, Andrew Hector^{b,*}

^aState Key Laboratory of Remote Sensing Science, Faculty of Geographical Science, Beijing Normal University, Beijing, China

^bDepartment of Plant Sciences, University of Oxford, Oxford, United Kingdom

^cDepartment of Geographical Sciences, University of Maryland College Park, College Park, MD, United States ^dDepartment of Land, Air and Water Resources, University of California, Davis, CA, United States

^eSoutheast Asia Rainforest Research Partnership (SEARRP), Kota Kinabalu, Malaysia

^fSchool of Environmental Sciences, University of Hull, Hull, United Kingdom

^gÁrea de Biodiversidad y Conservación, Universidad Rey Juan Carlos, Móstoles, Spain

*Corresponding authors: e-mail address: jwu@mail.bnu.edu.cn; andrew.hector@plants.ox.ac.uk

Contents

1.	. Introduction					
2.	Methodology	121				
	2.1 Location	121				
	2.2 Remote sensing data	123				
	2.3 Methods	125				
3.	Results					
	3.1 Effects of relogging on vegetation canopy attributes	127				
	3.2 Effects of enrichment planting on vegetation canopy attributes	130				
	3.3 Effects of planted tree diversity on vegetation canopy attributes	131				
	3.4 Effects of enhanced climber cutting on vegetation canopy attributes	133				
4.	Discussion					
	4.1 Impacts of selective logging	134				
	4.2 The effects of enrichment planting	135				
	4.3 The potential value of diversification of enrichment planting schemes	136				
	4.4 The consequences of liana removal	137				
	4.5 Limitations and future research	137				
5.	Conclusion	138				
Glo	Glossary					
Ac	Acknowledgements					
Re	References					

Abstract

Selective logging has been so extensive that harvested forest now exceeds unlogged areas in most tropical forest regions outside of the Amazon. In response, in Southeast Asia, enrichment planting with dipterocarp tree species is carried out in an attempt to accelerate restoration of forest structure and functioning. However, assessing the impacts of degradation (from selective logging and other causes) and subsequent restoration with field measurements is expensive and time-consuming. There is therefore a need to develop methods for the assessment of forest quality using remote sensing. Here, we use high spatial resolution satellite imagery and advanced remote sensing products to monitor the pattern and dynamics of estimated vegetation cover, Leaf Area Index (LAI), and the biomass of plots within a field-scale (500 ha) replicated and randomized manipulation that compares different forest restoration treatments with naturally regenerating controls within the Sabah Biodiversity Experiment (SBE). We also compare the biodiversity experiment plots with the surrounding area of the Malua Forest Reserve that was selectively logged for the second time in 2007. In general, satellite remote sensing detected differences in degradation between the once- and twice-logged areas as well as between the different experimental restoration treatments. We found that approximately 70% of the Malua Forest Reserve experienced a decrease of vegetation cover after the selective relogging in 2007, while the Sabah Biodiversity Experiment area that was not relogged showed increasing vegetation cover. Within the experiment, we found that plots restored using Enrichment line planting, had higher remote sensed vegetation cover (Mean \pm SE: 66.90 \pm 0.06 vs. 61.96 \pm 0. 16) and LAI (Mean \pm SE: 5.09 \pm 0.03 vs. 4.61 \pm 0.11) than that of unenriched plots. Among the enrichment planted plots, those planted with mixtures of (4 or 16) species exhibited higher vegetation cover (Mean \pm SE: 67.72 \pm 0.06 vs. 65.35 \pm 0.09) and LAI (Mean \pm SE: 5.29 ± 0.04 vs. 4.82 ± 0.06) than that of monoculture plots. Overall, when our test case of the Sabah Biodiversity Experiment was viewed through the lens of remote sensing indicators, satellite imagery was able to detect changes in forest quality due to selective logging and restoration enrichment planting. Furthermore, our results suggest that diverse mixtures of planted tree seedlings enhance restoration of forest canopies compared to planting with single species. Confirmation with ground data will be needed to validate these results and to better understand the biological processes determining tropical forest degradation and restoration.

1. Introduction

In most zones of tropical forest outside of the Amazon, the area that has been selectively logged now exceeds the area of old growth affecting their diversity, functioning and stability (Alvarado and Sandberg, 2001; Asner et al., 2004b; Laporte et al., 2007; Nepstad et al., 1999; Tuck et al., 2016) and sometimes predisposing them to conversion to other land uses such as oil palm plantation. In southeast Asia, enrichment planting with dipterocarp tree species is carried out to accelerate restoration of forest structure and functioning (Millet et al., 2013; Tigabu et al., 2010). Enrichment planting is practiced in a number of forms but the basic idea is to increase establishment and recovery of forests by planting seedlings of the timber tree species that have been selectively logged out (Hector, 2011). However, assessing the impacts of degradation on forest quality (from selective logging and other causes) and on the efficacy of restoration is expensive and timeconsuming using field measurements. There is therefore a need to develop complementary methods for the assessment of forest quality using remote sensing data that can be applied at larger spatial scales relevant to management and conservation.

Remote sensing has proven useful in large-scale vegetation monitoring because it enables consistent observations of vegetation across time and space (Chen et al., 2019; Liang, 2004; Liang et al., 2018; Turner, 2014; Zhu et al., 2016). Many studies have used remote sensing data to assess the impacts of logging on forest dynamics (Foody and Cutler, 2003; Matricardi et al., 2010; Perez et al., 2016; Rocchini et al., 2007; Turner, 2014; Turner et al., 2003). These previous studies have contributed to substantial improvement in remote sensing-based techniques to assess various aspects of forest diversity and structure and the ecosystem functions and services that they support. However, significant gaps exist in attempts to better link field ecology and remote sensing. Firstly, coupling remote sensing data and in-situ ecological field data is challenging, since the scale of the data from remote sensing and field ecology can differ substantially (Chambers et al., 2007; Kerr and Ostrovsky, 2003; Muraoka and Koizumi, 2009; Turner, 2014) with the spatial resolution of remote sensing data typically much coarser than that of data from measurements taken in the field. Secondly, in tropical regions, the obscuring effects of cloud cover are serious which leads to a large uncertainty of remote sensing data (de Souza et al., 2010; Gao and Li, 2000; Ju and Roy, 2008; Liou, 1992; Simpson et al., 2000; Xu et al., 2016). In recent years, with the progress that has been made on satellite technology and remote sensing inversion models, a number of high-quality and longterm quantitative remote sensing products (e.g. Leaf Area Index (LAI), Fraction of Absorbed Photosynthetically Active Radiation (FAPAR), Gross Primary Productivity (GPP) and Land Cover) have been developed to monitor the distribution and variation of terrestrial vegetation

(Claverie et al., 2016; Friedl et al., 2002; Liang, 2004; Liang et al., 2012; Myneni et al., 2002; Running et al., 2000; Xiao et al., 2016; Yuan et al., 2010; Zhu et al., 2013). In addition, some of these quantitative remote sensing products exhibit very high spatial resolution (Chen et al., 2015; Feng et al., 2016; Hansen et al., 2013; Liang et al., 2013; Sexton et al., 2013b; Song et al., 2016). This progress provides a great opportunity for comprehensively assessing the impacts of both degradation and restoration on forest quality which we do here using the Sabah Biodiversity Experiment as a test case.

The Sabah Biodiversity Experiment (SBE) covers 500 ha of Malua Forest Reserve, an area of selectively logged forest bordering primary forest located in the Malaysian state of Sabah, Borneo (Hector et al., 2011). Malua Forest Reserve was selectively logged in the early 1980s and again in the mid-2000s, although the 500 ha areas of the Sabah Biodiversity Experiment site was excluded from the second round of selective logging (in 2007) (Saner et al., 2012). We can therefore examine differences between the treatment plots within the experiment and compare the Sabah Biodiversity Experiment as a whole with the surrounding relogged forest in the rest of Malua Forest Reserve. Sabah Biodiversity Experiment, manipulates the identity, composition and diversity of enrichment planted dipterocarps to assess their impacts on the functioning and stability of selectively logged rainforests during restoration and compare them with those of unrestored plots within the same design (Tuck et al., 2016). The experiment contains 124 four-hectare $(200 \times 200 \text{ m})$ plots which include five different treatment groups that we compare here, namely unplanted plots, monoculture plots, 4-species mixture plots, 16-species mixture plots, and 16-species mixtures plots with enhanced climber cutting. Sabah Biodiversity Experiment is also part of a global network of tree diversity experiments and is one of only two representatives in the palaeo-tropics.

In this study, we use high spatial resolution satellite imagery and advanced remote sensing products to assess degradation of the once-logged area of the biodiversity experiment with the twice-logged area of the surrounding Malua Forest Reserve and to compare different forest restoration treatments within the Sabah Biodiversity Experiment (SBE). Specifically, we use Sabah Biodiversity Experiment as a test case to assess what differences in vegetation canopy attributes satellite remote sensing can detect between:

- (1) The areas of Malua forest reserve that was relogged in 2007 vs. the Sabah Biodiversity Experiment site that was not relogged.
- (2) The unplanted vs. enrichment planted plots within Sabah Biodiversity Experiment 15 years after the start of planting.

- (3) Sabah Biodiversity Experiment plots that have been enrichment planted with seedling mixtures of different diversity.
- (4) Sabah Biodiversity Experiment plots that have had lianas removed (enhanced climber cutting) vs. matched plots subject to standard Enrichment line planting with the same mixtures of 16 dipterocarp seedlings.

2. Methodology

2.1 Location

The Sabah Biodiversity Experiment is located in the southern part of the Malua Forest Reserve (Fig. 1). The Sabah Biodiversity Experiment covers 500 ha of the 35,000 ha Malua Forest Reserve. The climate is typical wet tropical with an average temperature of 27 °C and an annual rainfall of >3000 mm, distributed over two distinct wet seasons (Lussetti et al., 2016; Marsh and Greer, 1992; Saner, 2009). Malua Forest Reserve was logged in the 1980s and relogged in 2007, while the Sabah Biodiversity Experiment was excluded from the second round of logging since this area had been protected since the establishment of the experiment in 2002.

The experiment contains 124 four-hectare $(200 \times 200 \text{ m})$ plots, split between two blocks that are north and south of an old logging road. There are 64 plots in the south block and 60 plots in the north block. The experiment manipulates the identity, composition and diversity of the enrichment planted dipterocarp seedlings and forest management technique of liana removal (enhanced climber cutting). Ninety-six of these plots form a gradient in the diversity of enrichment planted seedlings with four levels: 1, 4, 16 enrichment planted species and 16 enrichment planted species with liana removal. The remaining plots are comprised of 12 unenriched naturally regenerating controls, and an additional 16 plots enrichment planted with the 16-species mixtures and subject to 2 rounds of liana removal (O'Brien et al., 2019). In this enhanced climber cutting treatment, climbers are cut throughout the whole plot, which is expected to improve recovery time during restoration. The design also manipulates the composition of the enrichment planted seedlings with, at the 2 extremes, 16 different single-species treatments vs. a single 'full mixture' of all 16 species combined (Table S1 in the online version at https://doi.org/10.1016/bs. aecr.2020.01.005). At the intermediate diversity level, species compositions within the 4-species mixtures provide a gradient of generic richness and are designed to produce a range of canopy structures once the planted seedlings



Fig. 1 Location of the Malua Forest Reserve (top) and Sabah Biodiversity Experiment with details of the Enrichment line planting.

mature but these treatments are not addressed further here. Each planted species richness level has 32 plots: the 1- and 4-species richness levels contain 16 different compositions, each replicated twice, plus 32 replicates of the 16-species mixture, all balanced equally across the 2 blocks.

Following standard enrichment planting practice, the initial cohort of seedlings (cohort 1 planted January 2002–September 2003) were

supplemented with a second cohort (cohort 2 planted September 2008– August 2011) that replaced initial mortality. Since establishment, the plots (sometimes all of them, sometimes only a subset) have been periodically surveyed. Further details of Sabah Biodiversity Experiment and Malua Forest Reserve can be found in previous publications (Hector et al., 2011; Saner et al., 2012; Tuck et al., 2016).

2.2 Remote sensing data

Landsat Vegetation Continuous Fields tree cover, MODIS MCD15A3H Leaf Area Index (LAI), Estimated Deforested Area Biomass, and RapidEye image were selected to monitor the vegetation canopy structure in this study based on considerations of data accuracy, the area of study zone and the time period of the experiment (Table 1).

2.2.1 Landsat vegetation continuous fields tree cover

The Landsat Vegetation Continuous Fields tree cover (Landsat tree cover) layers contain estimates of the percentage of horizontal ground in each 30 m pixel covered by vegetation greater than 5 m in height globally (Sexton et al., 2013a). In this study, we rename the Landsat tree cover as Landsat vegetation cover, since in Sabah, tropical rainforest, almost all plants Landsat can detect are higher than 5 m. The product is derived from all seven bands of Landsat-5 Thematic Mapper (TM) and/or Landsat Enhanced Thematic Mapper Plus (ETM+). The spatial resolution of Landsat tree cover dataset is 30 m, which is suitable for comparing the vegetation canopy structure among different kinds of the 200-by-200 m plots within Sabah

Data	Spatial resolution	Temporal resolution	Time cover
Landsat VCF vegetation cover	30 m	5-year	2000, 2005, 2010
MODIS MCD15A3H LAI	500 m	4-day	2001-2017
Estimated deforested area aboveground biomass	30 m	12-year	2000–2012
RapidEye-based vegetation cover	5 m	/	Aug. 2012
RapidEye-based leaf area index (LAI)	5 m	/	Aug. 2012
RapidEye-based aboveground biomass	5 m	/	Aug. 2012

Table '	1	Remote	sensina	datasets.
Tuble	•	nemote	Jenjing	autusets.

Biodiversity Experiment. To date, this dataset has four epochs—2000, 2005, 2010, and 2015—each of which is a composite of several years. For example, vegetation cover 2005 shows the average condition of tree cover from 2003 to 2008, because vegetation cover 2005 was calculated from satellite images which are collected from 2003 to 2008 (Gutman et al., 2008, 2013), while vegetation cover 2000 shows the average vegetation cover from 1999 to 2002 and vegetation cover 2010 shows the average vegetation cover from 2008 to 2012. To avoid confusion it is important to point out that in this study we use vegetation cover 2005 to monitor the vegetation cover of study zone after the 2007 logging, since the input satellite images of vegetation cover for the 2005 epoch in Sabah were mostly collected from 2008. Vegetation cover for the 2000, 2005 and 2010 epochs were therefore selected for this study.

2.2.2 MODIS MCD15A3H LAI

Leaf Area Index (LAI: one-sided green leaf area per unit ground area) is an important vegetation biophysical variable (Bréda, 2003; Watson, 1947; Xiao et al., 2014, 2016). MODIS MCD15A3H LAI has been widely used in forest monitoring, which exhibits very high accuracy (Brede et al., 2018; Li et al., 2018; Miller et al., 2019; Ranga Myneni and Yuri, 2015). The temporal range of this dataset is from 2003 to 2017 and the temporal resolution of MCD15A3H LAI is 4-day. The spatial resolution of MCD15A3H LAI is 500 m, which although larger than the 200 m plots could be used to compare the vegetation canopy structure between the selectively relogged area (Malua Forest Reserve) and the area protected from the 2007 relogging (the 500 ha area of Sabah Biodiversity Experiment as a whole). In the process of LAI calculation, the cloud contamination of albedo, one of the main input data for LAI calculation has been effectively removed. In addition, this dataset provides a layer of quality control (QC), which contains the cloud state pixel-by-pixel. That is very important for removing cloud effect, one of the serious effects in tropical area (Myneni et al., 2015). In this study, the maximum value composite (MVC) procedure was took to generate monthly LAI from 4-day LAI. By doing so, cloud contamination, shadow effects, aerosol and water vapour effects can be minimized (Knyazikhin, 1999). The yearly LAI was generated by averaging the monthly LAI.

2.2.3 Estimated deforested area biomass

This dataset provides estimates of aboveground biomass (AGB) loss from 2000 to 2012 at 30 m resolution (Baccini et al., 2016). The biomass estimates

are only for areas where deforestation occurred during the period 2000–2012. Estimates are derived using in-situ measurements and a RandomForest statistical model which correlated Geoscience Laser Altimeter System (GLAS) LiDAR data, Landsat 7 Enhanced Thematic Plus (ETM+) satellite imagery, reflectance, elevation, and biophysical variables. A separate RandomForest model is trained for each continent using a stratified sampling design of roughly 13,000 GLAS-based biomass estimates for each model. This dataset was selected to measure the biomass loss in Sabah Biodiversity Experiment and Malua Forest Reserve.

2.2.4 RapidEye image

In this study, the RapidEye satellite image of the Sabah Biodiversity Experiment site was acquired in August 2012. RapidEye satellite images exhibit a temporal resolution of 5.5 days and a high-resolution of 5 m (Jung-Rothenhäusler et al., 2007; Tyc et al., 2005). RapidEye's high spatial resolution provides a chance to monitor the forest canopy structure among different plots in a detailed way. The multi-spectral scanner on the satellites acquires data in five spectral bands. The blue $(0.44-0.51 \,\mu\text{m})$, green $(0.52-0.59 \,\mu\text{m})$, red $(0.63-0.68 \,\mu\text{m})$ and near-infrared $(0.76-0.85 \,\mu\text{m})$ bands are very similar to the corresponding Landsat spectral bands, while the sensor has an additional red-edge band $(0.69-0.73 \,\mu\text{m})$, giving additional sensitivity to changes in the reflectance of vegetation (Chander et al., 2013; Pfeifer et al., 2016).

2.3 Methods

A group of satellite imagery and remote sensing products were pre-processed (calibration, clip, cloud and cloud shadowing-masking) using ArcGIS and ENVI.

2.3.1 Vegetation metrics inversion from RapidEye image

We applied atmospheric correction to the RapidEye image using the FLAASH atmospheric correction model. The vegetation cover, Leaf Area Index (LAI), and aboveground biomass (AGB) were calculated from the empirical formulas which were developed in Pfeifer et al. (2016). In the development of these empirical formulas, the in-situ data used for model fitting were collected from tropical rainforest in Sabah, Borneo near to our site, and the remote sensing data they used were RapidEye images. Thus, we replicated the inversion method to calculate the vegetation cover, LAI, and biomass. These inversed metrics exhibited high accuracy, since the

accuracy had been validated. In addition, vegetation cover, Leaf Area Index, and biomass data exhibit very high spatial resolution since the spatial resolution of RapidEye images is 5 m. Further details of the inversion method and accuracy assessment can be found in the previous publication (Pfeifer et al., 2016).

Vegetation cover =
$$2.66 - 0.66$$
*Red + 0.3 *RedEdge - 0.08 *NearIR
+ 1.48 *DissB4 - 0.42 *DissB5 - 0.17 *DissB3 (1)
LAI = $0.9 - 0.59$ *Red + 0.41 *RedEdge - 0.11 *NearIR

$$-0.53*\text{DissB3} + 1.08*\text{DissB4} - 0.36*\text{DissB5}$$
(2)

$$Biomass = 19.45 - \exp(MSAVI2) - 2.39*Green + 1.08*RedEdge + 2.65*DissB2 - 0.28*DissB3 - 0.13*DissB5 + 0.09*DissB4$$
(3)

where Vegetation cover is the RapidEye-based vegetation cover, LAI is the RapidEye-based Leaf Area Index, Biomass is the RapidEye-based biomass, MSAVI2 is the Modified Soil-Adjusted Vegetation Index 2 (Qi et al., 1994), Green is the green band of RapidEye image, Red is the red band of RapidEye image, NearIR is the near-infrared band of RapidEye image, RedEdge is the red-edge band of RapidEye image, DissB2, DissB3, DissB4, and DissB5 are grey-level dissimilarities of green band, red band, near-infrared band, and red-edge band, respectively (Gallardo-Cruz et al., 2012).

2.3.2 Statistical analysis

Our focus for the analysis of the satellite indicators of vegetation cover, Leaf Area Index (LAI), and biomass was on the estimation of means and variabilities, so we derived pixel-level estimates with standard errors (mean \pm SE), for each of the key questions of interest listed at the end of the introduction: unenriched plots vs. enriched plots; monoculture plots vs. mixture plots; 4-species mixture plots vs. 16-species mixture; and, 16-species mixture with climber cutting vs. 16-species mixture without climber cutting. We focus on graphical presentation of means and confidence intervals where degree of (non-)overlap can be used to judge statistical significance (e.g. means with 95% CIs that are at the point of overlap are significantly different at P < 0.01 approximately). Assessing the effects of the 2007 relogging by comparing the Sabah Biodiversity Experiment with the surrounding Malua Forest Reserve is complicated by the difference in size of the two areas. We addressed this in two ways. First, we randomly selected 100 samples in Malua Forest Reserve with the same 500-ha area as Sabah Biodiversity Experiment and calculated the mean and standard error of vegetation cover and LAI of these as a representative sample of the whole area. However, the intensity of the 2007 relogging varied across the Malua Forest Reserve so we also selected 10 samples (of the same area as the biodiversity experiment) in the most heavily logged area of Malua Forest Reserve as a representative sample of the most heavily relogged areas (worst case scenario).

3. Results

In our study, we first divided the Malua Forest Reserve into two parts to compare the once-logged (1984–86) 500-ha area of Sabah Biodiversity Experiment, with the remaining surrounding area of the Malua Forest Reserve that was relogged in 2007 before comparing different treatments within the biodiversity experiment design.

3.1 Effects of relogging on vegetation canopy attributes

After the 2007 relogging the vegetation cover of the Malua Forest Reserve declined by 3% on average and by 7% in its most severely logged parts, while the vegetation cover of Sabah Biodiversity Experiment that was protected from the relogging exhibited a 5% increase (Fig. 2).

Although the change of mean vegetation cover was not large in Malua Forest Reserve, the proportion of the area affected was high. To examine the spatial variability in relogging intensity we divided Malua Forest Reserve into six parts: 56.96% (19,936 ha) of the area of Malua Forest Reserve showed 0–9% decrease of vegetation cover, 3.99% (1396.5 ha) of the area of the reserve showed 9–18% decrease of vegetation cover, and 1.54% (539 ha) of the area of the reserve showed over 18% decrease of vegetation cover. 36.18% (12,633 ha), 0.94% (329 ha), and 0.39% (136.5 ha) of the reserve showed 0–9%, 9–18%, and over 18% increase of vegetation cover (Fig. 3). After the 2007 relogging, there was a considerable decrease of vegetation cover in the centre of Malua Forest Reserve, while the 500 ha of the Sabah Biodiversity Experiment protected from the



Fig. 2 Landsat vegetation cover with 95% confidence intervals of Sabah Biodiversity Experiment and Malua Forest Reserve before, during and after the selective relogging in 2007 (values jittered to avoid overlap).

relogging mostly exhibited an increasing trend of vegetation cover. Among the areas of Malua Forest Reserve where vegetation cover increased, we found that some areas were caused by rivers drying up followed by vegetation regrowth which locally offset the decline in cover due to relogging. We cannot tell whether the drying up of small water courses was associated with the relogging or not.

The Leaf Area Index (LAI) of Sabah Biodiversity Experiment was higher than that of the surrounding Malua Forest Reserve, particularly its most heavily relogged areas (Fig. 4). The LAI of Sabah Biodiversity Experiment and Malua Forest Reserve remained relatively stable from 2004 to 2007. After the 2007 relogging, the LAI of Malua Forest Reserve exhibited a significant decrease (Fig. 4). In heavily logged areas, the LAI began to decrease earlier than whole Malua Forest Reserve, suggesting the most heavily relogged areas were those where the relogging started earliest and went on longest. The average LAI of Malua Forest Reserve reached its lowest levels in 2009 shortly after the relogging and then recovered. In comparison, the LAI of Sabah Biodiversity Experiment did not show significant fluctuation from 2007 to 2013 consistent with its protection from relogging. The LAI of both the Sabah Biodiversity Experiment



Fig. 3 Landsat vegetation cover of Sabah Biodiversity Experiment and Malua Forest Reserve with the change in cover after the selective relogging in 2007 (right).



Fig. 4 Variation of mean annual MODIS Leaf Area Index (LAI) with 95% Confidence Intervals (values jittered for clarity).

site and the rest of the surrounding Malua Forest Reserve showed significant increases from 2013 to 2015. The selective relogging in 2007 led to differences between Malua Forest Reserve and Sabah Biodiversity Experiment in both LAI (Fig. 4) and vegetation cover (Fig. 2), so that the two satellite remote sensing indicators agreed and provided a consistent picture of changes in forest quality.

The area with biomass loss was mainly in the middle part of Malua Forest Reserve. In total, we estimate that the Malua Forest Reserve lost approximate 2.7 million Mg of aboveground biomass from the 11,433 ha of deforested area during the period 2000 through 2012.

3.2 Effects of enrichment planting on vegetation canopy attributes

The Landsat vegetation cover showed that the unenriched plots exhibited lower vegetation cover and less change from 1999 to 2012 (Fig. 5). There were no consistent differences in the vegetation cover of planted and unplanted plots before the enrichment planting. After the enrichment planting in 2002/03, the unenriched plots exhibited $\sim 4\%$ higher vegetation cover than the unplanted plots, and this difference in vegetation cover then



Fig. 5 Landsat vegetation cover of different enrichment planting groups with 95% confidence intervals. Note that the first round of enrichment planting was only completed in 2003 and of climber cutting in 2011.



Fig. 6 RapidEye-based vegetation cover of different enrichment planting groups with 95% confidence intervals in August 2012.

increased over time. The value of RapidEye-based vegetation cover was lower than that of Landsat vegetation cover, and the RapidEye-based vegetation cover showed that the gap between enriched plots and unenriched plots was slightly larger than that in Landsat vegetation cover (Fig. 6). In both of these two datasets, the standard errors of vegetation cover in planted plots was relatively lower than that in unplanted plots (consistent with standard deviations). Moreover, the standard errors of vegetation cover in enrichment planted plots and unenriched plots did not change substantially during the period of 1999–2012.

For the RapidEye-based LAI, we found the enriched plots (N=110, two plots were excluded since the cloud cover) exhibited LAI values 0.48 units higher on average than that of unenriched plots (N=12) (Fig. 7). For RapidEye-based biomass, we found the same pattern as found with the LAI dataset (Fig. 8).

3.3 Effects of planted tree diversity on vegetation canopy attributes

After the enrichment planting was carried out, the vegetation cover of mixture plots became 2% higher than that of monoculture plots, and this difference in vegetation cover has persisted to the most recent



Fig. 7 RapidEye-based leaf area index (LAI) of different enrichment planting groups with 95% confidence intervals in August 2012.



Fig. 8 RapidEye-based biomass of different enrichment planting groups with 95% confidence intervals in August 2012.

measurements (Fig. 5). The RapidEye-based vegetation cover also showed that the vegetation cover of mixture plots was higher than that of monoculture plots (Fig. 6). Moreover, we found mixture plots exhibited differences of 0.47 LAI units and 2Mg/plot biomass higher than monoculture plots (Figs 7 and 8).

In the Landsat data, the vegetation cover of 16-species mixture plots became higher than that of 4-species mixture plots after the enrichment planting, a difference that became wider over time (Fig. 5). For the RapidEye-based vegetation cover, LAI, and biomass, the 16-species mixture plots also generally exhibit higher cover estimates (Figs 6–8).

3.4 Effects of enhanced climber cutting on vegetation canopy attributes

For the Landsat vegetation cover data, with the different enrichment planting strategies, the plots of 16-species mixtures with enhanced climber cutting exhibited similar vegetation cover to that of 16-species mixture plots without climber cutting (Fig. 5). The vegetation cover of the 16-species mixtures both with and without enhanced climber cutting exhibited a 6% increase from 1999 to 2012. For the RapidEye-based vegetation cover data, the plots of 16-species mixture with climber cutting exhibited lower vegetation cover than 16-species mixture plots without climber cutting, which was not consistent to the result we get from Landsat vegetation cover (Fig. 6). However, there was no clear effect of climber cutting on the RapidEye estimates of biomass and LAI (Figs 7 and 8). Overall, the effects of enhanced climber cutting were more mixed that those for enrichment planting – probably due to the inability to distinguish between tree cover and liana cover.

4. Discussion

In this study, we used Sabah Biodiversity Experiment as a test case to assess to what degree easily-accessible satellite remote sensing imagery could assess the effects of degradation and restoration on indicators of forest canopy quality. In general, our results confirm the ability of the satellite remote sensing to detect both the effects of forest degradation and of different restoration practices (although the ability of different satellite remote sensing products to distinguish the climber cutting treatments was inconsistent). In particular, our results suggest that enrichment planting enhances restoration and that diverse mixtures of tree seedlings are more effective than using single-species treatments.

4.1 Impacts of selective logging

Previous studies have assessed the process of forest degradation using a variety of remote sensing approaches to estimate the extent and impacts of selective logging on forest quality (Asner et al., 2002, 2004a, 2005; de Wasseige and Defourny, 2004; Matricardi et al., 2010; Souza Jr and Barreto, 2000). In this study, we used Sabah Biodiversity Experiment as a test case to assess to what degree easily available satellite remote sensing imagery could assess the effects of degradation and restoration on indicators of forest quality. We found the vegetation cover of the Malua Forest Reserve and its most heavily logged area exhibited 3% and 7% decreases, respectively, in the years after the 2007 relogging, while the vegetation cover of Sabah Biodiversity Experiment exhibited a 5% increase during the same period confirming that satellite remote sensing was able to distinguish between areas of selectively logged forest that had been subjected to a second round of selective logging or not. Although these numerical differences between Malua Forest Reserve and Sabah Biodiversity Experiment are consistent with what we would expect following relogging (or not) we raise a note of caution-because visible light does not penetrate leaves (Rees, 2013) optical remote sensing data may underestimate effects of selective logging on the multilayered structure of tropical forests. Furthermore, with selective logging, it is typically only the larger, highly valuable trees that are removed from the forest (Asner et al., 2004a, 2005; Edwards et al., 2014; Lambert, 1992; Laporte et al., 2007; Verissimo et al., 1995) and the indicators of canopy cover and related variables used in our study may be reduced less than other properties that the satellite data available to us could not address as well-stocks of carbon for example. It is known that in tropical rainforests, selective logging can result in smaller changes in cover than clear-cut logging because the logged areas remain covered by leaves of surrounding trees when the harvested trees are removed (Gatti et al., 2015; Souza Jr et al., 2005; Thiollay, 1992). Thus, in this study, the effects of selective logging detected using the 30-by-30 m and 500-by-500 m resolution remote sensing data reflects only the places where no trees are found around or under the selectively logged trees. While the vegetation cover and LAI data in this study generally give consistent results it

is important to note that these measures are only expected to agree under limited circumstances. For example, if an area of forest were (hypothetically) covered by a single layer of leaves it would have a vegetation cover of 100% and an LAI of one. However, tropical forests are often characterized by tall, multilayered canopies meaning that LAI can range up to several LAI units while vegetation cover reaches its maximum at 100%.

We estimate that Malua Forest Reserve lost approximately 2.7 million Mg of biomass from the 11,433 ha deforested area from 2000 to 2012 due to the relogging in 2007, while the Sabah Biodiversity Experiment lost none during the same period (as expected since it was protected from the relogging). This loss of biomass through selective logging is qualitatively consistent with the result from field estimates (although at the higher end of previous estimates), which found that the initial selective logging in the 1980s decreased the dipterocarp stock of the Sabah Biodiversity Experiment by 55–66% in Malua Forest Reserve compared to the old growth forest in nearby Danum Valley conservation area even 22 years after logging (Saner et al., 2012).

The differences in tree cover and LAI after the relogging become smaller within a few years, presumably due to growth of unlogged vegetation and new recruits (dipterocarps do not re-sprout from the stump when cut). This is consistent with previous studies that have found rapid recovery of canopy cover estimates in some tropical rainforests, where, for example, half of the logging trails could no longer be seen from satellite remote sensing data about 5 years after the logging activities because of a decrease in the spectral difference between the forest and the trails (de Wasseige and Defourny, 2004; Gatti et al., 2015). Overall, while our remote sensing analysis was able to distinguish canopy characteristics of the area of Malua Forest Reserve that had been relogged from the areas that had not, the approach may underestimate effects of selective logging on other aspects of forest quality (e.g. carbon stocks).

4.2 The effects of enrichment planting

Enrichment planting is intended to increase seedling establishment and recovery of forests by planting seedlings of the timber tree species that have been selectively logged. Enrichment planting is generally done in poorly-stocked areas of logged-over forests and associated degraded area (abandoned logging roads and log-yards, abandoned shifting cultivation area, etc.) (Chan et al., 2008). A total of 25,857 ha of forest plantation had been

created using enrichment planting techniques in peninsular Malaysia (Safa et al., 2004). Previous field studies have found that enrichment planting improved the soil biological status where biomass C and N content were significantly higher than in unenriched areas (Karam et al., 2012). However, few studies have used remote sensing data to assess the effects of enrichment planting. In this study, we found enrichment planting improved vegetation canopy attributes where the vegetation cover, LAI, and biomass were higher than unenriched forest, and the difference in vegetation cover increased over time. This is probably the first regional-scale study utilizing satellite observations to quantify the effects of enrichment planting in Sabah, Malaysia.

4.3 The potential value of diversification of enrichment planting schemes

Most enrichment planting restores areas with single-species planting or lowdiversity mixtures. However, the demonstration of a general positive relationship between biodiversity and ecosystem functioning raises the potential value of diversifying enrichment planting (Cardinale et al., 2006, 2007, 2011; César et al., 2016; Duffy, 2009; Forshed et al., 2008; Gravel et al., 2011; Hector, 2009; Hector et al., 2010; Hector and Bagchi, 2007; Hector and Hooper, 2002; Lussetti et al., 2016; Schnitzer et al., 2004; Yachi and Loreau, 1999). In this study, we found that multi-species mixtures exhibited higher vegetation cover, LAI, and biomass than that of monoculture plots. In addition, the LAI of multi-species mixture plots increased more rapidly over time than that of monocultures. That could be because an ecosystem with a high species richness functions more effectively in terms of resource capture and cycling, and higher levels of productivity (Huang et al., 2018; Liang et al., 2016). Indeed, our results provide some support for higher vegetation cover, LAI and biomass values of 16-species mixture plots, compared with 4-species mixture plots (although the degree of differences varied with response variable and source of remote sensing data—see figures).

The assessment of changes in vegetation canopy attributes also depends on the resolution of the remote sensing data (Benediktsson et al., 2012). We found 5 m resolution remote sensing data provided more three-dimensional structure information of LAI, compared with 30 m or 500 m resolution data. For example, the 5 m resolution RapidEye-based metrics, produced a larger difference in LAI between mixture and monoculture plots than the smaller difference in vegetation cover from the coarser resolution data.

4.4 The consequences of liana removal

Some studies have found that climber cutting can speed-up restoration of selectively logged forests (César et al., 2016; Forshed et al., 2008; Lussetti et al., 2016; Schnitzer et al., 2004). In this study, there was some inconsistency between the different remote sensing data: the Landsat vegetation cover and RapidEye-based vegetation cover showed inconsistent and sometimes opposing results about the effects of climber cutting. This is probably because Landsat vegetation cover 2010 shows the vegetation cover average condition from 2008 to 2012, while the vegetation cover RapidEye image is the condition of that day in August 2012. The image quality for a single day is uncertain, since it may be affected by the weather, tree condition, sensor viewing and sun illumination angles of that day, while these effects can be minimized by integrating long-term images (e.g. Landsat vegetation cover 2010). In addition, under normal climate conditions (excluding ENSO events) climber cutting can decrease the mortality of dipterocarp species and increase the compensatory regrowth of their canopies (Lussetti et al., 2016).

4.5 Limitations and future research

Although the high accuracy and high-resolution quantitative remote sensing datasets used here lead to better performance on terrestrial vegetation monitoring compared with previous moderate-resolution or qualitative remote sensing datasets (Hansen et al., 2010, 2013; Hansen and DeFries, 2004; Wilson and Jetz, 2016; Xie et al., 2008), they still face two known limitations. Firstly, compared with the in-situ ecology data, the spatial resolution of current remote sensing datasets still requires improvements, especially for specific tree species monitoring. Secondly, the performance of current quantitative remote sensing datasets is relatively limited when being used to detect three-dimension tree structure, such as tree height and diameter at breast height which are important factors for monitoring vegetation structure (Carlson and Ripley, 1997; Lefsky et al., 2002; Turner et al., 1999; Waring et al., 1995). For example, the monoculture plots and the 4-species mixture plots both contain different compositions (Table S1 in the online version at https://doi.org/10.1016/bs.aecr.2020.01.005), but each is replicated only twice and we therefore did not compare them using the satellite data available for this study. To detect the performance of each composition, it is necessary to add airborne LiDAR data for tree structure monitoring. However, there are few airborne LiDAR data continuously available for

vegetation monitoring on a large scale. During recent years, there are some studies that integrate airborne LiDAR data and optical remote sensing data to develop high-quality products (Lefsky, 2010; Lim et al., 2003; Simard et al., 2011). Progress has been made by ecologists and geographers in Malaysian Borneo (Asner et al., 2018). The advantage of these methods is that they can get more structural information from earth's surface, though the spatial-temporal coverage of these products may be limited. Future research will consider the development of long-term high-resolution remote sensing datasets when coupled with the LiDAR data to improve the ability of comprehensive vegetation monitoring. This remote sensing data will need appropriate validation by in-situ field measurements, something that is absent in this study. The replication and randomization of treatments within the blocked design of Sabah Biodiversity Experiment should ensure that the ability of the satellite remote sensing to discriminate among the different plots is reliable but validation with field measurements will provide additional assurance as well as being essential in order to understand the biological processes underlying the different treatment effects.

5. Conclusion

In this study, we used a large scale, long-term field manipulation (Sabah Biodiversity Experiment) as a test of the ability of high spatial resolution satellite imagery and advanced remote sensing products to assess the effects of selective logging and of different restoration treatments on forest canopy quality. In general, our study was able to detect differences in estimated vegetation cover, Leaf Area Index (LAI), and biomass due to selective logging as well as differences among the different forest restoration treatments, namely enrichment planting, climber cutting and natural (unassisted) recovery. In particular, our results suggest that enrichment planting enhances restoration and that diverse mixtures of tree species are more effective than single-species plantings. However, the monitoring ability of optical remote sensing data to detect these impacts is still limited. In the longerterm, LiDAR will allow more comprehensive assessments of forest restoration. Remote sensing measurements of forest quality will also need to be accompanied by field measurements to validate the treatment effects and to better understand the biological processes affecting forest degradation and restoration.

Glossary

- Landsat Landsat refers a series of artificial satellites that monitor the earth's resources by photographing the surface at different wavelengths and resolutions. Since 1972, eight Landsat satellites have been launched. The Landsat program is the longest-running enterprise for acquisition of satellite imagery of Earth.
- **MODIS (Moderate Resolution Imaging Spectroradiometer)** MODIS (or Moderate Resolution Imaging Spectroradiometer) is a key instrument aboard the Terra and Aqua satellites. The instrument capture data in 36 spectral bands ranging in wavelength from 0.4 to 14.4 µm and at varying spatial resolutions (2 bands at 250 m, 5 bands at 500 m and 29 bands at 1 km).
- RapidEye RapidEye refers to the constellation of five earth observation satellites owned and operated by Planet Labs. Each sensor capture data in five distinct bands of the electromagnetic spectrum: Blue (440–510 nm), Green (520–590 nm), Red (630–690 nm), Red-Edge (690–730 nm) and Near-Infrared (760–880 nm), and at varying spatial resolution of 5 m.
- Leaf Area Index (LAI) The total one-sided green leaf area per unit ground surface area. Leaves are the major eco-physiological parts of a plant that interact with the atmosphere, including absorbing and assimilating carbon dioxide, intercepting light necessary for photosynthesis, releasing oxygen that is formed as a byproduct of photosynthesis and so on. LAI is a reliable parameter for plant growth.
- **Vegetation cover** The fraction or percentage of the unit ground surface covered by green leaves.
- **Gross Primary Productivity (GPP)** GPP refers the rate of how an ecosystem's producers or autotrophs collect and save a certain amount of chemical energy referred to as biomass at a specific time. In other words, it's the rate at which energy is stored as biomass by plants or other primary producers and made available to the consumers in the ecosystem.
- **Spatial resolution** Spatial resolution measures the smallest angular separation between two objects. For satellite images, this is represented in pixels and the spatial resolution for a given image is noted as how many metres that pixel represents.
- **Temporal resolution** Temporal resolution refers to the frequency at which imagery is recorded for a particular area.
- **Atmospheric correction** Atmospheric correction refers the process of removing the effects of the atmosphere on the reflectance values of images taken by satellite or airborne sensors.
- **ArcGIS** ArcGIS is a geographic information system (GIS) for working with maps and geographic information maintained by Esri.
- **ESRI** Esri is an international supplier of geographic information system (GIS) software, web GIS and geodatabase management applications.
- **ENVI** ENVI is an image analysis software for working with remote sensing and geographic information maintained by L3Harris Geospatial.

Acknowledgements

Thanks to all the many people who have supported and worked on Sabah Biodiversity Experiment. Our thanks also to Tommaso Jucker and two anonymous reviewers for their constructive criticism of earlier versions of this chapter. J.W. was supported by the National Key Research and Development Program of China (2016YFA0600101) and the China-UK Joint Research and Innovation Partnership Fund (China Scholarship Council). M.J.O'B. was supported by the Atracción de Talento Investigador Modalidad I Fellowship from the Comunidad de Madrid (2018-T1/AMB-11095) and the University of Zurich URPP GCB. A.H. was supported by the NERC Human Modified Tropical Forests thematic programme (Biodiversity and Land-use Impacts on tropical ecosystem function consortium). This chapter is a product of the South East Asia Rainforest Research Partnership programme and Sabah Biodiversity Experiment publication 21.

References

- Alvarado, E., Sandberg, D., 2001. Logging in Tropical Forest: Literature Review on Ecological Impacts. University of Washington, USDA Forest Service.
- Asner, G.P., Keller, M., Pereira Jr., R., Zweede, J.C., 2002. Remote sensing of selective logging in Amazonia: assessing limitations based on detailed field observations, Landsat ETM+, and textural analysis. Remote Sens. Environ. 80, 483–496.
- Asner, G.P., Keller, M., Pereira Jr., R., Zweede, J.C., Silva, J.N., 2004a. Canopy damage and recovery after selective logging in Amazonia: field and satellite studies. Ecol. Appl. 14, 280–298.
- Asner, G.P., Keller, M., Silva, J.N., 2004b. Spatial and temporal dynamics of forest canopy gaps following selective logging in the eastern Amazon. Glob. Chang. Biol. 10, 765–783.
- Asner, G.P., Knapp, D.E., Broadbent, E.N., Oliveira, P.J., Keller, M., Silva, J.N., 2005. Selective logging in the Brazilian Amazon. Science 310, 480–482.
- Asner, G.P., Brodrick, P.G., Philipson, C., Vaughn, N.R., Martin, R.E., Knapp, D.E., Heckler, J., Evans, L.J., Jucker, T., Goossens, B., 2018. Mapped aboveground carbon stocks to advance forest conservation and recovery in Malaysian Borneo. Biol. Conserv. 217, 289–310.
- Baccini, A., Walker, W., Farina, M., Houghton, R.A., 2016. CMS: Estimated Deforested Area Biomass, Tropical America, Africa, and Asia, 2000. ORNL Distributed Active Archive Center.
- Benediktsson, J.A., Chanussot, J., Moon, W.M., 2012. Very high-resolution remote sensing: challenges and opportunities [point of view]. Proc. IEEE 100, 1907–1910.
- Bréda, N.J., 2003. Ground-based measurements of leaf area index: a review of methods, instruments and current controversies. J. Exp. Bot. 54, 2403–2417.
- Brede, B., Gastellu-Etchegorry, J.-P., Lauret, N., Baret, F., Clevers, J., Verbesselt, J., Herold, M., 2018. Monitoring forest phenology and leaf area index with the autonomous, low-cost transmittance sensor PASTiS-57. Remote Sens. (Basel) 10, 1032.
- Cardinale, B.J., Srivastava, D.S., Duffy, J.E., Wright, J.P., Downing, A.L., Sankaran, M., Jouseau, C., 2006. Effects of biodiversity on the functioning of trophic groups and ecosystems. Nature 443, 989.
- Cardinale, B.J., Wright, J.P., Cadotte, M.W., Carroll, I.T., Hector, A., Srivastava, D.S., Loreau, M., Weis, J.J., 2007. Impacts of plant diversity on biomass production increase through time because of species complementarity. Proc. Natl. Acad. Sci. 104, 18123–18128.
- Cardinale, B.J., Matulich, K.L., Hooper, D.U., Byrnes, J.E., Duffy, E., Gamfeldt, L., Balvanera, P., O'connor, M.I., Gonzalez, A., 2011. The functional role of producer diversity in ecosystems. Am. J. Bot. 98, 572–592.
- Carlson, T.N., Ripley, D.A., 1997. On the relation between NDVI, fractional vegetation cover, and leaf area index. Remote Sens. Environ. 62, 241–252.

- César, R.G., Holl, K.D., Girão, V.J., Mello, F.N., Vidal, E., Alves, M.C., Brancalion, P.H., 2016. Evaluating climber cutting as a strategy to restore degraded tropical forests. Biol. Conserv. 201, 309–313.
- Chambers, J.Q., Asner, G.P., Morton, D.C., Anderson, L.O., Saatchi, S.S., Espírito-Santo, F.D., Palace, M., Souza Jr., C., 2007. Regional ecosystem structure and function: ecological insights from remote sensing of tropical forests. Trends Ecol. Evol. 22, 414–423.
- Chan, H.T., Shamsudin, I., Ismail, P., 2008. An In-Depth Look at Enrichment Planting (Malaysian Forest Records No. 47). Forest Research Institute Malaysia, Kuala Lumpur, Malaysia.
- Chander, G., Haque, M.O., Sampath, A., Brunn, A., Trosset, G., Hoffmann, D., Roloff, S., Thiele, M., Anderson, C., 2013. Radiometric and geometric assessment of data from the RapidEye constellation of satellites. Int. J. Remote Sens. 34, 5905–5925.
- Chen, J., Chen, J., Liao, A., Cao, X., Chen, L., Chen, X., He, C., Han, G., Peng, S., Lu, M., 2015. Global land cover mapping at 30 m resolution: a POK-based operational approach. ISPRS J. Photogramm. Remote Sens. 103, 7–27.
- Chen, C., Park, T., Wang, X., Piao, S., Xu, B., Chaturvedi, R.K., Fuchs, R., Brovkin, V., Ciais, P., Fensholt, R., Tømmervik, H., Bala, G., Zhu, Z., Nemani, R.R., Myneni, R.B., 2019. China and India lead in greening of the world through land-use management. Nat. Sustain. 2, 122–129.
- Claverie, M., Matthews, J., Vermote, E., Justice, C., 2016. A 30+ year AVHRR LAI and FAPAR climate data record: algorithm description and validation. Remote Sens. (Basel) 8, 263.
- de Souza, E.G., Scharf, P.C., Sudduth, K.A., 2010. Sun position and cloud effects on reflectance and vegetation indices of corn. Agron. J. 102, 734–744.
- de Wasseige, C., Defourny, P., 2004. Remote sensing of selective logging impact for tropical forest management. For. Ecol. Manage. 188, 161–173.
- Duffy, J.E., 2009. Why biodiversity is important to the functioning of real-world ecosystems. Front. Ecol. Environ. 7, 437–444.
- Edwards, D.P., Tobias, J.A., Sheil, D., Meijaard, E., Laurance, W.F., 2014. Maintaining ecosystem function and services in logged tropical forests. Trends Ecol. Evol. 29, 511–520.
- Feng, M., Sexton, J.O., Channan, S., Townshend, J.R., 2016. A global, high-resolution (30-m) inland water body dataset for 2000: first results of a topographic–spectral classification algorithm. Int. J. Digital Earth 9, 113–133.
- Foody, G.M., Cutler, M.E., 2003. Tree biodiversity in protected and logged Bornean tropical rain forests and its measurement by satellite remote sensing. J. Biogeogr. 30, 1053–1066.
- Forshed, O., Karlsson, A., Falck, J., Cedergren, J., 2008. Stand development after two modes of selective logging and pre-felling climber cutting in a dipterocarp rainforest in Sabah, Malaysia. For. Ecol. Manage. 255, 993–1001.
- Friedl, M.A., McIver, D.K., Hodges, J.C., Zhang, X.Y., Muchoney, D., Strahler, A.H., Woodcock, C.E., Gopal, S., Schneider, A., Cooper, A., 2002. Global land cover mapping from MODIS: algorithms and early results. Remote Sens. Environ. 83, 287–302.
- Gallardo-Cruz, J.A., Meave, J.A., González, E.J., Lebrija-Trejos, E.E., Romero-Romero, M.A., Pérez-GarcíA, E.A., Gallardo-Cruz, R., Hernández-Stefanoni, J.L., Martorell, C., 2012. Predicting tropical dry forest successional attributes from space: is the key hidden in image texture? PLoS One 7, e30506.
- Gao, B.-C., Li, R.-R., 2000. Quantitative improvement in the estimates of NDVI values from remotely sensed data by correcting thin cirrus scattering effects. Remote Sens. Environ. 74, 494–502.

- Gatti, R.C., Castaldi, S., Lindsell, J.A., Coomes, D.A., Marchetti, M., Maesano, M., DI Paola, A., Paparella, F., Valentini, R., 2015. The impact of selective logging and clearcutting on forest structure, tree diversity and above-ground biomass of African tropical forests. Ecol. Res. 30, 119–132.
- Gravel, D., Bell, T., Barbera, C., Bouvier, T., Pommier, T., Venail, P., Mouquet, N., 2011. Experimental niche evolution alters the strength of the diversity–productivity relationship. Nature 469, 89.
- Gutman, G., Byrnes, R.A., Masek, J., Covington, S., Justice, C., Franks, S., Headley, R., 2008. Towards monitoring land-cover and land-use changes at a global scale: the global land survey 2005. Photogramm. Eng. Remote. Sens. 74, 6–10.
- Gutman, G., Huang, C., Chander, G., Noojipady, P., Masek, J.G., 2013. Assessment of the NASA–USGS global land survey (GLS) datasets. Remote Sens. Environ. 134, 249–265.
- Hansen, M.C., 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.
- Hansen, M.C., Stehman, S.V., Potapov, P.V., 2010. Quantification of global gross forest cover loss. Proc. Natl. Acad. Sci. 107, 8650–8655.
- Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S., Tyukavina, A., Thau, D., Stehman, S., Goetz, S., Loveland, T., 2013. High-resolution global maps of 21st-century forest cover change. Science 342, 850–853.
- Hector, A., 2009. Darwin's 'principle of divergence' and the link between biodiversity and ecosystem functioning. In: Stocklin, J., Hoxterman, E. (Eds.), Darwin und die botanik. Vierteljahrsschrift der Naturforschenden Gesellschaft in Zürich, pp. 182–191.
- Hector, A., 2011. Ecology: diversity favours productivity. Nature 472, 45.
- Hector, A., Bagchi, R., 2007. Biodiversity and ecosystem multifunctionality. Nature 448, 188.
- Hector, A., Hooper, R., 2002. Darwin and the first ecological experiment. Science 295, 639–640.
- Hector, A., Hautier, Y., Saner, P., Wacker, L., Bagchi, R., Joshi, J., Scherer-Lorenzen, M., Spehn, E.M., Bazeley-White, E., Weilenmann, M., 2010. General stabilizing effects of plant diversity on grassland productivity through population asynchrony and overyielding. Ecology 91, 2213–2220.
- Hector, A., Philipson, C., Saner, P., Chamagne, J., Dzulkifli, D., O'Brien, M., Snaddon, J.L., Ulok, P., Weilenmann, M., Reynolds, G., 2011. The Sabah biodiversity experiment: a long-term test of the role of tree diversity in restoring tropical forest structure and functioning. Philos. Trans. R. Soc. Lond. B Biol. Sci. 366, 3303–3315.
- Huang, Y., Chen, Y., Castro-Izaguirre, N., Baruffol, M., Brezzi, M., Lang, A., Li, Y., Härdtle, W., Von Oheimb, G., Yang, X., 2018. Impacts of species richness on productivity in a large-scale subtropical forest experiment. Science 362, 80–83.
- Ju, J., Roy, D.P., 2008. The availability of cloud-free Landsat ETM + data over the conterminous United States and globally. Remote Sens. Environ. 112, 1196–1211.
- Jung-Rothenhäusler, F., Weichelt, H., Pach, M., 2007. RapidEye—a novel approach to space borne geo-information solutions. In: Proceedings of ISPRS Hannover Workshop, pp. 1–4.
- Karam, D., Arifin, A., Radziah, O., Shamshuddin, J., Majid, N., Hazandy, A., Zahari, I., Nor Halizah, A., Rui, T., 2012. Impact of long-term forest enrichment planting on the biological status of soil in a deforested dipterocarp forest in Perak, Malaysia. Scientific World Journal 2012, 641346.
- Kerr, J.T., Ostrovsky, M., 2003. From space to species: ecological applications for remote sensing. Trends Ecol. Evol. 18, 299–305.

- Knyazikhin, Y., 1999. MODIS Leaf Area Index (LAI) and Fraction of Photosynthetically Active Radiation Absorbed by Vegetation (FPAR) Product (MOD 15) Algorithm Theoretical Basis Document. http://eospso.gsfc.nasa.gov/atbd/modistabls.heml.
- Lambert, F., 1992. The consequences of selective logging for Bornean lowland forest birds. Philos. Trans. R. Soc. Lond. B Biol. Sci. 335, 443–457.
- Laporte, N.T., Stabach, J.A., Grosch, R., Lin, T.S., Goetz, S.J., 2007. Expansion of industrial logging in Central Africa. Science 316, 1451.
- Lefsky, M.A., 2010. A global forest canopy height map from the moderate resolution imaging spectroradiometer and the geoscience laser altimeter system. Geophys. Res. Lett. 37, 15.
- Lefsky, M.A., Cohen, W.B., Parker, G.G., Harding, D.J., 2002. Lidar remote sensing for ecosystem studies: lidar, an emerging remote sensing technology that directly measures the three-dimensional distribution of plant canopies, can accurately estimate vegetation structural attributes and should be of particular interest to forest, landscape, and global ecologists. AIBS Bull. 52, 19–30.
- Li, C., Wulf, H., Schmid, B., He, J.-S., Schaepman, M.E., 2018. Estimating plant traits of alpine grasslands on the Qinghai-Tibetan plateau using remote sensing. IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens. 11, 2263–2275.
- Liang, S., 2004. Quantitative Remote Sensing of Land Surfaces. John Wiley & Sons.
- Liang, S., Li, X., Wang, J., 2012. Advanced Remote Sensing: Terrestrial Information Extraction and Applications. Academic Press.
- Liang, S., Zhao, X., Liu, S., Yuan, W., Cheng, X., Xiao, Z., Zhang, X., Liu, Q., Cheng, J., Tang, H., 2013. A long-term Global LAnd Surface Satellite (GLASS) data-set for environmental studies. Int. J. Digital Earth 6, 5–33.
- Liang, J., Crowther, T.W., Picard, N., Wiser, S., Zhou, M., Alberti, G., Schulze, E.-D., McGuire, A.D., Bozzato, F., Pretzsch, H., 2016. Positive biodiversity-productivity relationship predominant in global forests. Science 354, aaf8957.
- Liang, S., Shi, J., Yan, G., 2018. Recent Progress in Quantitative Land Remote Sensing in China. Multidisciplinary Digital Publishing Institute.
- Lim, K., Treitz, P., Wulder, M., St-Onge, B., Flood, M., 2003. LiDAR remote sensing of forest structure. Prog. Phys. Geogr. 27, 88–106.
- Liou, K.-N., 1992. Radiation and Cloud Processes in the Atmosphere. Theory, Observation, and Modeling. Oxford University Press.
- Lussetti, D., Axelsson, E.P., Ilstedt, U., Falck, J., Karlsson, A., 2016. Supervised logging and climber cutting improves stand development: 18 years of post-logging data in a tropical rain forest in Borneo. For. Ecol. Manage. 381, 335–346.
- Marsh, C.W., Greer, A.G., 1992. Forest land-use in Sabah, Malaysia: an introduction to Danum Valley. Philos. Trans. R. Soc. Lond. B Biol. Sci. 335, 331–339.
- Matricardi, E.A., Skole, D.L., Pedlowski, M.A., Chomentowski, W., Fernandes, L.C., 2010. Assessment of tropical forest degradation by selective logging and fire using Landsat imagery. Remote Sens. Environ. 114, 1117–1129.
- Miller, P., Kumar, A., Mote, T., Moraes, F., Mishra, D., 2019. Persistent hydrological consequences of hurricane Maria in Puerto Rico. Geophys. Res. Lett. 46 (3), 1413–1422.
- Millet, J., Tran, N., Ngoc, N.V., Thi, T.T., Prat, D., 2013. Enrichment planting of native species for biodiversity conservation in a logged tree plantation in Vietnam. New For. 44, 369–383.
- Muraoka, H., Koizumi, H., 2009. Satellite ecology (SATECO)—linking ecology, remote sensing and micrometeorology, from plot to regional scale, for the study of ecosystem structure and function. J. Plant Res. 122, 3–20.
- Myneni, R., Knyazikhin, Y., Park, T., 2015. MCD15A3H MODIS/Terra+Aqua Leaf Area Index/FPAR 4-day L4 Global 500m SIN Grid V006. [Dataset], NASA EOSDIS Land Processes DAAC. https://doi.org/10.5067/MODIS/MCD15A3H.006. (Accessed 9 February 2020).

- Myneni, R.B., Hoffman, S., Knyazikhin, Y., Privette, J., Glassy, J., Tian, Y., Wang, Y., Song, X., Zhang, Y., Smith, G., 2002. Global products of vegetation leaf area and fraction absorbed PAR from year one of MODIS data. Remote Sens. Environ. 83, 214–231.
- Nepstad, D.C., Verssimo, A., Alencar, A., Nobre, C., Lima, E., Lefebvre, P., Schlesinger, P., Potter, C., Moutinho, P., Mendoza, E., 1999. Large-scale impoverishment of Amazonian forests by logging and fire. Nature 398, 505.
- O'Brien, M.J., Philipson, C.D., Reynolds, G., Dzulkifli, D., Snaddon, J.L., Ong, R., Hector, A., 2019. Positive effects of liana cutting on seedlings are reduced during El Niño-induced drought. J. Appl. Ecol. 56, 891–901.
- Perez, L., Nelson, T.A., Coops, N.C., Fontana, F., Drever, C.R., 2016. Characterization of spatial relationships between three remotely sensed indirect indicators of biodiversity and climate: a 21years' data series review across the Canadian boreal forest. Int. J. Digital Earth 9 (7), 676–696.
- Pfeifer, M., Kor, L., Nilus, R., Turner, E., Cusack, J., Lysenko, I., Khoo, M., Chey, V., Chung, A., Ewers, R., 2016. Mapping the structure of Borneo's tropical forests across a degradation gradient. Remote Sens. Environ. 176, 84–97.
- Qi, J., Chehbouni, A., Huete, A., Kerr, Y., Sorooshian, S., 1994. A modified soil adjusted vegetation index. Remote Sens. Environ. 48, 119–126.
- Ranga Myneni, K., Yuri, T.P., 2015. MOD15A3H MODIS/Combined Terra + Aqua Leaf Area Index/FPAR Daily L4 Global 500m SIN Grid.
- Rees, W.G., 2013. Physical Principles of Remote Sensing. Cambridge University Press.
- Rocchini, D., Ricotta, C., Chiarucci, A., 2007. Using satellite imagery to assess plant species richness: the role of multispectral systems. Appl. Veg. Sci. 10, 325–331.
- Running, S.W., Thornton, P.E., Nemani, R., Glassy, J.M., 2000. Global terrestrial gross and net primary productivity from the earth observing system. In: Methods in Ecosystem Science. Springer.
- Safa, M.S., Ibrahim, Z., Abdu, A., 2004. Potentialities of New Line Planting Technique of Enrichment Planting in Peninsular Malaysia: a Review of Resource Sustainability and Economic Feasibility. In: KUSTEM 3rd Annual Seminal, Kuala Terenganu, Terenganu Darul Iman, 4–5 May, Malaysia.
- Saner, P., 2009. Ecosystem Carbon Dynamics in Logged Forest of Malaysian Borneo. PhD thesis, University of Zurich, Zurich, Switzerland.
- Saner, P., Loh, Y.Y., Ong, R.C., Hector, A., 2012. Carbon stocks and fluxes in tropical lowland dipterocarp rainforests in Sabah, Malaysian Borneo. PLoS One 7, e29642.
- Schnitzer, S.A., Parren, M.P., Bongers, F., 2004. Recruitment of lianas into logging gaps and the effects of pre-harvest climber cutting in a lowland forest in Cameroon. For. Ecol. Manage. 190, 87–98.
- Sexton, J.O., Song, X.-P., Feng, M., Noojipady, P., Anand, A., Huang, C., Kim, D.-H., Collins, K.M., Channan, S., Dimiceli, C., 2013a. Global, 30-m resolution continuous fields of tree cover: landsat-based rescaling of MODIS vegetation continuous fields with lidar-based estimates of error. Int. J. Digital Earth 6, 427–448.
- Sexton, J.O., Song, X.-P., Huang, C., Channan, S., Baker, M.E., Townshend, J.R., 2013b. Urban growth of the Washington, DC–Baltimore, MD metropolitan region from 1984 to 2010 by annual, Landsat-based estimates of impervious cover. Remote Sens. Environ. 129, 42–53.
- Simard, M., Pinto, N., Fisher, J.B., Baccini, A., 2011. Mapping forest canopy height globally with spaceborne lidar. J. Geophys. Res. Biogeo. 2005–2012, 116.
- Simpson, J.J., Jin, Z., Stitt, J.R., 2000. Cloud shadow detection under arbitrary viewing and illumination conditions. IEEE Trans. Geosci. Remote Sens. 38, 972–976.

- Song, X.-P., Sexton, J.O., Huang, C., Channan, S., Townshend, J.R., 2016. Characterizing the magnitude, timing and duration of urban growth from time series of Landsat-based estimates of impervious cover. Remote Sens. Environ. 175, 1–13.
- Souza Jr., C., Barreto, P., 2000. An alternative approach for detecting and monitoring selectively logged forests in the Amazon. Int. J. Remote Sens. 21, 173–179.
- Souza Jr., C.M., Roberts, D.A., Cochrane, M.A., 2005. Combining spectral and spatial information to map canopy damage from selective logging and forest fires. Remote Sens. Environ. 98, 329–343.
- Thiollay, J.-M., 1992. Influence of selective logging on bird species diversity in a Guianan rain forest. Conserv. Biol. 6, 47–63.
- Tigabu, M., Savadogo, P., Odén, P.C., Xayvongsa, L., 2010. Enrichment planting in a logged-over tropical mixed deciduous forest of Laos. J. For. Res. 21, 273–280.
- Tuck, S.L., O'Brien, M.J., Philipson, C.D., Saner, P., Tanadini, M., Dzulkifli, D., Godfray, H.C.J., Godoong, E., Nilus, R., Ong, R.C., 2016. The value of biodiversity for the functioning of tropical forests: insurance effects during the first decade of the Sabah biodiversity experiment. Proc. R. Soc. B Biol. Sci. 283, 20161451.
- Turner, W., 2014. Sensing biodiversity. Science 346, 301-302.
- Turner, D.P., Cohen, W.B., Kennedy, R.E., Fassnacht, K.S., Briggs, J.M., 1999. Relationships between leaf area index and Landsat TM spectral vegetation indices across three temperate zone sites. Remote Sens. Environ. 70, 52–68.
- Turner, W., Spector, S., Gardiner, N., Fladeland, M., Sterling, E., Steininger, M., 2003. Remote sensing for biodiversity science and conservation. Trends Ecol. Evol. 18, 306–314.
- Tyc, G., Tulip, J., Schulten, D., Krischke, M., Oxfort, M., 2005. The RapidEye mission design. Acta Astronaut. 56, 213–219.
- Verissimo, A., Barreto, P., Tarifa, R., Uhl, C., 1995. Extraction of a high-value natural resource in Amazonia: the case of mahogany. For. Ecol. Manage. 72, 39–60.
- Waring, R.H., Way, J., Hunt, E.R., Morrissey, L., Ranson, K.J., Weishampel, J.F., Oren, R., Franklin, S.E., 1995. Imaging radar for ecosystem studies. Bioscience 45, 715–723.
- Watson, D., 1947. Variation in net assimilation rate and leaf area between species and varieties and within and between years. Ann. Bot. N. S. XI (41), 41–76.
- Wilson, A.M., Jetz, W., 2016. Remotely sensed high-resolution global cloud dynamics for predicting ecosystem and biodiversity distributions. PLoS Biol. 14, e1002415.
- Xiao, Z., Liang, S., Wang, J., Chen, P., Yin, X., Zhang, L., Song, J., 2014. Use of general regression neural networks for generating the GLASS leaf area index product from time-series MODIS surface reflectance. IEEE Trans. Geosci. Remote Sens. 52, 209–223.
- Xiao, Z., Liang, S., Wang, J., Xiang, Y., Zhao, X., Song, J., 2016. Long-time-series global land surface satellite leaf area index product derived from MODIS and AVHRR surface reflectance. IEEE Trans. Geosci. Remote Sens. 54, 5301–5318.
- Xie, Y., Sha, Z., Yu, M., 2008. Remote sensing imagery in vegetation mapping: a review. J. Plant Ecol. 1, 9–23.
- Xu, M., Jia, X., Pickering, M., Plaza, A.J., 2016. Cloud removal based on sparse representation via multitemporal dictionary learning. IEEE Trans. Geosci. Remote Sens. 54, 2998–3006.
- Yachi, S., Loreau, M., 1999. Biodiversity and ecosystem productivity in a fluctuating environment: the insurance hypothesis. Proc. Natl. Acad. Sci. 96, 1463–1468.
- Yuan, W., Liu, S., Yu, G., Bonnefond, J., Chen, J., Davis, K.J., Desai, A.R., Goldstein, A.H., Gianelle, D., Rossi, F., 2010. Global estimates of evapotranspiration and gross primary production based on MODIS and global meteorology data. Remote Sens. Environ. 114, 1416–1431.

- Zhu, Z., Bi, J., Pan, Y., Ganguly, S., Anav, A., Xu, L., Samanta, A., Piao, S., Nemani, R.R., Myneni, R.B., 2013. Global data sets of vegetation leaf area index (LAI) 3g and fraction of photosynthetically active radiation (FPAR) 3g derived from global inventory modeling and mapping studies (GIMMS) normalized difference vegetation index (NDVI3g) for the period 1981 to 2011. Remote Sens. (Basel) 5, 927–948.
- Zhu, Z., Piao, S., Myneni, R.B., Huang, M., Zeng, Z., Canadell, J.G., Ciais, P., Sitch, S., Friedlingstein, P., Arneth, A., Cao, C., Cheng, L., Kato, E., Koven, C., Li, Y., Lian, X., Liu, Y., Liu, R., Mao, J., Pan, Y., Peng, S., Peñuelas, J., Poulter, B., Pugh, T.A.M., Stocker, B.D., Viovy, N., Wang, X., Wang, Y., Xiao, Z., Yang, H., Zaehle, S., Zeng, N., 2016. Greening of the Earth and its drivers. Nat. Clim. Chang. 6, 791.