Charters, LJ, Aplin, P, Marston, CG, Padfield, R, Rengasamy, N, Bin Dahalan, MP and Evers, SL

Peat swamp forest conservation withstands pervasive land conversion to oil palm plantation in North Selangor, Malaysia

http://researchonline.ljmu.ac.uk/id/eprint/10576/

Article

Citation (please note it is advisable to refer to the publisher's version if you intend to cite from this work)

Charters, LJ, Aplin, P, Marston, CG, Padfield, R, Rengasamy, N, Bin Dahalan, MP and Evers, SL (2019) Peat swamp forest conservation withstands pervasive land conversion to oil palm plantation in North Selangor, Malaysia. International Journal of Remote Sensing. ISSN 0143-

Peat swamp forest conservation withstands pervasive land conversion to oil palm plantation in North Selangor, Malaysia

Lewis J. Charters[a], Paul Aplin[a*], Christopher G. Marston[a], Rory Padfield[bc], Nagarajan Rengasamy[d], Mohd Puat Bin Dahalan[e] and Stephanie Evers[cfg]

[a]*Department of Geography, Edge Hill University, Ormskirk, United Kingdom*

[b]*Department of Social Sciences, Oxford Brookes University, Oxford, United Kingdom*

[c]*TROCARI (Tropical Catchment Research Initiative), Kuala Lumpur, Malaysia*

[d]*Global Environment Centre, Kuala Lumpur, Malaysia*

[e]*Selangor State Forestry Department, Malaysia*

[f]*School of Natural Sciences and Psychology, Liverpool John Moores University, Liverpool, United Kingdom*

[g]*School of Biosciences, University of Nottingham Malaysia Campus, Kuala Lumpur, Malaysia*

*Corresponding author: paul.aplin@edgehill.ac.uk; Tel.: (+44) 01695 584425

Peat swamp forest conservation withstands pervasive land conversion to oil palm plantation in North Selangor, Malaysia

Abstract: Tropical deforestation remains one of the major global challenges of the 21st Century driven to a large extent by the conversion of land for agricultural purposes, such as palm oil production. Malaysia is one of the world's largest palm oil producers and has seen widespread conversion to oil palm from primary forest, including peat swamp forest (PSF). This study investigates the rate and extent of pervasive oil palm expansion in and around North Selangor Peat Swamp Forest (NSPSF) over the last three decades, exploring how land conversion has affected the region's tropical forests, and assessing the relative success of PSF conservation measures. Time-series Landsat imagery was used to assess thematic land cover change and improvement in vegetation condition since NSPSF was given protected status in 1990. The results show a near tripling in oil palm cover throughout North Selangor, from 24,930 ha in 1989 to 70,070 ha in 2016; while at the same time tropical forest cover shrank from 145,570 ha to 88,400 ha. Despite concerns over the sustainability and environmental impact of such rapid oil palm conversion at a regional level, at the local scale NSPSF represents a relative conservation success story. Effective land stewardship by government and non-governmental organisation (NGO) management actors has limited illegal encroachment of oil palm around the reserve boundary. PSF rehabilitation measures have also markedly improved vegetation condition in NSPFS's interior. These findings have broad significance for how oil palm agriculture is managed and especially for PSF stewardship and conservation, and the approaches described here may be usefully adopted elsewhere in Southeast Asia and around the world.

1. Introduction

Originally introduced as an ornamental plant from Nigeria in the late 19th century (Sulaiman et al., 2012), the most rapidly expanding, though often controversial, of equatorial crops in Southeast Asia is oil palm (*elaeis guineensis).* In recent decades, oil palm has become established as a highly profitable and efficient oil crop due to relatively high yields, easy establishment and minimal maintenance costs (Dislich et al., 2017). The industry generates over $50 billion annually and it is estimated that palm oil can be found in one in ten supermarket products, as well as being a source of biofuels (Choo et al., 2011; Paterson and Lima, 2017). In spite of the economic success, the industry has been criticised for contributing to major environmental issues such as deforestation, habitat degradation, biodiversity loss and climate change (Meijaard et al., 2018). Austin et al. (2017) claim that Indonesia and Malaysia, the two biggest palm oil producing nations, continue to prioritise oil palm expansion over protection of remaining primary forests. Despite attempts by both public and private actors to address the expansion of oil palm on primary forest, such policy initiatives are unlikely to prevent unsustainable expansion occurring in the future (Padfield et al., 2016). Southeast Asia could potentially lose 75% of its original forest cover, and up to 42% of its biodiversity by 2100 if current expansion continues on the same scale (Sodhi et al., 2004).

Tropical peatlands are increasingly targeted for oil palm conversion as alternative land for cultivation becomes scarcer (Goldstein, 2015). Covering 247,778 km^2 in Southeast Asia and 441,025 km^2 globally (Page et al., 2011; Posa et al., 2011), peat swamp forests (PSFs) are uniquely biodiverse ecosystems. By the early 2000s, 6% (or approximately 8,800 km^2) of the PSFs in Southeast Asia had been converted to oil palm plantations, and this has led to a biodiversity decline of 1.0% in Borneo (equivalent to four species of forest-dwelling birds), 3.4% in Sumatra (16 species), and 12.1% in Peninsular Malaysia (46 species) (Koh et al., 2011). By 2010, an additional 23,000 km^2 of PSF in Southeast Asia had been clear-felled and subsequently abandoned as degraded land (Koh et al., 2011). Currently, 36% of Southeast Asia’s original PSFs remain, and only a quarter of these are located in designated protection zones (Posa et al., 2011). The clearance of tropical forest not only reduces biodiversity, it also contributes to the emission of environmentally harmful greenhouse gases such as carbon dioxide, methane and nitrous oxide (Germer and Sauerborn, 2008). This problem is exacerbated by the oxidation of peat in degraded PSF environments, which promotes aerobic decay of organic matter (as opposed to anaerobic decomposition), subsequently releasing carbon dioxide in the process (Koh et al., 2001; Dislich et al., 2017). To put this in a wider context, it is estimated that 42,000 megatons of ancient carbon are stored in peatlands covering 12% of the total land area of Southeast Asia, making this one of the largest stores of terrestrial carbon on Earth (Wetlands International, 2014). This highlights the need for an increase in PSF conservation initiatives as well as the establishment of effective management and monitoring techniques, to prevent the release of greenhouse gases and to ensure the survival of indigenous species (Posa et al., 2011).

In the present day, there is considerable demand for cost-effective solutions to monitor oil palm expansion and peatland conservation which enable governments and land management authorities to better understand past changes and inform future land management practices (Padfield et al., 2014; Khatun et al., 2017). For this reason, remote sensing provides a valuable opportunity for retrospective vegetation, land cover and land use monitoring at broad geographical scales, while complementing ground-based field investigations (Campbell and Wynne, 2011; Marston et al., 2017). In particular, the Landsat programme now provides a global image archive dating back almost half a century. This imagery has broad coverage, with medium spatial resolution (30 m multispectral, 15 m pan-sharpened) suitable for regional scale studies, with pre-processed (e.g. surface reflectance) products available enabling straightforward temporal analysis. Furthermore, importantly, the entire Landsat archive is now available free of charge. Alternatively, very high resolution (VHR) satellite imagery has previously been used for oil palm assessment (Buchanan et al., 2008; Shafri et al., 2011; Gaveau et al., 2014; Razali et al., 2014; Srestasathiern and Rakwatin, 2014; Chong et al., 2017), though these data products can often be prohibitively expensive. Other remote sensing data products that have been applied to peatland conservation include airborne light detection and ranging (lidar) data that enable characterisation of vegetation structure and biomass (Brown et al., 2018).

In Peninsular Malaysia, as elsewhere in Southeast Asia, conversion of tropical forest to oil palm plantation is widespread. North Selangor Peat Swamp Forest (NSPSF) represents the second largest contiguous PSF in Peninsular Malaysia (Dahalan et al., 2016). Its continued existence is due in part to effective land stewardship by government (Selangor State Forestry Department (SSFD)) and non-governmental organisation (NGO, Global Environment Centre (GEC)) actors, whereby long-term conservation measures have been implemented and, importantly, enforced. Nonetheless, NSPSF faces constant pressure, and possibilities of encroachment, from both industrial and smallholder oil palm plantations. Add to this the drivers of land scarcity, often weak environmental legislation and the economic gains of palm oil production, and NSPSF becomes an important test of tropical peatland conservation practices at the local and regional scale. Thus, if and where successful, the conservation programme initiated in NSPSF in 1990 could serve as a valuable example for other such initiatives in Southeast Asia and elsewhere around the world.

In this study, we investigate the rate and extent of oil palm expansion in North Selangor, Malaysia over the last three decades, exploring in particular how this land conversion has impacted rainforest (outside NSPSF) and peat swamp forest (NSPSF). For this purpose, we use time-series remotely sensed imagery from the Landsat archive, conducting land cover classification and normalised difference vegetation index (NDVI) analysis to examine changes in land cover theme and vegetation condition between 1989, 2001 and 2016. There are two primary research questions: (1) To what extent has oil palm expansion occurred in North Selangor, and how much of this land conversion involved deforestation of rainforest or peat swamp forest? (2) How successful has NSPSF's conservation programme been in preventing illegal deforestation and improving vegetation condition? The findings from this study will advance our understanding of the nature and speed of land conversion from tropical forest to oil palm plantation in Peninsular Malaysia, and demonstrate the effectiveness of PSF conservation measures. This enables detailed commentary on oil palm sustainability and PSF conservation, as well as the role of future remote sensing technology in these environmental monitoring programmes. The conclusions drawn from this investigation can have broad significance for how oil palm agriculture is managed, especially for PSF stewardship and conservation, and the approaches described here may be usefully adopted elsewhere in Southeast Asia and around the world.

2. Materials and methods

2.1 Study area

The study area is NSPSF and surroundings, in Selangor State, Peninsular Malaysia. Overall, the study area (Figure 1) covers approximately 3,780 km² and incorporates a diverse range of land uses: PSF, lowland dipterocarp rainforest, oil palm plantations, the Sekinchan rice paddy fields, the former Bestari Jaya tin mining (later, sand mining) operations, two major towns (Rawang and Kuala Selangor), a host of other minor ecosystems and agricultural activities, and extends west into the sea (Malacca Strait). The average annual temperature and humidity are 27 °C and 79.3% respectively, while the mean annual rainfall ranges between 1,359 mm and 2,480 mm.

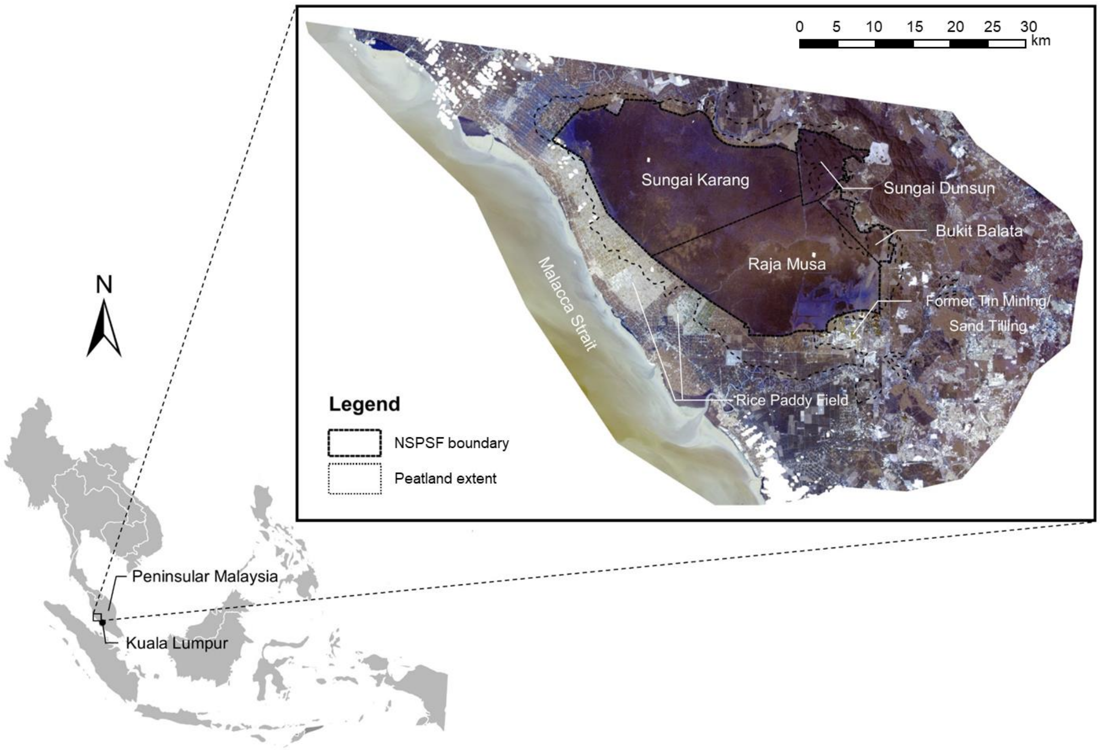

Figure 1. Location of NSPSF, Malaysia within Southeast Asia. Cropped image backdrop (2016 Landsat OLI data, supplied by USGS) shows the full extent of the study area. Overlaid on the image are the peatland extent (supplied by Wetlands International) and the boundaries of the four reserves comprising NSPSF (supplied by GEC).

Situated on a flat coastal plain about 10 km inland on the west coast of Peninsular Malaysia (Yule and Gomez, 2008), NSPSF is a globally significant site, both in terms of its unique biodiversity and as one of the largest carbon sequestration stores in Malaysia. The NSPSF reserve is home to a range of flora and fauna, consisting of 126 species of plants and around 262 terrestrial and aquatic species such as the Black Panther (*Panthera pardus*), Asian Tapir (*Tapirus indicus*), Malayan Sun Bear (*Helarctos malayanus*) and the rare Bearded Pig (*Sus barbatus*) (Adila et al., 2017). Many of these species have experienced population declines between 1980 and 2013, with the reserve considered one of the last sanctuaries of the Sumatran Rhinoceros (*dicerorhinus sumatrensis*), before they were declared extinct in the wild of Malaysia in 2015. In terms of flora, PSFs are distinct from dryland rainforests (e.g. lowland dipterocarp forests) because their native plant species require many adaptations to survive in the waterlogged, unstable (toxic, acidic) peat environment where the forest floor is seasonally flooded (Posa et al., 2011; Evers et al., 2016). The underlying geology consists of a vast clay mangrove deposit which is believed to have formed due to rising sea levels, brought about by the last ice age approximately 10,000 years ago (Tonks et al., 2016). The depth of peat ranges between 125 cm and 273 cm and its water content is estimated at approximately 627 ± 90% (gravimetric water content (dry weight basis)) (Tonks et al., 2016).

NSPSF is a largely logged-over forest (Sasidhran et al., 2016), which covers an area of 813 km² and is comprised of four forest reserve compartments: Raja Musa, Sungai Dusun, Sungai Karang and Bukit Belata (GEC, 2014). It is bordered by the Bernam River to the North, the Selangor River to the South, and traversed by the Tengi River. To the west of NSPSF lies the Tanjung Karang irrigation scheme that predominantly serves the Sekinchan rice paddy fields, and to the South East lies the former Bestari Jaya mining operations (Figure 1). Prior to the 20th century, there had been little utilisation of the NSPSF and the population was relatively sparse; therefore, most people preferred to establish themselves westward along the coast of the Malacca Strait (GEC, 2014). In the 1930s, the logging of the NSPSF began to intensify following advancements in infrastructure which improved access to the forest. Under the imperial rule of both the British colonial government and the Japanese occupation, the local population were encouraged to clear the NSPSF to make way for rice paddy fields (GEC, 2014). The first commercial oil palm plantation in the whole of Malaysia (The Tennamaram Estate) was also established along the eastern border of the NSPSF in 1917 (GEC, 2014); however, cultivation of oil palm did not expand significantly until the decline of the rubber industry during the 1980s. To address this decline, the Malaysian government introduced the crop diversification programme, which prioritised oil palm as the country's future prime crop (Jaafar, 1994). The area surrounding NSPSF underwent rapid transformation, with the number of rubber plantations declining rapidly, and the number of oil palm plantations expanding (GEC, 2014), accelerating after 1980.

Prior to gaining reserve status in 1990 (Kumari, 1996), NSPSF was formerly demarcated as state land forest and was subject to few or no restrictions on use (GEC, 2014). Since 1990 the reserve has been protected, though selective timber production was still permitted after this time (Tonks et al., 2016). The conservation measures implemented included blocking over 500 km of drainage canals, introducing strict no burning legislation, rehabilitating degraded PSF areas and demarcating the reserve boundary (Dahalan et al., 2016; Rengasamy et al., 2016). Recently, there has been considerable emphasis on participatory conservation, whereby local communities are actively involved in educational and conservation initiatives (Nath et al., 2016). Logging permits were still being issued up until 2010 when Malaysia's federal government enacted a total ban on all logging activity within the state of Selangor (GEC, 2014).

In the present day, NSPSF continues to face a range of conservation and ecological problems associated with anthropological encroachment: urban development, agricultural conversion, logging, fire and poaching (Hansen et al., 2009; Yule, 2010; Rengasamy et al., 2016). For instance, Tonks et al. (2016) suggested that the conversion of land for oil palm plantations, through the drainage of peatland in and around the NSPSF, has irreversibly changed peat physical properties. As a result, prolonged peat degradation has significant negative implications on some ecosystem services linked to the physical properties of peat (e.g. greenhouse gas (GHG) emissions and water retention capacity) (Rahim and Yusop, 1999). Recently it was estimated that a potential two million tonnes of carbon dioxide are emitted every year from the NSPSF due to drainage and fire (GEC, 2014). Furthermore, it has been suggested that the continued peat degradation could potentially impact the Tanjung Karang irrigation project, which relies on the NSPSF as a natural water supply for its rice paddies (GEC, 2014).

There is now a widespread curfew on the deliberate burning of the forest (as part of the 2014-2023 integrated management plan), due to events such as the haze experienced in Kuala Lumpur during the Indonesian fires of 2015 (Tan et al., 2017). However, wild fires remain commonplace, especially during El Nino events, dry seasons and as illegal oil palm conversion (predominantly by smallholders) continues to take place (GEC, 2014). Despite biomass burning being outlawed, smallholders and those living in poverty throughout the reserve continue to burn domestic and agricultural waste as rural areas receive little or no waste disposal infrastructure.

For this study, the period 1989-2016 was chosen for investigation principally to match the lifetime of the conservation initiative in NSPSF. Results from 1989 would show the status of regional oil palm cultivation and PSF vegetation condition immediately prior to the establishment of the NSPSF reserve in 1990 (GEC, 2014). Results from 2001 would show the interim picture and, in particular, show how PSF condition had changed a decade after conservation measures were implemented, but before the full logging ban was imposed later in 2010. Results from 2016 show the present day situation, including how PSF condition may have further improved since the logging ban. Also, the two time periods may show interesting variations in the regional pace and extent of oil palm conversion, whereby land availability for oil palm plantation diminishes rapidly as time passes, implying conversion may have been widespread in the first time period (1989-2001), but markedly slower in the second (2001-2016). Koh et al. (2011) suggest that, across Peninsular Malaysia, increasing land scarcity around the turn of the millennium led to increasing illegal encroachment of smallholder oil palm plantations into PSF.

2.2 Remotely sensed imagery

A time-series of Landsat Thematic Mapper (TM) and Operational Land Imager (OLI) images were collected to facilitate monitoring of the land cover in and around NSPSF, as well as forest condition inside the reserve, over the last three decades. Three images were used – 16 June 1989, 12 September 2001 and 3 July 2016 – enabling change to be assessed over three periods: (a) the period following the original gazettement (in 1990) of the NSPSF reserve (1989-2001), (b) the later period after the logging moratorium (2010) was imposed in NSPSF (2001-2016), and (c) the whole project timescale (1989-2016). The images were downloaded from the United States Geological Survey's (USGS) Earth Explorer database (USGS, 2018) as surface reflectance products, thus ensuring any atmospheric influence was removed enabling straightforward comparison over time. To ensure direct comparative analysis between the three images, standardised spectral band sets were used (six bands: blue, green, red, near infrared, shortwave infrared 1, shortwave infrared 2; other bands were omitted), with each of the three multispectral images having a spatial resolution of 30 m.

Pre-processing steps were performed on each of the three images, including cloud masking (using a red band thresholding approach to distinguish cloud presence based on the increased brightness of cloud in the visible spectra compared to typical terrestrial features) and cloud shadow masking. This was performed for each of the three images, with the three sets of cloud and cloud shadow masks then merged to produce a single combined cloud and cloud shadow mask. This combined mask was applied to each of the three images, excluding all areas that were cloud-affected in any of the three images to ensure a consistent image analysis extent.

To ensure accurate spatial comparison between the three images, image-to-image geometric registrations were conducted. Geographically referenced ground control points (GCPs) were identified throughout the study area based on features clearly identifiable in both image pairs (1989-2016 and 2001-2016), and that remain unchanged over time (e.g. road junctions, large buildings, airport runways etc.). In total, 30 GCPs were used with geometric registration conducted using a polynomial model and nearest neighbour resampling. The 1989 and 2001 images were each registered to the 2016 image, using the Universal Transverse Mercator projection (zone 47 North), achieving root mean square errors of 17 m (1989-2001) and 18 m (2001-2016). Visual assessment confirmed the images were spatially consistent.

2.3 Reference data

Reference data were acquired from three sources: (1) field land cover survey; (2) expert knowledge elicited through discussions with local stakeholders and residents, and; (3) high spatial resolution imagery available through Google Earth. A field survey was conducted in September 2017, where a total of 230 points were surveyed. Points were selected carefully to represent the range of land cover types within the study area. At each point, location was recorded using a handheld global positioning system (GPS) and land cover class was identified. Also, cardinal photographs (north, east, south, west) were taken, providing a record of nearby land cover, thus enabling further reference (training and testing) points to be elicited. E.g., a point situated in a rice paddy field, but bordered to the north by peat swamp forest and to the east by oil palm plantation, enables multiple training and testing pixels to be selected for each of these three classes. The field survey was used principally to identify reference points for the 2016 image, though for classes comprising mature vegetation such as the forest categories, it was possible to infer reference points for the historical images.

During the field campaign, opportunistic discussions were held with a range of stakeholders and residents in and around NSPSF. In total, information was provided from around ten individuals, including officials in the Malaysian Agricultural Ministry, the Tanjung Karang irrigation scheme and the oil palm industry, as well as local plantation workers. This information was useful for constructing a reference map of land cover to support the later classification analysis, especially for the historical images where reference data were otherwise relatively scarce. Additionally, the discussions were useful for eliciting information and narratives about land use around the study area and how this has changed over time, shedding interesting light on aspects of sustainability of oil palm agriculture and peat swamp forest conservation. Finally, high spatial resolution imagery available through Google Earth's historical archive (dating back as early as 1984) was used to identify the changing land cover types (Song et al., 2015).

2.4 Land cover classification

Land cover classification was performed on the 1989, 2001 and 2016 Landsat images to determine how NSPSF and the surrounding area has changed over the last three decades. In the first instance, individual land cover classes were identified for analysis, selected on the basis of field observation (dominant classes in the study area), image familiarisation (spectral class separability) and project objectives (distinguishing peat swamp forest and oil palm plantation from other classes). Overall, a nine class classification system was used (Table 1), comprising: (1) peat swamp forest, (2) rainforest, (3) mangrove forest, (4) grassland, (5) oil palm plantation, (6) rice paddy field, (7) bare soil, (8) urban development and (9) water.

Table 1. Land cover classes.

Land cover class	Description

Peat swamp forest	Dominant species include *Koompassia malaccencis*, *Shorea uliginosa*, *Xylopia fusca*, *Syzygium sp.* and
Rainforest	A combination of lowland *dipterocarp* forest and lowland alluvial forest (75% - 100% canopy cover).
Mangrove forest	Closed *Rhizophora* forest (75% - 100% canopy cover).
Grassland	Mainly dominated by species belonging to the *Poaceae* family as well as scrubland.
Oil palm plantation	Large monoculture and small holder plantations (75% - 100% canopy cover) cultivating *Elaeis guineensis*.
Rice paddy field	Large monoculture paddy fields cultivating O*ryza*
Bare soil	Exposed top soil caused by building works, agricultural cultivation and/or climate.
Urban development	Towns, villages, buildings, infrastructure, roads, impervious surfaces (concrete, asphalt etc.).
Water	Open sea, river systems, canals, reservoirs, small lakes/ponds, aquaculture.

Training classes were constructed for each class by selecting a relatively large number (between 29 and 45) of small polygons distributed throughout the study area. The polygons varied from 0.05 km^2 to 0.20 km^2 in size, containing between approximately 10 pixels and > 200 pixels. The quality of the training data was assessed using the transformed divergence (TD) measurement to assess spectral separability between all class pairs. The TD results were consistently higher than the recommended value of 1,900 (Momeni et al., 2016) which indicates high separability (TD values range from 0 to 2,000) in each of the three classified images, with one exception: the two tropical forest classes (PSF and rainforest) were spectrally confused with TD values around 1,200. This class confusion is relatively unsurprising. Though the two classes do contain some different tree species (e.g. PSFs are more commonly inhabited by *Koompassia malaccencis*, *Shorea uliginosa* and *Xylopia fusca*), hence our attempt to distinguish them spectrally, they have strong similarities in overall structure and form, leading to spectral overlap when observed via 30 m Landsat pixels. To overcome spectral confusion between, and subsequent misclassification of, peat swamp forest and rainforest, post-processing was conducted with the aid of a peatland map to constrain the extent of these two classes. This is described further below. Once land cover class training was complete, a straightforward supervision classification approach was conducted using the maximum likelihood (ML) rule. Although various contemporary approaches are now available, the ML is a well-known approach that is accurate where training classes are selected appropriately, as here, to ensure that parametric assumptions of normality are met (Momeni et al., 2016).

Visual inspection of the classified images confirmed widespread misclassification between the peat swamp forest and rainforest classes (as mentioned above). To correct this, first, the two classes were combined to form a single forest class, and a peatland extent map generated by Wetlands International was overlaid onto the land cover classifications. Any pixels classified as forest within the peatland area were recoded to peat swamp forest, while pixels classified as forest out of the peatland area were recoded to rainforest.

Finally, accuracy assessment was conducted on each of the three land cover maps by comparing a sample of classified pixels against the reference data (Miettinen et al., 2016). Relatively large samples were used to ensure statistical reliability, and equal numbers of points were used per class to enable comparability. In total, 450 random points were used for each classification, corresponding to 50 points per class. To avoid bias in the classification results, all accuracy assessment points were independent of the training samples (i.e. outside the training polygons).

2.5 Change detection

Post-classification comparison was used to compare the classification results, identifying the spatial distribution of change over time, as well as quantifying area of change (El-Hattab, 2016). This involved overlaying image pairs (1989 and 2001, 2001 and 2016, 1989 and 2016) and calculating pixel-by-pixel variation over time (spatial change) and overall class variation over time (areal change).

As well as interpretation of overall change in class areas, detailed examination was made of both deforestation and oil palm expansion. For this purpose, first, the two main forest classes (PSF and rainforest) were combined as a single class and extracted from each of the three land cover maps, before being overlaid in reverse chronological order (2016 forest layer overlaid on 2001 forest layer, overlaid on 1989 forest layer) to present the spatial pattern of forest loss over time. Conversely, the oil palm class was similarly extracted from the three land cover maps, but then overlaid in chronological order (1989 on 2001, on 2016), thus showing the spatial pattern of oil palm gain over time. Finally, here, specific inter-class land cover change between the different time periods (1989-2001, 2001-2016, 1989-2016) was presented by constructing change detection matrices.

2.6 Monitoring vegetation condition

NDVI maps were calculated to assess how peat swamp forest condition changes over the period of study. This standard and well-known approach is suitable and commonly used for examining vegetation in wetland environments (Antico, 2011; Mutanga et al., 2012; Kandus et al., 2017). The Landsat images used here were surface reflectance products, thus negating atmospheric influence on the NDVI values and ensuring the output images were directly comparable. NDVI maps were created for 1989, 2001 and 2016 across the whole study area, though attention focused principally on NSPSF. The intention here was to determine the effect of conservation measures put in place in the PSF reserve; specifically did vegetation condition improve (as represented by increasing NDVI values) after the conservation area was first gazetted in 1990-1991, and again after the logging moratorium in 2008-2010? Assessment of vegetation condition was conducted both quantitatively, whereby average NDVI values were calculated for the NSPSF footprint, and qualitatively, by visually examining spatial patterns of NDVI throughout NSPSF. Visual assessment was particularly useful to identify and interpret anthropogenic and environmental disturbances such as logged areas (often exhibiting a characteristic herringbone pattern) (Vergopolan and Fisher, 2016), drainage canals and burn scars after fire events.

3. Results

3.1 Land cover classification

The three land cover classifications are presented in Figure 2. The land cover maps all depict NSPSF (mid green) fairly clearly in the centre of the study area, bordered to the west by Sekinchan rice paddy fields (orange), and a mixture of rainforest (dark green), grassland (light green) and oil palm plantation (red) to the west. The former industrial mining area (Bestari Jaya) to the southeast of NSPSF is also clearly visible as a mixture of urban development (grey), bare soil (yellow) and water (blue) where quarries have been flooded from peat swamp run-off.

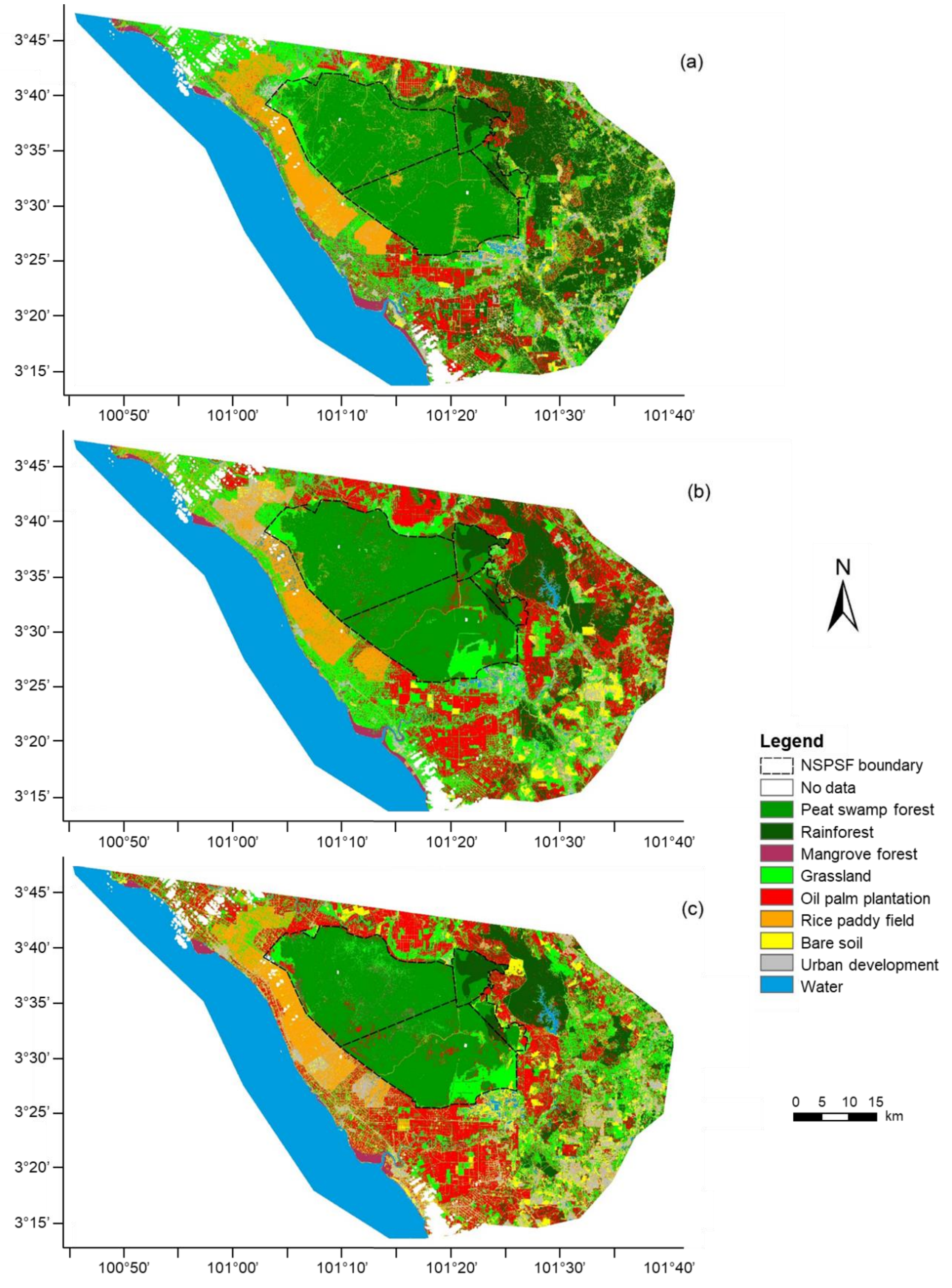

Figure 2. Land cover maps of North Selangor for (a) 1989, (b) 2001 and (c) 2016 generated from Landsat TM (1989, 2001) and OLI (2016) data (supplied by USGS).

Overlaid on the image are the NSPSF boundaries (supplied by GEC). No data refers to areas of cloud and cloud shadow.

The error matrices for the three land cover maps are presented in Tables 2-4 (presented at the end of the manuscript). Classification accuracy was relatively high in general, with the 1989, 2001 and 2016 land cover maps yielding overall classification accuracies of 80.2%, 84.4% and 84.7% respectively. The class of principal interest in this study – peat swamp forest – was classified well in general. Indeed, both the users and producers accuracy of PSF exceeded 95.5% in all three images, barring 2016 producers accuracy where the class was confused with mangrove. It is clear the post-processing operation to demarcate PSF and rainforest was successful.

The other class of central interest in this study – oil palm plantation – was also often classified well, with users and producers accuracy reaching 100.0% (1989) and 89.0% (2016) respectively, but on other occasions suffering from misclassification with, for instance, grassland (1989). This particular class confusion may be caused where oil palm plantation is being newly established: land is cleared of trees and other woody vegetation, but may have a grass or herb understorey, while oil palm seedlings are planted. The understorey can be confused easily with the grassland class. Moreover, sometimes land being cleared and prepared for oil palm plantation is cultivated for small crops (especially by smallholder farmers) for the first five years of the oil palm cycle while the canopy is open (e.g. pineapple, winter melon and cassava) to contribute to income strategies, or in the case of upland and industrial plantations, a cover crop (normally legume) to enhance soil nitrogen levels and reduce soil erosion, and this vegetation may also be confused with grassland.

Of the other land cover classes, most class accuracies were relatively high, regularly exceeding 85.0% or 90.0%, though there were certain consistent patterns of misclassification. For instance, grassland was confused with rice paddy fields in all three land cover maps, likely a consequence of the similar spectral appearance of flush, well-grown rice crops (where underlying water is not generally visible) with grass. It is also important to note that the term ‘grassland’ is a rather simplistic expression for the vegetation present within this class throughout the study area. As Table 1 states, this class includes scrubland (i.e. a mixture of low-lying grasses and herbs, and even small shrubs), and it essentially also acts as a catch-all class for other small-scale agriculture. As such, it is unsurprising there is confusion between grassland and other vegetation classes. Finally, the bare soil and urban development classes were confused in both the 1989 and 2001 land cover maps, probably due to the similar spectral appearance of dry soil and light impervious surfaces such as concrete.

3.2 Land cover change

The spatial distribution of land cover and patterns of change between 1989, 2001 and 2016 are displayed in Figure 2, with Table 5 (presented at the end of the manuscript) presenting land cover class areas and changes thereof over the study period. Although there has been some loss of peat swamp forest, falling from 746 km^2 in 1989 to 635 km^2 in 2016 (our main conservation concern in this paper), this is relatively modest compared to the loss of rainforest, which lacking protection from agricultural and other land conversion, has experienced substantial reductions from 710 km^2 in 1989 to 249 km^2 in 2016. In this context, it appears that the conservation programme put in place in NSPSF has had some success overall in reducing peat swamp forest loss.

Offsetting these losses, as expected, is a considerable gain in oil palm plantation, from 249 km^2 in 1989 to 700 km^2 in 2016. Elsewhere, rice paddy fields reduced in extent, especially in the first time period (1989-2001), while grassland area fluctuated, first expanding significantly (1989-2001), followed by a more modest contraction (2001-2016). Urban development and bare soil grew steadily between 1989 and 2001, followed by significantly accelerated growth between 2001 and 2016. Though only covering a small proportion of the study area, mangrove forest decreased rapidly over the study period, severely increasing the exposure of the coastal population to future storm surges and even tsunamis (E.H. Siow, personal communication, 2017). Finally, the extent of water was largely static throughout the study period.

3.2.1 Conversion of forest to oil palm

Further spatial detail of forest loss and oil palm gain is shown in Figure 3. Here, peat swamp forest and rainforest are combined as a single forest class (the two original classes can still be identified according to underlying substrate; any forest lying on peatland (the peatland boundary is overlaid on the map) is peat swamp forest, while forest outside the peatland boundary is rainforest). Widespread deforestation is apparent across the study area between 1989 and 2001 (Figure 3 (a), blue), a small area of which is in the southeast corner of NSPSF and corresponds to a set of major burn events brought about by the drainage infrastructure originating from old timber transport canals (Evers et al., 2016). In addition, the lack of on-the-ground demarcation of NSPSF's boundaries during these early years of the reserve meant there was a high incidence of fire being used as a tool for forest clearance prior to oil palm plantation (GEC, 2014). The blue crescent area immediately north of NSPSF shows where an area of peat swamp forest (on tropical peatland, but outside the NSPSF boundary so unprotected from development) was cleared. Most of the land deforested between 1989 and 2001, though, is scattered throughout the eastern part of the study area, well away from the peatland.

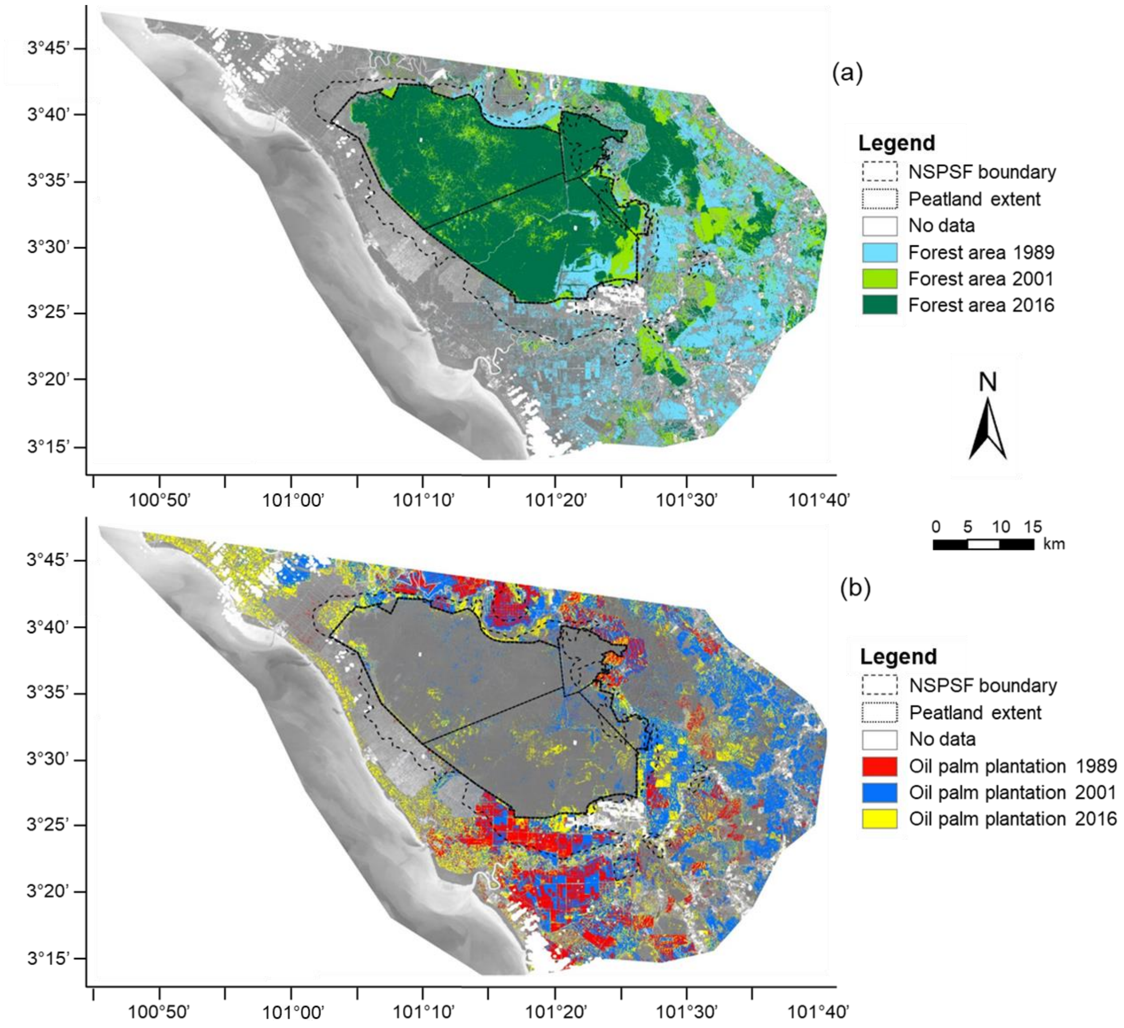

Figure 3. Land cover change in North Selangor between 1989, 2001 and 2016, showing (a) loss of tropical forest and (b) gain of oil palm plantation. The forest category includes both peat swamp forest and rainforest, and the later distributions are overlaid on the earlier ones (i.e. 2016 on 2001 on 1989), showing forest loss over time. For oil palm, the earlier distributions are overlaid on the later ones (i.e. 1989 on 2001 on 2016), showing gain over time. Overlaid on the image are the peatland extent (supplied by Wetlands International) and the NSPSF boundaries (supplied by GEC).

Deforestation slowed after 2001 (Figure 3 (a), light green), though is still widespread throughout the study area. This slow-down is likely related to the ease with which forest can be cleared; the easiest areas (most accessible, shallowest gradients etc.)

were deforested first (1989-2001), leaving more challenging terrain for later (2001-2016). There is further deforestation in the southeast corner of NSPSF, and this is again related to burn events. However, stronger enforcement of reserve boundaries around this time meant the plantation expansion was minimal (GEC, 2014). The burn events have led to an increasing area of stable scrubland (classified grassland in Figure 2), which remains vulnerable to annual fire events even now. Elsewhere within NSPSF, there is evidence of scattered forest loss, though this is not substantial, and is in any case often attributed to misclassified pixels in the land cover maps.

Forested areas in 2016 (Figure 3 (a), dark green) are confined mainly to NSPSF and another protected area of rainforest to its northeast (which comprises rough terrain and is therefore difficult to convert), and a few patches to the east of the study area. Figure 3 does not explicitly show forest gain, since the later (2001, then 2016) forest extents are simply overlaid on the former (1989), but over each time period (1989-2001 and 2001-2016) there is some evidence on infilling within NSPSF where new PSF replaces other classes (often grassland).

Figure 3 (b) shows increase in the spatial extent of oil palm over the study period, which to a great extent mirrors the loss of forest. Though oil palm is widespread in 1989 (Figure 3 (b), red), it occupies a fairly small proportion of the study area, concentrated mainly around the basins of the rivers Bernam (in the north) and Selangor (in the south). By 2001, large expanses of land to the east, north and south of NSPSF have been converted to oil palm (Figure 3 (b), blue). At this time, there is some evidence of oil palm within NSPSF, and as mentioned above some of this corresponds to illegal encroachment from smallholders along the eastern and south-eastern borders, though this is relatively minor. Scattered oil palm shown throughout NSPSF is generally a result of misclassified pixels. As of 2016, further land has been converted to oil palm, though the pace of conversion has dropped significantly. Much of this change is along the coast on the west of the study area since much of the accessible rainforest in the east has already been converted. These new oil palm plantations tend to be relatively small and fragmented compared to the large plantations established in the east. Again, there are some, though modest, new areas of oil palm in NSPSF. Illegal encroachment is evident along the northwest and southeast boundaries, facilitated by the easy access to the forest at these points (whereas the rest of the reserve perimeter is bordered by large drainage canals making access difficult), but again the scattered oil palm shown throughout the reserve is mainly caused by misclassified pixels.

3.2.2 Inter-class change

Inter-class change is presented in change matrices for 1989-2001, 2001-2016 and 2001-2016 (Tables 6-8). Significantly, these corroborate that new oil palm plantation is being established at the expense of forested land, especially rainforest. While there is some evidence of peat swamp forest being converted to oil palm (59 km^2 overall between 1989 and 2016), there is much more incidence of rainforest to oil palm conversion (e.g. 230 km^2 in only the first 1989-2001 time period). Moreover, there is a clear pattern of grassland acting as a pioneer class for forest to oil palm conversion, whereby cleared forest and new plantation resembles grassland until the oil palms become established. Change from grassland to oil palm is evident throughout the study (177 km^2 overall between 1989 and 2016). While most new oil palm is planted on forest or grassland, a separate agricultural trend shows a shift from rice to palm oil cultivation (e.g. 73 km^2 converted from rice to oil palm between 1989 and 2001).

Table 6. Inter-class land cover change between 1989 and 2001 in North Selangor.

1989 land cover class (km^2)	2001 land cover class (km^2)								
	Peat swamp forest	Rain forest	Mangrove forest	Grassland	Oil palm plantation	Rice paddy field	Bare soil	Urban development	Water
Peat swamp forest	624.7	0.1	0.1	59.5	49.3	6.7	1.4	4.2	0.0
Rainforest	0.1	254.7	0.6	127.4	230.2	23.0	32.1	36.1	5.2
Mangrove forest	0.3	0.7	22.3	37.5	2.5	16.0	0.5	5.2	1.4
Grassland	20.6	27.4	4.3	4.3	135.2	59.7	11.4	31.6	3.2
Oil palm plantation	2.1	18.5	0.1	64.4	139.0	6.4	7.9	10.4	0.5
Rice paddy field	40.6	36.0	2.6	103.3	72.5	165.1	12.5	48.8	9.1
Bare soil	0.0	2.3	0.4	11.8	12.5	8.3	3.6	12.9	3.3
Urban development	1.3	5.2	3.2	61.2	26.8	35.3	6.5	45.7	7.9
Water	0.0	0.2	3.2	4.4	0.1	6.4	0.5	3.6	709.8

Table 7. Inter-class land cover change between 2001 and 2016 in North Selangor.

2001 land cover class (km^2)	2016 land cover class (km^2)								
	Peat swamp forest	Rain forest	Mangrove forest	Grassland	Oil palm plantation	Rice paddy field	Bare soil	Urban development	Water

Peat swamp forest	595.9	0.0	11.4	44.4	29.2	2.1	4.7	1.8	0.2
Rainforest	0.0	186.5	0.4	62.8	65.6	8.9	13.5	6.2	1.1
Mangrove forest	0.0	0.3	16.3	2.8	2.8	5.1	3.1	3.4	2.9
Grassland	12.1	19.0	7.2	220.5	228.7	93.1	47.2	64.3	3.7
Oil palm plantation	20.3	36.5	1.0	188.5	321.2	40.8	37.7	21.6	0.5
Rice paddy field	5.7	3.0	4.0	45.0	25.0	149.5	24.0	61.7	9.1
Bare soil	0.1	1.1	0.1	9.6	9.5	12.8	14.7	27.8	0.7
Urban development	0.9	2.4	1.0	36.4	18.0	47.5	23.7	64.5	4.3
Water	0.0	0.1	3.8	3.0	0.3	10.0	5.4	3.0	715.7

Table 8. Inter-class land cover change between 1989 and 2016 in North Selangor.

1989 land cover class (km^2)	2016 land cover class (km^2)								
	Peat swamp forest	Rainforest	Mangrove forest	Grassland	Oil palm plantation	Rice paddy field	Bare soil	Urban development	Water
Peat swamp forest	577.5	0.1	10.4	8.4	58.8	5.0	6.4	3.6	0.3
Rainforest	0.1	193.2	0.9	182.7	192.4	36.8	49.2	47.8	6.5
Mangrove forest	0.3	0.6	16.0	13.7	18.9	16.4	7.1	9.7	3.7
Grassland	18.9	16.6	6.2	143.2	176.5	75.1	33.4	45.8	3.9

Oil palm plantation	1.9	11.3	0.3	42.6	152.1	17.7	12.4	10.2	0.7
Rice paddy field	34.8	20.9	2.6	97.0	63.1	172.5	30.8	64.4	4.6
Bare soil	0.1	1.7	0.5	11.6	9.5	7.1	8.4	12.6	3.7
Urban development	1.5	4.4	2.4	33.7	28.7	34.7	21.7	57.0	9.2
Water	0.0	0.1	5.9	4.6	0.5	4.5	4.7	3.2	704.9

Other notable trends in inter-class change relate to the urban development class. Urban land expands significantly throughout the study, especially between 2001 and 2016, with much urban development takes place on grassland (64 km^2) and rice paddy fields (62 km^2).

3.3 Peat swamp forest condition

The general condition of the vegetation in NSPSF, and how this has changed over time, is presented in the 1989, 2001 and 2016 NDVI maps (Figure 4). Quantitatively, there is a clear increase in NDVI value over the period of study, rising from an average value of 0.57 in 1989 to 0.85 in 2016. Though there is small drop in average NDVI between 1989 and 2001 (from 0.57 to 0.54), this can be explained in part by a large burn scar in the southeast of the reserve in the 2001 image. This interpretation is reinforced by the facts that minimum NDVI (i.e. representing the burn scar) is lower in 2001 than 1989, while maximum NDVI (e.g. representing healthy forest) is higher in 2001 than 1989.

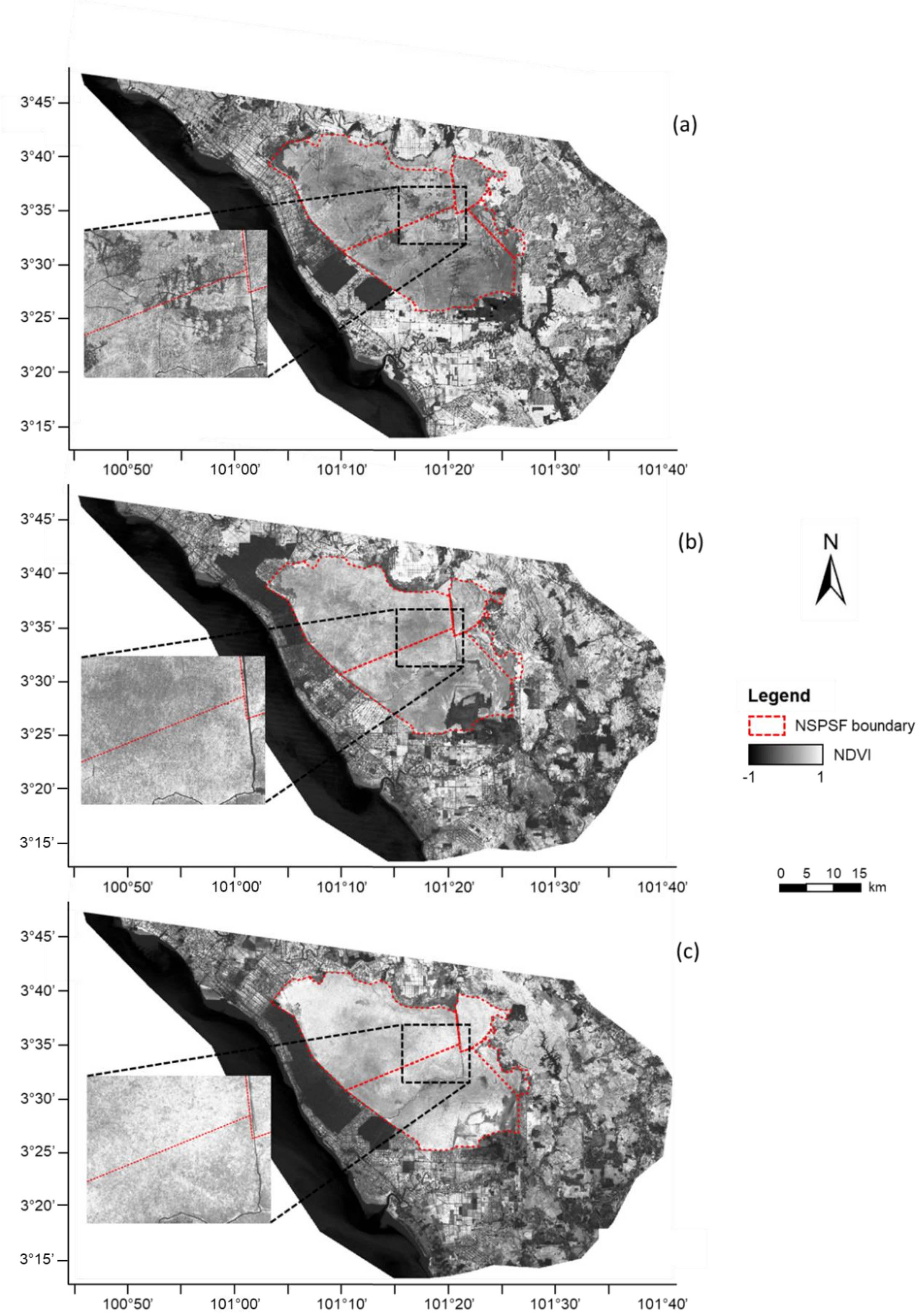

Figure 4. Vegetation condition maps of NSPSF for (a) 1989, (b) 2001 and (c) 2016, calculated using the NDVI on Landsat TM (1989, 2001) and OLI (2016) data (supplied by USGS). Summary NDVI statistics calculated for the NSPSF footprint: (a) Minimum

= -0.111, Mean = 0.571, Maximum = 0.712 and Standard deviation = 0.041; (b) Minimum = -0.258, Mean = 0.543, Maximum = 0.873 and Standard deviation = 0.070; and (c) Minimum = -0.112, Mean = 0.846, Maximum = 0.960 and Standard deviation = 0.041. NSPSF boundary supplied by GEC.

Visually, clear patterns of disturbance are evident in 1989 (Figure 4 (a) inset), just prior to when the reserve was established, and conservation measures first implemented. In particular, the dark herringbone patterns characteristic of logging activities is clear, as are the even darker linear drainage channels. By 2001, there is much less evidence of disturbance, and vegetation has recovered significantly. Notably, the dark logging and drainage features present in 1989 have largely disappeared, with the area displayed in more homogenous lighter grey tones (Figure 4 (b) inset). By 2016, the recovery has continued, with few darker linear features detectable at all, and the area display in brighter tones (Figure 4 (c) inset).

The burn scars present in the 2001 and 2016 NDVI maps reference an ongoing conservation concern in NSPSF. Fire is extremely damaging to peat swamp forests (and, indeed, to peatlands in general), rapidly eroding the peat layer and thus releasing unrecoverable carbon into the atmosphere, and in severe cases killing mature trees. Nonetheless, fire damage from the past continues to hinder recovery, and here the NDVI maps perhaps give an overly positive impression of the current situation. For instance, the large burn scar in 2001 appears to have recovered considerably by 2016 (Figure 4 (b) – (c)), but in fact the vegetation exhibiting the bright NDVI tones in the 2016 image is principally low-lying grasses and shrubs rather than mature trees. Clearly, the conservation value of this scrubland vegetation is far lower than the original forest prior to the burn event.

4. Discussion

4.1 Oil palm expansion: an ongoing threat to tropical peatlands

This study sought to determine to what extent oil palm expansion has occurred within NSPSF and the surrounding area, as well as how much of this expansion can be linked to the loss of indigenous forest, especially PSF. The results show that oil palm expansion has been rapid and widespread throughout the study area, and that most of this new development did indeed occur on previously forested land (Figure 2, Table 5). However, of the converted forest, by far the majority was rainforest, with the more environmentally sensitive PSF much less prone to oil palm development. One likely explanation for this finding is that it is more cost-effective to develop new plantations on mineral soils (formerly occupied by rainforest) as opposed to peatlands. This is due to the additional construction and labour costs associated with the land preparation of peatland (i.e. peatlands need to be sufficiently drained before planting) (Corley and Tinker, 2008; Koh and Wilcove, 2008), as well as the often lower yields associated with oil palm on peat. Therefore, this study reflects similar trends observed by Koh et al. (2011) who found that almost 90% of oil palm development in Southeast Asia before the early 2000s occurred on non-peatland areas, only 6% occurring on PSF. However, the study did concede that regional variations can be significant, and in Peninsular Malaysia, for instance, approximately 27% of PSFs had been lost to oil palm agriculture (Koh et al., 2011).

It has also been suggested that as global demand for palm oil increases, and the availability of more profitable and productive land becomes scarcer, future oil palm expansion could increasingly encroach onto peatlands and other marginal areas (Koh, 2007; Koh and Wilcove, 2007; Fitzherbert et al., 2008). Early warning signs of this transition are already starting to present themselves; for instance, the Malaysian oil palm industry is believed to have reached its maximum quota of available non-forested land suitable for conversion to oil palm, in Peninsular Malaysia, Sarawak and Sabah, Borneo (Pirker et al., 2016). Moreover, the country has already surpassed its 21,000 km² (45.7%) of available land (i.e. non-occupied land with a low conservation value), as 46,000 km² are currently planted with oil palm, causing it to exceed its sustainable area (Pirker et al., 2016; FAO, 2016).

In NSPSF, evidence of illegal encroachment of oil palm plantation can be observed (Figure 3), particularly between 2001 and 2016. Furthermore, by 2001 there had been a significant increase in the amount of large-scale monoculture plantations which continue to dominate along the northern and eastern fringes of the NSPSF today. According to GEC (2014), approximately 15 km² of oil palm plantations had been established within the boundary of NSPSF.

Though the oil palm industry is obviously a significant player in the immediate clearance of Malaysia’s tropical forests, it by no means carries sole responsibility for this. A combination of other influences such as the timber industry, governmental policy, financial entities and the modernisation of the country all serve to facilitate oil palm expansion at the expense of the region’s forests. For instance, logged-over or burned forests are considered by the government to be degraded habitats and are therefore allowed to be cleared for agricultural use (McMorrow and Talip, 2001; Margono et al., 2014). Subsequently, this has encouraged the ‘legal’ conversion of secondary forest to oil-palm plantation, in both Malaysia and Indonesia (Casson, 2000). Indications of this occurring within the study area could be inferred from the amount of tropical forest converted first to grassland, and then from grassland to oil palm throughout the study period (Tables 6 and 7).

Kamlun et al. (2016) noticed that the relocation and expansion of large commercial oil palm plantations in Indonesia caused the displacement of smallholder plantations, forcing them to relocate cultivation to the forest frontier, further increasing deforestation (Gatto et al., 2015). It could be argued that due to increasing land scarcity and the monopoly of large commercial plantations, smallholders in North Selangor are forced to construct plantations along the NSPSF reserve boundary. There is certainly some evidence of this along the southeastern boundary of the reserve.

Other negative consequences of oil palm development in North Selangor in recent years include periodic water shortages in the Sekinchan rice paddy fields, caused by the irrigation needs of upstream plantations (GEC, 2014). Instability in North Selangor's well-established rice industry could result in high unemployment and possible food shortages if sustainable land management strategies are continually undermined. Furthermore, the discovery that young oil palm plantations have replaced secondary rainforest on the hillslopes to the east of NSPSF shows that even catchment areas which serve as water supplies for NSPSF and the Sekinchan rice paddy fields are vulnerable to deforestation. This could be detrimental to local communities if flooding and landslide events become more frequent during heavy rainfall events (GEC, 2014) due to reduced vegetation interception and poor soil consolidation in catchment areas.

The abandonment of the former tin mining/sand tilling operations to the southeast of NSPSF have allowed for the formation of a natural wetland which is currently exacerbating the drainage of the surrounding hydrology and increasing the susceptibility of nearby vegetation to wildfire (initially started by 'slash and burn' clearance) during the dry season. There is also evidence that oil palm plantation around NSPSF is leading to severe subsidence and ground collapse due to the unstable composition and nutrient depletion of the peat soil (Tonks et al., 2016). More broadly, this process is increasing susceptibility to flooding and saline intrusion throughout Southeast Asia's peatlands (Evers et al., 2016).

4.2 Peat swamp forest conservation: NSPSF an example of best practice?

This study also focused on the conservation initiative in NSPSF and examined whether its protected status since 1990 has improved PSF condition. The results here show strong PSF recovery following the uncontrolled logging activity that occurred prior to the gazettement of the reserve (Kumari, 1996). Between 1989 and 2001, NSPSF's interior improved markedly, both in terms of PSF gain (Figure 2 (a) – (b)) and general vegetation condition (Figure 4 (a) – (b)).

Despite the improved general condition of vegetation in much of the interior of NSPSF, assessed using straightforward NDVI analysis, other problems are evident, including burn scars from ongoing fire events (Figure 4). These issues have negative implications for the tree layer, as well as the underlying peat. The area around the southeast boundary of the reserve has experienced deforestation (Figure 3 (a)) as a result of fire; in addition, in these areas, as well as on the northwest boundary, there is evidence of illegal encroachment of oil palm. Historically, fire has been used to clear forest for oil palm development (Cattau et al., 2016) and there is some suggestion that this has occurred illegally in and around the southeast border of NSPSF. Fire prevention activities, including raising general public awareness of the severe environmental damage caused by burning peatland has improved in recent times, as have security and patrolling measures (Dahalan et al., 2016; Rengasamy et al., 2016). Overall, while conservation interventions have clearly improved the condition of NSPSF as a whole, areas of concern remain, and current enforcement and monitoring techniques could be further strengthened.

In view of the relative conservation success at NSPSF, it is worth acknowledging the roles played by the managing bodies, GEC and SSFD, respectively. In particular, GEC has been a consistent advocate for enhanced protection and conservation of the NSPSF, at times confronting both corporate and governmental actors in periods of oil palm encroachment, while also establishing a monitoring and response system to help tackle peat fires (E.H. Siow, personal communication, 2017). Another important contribution by GEC has been in the development of a site-specific management plan for the NSPSF (Evers et al., 2016). The plan sets out recommended management strategies for different parts of the forest with emphasis placed based on protection of peatlands while respecting the demands for agricultural development along its borders. This zonal approach to the management of the NSPSF and adjacent areas has been met with support from key actors within the Selangor state government which has the potential to affirm future protection of the peatlands in North Selangor.

At a broader scale, despite the introduction of a logging ban across Selangor State in 2010, the Malaysian government has continued to permit selective logging practices within areas of low catchment and conservation value. Accordingly, designating a PSF 'protected status' does not guarantee complete protection in the long term. Thus, the conservation successes achieved at NSPSF – as demonstrated in this study – appear an example of best practice and potentially offer a path forward for other areas of intact PSF in Southeast Asia. The experience in North Selangor draws parallels with other participatory conservation initiatives whereby local stakeholders (e.g. members of public, resident associations, community groups, NGOs) are directly involved (Watson et al., 2014; Oldekop et al., 2015; Nath et al., 2016). Such approaches may provide an alternative to market-driven conservation initiatives, such as Reducing Emissions from Deforestation and Forest Degradation (REDD+), which to date have experienced limited success (Mbatu, 2016). Likewise, many of the large policy initiatives run by the Malaysian Palm Oil Board (MPOB), the Indonesian Palm Oil Board (IPOB) and the Roundtable on Sustainable Palm Oil (RSPO) are not enforceable or legally binding and are instead are promoted as 'preferred management guidelines' (Evers et al., 2016;

Padfield et al., 2016). Considering the threat posed to remaining peatlands in Southeast Asia, exploring similar options for the participation of community and NGO groups in PSF management plans and conservation activities would certainly be timely.

5. Conclusions

The pervasive expansion of the oil palm industry in Southeast Asia is a growing environmental concern, and it seems clear that increasing global demand for palm oil is causing unsustainable development of oil palm plantations. This study shows unequivocally that large swathes of rainforest throughout Northern Selangor, Malaysia have been converted to oil palm over the last three decades, and this is contributing to a loss of ecosystem services including substantial emission of GHGs and widespread reduction in biodiversity. Meanwhile, comparing the regional picture of oil palm expansion against the minimal presence of oil palm inside NSPSF, the conservation initiative could be considered broadly successful, protecting the reserve from oil palm encroachment in all but a few boundary zones, and also enhancing the condition of the peat swamp forest interior through conservation measures, such as banning commercial logging, blocking drainage channels, rehabilitating degraded land, demarcating the reserve boundary and protecting biodiversity. Without the long-term oversight of the SSFD and GEC, NSPSF may well have suffered the same high rate of deforestation as the region’s dryland rainforests. Here, the value of a local NGO, coupled with the concept of community-led conservation has been demonstrated.

The Landsat imagery archive has here been shown to be an unparalleled tool in monitoring historical and current conversion of native forests to oil palm plantations, and also provides a present day land cover inventory against which future change can be assessed. While Landsat data will continue to be available (Landsat 9 is tentatively scheduled for launch in 2020 (NASA, 2018)), other remote sensing products such as those offered by the European Space Agency's Sentinel programme (ESA, 2018) offer further opportunity for ongoing long-term and broad-scale assessment of oil palm encroachment. Additionally, data from VHR satellite imagery, although not cost free, enable more detailed investigation of oil palm encroachment, with drones also offering cheap options for targeted, flexible and regular environmental monitoring in support of conservation initiatives. Therefore, future broad scale PSF monitoring efforts may build on the methods presented here, incorporating additional data sources including Sentinel, VHR, drone and potentially airborne lidar data, along with the upcoming spaceborne lidar mission, Global Ecosystem Dynamics Investigation (GEDI), which holds enormous potential for broad scale analysis of vegetation structure (GEDI, 2018), potentially revolutionising routine environmental monitoring, and characterisation of PSF, oil palm plantation and other woody vegetation.

The picture presented in this study of pervasive oil palm expansion across North Selangor is representative of change across Southeast Asia, and serves to remind us of the importance of controlling and managing the palm oil industry at the broad scale. The example of NSPSF, whereby conservation measures such as drain blocking, fire prevention, PSF rehabilitation and reserve boundary demarcation have been practiced over the last three decades, suggests that careful stewardship of PSF environments may be successful in ensuring their persistence and their health. It is recommended that similar management practices and conservation initiatives are adopted in other PSFs, exploiting the growing resource of remote sensing technology to establish effective monitoring programmes, to safeguard this valuable and diminishing ecosystem throughout Southeast Asia and around the world.

Acknowledgments

We extend our warm gratitude to Mr Eng Huwat Siow for his enormous generosity and invaluable knowledge regarding oil palm cultivation and the natural history of North Selangor, as well as facilitating our field data collection. We are also grateful for the information provided to us regarding land cover change in and around NSPSF by various local stakeholders, residents and plantation workers.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Lewis J. Charters https://orcid.org/0000-0001-6567-5760

Paul Aplin https://orcid.org/0000-0002-9394-5630

Christopher G. Marston https://orcid.org/0000-0002-2070-2187

Rory Padfield https://orcid.org/0000-0002-1659-6932

Stephanie Evers https://orcid.org/0000-0002-6639-5776),

References

1. Adila, N., Sasidhran, S., Kamarudin, N., Puan, C., Azhar, B. and Lindenmayer, D. (2017). Effects of peat swamp logging and agricultural expansion on species richness of native mammals in Peninsular Malaysia. *Basic and Applied Ecology*, 22, 1-10.
2. Antico, A. (2011). Independent component analysis of MODIS-NDVI data in a large South American wetland. *Remote Sensing Letters*, 3(5), 383-392.
3. Austin, K., Mosnier, A., Pirker, J., McCallum, I., Fritz, S. and Kasibhatla, P. (2017). Shifting patterns of oil palm driven deforestation in Indonesia and implications for zero-deforestation commitments. *Land Use Policy*, 69, 41-48.

4. Brown, C., Boyd, D.S., Sjogersten, S., Clewley, D., Evers, S.L. and Aplin, P. (2018). Tropical peatland vegetation structure and biomass: optimal exploitation of airborne laser scanning. *Remote Sensing*, 10, 671.
5. Buchanan, G., Butchart, S., Dutson, G., Pilgrim, J., Steininger, M., Bishop, K. and Mayaux, P. (2008). Using remote sensing to inform conservation status assessment: Estimates of recent deforestation rates on New Britain and the impacts upon endemic birds. *Biological Conservation*, 141(1), 56-66.
6. Campbell. J. and Wynne, R.H. (2011). *Introduction to Remote Sensing*. 5th edition. New York, NY: The Guilford Press.
7. Casson, A. (2000) The Hesitant Boom: Indonesia's oil palm sub-sector in an era of economic crisis and political change. *CIFOR Program on the Underlying Causes of Deforestation*. Accessed 6 November 2018. http://www.cifor.cgiar.org/publications/pdf_files/CASSON.pdf
8. Cattau, M., Harrison, M., Shinyo, I., Tungau, S., Uriarte, M. and DeFries, R. (2016). Sources of anthropogenic fire ignitions on the peat-swamp landscape in Kalimantan, Indonesia. *Global Environmental Change*, 39, 205-219.
9. Chong, K., Kanniah, K., Pohl, C. and Tan, K. (2017). A review of remote sensing applications for oil palm studies. *Geo-spatial Information Science*, 20(2), 184-200.
10. Choo, Y., Muhamad, H., Hashim, Z., Subramaniam, V., Puah, C. and Tan, Y. (2011). Determination of GHG contributions by subsystems in the oil palm supply chain using the LCA approach. *The International Journal of Life Cycle Assessment*, 16(7), 669-681.
11. Corley, R. and Tinker, P. (2008). *The Oil Palm*. 4th edition. New York, NY: John Wiley & Sons.

12. Dahalan, M.P., Manaf, M.B.A., Rahman, B.H.A., Khalid, S.M.A.S., Sukri, A.M., Yusoff, D.M., M., Muda, Y., Napiah, H., Parish, F., Rengasamy, N., Lew, S.Y. and Lo, J. (2016) Implementation of Integrated Management Plan for North Selangor Peat Swamp Forest 2014-2023. Paper presented at 15th International Peat Congress, Sarawak, Malaysia, August 15-19.
13. Dislich, C., Keyel, A., Salecker, J., Kisel, Y., Meyer, K., Auliya, M., Barnes, A., Corre, M., Darras, K., Faust, H., Hess, B., Klasen, S., Knohl, A., Kreft, H., Meijide, A., Nurdiansyah, F., Otten, F., Pe'er, G., Steinebach, S., Tarigan, S., Tölle, M., Tscharntke, T. and Wiegand, K. (2017). A review of the ecosystem functions in oil palm plantations, using forests as a reference system. *Biological Reviews*, 92(3), 1539-1569.
14. El-Hattab, M. (2016). Applying post classification change detection technique to monitor an Egyptian coastal zone (Abu Qir Bay). *The Egyptian Journal of Remote Sensing and Space Science*, 19(1), 23-36.
15. Evers, S., Yule, C., Padfield, R., O'Reilly, P. and Varkkey, H. (2016). Keep wetlands wet: the myth of sustainable development of tropical peatlands - implications for policies and management. *Global Change Biology*, 23(2), 534-549.
16. European Space Agency (ESA). (2018). "*Overview*". Accessed 6 November 2018. https://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Overview4
17. Fitzherbert, E., Struebig, M., Morel, A., Danielsen, F., Bruhl, C., Donald, P. and Phalan, B. (2008). How will oil palm expansion affect biodiversity? *Trends in Ecology & Evolution*, 23(10), 538-545.
18. Gatto, M., Wollni, M. and Qaim, M. (2015). Oil palm boom and land-use dynamics in Indonesia: The role of policies and socioeconomic factors. *Land Use Policy*, 46, 292-303.

19. Gaveau, D., Sloan, S., Molidena, E., Yaen, H., Sheil, D., Abram, N., Ancrenaz, M., Nasi, R., Quinones, M., Wielaard, N. and Meijaard, E. (2014). Four Decades of Forest Persistence, Clearance and Logging on Borneo. *PLoS ONE*, 9(7), 101654.
20. GEC (Global Environment Centre). (2014). Integrated Management Plan for North Selangor Peat Swamp Forest 2014–2023 for Selangor State Forestry Department, (June).
21. GEDI (Global Ecosystem Dynamics Investigation). (2018). *High resolution laser ranging of Earth's forests and topography from the International Space Station (ISS).* Accessed 6 November 2018. https://gedi.umd.edu/
22. Germer, J. and Sauerborn, J. (2008). Estimation of the impact of oil palm plantation establishment on greenhouse gas balance. *Environment Development and Sustainability*, 10(6), 697-716.
23. Goldstein, J. (2015). Knowing the subterranean: Land grabbing, oil palm, and divergent expertise in Indonesia's peat soil. *Environment and Planning A*, 48(4), 754-770.
24. Hansen, M.C., Stehman, S.V., Potapov, P.V., Arunarwati, B., Stolle, F. and Pittman, K. (2009). Quantifying changes in the rates of forest clearing in Indonesia from 1990 to 2005 using remotely sensed data sets. *Environmental Research Letters*, 4.
25. Jaafar, M., (1994). "The Malaysian palm oil – a dynamic industry" in Selected Readings on Palm Oil and Its Uses, PORIM Publication, Bangi, Selangor.
26. Kamlun, K., Bürger Arndt, R. and Phua, M. (2016). Monitoring deforestation in Malaysia between 1985 and 2013: Insight from South-Western Sabah and its protected peat swamp area. *Land Use Policy*, 57, 418-430.
27. Kandus, P., Minotti, P., Morandeira, N., Grimson, R., González Trilla, G., González, E., San Martín, L. and Gayol, M. (2017). Remote sensing of wetlands in South

America: status and challenges. *International Journal of Remote Sensing*, 39(4), 993-1016.

28. Khatun, R., Reza, M., Moniruzzaman, M. and Yaakob, Z. (2017). Sustainable oil palm industry: The possibilities. *Renewable and Sustainable Energy Reviews*, 76, 608-619.
29. Koh, L. (2007). Potential Habitat and Biodiversity Losses from Intensified Biodiesel Feedstock Production. *Conservation Biology*, 21(5), 1373-1375.
30. Koh, L. P., Miettinen, J., Liew, S.C. and Ghazoul, J. (2011). Remotely sensed evidence of tropical peatland conversion to oil palm. *Proceedings of the National Academy of Sciences*, 108(12), 5127-5132.
31. Koh, L. and Wilcove, D. (2007). Cashing in palm oil for conservation. *Nature*, 448(7157), 993-994.
32. Koh, L. and Wilcove, D. (2008). Is oil palm agriculture really destroying tropical biodiversity? *Conversation Letters*, 1(2), 60-64.
33. Kumari, K. (1996). An Application of the Incremental Cost Framework to Biodiversity Conservation: A Wetland Case Study in Malaysia. Centre for Social and Economic Research on the Global Environment Working Paper GEC 96-15.
34. Malaysian Palm Oil Board (MPOB). (2018). *The Official Portal of Malaysian Palm Oil Board*. Accessed 6 November 2018. http://www.mpob.gov.my/
35. Margono, B., Potapov, P., Turubanova, S., Stolle, F. and Hansen, M. (2014). Primary forest cover loss in Indonesia over 2000–2012. *Nature Climate Change*, 4(8), 730-735.
36. Marston, C.G.; Aplin, P.; Wilkinson, D.M.; Field, R.; O'Regan, H.J. (2017). Scrubbing Up: Multi-Scale Investigation of Woody Encroachment in a Southern African Savannah. *Remote Sensing*. 9, 419.

37. Mbatu, R. (2016). REDD + research: Reviewing the literature, limitations and ways forward. *Forest Policy and Economics*, 73, 140-152.

38. McMorrow, J. and Talip, M. (2001). Decline of forest area in Sabah, Malaysia: Relationship to state policies, land code and land capability. *Global Environmental Change*, 11(3), 217-230.

39. Meijaard, E., Garcia-Ulloa, J., Sheil, D., Wich, S., Carlson, K., Juffe-Bignoli, D. and Brooks, T. (2018). *Oil palm and biodiversity: a situation analysis by the IUCN Oil Palm Task Force*. [online] Gland, Switzerland: IUCN, xiii - 116. Accessed 6 November 2018. https://doi.org/10.2305/IUCN.CH.2018.11.en

40. Miettinen, J., Shi, C. and Liew, S. (2016). Land cover distribution in the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015 with changes since 1990. *Global Ecology and Conservation*, 6, 67-78.

41. Momeni, R., Aplin, P. and Boyd, D. (2016). Mapping Complex Urban Land Cover from Spaceborne Imagery: The Influence of Spatial Resolution, Spectral Band Set and Classification Approach. Remote Sensing, 8(2), 88.

42. Mutanga, O., Adam, E. and Cho, M. (2012). High density biomass estimation for wetland vegetation using WorldView-2 imagery and random forest regression algorithm. *International Journal of Applied Earth Observation and Geoinformation*, 18, 399-406.

43. Nath, T.K., Dahalan, M.P.B., Parish, F. and Rengasamy, N. (2016). Local peoples' appreciation on and contribution to conservation of peatland swamp forests: experience from Peninsular Malaysia. Paper presented at 15th International Peat Congress, Sarawak, Malaysia, August 15-19.

44. National Aeronautics and Space Administration (NASA) (2018). *Landsat 9*. Accessed 6 November 2018. https://landsat.gsfc.nasa.gov/landsat-9/

45. Oldekop, J., Holmes, G., Harris, W. and Evans, K. (2015). A global assessment of the social and conservation outcomes of protected areas. *Conservation Biology*, 30(1), pp.133-141.

46. Padfield, R., Drew, S., Syayuti, K., Page, S., Evers, S., Campos-Arceiz, A., Kangayatkarasu, N., Sayok, A., Hansen, S., Schouten, G., Maulidia, M., Papargyropoulou, E. and Tham, M. (2016). Landscapes in transition: an analysis of sustainable policy initiatives and emerging corporate commitments in the palm oil industry. *Landscape Research*, 41(7), 744-756.

47. Padfield, R., Waldron, S., Drew, S., Papargyropoulou, E., Kumaran, S., Page, S., Gilvear, D., Armstrong, A., Evers, S., Williams, P., Zakaria, Z., Chin, S., Balle Hansen, S., Campos-Arceiz, A., Latif, M., Sayok, A. and Tham, M. (2014). Research agendas for the sustainable management of tropical peatland in Malaysia. *Environmental Conservation*, 42(01), 73-83.

48. Page, S.E., Rieley, J.O., Banks, C.J. (2011). Global and regional importance of the tropical peatland carbon pool. *Global Change Biology*. 17, 798–818.

49. Paterson, R. and Lima, N. (2017). Climate change affecting oil palm agronomy, and oil palm cultivation increasing climate change, require amelioration. *Ecology and Evolution*, 8(1), 452-461.

50. Pirker, J., Mosnier, A., Kraxner, F., Havlík, P. and Obersteiner, M. (2016). What are the limits to oil palm expansion? *Global Environmental Change*, 40, 73-81.

51. Posa, M.R.C., Wijedasa, L.S., Corlett, R.T. (2011). Biodiversity and Conservation of Tropical Peat Swamp Forests. *BioScience*, 61(1), 49–57.

52. Rahim, A.N. and Yusop, Z., (1999). Hydrological impacts of forestry and land-use activities: Malaysian and regional experience. *Water: Forestry and Land Use Perspectives; Technical Documents in Hydrology*, 70, 86-105.

53. Razali, S., Marin, A., Nuruddin, A., Shafri, H. and Hamid, H. (2014). Capability of Integrated MODIS Imagery and ALOS for Oil Palm, Rubber and Forest Areas Mapping in Tropical Forest Regions. *Sensors*, 14(5), 8259-8282.
54. Rengasamy, N., Parish, F., Lew, S.Y. and Azura, N. (2016). Peatland rehabilitation efforts in North Selangor Peat Swamp Forests. Paper presented at 15th International Peat Congress, Sarawak, Malaysia, August 15-19.
55. Sasidhran, S., Adila, N., Hamdan, M., Samantha, L., Aziz, N., Kamarudin, N., Puan, C., Turner, E. and Azhar, B. (2016). Habitat occupancy patterns and activity rate of native mammals in tropical fragmented peat swamp reserves in Peninsular Malaysia. *Forest Ecology and Management*, 363, 140-148.
56. Shafri, H., Hamdan, N. and Saripan, M. (2011). Semi-automatic detection and counting of oil palm trees from high spatial resolution airborne imagery. *International Journal of Remote Sensing*, 32(8), 2095-2115.
57. Sodhi, N., Koh, L., Brook, B. and Ng, P. (2004). Southeast Asian biodiversity: an impending disaster. *Trends in Ecology and Evolution*, 19(12), 654-660.
58. Song, D., Huang, C., Sexton, J., Channan, S., Feng, M. and Townshend, J. (2015). Use of Landsat and Corona data for mapping forest cover change from the mid-1960s to 2000s: Case studies from the Eastern United States and Central Brazil. *ISPRS Journal of Photogrammetry and Remote Sensing*, 103, 81-92.
59. Srestasathiern, P. and Rakwatin, P. (2014). Oil Palm Tree Detection with High Resolution Multi-Spectral Satellite Imagery. *Remote Sensing*, 6(10), 9749-9774.
60. Sulaiman, O., Salim, N., Nordin, N., Hashim, R., Ibrahim, M. and Sato, M. (2012). The potential of oil palm trunk biomass as an alternative source for compressed wood. *BioResources*, 7(2), 2688-2706.

61. Tan, S., Hashim, H., Abdul Rashid, A., Lim, J., Ho, W. and Jaafar, A. (2017). Economic and spatial planning for sustainable oil palm biomass resources to mitigate transboundary haze issue. *Energy*, 146, 169-178.
62. Tonks, A.J., Aplin, P., Beriro, D.J., Cooper, H., Evers, S., Vane, C.H. and Sjögersten, S. (2016). Impacts of conversion of tropical peat swamp forest to oil palm plantation on peat organic chemistry, physical properties and C stocks. *Geoderma*, 289, 36-45.
63. United Nations Food and Agriculture Organization (FAO). (2016). "FAOSTAT: Online Statistical Service". Accessed 6 November 2018. http://faostat.fao.org
64. United States Geological Survey (USGS). (2018). "*EarthExplorer*". Accessed 6 November 2018. https://earthexplorer.usgs.gov
65. Vergopolan, N. and Fisher, J. (2016). The impact of deforestation on the hydrological cycle in Amazonia as observed from remote sensing. *International Journal of Remote Sensing*, 37(22), 5412-5430.
66. Watson, J., Dudley, N., Segan, D. and Hockings, M. (2014). The performance and potential of protected areas. *Nature*, 515(7525), 67-73.
67. Wetlands International (2014). "Tropical Peat Swamp Forests". Accessed 6 November 2018. http://www.wetlands.org/Whatarewetlands/Peatlands/Tropicalpeatswampforests/tabid/2739/Default.aspxN
68. Yule, C.M. and Gomez, L. (2008). Leaf litter decomposition in a tropical peat swamp forest in Peninsular Malaysia. *Wetlands Ecology and Management*, 17(3), 231-241.
69. Yule, C.M. (2010). Loss of biodiversity and ecosystem functioning in Indo-Malayan peat swamp forests. *Biodiversity and Conservation*, 19, 393–409.

Table 2. Classification accuracy for 1989 land cover map of North Selangor.

Classified data	Reference data									Users accuracy (%)
	Peat swamp forest	Rainforest	Mangrove forest	Grassland	Oil palm plantation	Rice paddy field	Bare soil	Urban development	Water	
Peat swamp forest	50	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	100.0
Rainforest	N/A	43	N/A	N/A	7	N/A	N/A	N/A	N/A	86.0
Mangrove forest	1	N/A	43	1	5	N/A	N/A	N/A	N/A	86.0
Grassland	N/A	2	2	27	18	1	N/A	N/A	N/A	54.0
Oil palm plantation	N/A	N/A	N/A	N/A	50	N/A	N/A	N/A	N/A	100.0
Rice paddy field	1	N/A	N/A	23	N/A	25	N/A	1	N/A	50.0
Bare soil	N/A	N/A	N/A	N/A	N/A	N/A	44	3	3	88.0
Urban development	N/A	N/A	N/A	3	1	N/A	14	29	3	58.0
Water	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	50	100.0
Producers accuracy (%)	96.2	95.6	95.6	50.0	61.7	96.2	75.9	87.9	89.3	
Overall classification accuracy (%) = 80.2										

Table 3. Classification accuracy for 2001 land cover map of North Selangor.

Classified data	Reference data									Users accuracy (%)
	Peat swamp forest	Rainforest	Mangrove forest	Grassland	Oil palm plantation	Rice paddy field	Bare soil	Urban development	Water	
Peat swamp forest	49	N/A	N/A	N/A	1	N/A	N/A	N/A	N/A	98.0
Rainforest	N/A	48	N/A	1	1	N/A	N/A	N/A	N/A	96.0
Mangrove forest	N/A	1	44	N/A	5	N/A	N/A	N/A	N/A	88.0
Grassland	N/A	N/A	N/A	48	2	N/A	N/A	N/A	N/A	96.0
Oil palm plantation	2	6	N/A	3	39	N/A	N/A	N/A	N/A	78.0
Rice paddy field	N/A	N/A	N/A	23	1	24	1	1	N/A	48.0
Bare soil	N/A	N/A	N/A	1	N/A	2	44	3	N/A	88.0
Urban development	N/A	N/A	N/A	2	N/A	4	9	34	1	68.0
Water	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	50	100.0
Producers accuracy (%)	96.1	87.3	100.0	61.5	79.6	80.0	81.5	89.5	98.0	
Overall classification accuracy (%) = 84.4										

Table 4. Classification accuracy for 2016 land cover map of North Selangor.

Classified data	Reference data									Users accuracy (%)
	Peat swamp forest	Rainforest	Mangrove forest	Grassland	Oil palm plantation	Rice paddy field	Bare soil	Urban development	Water	
Peat swamp forest	50	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	100.0
Rainforest	N/A	45	N/A	N/A	5	N/A	N/A	N/A	N/A	90.0
Mangrove forest	12	N/A	35	3	N/A	N/A	N/A	N/A	N/A	70.0
Grassland	N/A	3	N/A	47	N/A	N/A	N/A	N/A	N/A	94.0
Oil palm plantation	N/A	2	N/A	N/A	48	N/A	N/A	N/A	N/A	96.0
Rice paddy field	N/A	N/A	N/A	28	1	20	1	N/A	N/A	40.0
Bare soil	N/A	N/A	N/A	4	N/A	1	40	5	N/A	80.0
Urban development	N/A	N/A	N/A	N/A	N/A	1	3	46	N/A	92.0
Water	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	50	100.0
Producers accuracy (%)	80.7	90.0	100.0	57.3	88.9	90.9	90.9	90.2	100.0	
Overall classification accuracy (%) = 84.7										

Table 5. Overall land cover change between 1989, 2001 and 2016 in North Selangor.

Land cover class	Area 1989 (km²)	Area 1989 (% study area)	Change 1989-2001 (km²)	Area 2001 (km²)	Area 2001 (% study area)	Change 2001-2016 (km²)	Area 2016 (km²)	Area 2016 (% study area)	Change 1989-2016 (km²)
Peat swamp forest	746.1	19.7	-56.3	689.8	18.2	-54.8	635.0	16.8	-111.1
Rainforest	709.6	18.8	-364.7	345.0	9.1	-96.0	249.0	6.6	-460.7
Mangrove forest	86.5	2.3	-49.7	36.8	1.0	+8.4	45.2	1.2	-41.3
Grassland	520.2	13.8	+176.3	696.5	18.4	-83.3	613.3	16.2	+93.0
Oil palm plantation	249.3	6.6	+419.1	668.4	17.7	+32.3	700.7	18.5	+451.4
Rice paddy field	491.0	13.0	-163.6	327.4	8.7	+42.6	369.9	9.8	-121.1
Bare soil	55.2	1.5	+21.2	76.4	2.0	+97.7	174.0	4.6	+118.8
Urban development	193.2	5.1	+5.6	198.8	5.3	+55.5	254.3	6.7	+61.1
Water	728.5	19.3	+13.5	742.0	19.6	-3.6	738.4	19.5	+9.9