Authors: Chintan Sheth[1], Aparajita Datta[2], Devathi Parashuram[2]

Title: Persistent loss of biologically-rich tropical forests in the Indian Eastern Himalaya

[1]Chintan Sheth
National Centre for Biological Sciences
Tata Institute of Fundamental Research
Bellary Road
Bangalore 560065
Karnataka, India

[2]Aparajita Datta
Nature Conservation Foundation
1311,"Amritha", 12th Main
Vijayanagar 1st Stage
Mysore 570017
Karnataka, India

[2]Devathi Parashuram
Nature Conservation Foundation
1311, "Amritha", 12th Main
Vijayanagar 1st Stage
Mysore 570017
Karnataka, India

Corresponding author

Aparajita Datta

Email: aparajita@ncf-india.org

Ph: +91 9448351560

Abstract

Deforestation is a major cause of biodiversity loss in Asia. India's biologically-diverse state of Arunachal Pradesh has been undergoing forest loss due to multiple drivers. We assessed the change in forest cover in a state-managed Reserved Forest adjoining an important Protected Area (PA), i.e. the Pakke Tiger Reserve using satellite imagery at a fine spatial resolution. A conservation program to protect three species of endangered hornbills and their nesting habitat outside the PA had been set up in 2011-12. We assessed the effectiveness of the conservation programme in protecting forests. We report a loss of 32 km^2 of forest cover between 2013 and 2017 with a 5% decline in total forest area in four years. In the habitat around the 29 hornbill nest trees we estimated a loss of 35% of forest cover. This loss occurred despite varied efforts through the conservation program and by individuals in the community/government. We identify illegal logging (despite a ban by the Supreme Court of India) as the main driver that is depleting forest cover within this important area. Our results highlight the ongoing threats to biologically-rich forests and the need for urgent measures to halt this loss. We suggest that this study has general practical implications for the governance of non-PA state-managed forests in Arunachal Pradesh. The ongoing deforestation appears to be due to organized crime, institutional inadequacy from a combination of limited resources, bureaucratic apathy, and/or ambiguity in use and ownership of forest land compared to other community forests which appear to have robust governance systems.

Keywords: Arunachal Pradesh; biodiversity hotspot; deforestation; forest cover change; illegal logging; north-east India

Introduction

Tropical forests are not only the most biodiverse terrestrial ecosystems on Earth (Gibson et al. 2011) but also amongst the most threatened. Globally, 2.3 million square kilometers of forest were lost from 2000 to 2012, with tropical forests undergoing the highest losses (Hansen et al. 2013). Deforestation is one of the major causes of biodiversity loss across the world (Gibbs et al. 2010; Curtis et al. 2018).

India's state of forest is assessed biennially by the Government's Forest Survey of India (FSI). While the remote sensing methods used by FSI provide information on forest cover and the change, these data combine native forests, secondary regrowth, plantations and cropland and do not validate classifications with ground-truthing (Puryavud et al. 2010 a, b). According to FSI, India has lost 80% of its native forest cover and forests continue to be lost at the rate of 1.5 to 2.7% per year. However, this does not provide an accurate estimate of the true extent of native forests and deforestation rates (Puryavud et al. 2010a). Puryavud et al. (2010b) highlighted the cryptic destruction of India's native forests as a challenge to understanding the trends in the state of India's forests. It is not possible to accurately distinguish between native forests and plantations/man-modified green cover using FSI data.

Global Forest Watch (GFW) data show that India lost about 15,400 km^2 of forest (>30% canopy cover) between 2001 and 2017 amounting to 172 mega tonnes of CO_2 emissions (Hansen et al. 2013; Global Forest Watch 2019). North-east India, which encompasses two global biodiversity hotspots – Indo-Burma and the Himalaya (Mittermeir et al. 2005) – appears to be severely affected by deforestation (Pandit et al. 2007). The GFW assessment estimated 11,400 km^2 of lost from north-east India in the same period (Global Forest Watch 2019).

Arunachal Pradesh in north-east India is the richest terrestrial biodiversity region in India (Mishra & Datta 2007). Arunachal is home to nearly 6000 flowering plants and half of the bird species known from India (Praveen et al. 2016, 2019). Recent research and exploration has led to the discovery of new records, range extensions and new species of plants and animals from the state (Gajurel et al. 2001; Ahti et al. 2002; Ahmad et al. 2004; Sinha et al. 2005; Athreya 2006; Tamang et al. 2008; Sondhi & Ohler 2011; Zanan & Nadaf 2012; Dalvi 2013; Roy 2013; Hareesh et al. 2016; Siliwal et al. 2017; Captain et al. 2019).

Forest cover in Arunachal Pradesh has been steadily declining in the last decade although forests still cover 79% of the total land area (Global Forest Watch 2019; Supplementary Table 1 & Supplementary Figure 1). About 486 km^2 of forest was lost from 2003 to 2017 in Arunachal Pradesh (FSI 2003, 2005, 2009, 2011, 2013, 2017). However, GFW data, shows that 2000 km^2 of forest was lost between 2001 and 2018, comparable to a 3.2% decrease in forest cover since 2000 and 82.6 mega tonnes of CO_2 emissions (Global Forest Watch 2019, Supplementary Table 2).

In terms of their legal status, 11.37 % percent (9528 km^2) of the geographical area of Arunachal Pradesh is under the Protected Area (PA) network (Wildlife Sanctuaries and National Parks, some of which also encompass Tiger Reserves). The PAs are generally better protected than Unclassed State Forests (USF) and Reserved Forests (RF) with stricter implementation of the country's forest and wildlife laws. Thirty-seven percent (30,965 km^2) of the state's geographical area are classified as USF, which in practice, are used and/or owned by the community (*de facto* rights), although recorded as being under the Forest Department. In some areas, USFs appear to be better managed and have good forest cover compared to the state-managed RFs where protection and enforcement by the state Forest Department is relatively poor. The RFs constitute around 11.61% of the geographical area (9,722.69 km^2) and despite being legally under the control of the state Forest Department are often also subject to various anthropogenic pressures such as agricultural expansion, conversion to plantations and/or logging (Naniwadekar et al. 2015a). A few other categories such as Protected Forest/Anchal Reserve Forest/Village Reserve Forest constitute 1.57% of the geographical area.

With 80% of the population practicing subsistence farming, people were primarily dependent on shifting cultivation, the main viable option in the hilly terrain which is mainly carried out in the USF or community forests. Shifting cultivation was estimated to cover 2040 km^2 in 2008-09 (Wasteland Atlas 2011). Today, shifting cultivation is on the decline among many communities (see Teegalapalli & Datta 2016). Although shifting cultivation is usually cited as the main driver of forest loss or changes in the state, there has been no evidence presented to distinguish between different causes of forest loss and gain. The drivers of forest loss can be multiple such as: agricultural expansion, growth of plantation crops such as oil palm, rubber, tea, opium, illegal logging and road expansion (Srinivasan 2014; Velho et al. 2016; Khandekar 2019).

With an increasing population and need for agricultural land and development, and lack of land demarcation and cadastral surveys, there is forest clearing (mostly Reserved Forests) for agriculture expansion and plantations along with illegal logging in Arunachal Pradesh (Naniwadekar et al. 2015a; Velho et al. 2016; Rina 2017, 2019; Mamai 2018; Khandekar 2019).

Ethno-civil conflict and illegal logging

The main sources of revenue for Arunachal Pradesh were forest-based industries till 1996, after which the Supreme Court banned logging. Despite the ban, illegal clearing driven by ethno-civil conflict in Sonitpur district in neighbouring Assam resulted in the complete disappearance of three Reserved Forests that bordered Nameri Tiger Reserve in Assam in the last two decades (Srivastava et al. 2002; Kushwaha & Hazarika 2004; Mazoomdar 2011; Velho et al. 2014; Srinivasan 2018). Srivastava et al. (2002) estimated that 232 km^2 of forests was cleared in Sonitpur District (Assam state) between 1994 and 2001 with the overall loss rate of 28.65%, possibly the highest deforestation rate in the country at that time. Kushwaha and Hazarika (2004) found the overall forest loss was 344 km^2 between 1994 and 2002 in the Kameng and Sonitpur Elephant Reserves. Velho et al. (2014) reported continuing forest loss in the same region around the southern boundaries of both Pakke and Nameri Tiger Reserves. Between 2001 and 2018, 170 km^2 of forest was lost from Sonitpur district (Global Forest Watch 2019). Forest loss over twenty-five years has resulted in substantial habitat loss for wildlife that include tigers, elephants and large birds such as hornbills.

After the 1996 ban, selective logging has re-started under the Forest Department in some forest divisions in Arunachal Pradesh since 2008-2009. However, apart from these state-controlled and permitted logging activities, ground observations and local media reports indicate that illegal logging is becoming a major driver of deforestation in Reserved Forests in Arunachal Pradesh (Rina 2017; Anonymous 2019) and other areas in Arunachal Pradesh (Mamai 2018; Anonymous 2019).

This area is among the few remaining areas of low-elevation forest and is among the best areas for hornbills in South Asia (Datta 1998, 2001; Datta & Rawat 2003, 2004; Dasgupta & Hilaluddin 2012; Datta et al. 2012; Datta & Naniwadekar 2015) due to protection measures by forest authorities (Velho et al. 2011) and control of hunting by local people. The main nesting habitat for the Great hornbill *Buceros bicornis*, Wreathed hornbill *Rhyticeros undulatus* and Oriental Pied hornbill *Anthracoceros albirostris* lies along the low-elevation areas near the Assam-Arunachal Pradesh border (Datta & Rawat 2004). Several important hornbill roosting sites are also located in the area. In 2012, the Hornbill Nest Adoption Programme (HNAP) was initiated to protect hornbill nest trees and habitat in the Papum Reserved Forest (Fig. 1) outside Pakke Tiger Reserve in a partnership with local communities and the state Forest Department (Datta et al. 2012; Rane & Datta 2015). Since the programme began, it has been effective in increased local awareness and interest in hornbills and in protecting 37 nest trees of three hornbill species. An estimated 119 hornbill chicks have successfully fledged from these protected nests in the last 7 years till 2018 (Parashuram & Datta 2018).

However, our ground observations indicated increasing levels of illegal tree felling from 2016, with the use of mechanized chainsaws, hired labour from outside and the transport of timber outside the state. Local efforts to contain the illegal felling included circulars and letters issued by various members of the public, non-governmental organizations and scientists to concerned authorities in the Forest Department and District Administration. Sporadic measures such as seizures of logs and trucks or efforts to disrupt road connectivity were taken by local people, few concerned administrative officials and Forest Department staff. However, these actions have been ineffective in stopping the felling and transport of illegal timber out of the state. A member of the Nyishi tribal community has also filed a public interest litigation in 2019 (Rina 2019) in the National Green Tribunal of India, India's special court to deal with cases pertaining to environmental protection and forest conservation.

In this paper, we aimed to assess the extent of forest loss and the effectiveness of the Hornbill Nest Adoption Program in protecting hornbill habitat. Our specific purpose is to 1) estimate forest loss in the Papum RF using satellite data at a fine-scale resolution (3, 5 m) from 2013 to 2017 since the HNAP began and 2) to determine forest loss within 1 km of hornbill nest trees at a fine-scale.

METHODS

Study area

Papum RF covers an area of 1064 km^2 and adjoins Pakke Wildlife Sanctuary and Tiger Reserve (henceforth, TR) (Fig. 1; 861.95 km^2, 92.5932º – 93.1006ºN; 26.9351º - 27.2283ºE). The Papum RF was constituted under a Government notification number FOR 34/54 dated 1st July 1960. Reserved Forest is a category of forest notified under the Indian Forest Act, 1927. The existing rights or claims are acquired/settled by the state government under the provisions of the Act. In Reserved Forests, all extractive activities are prohibited unless legally permitted (Indian Forest Act 1927).

Part of Papum RF (346.25 km^2) is included in the buffer area of Pakke TR as per the National Tiger Conservation Authority (NTCA 2012), India. Of this 318.25 km^2 is forested, while 28 km^2 is demarcated as multiple use area (NTCA 2012). Within Papum RF, there are 19 small towns/villages and settlements that are administered by the Seijosa and Dissing-Passo circles with a population of 3789 (2011 Census of India). Towards the south and east, Papum RF is bordered by Assam and Papumpare district respectively. To the west, lies the Pakke River and Pakke TR; and to the north by community forests of Pakke Kessang.

With an elevational range from 200 to 1500 m above sea level, Papum RF receives an average total annual rainfall of 2500 mm. Mean (± standard deviation) maximum temperature is 29.3°C (± 4.2) and the minimum temperature is 18.3°C (± 4.7). The vegetation is classified as the Assam Valley tropical semi-evergreen forest (Champion & Seth 1968). In adjoining Pakke TR which has a similar floral and faunal composition as the Papum RF, more than 78% of trees are animal-dispersed (Datta & Rawat 2008). Hornbill densities and abundance of key faunal groups such as primates and squirrels in the Papum RF is known from past studies (Datta 1998; Datta & Goyal 2008; Dasgupta & Hilaluddin 2012). Nameri Tiger Reserve in neighbouring Assam state is contiguous with Pakke TR in the south.

Some of the main commercially valuable species extracted were: *Terminalia myriocarpa*, *Duabanga grandiflora*, *Gmelina arborea*, *Aglaia spectabilis*, *Terminalia chebula*, *Canarium resiniferum*, *Artocarpus chaplasha*, *Altingia excelsa*, *Phoebe cooperiana*, *Michelia* sp., *Mesua ferrea* and *Phoebe goalparensis*. Due to excessive extraction of some species, several species are quite rare and natural regeneration is low.

The total area of Papum RF is 1064 km^2, however for this study, we marked out an area of 737 km^2 for classifying the forest and analysis of change in forest cover (Fig. 1). We restrict our analyses to 70% of the total area for two reasons: 1) the geographical focus of the HNAP program is within this area, 2) the boundary of entire Papum RF is uncertain and 3) the region of our analysis also forms part of the buffer area of neighboring Pakke Tiger Reserve. A digitized boundary of Papum RF (737 km^2, including a 500-m buffer; 92.9209º – 93.2826ºN; 26.9446º - 27.2116ºE) was used for the analyses.

RapidEye and PlanetScope satellite data processing and classification

We obtained ortho-rectified surface/top-of-atmosphere (TOA) reflectance data imaged by either the RapidEye (5 m spatial resolution) or PlanetScope (3 m spatial resolution) constellations, to ensure a complete cloud-free coverage of the area (for a list of images acquired refer to Supplementary Table 3; a description of the datasets can be obtained from Planet Labs Inc. 2019). We combined both datasets for analyses (RapidEye data was available from 2011, and when RapidEye images were unsuitable, we used PlanetScope data which was available from 2016). Our analyses combined results from both satellite datasets as we found the classification accuracies to be comparable. A two-sample permutation test was performed on the distribution of all possible differences between accuracies of the observed years and then compared to the observed difference between the mean accuracies of the respective datasets (observed mean = 0.03351667, p-value = 0.2457542; Manly 2018).

Ortho-rectification of satellite images is a process of terrain correction in a region with irregular topography. Ortho-rectification is applied to ensure the same geographical region is analyzed year-to-year within a region of interest (ROI) (Tucker et al. 2004). We used images that were corrected to surface reflectance or TOA reflectance since a year's image was classified independently from another year. Our analysis did not compare the spectral nature of the land-cover areas. The advantage of using fine-scale satellite images is the ability to robustly resolve forest loss and other ecological phenomena below the 30-m scale (Hansen et al. 2013, Milodowski et al. 2017). Scenes were chosen if they were entirely cloud-free and taken by the same satellite on the same day, thereby preventing complications of image stitches and loss of information due to cloud cover. Land-cover classification of the entire Papum RF using fine-scale data was only possible for the years (2013, 2014, 2017) that fulfilled the above coverage criteria. However, forest loss analysis around the hornbill nest trees, utilized images from 2011 – 2019.

Using a combination of field sampling (using a global positioning unit) and Google Earth imagery, ROIs were identified for three land-cover classes. Each scene (or partial scene) was independently classified as stable forest, stable non-forest and logged-forest using the randomForest library 4.6-14 in the R (R version 3.3., R Core Development Team 2016). Stable forest regions comprised ROIs of uncut closed canopy forests with little or no detectable anthropogenic disturbance. Stable non-forest regions comprised water bodies, grasslands, permanent settlements, sand bars and landslides. Logged-forest ROIs were defined using ground reports of active/past logging, studying satellite images at GFW deforestation hot-spots, and for roads, new clearings, plantations and fire scars. Logged-forest ROIs generally comprise areas previously under forest but currently with higher albedo than forest. The shape of the clearings is often geometrical and close to older forest clearings. Roads are linear in shape with the lower slope scarred with discarded debris. The training datasets of the above three classes consisted of at least 40 ROIs and ~29 million pixels, per year.

Land cover change around hornbill nest trees

The HNAP is confined to the lower and south-western parts of Papum RF (Fig. 1) that fall within Seijosa circle – from Darlong up to Jolly/Lanka in the north and towards the Mabuso 2/Margasso settlements to the east. A total of 37 hornbills nest trees are currently known in Papum RF (Parashuram & Datta 2018).

To investigate if the habitat around the monitored and protected hornbill nest trees were affected by forest loss, scenes that covered >90% of the hornbill nest sites were chosen. In the latter case, cloud-free, single day scenes were available and could be analysed from 2011 to 2019. This allowed us to make comprehensive fine-scale forest loss estimations for 9 years. Cloud-free satellite images for all years were from November-December, except for 2018 and 2019 which were from April-May) (dry season). During the dry season, secondary vegetation in clear felled areas is visibly dissimilar from primary forest. While we do not test for this difference, we think the visible difference may be attributed to the drying and browning of vegetation in the summer season when soil moisture and rainfall are low. Secondary vegetation in winter months (post-monsoon) are visibly greener as the soil moisture is still high. An identical approach (to that used for classifying forest loss in Papum RF) was implemented to classify the area around 29 hornbill nests. A 1-km buffer was created and the satellite scenes were clipped to the buffered extent (48 km^2). Three land-cover classes were defined (see above) comprising 20 ROIs and ~ 2 million pixels (RapidEye data) or ~ 5 million pixels (PlanetScope data, refer to Supplementary Table 3).

The spatial accuracy of the land-cover classification was assessed by manual checking of the scenes coupled with a stratified random sampling method (Olofsson et al. 2014). A random sample of every land-cover class in each training dataset was used to test the accuracy of the classified image providing a bias corrected estimate of land-cover area in each class. The associated standard errors, prediction accuracy and rates of commission and omission errors were estimated as recommended by Olofsson et al. (2014). For the full area estimates of forest loss in Papum RF, the overall accuracy and standard error of the classification (for three years' of RapidEye data) is 98.4 ± 3.0%. For forest loss estimates around hornbill nest sites, the overall classification accuracy is 96.4 ± 7.5%. Accuracy statistics and confusion matrices for both Papum RF and the nest-sites are tabulated in the supplementary material (Supplementary Table 4 and Table 5).

Post land-cover classification, we calculated the annual rate of forest area loss using a modified compound-interest-rate formula for its mathematical clarity and biological relevance (Puyravaud 2003):

$$P = \frac{100}{t_2 - t_1} ln \frac{A_2}{A_1}$$

where A_1 and A_2 is the forest area in time periods t_1 and t_2, respectively. P is the annual percentage of area lost.

Results

Forest loss in Papum RF: 2013 – 2017

There was very high forest loss in Papum RF as determined from analysis at a fine-scale resolution. Table 1 shows the loss of forest from 2013 – 2017 within Papum RF. While 81% of the RF was under forest in 2013, it declined to around

76% in 4 years. The area under forest, as of winter 2017, is 561 km^2 (Supplementary Figure 2). From 2013 to 2017, there was a loss of 32 km^2 of forest, with an increase in logged-forest (27.22 km^2) and of area under non-forest (4.76 km^2). Out of a total area of 737 km^2 classified, 156 km^2 was logged-forest by 2017.

Our analyses recorded forest loss to be lower in 2017 than in 2014, for two reasons: (1) an area (~5 km^2) in the eastern part of Papum RF was logged in 2014 but shows growth of secondary vegetation in 2017. The spectral nature of this 5 km^2 area is very similar to forest and in 2017, the area is classified as forest. (2) Images in 2017 had a higher illumination elevation angle (46.05º), than in 2014 (39.48º), illuminating mountain slopes and forests that were previously under shadows. The illumination of river beds in 2017 also explains the increase in non-forest areas. The annual rate of forest area loss was 1.4 % $year^{-1}$ corresponding to 8.2 km^2 $year^{-1}$.

Forest loss around hornbill nests: 2011 – 2019

Forest area consistently dropped from 2011 to 2016, then increased in 2017, and decreased again up to 2019 (Fig. 2a). However, by 2019, only 45% of the 48 km^2 of the 1-km buffer area around 29 hornbill nests was forested as compared to 80% in 2011 (Table 2). Forest loss is also evident from the construction of roads, burn scars and clear-cut felling of primary forest areas (Supplementary Figure 3). During the period from 2011 to 2015, the total forest loss around nest trees was about 6 km^2, however this increased to a loss of 4 km^2 in just one year in 2016, followed by a gain shown in 2017, with a loss of 8.59 km^2 showing up in 2018 (Table 2). In the last 9 years, there has been a total loss of 16.61 km^2 in a 1 km buffer around the 29 nest sites (Fig. 2b). Annual rate of forest area loss around the nest trees was 7% $year^{-1}$, corresponding to 2.07 km^2 $year^{-1}$.

Discussion

The forest loss has serious consequences for tropical biodiversity, as the destruction of suitable habitat threatens the survival of forest specialist species (Tracewski et al. 2016). Several prior studies in the area have documented the negative effects of logging on key faunal groups, vegetation structure and composition, food abundance and seed dispersal (Datta 1998; Datta & Goyal 2008; Sethi & Howe 2009; Velho et al. 2012; Naniwadekar et al. 2015b).

Selective logging on a commercial scale occurred in these Reserved Forests till the Supreme Court ban in 1996 (Datta 1998; Datta & Goyal 2008). Some level of illegal timber felling continued to occur in some pockets, however officially timber extraction for commercial purposes has been banned since 1996. Forest loss and degradation continued due to various other factors. Several current settlements existed prior to the declaration of the Reserved Forest, however population and settlements have grown subsequently leading to ambiguity and conflict in terms of people's land rights and legal status of forests in the area. After devastating floods in May 2004, many families lost agricultural land to erosion, and some areas along the Assam-Arunachal border were occupied in anticipation of future needs of the population. Over the last ten years, most households in the area stopped cultivating due to loss of land to floods and repeated damage to their subsistence rice crops by elephants (Tewari et al 2017). Rubber and tea plantations also came up in the lower areas bordering Assam after 2007. These factors have led to some loss of forest cover along the border areas in the 2001-2009 period. Apart from the loss of forest due to these factors, till 2011-12, the timber extraction in the Seijosa area was mainly for household needs and subsistence use by people.

On-ground observations/media reports show that tree felling increased after 2015 and coincided with the use of mechanized chainsaws and the use of hired labour from Assam who camped in the forest. Reports of movement of trucks transporting timber in the night and the use of various routes for covert transport of timber became more frequent after 2015. From 2017, there was construction of several link roads in the area and the clearing of tree cover near Jolly-Galoso area for the development of an herbal garden by Patanjali Ayurveda Limited in the area which also resulted in the loss of forest cover. Since 2018, after road construction started, there is also loss of forest cover along the stretch from Pakke Kessang-Saibung.

Possible effects of illegal logging on hornbill breeding

The loss of around 35% of the forest area around the hornbill nest trees from 2011 to 2019 is alarming. From *ca.* 38 km^2 in 2011, the area under forest declined to 21.94 km^2 in 2019. This loss has occurred despite the monitoring and community efforts to contain logging through the HNAP that began in 2012 (Datta et al 2012; Rane & Datta 2015).

The HNAP has been successful in protecting individual hornbill nest trees and the immediate habitat surrounding the nest trees. An estimated 119 hornbill chicks have fledged from the protected nest trees from 2012 to 2018. After the 1st year of the programme (2012) when 4-5 nest trees were lost to fire and tree cutting, no further nest trees have been lost due to human disturbance (Rane & Datta 2015). After the 1st year, measures were taken to protect trees by creating fire lines before the start of the hornbill breeding season. In 2013-14, meetings were held with local community leaders and villagers to contain tree felling, awareness programs were done periodically in villages, signs were put up in a 100-m radius around the nest trees to dissuade people from felling trees near the marked hornbill nest trees. In 2015, individual trees of important hornbill food plant species and nest tree species were also marked in the surrounding habitat to act as a deterrent to felling.

However, the forest cover change analysis shows that the loss and degradation of the surrounding habitat and hornbill food trees continued despite these protection efforts. This will likely have negative consequences for hornbill nesting and persistence in the Papum RF. Tree density/basal area and food and nest tree density is considerably lower in the RF than in the Pakke TR (Datta et al. unpublished data). An earlier study has documented the negative effects of logging on hornbills and vegetation structure and composition in the area (Datta 1998, Datta & Goyal 2008). Logging also reduces food abundances for hornbills and together with hunting has consequences for seed dispersal by hornbills (Sethi &

Howe 2010, Naniwadekar et al. 2015b). In any case, while most of the earlier studies have all looked at the effects of 'selective' logging after some years since logging or when the logging was officially permitted before 1996, this study notes the alarming loss of forest despite the 1996 Supreme Court ban and the lack of any working plan under which the current logging is occurring within Papum RF.

Hornbills are highly mobile species with large home ranges, and nesting males move from the RF to the Pakke TR to forage for fruits. Our telemetry data of tagged Great and Wreathed hornbills show that some individual hornbills move between the Pakke TR and the RF (Naniwadekar et al. 2019). However, despite their ability to move between these areas, a continuing loss of forest cover will result in nest trees in the RF becoming inactive. As the forest is becoming more degraded and is being logged it has also become more common to find only nests of the more adaptable Oriental Pied hornbill in the RF (Parashuram & Datta 2018), which is more common in open secondary forests (Datta 1998).

The tree felling occurs mainly in the drier months starting from September to March-April, but in some years, illegal logging activity has continued in the wetter period. March is the beginning of the breeding season for the larger-sized Great Hornbill and Wreathed hornbill when the females start entering the nest cavities, sealing them and laying eggs. Apart from the direct loss of forest habitat and individual trees, the sound of mechanized chainsaws, movement and presence of hired labour in camps and trucks results in disturbance during this critical time in the hornbill breeding season. It is likely that hornbill breeding is being negatively affected by the ongoing illegal logging activities which has increased in intensity in the last 2-3 years. Our long-term monitoring of hornbill roost sites located along the southern boundary of Pakke TR near the Pakke River, also shows movement of hornbills from Pakke TR to the Papum RF. The disturbance from illegal logging and loss of habitat, may also affect the use of roost sites by hornbills in the future.

The loss of 32 km^2 of forest over 4 years within Papum RF is a cause for concern also because the area receives heavy rainfall often resulting in floods and landslides. The depletion of tropical forests in Papum RF severely threatens the future subsistence needs of the local and regional population. Although we do not explicitly test for these effects of deforestation, it is expected that landslides will increase if forest cover is lost at such a rapid rate (Bradshaw et al. 2007; Kumar & Bhagavanulu 2007; Horton et al. 2017; Stanley & Kirschbaum 2017). Soils along river valleys are destabilized accelerating river erosion rates (Horton et al. 2017) and amplifying flood risk and severity (Bradshaw et al 2007). In mountainous regions, deforestation weakens slopes exacerbating rainfall-triggered landslides (Kumar & Bhagavanulu 2007; Stanley & Kirschbaum 2017), significantly altering river sedimentation and geomorphology (Latrubesse et al. 2009), leading to cascading natural hazards like landslide dams.

Deforestation alters local climate resulting in drier, warmer conditions and reduced agricultural productivity (Lawrence & Vandecar 2014) and decreased access to clean drinking water (Mapulangaa & Naito, 2019). Our work also points to the degradation of ecosystem services evidenced from burned area scars. Burning volatilizes soil nutrients altering available organic material and additionally may prevent regeneration of forest species (Neary et al. 2005; Stevens-Rumann et al. 2018). Furthermore, with climate change rapidly altering weather patterns, securing forests for their ecosystem services will be a pragmatic goal for all privileged and underprivileged stake-holders as per several sustainable development goals laid out by the United Nations.

Some amount of timber extraction for local house construction and subsistence needs is legitimate. However, the spurt in illegal commercial logging activities on a large-scale, with timber being sold and transported out of the state, using mechanized chainsaws and hired labourers from a neighbouring community, is driving an alarming loss of forest cover in this area. In addition, with the construction of new roads, the continuation of these illegal activities to newer areas in the higher northern parts of the RF deeper inside Arunachal Pradesh is also being facilitated and is a threat to the long-term status of this important forest area for both people and wildlife.

One of the challenges in our study was the strict classification of land-cover as non-forest and logged-forest. Our ROI includes areas that often flood in the monsoon changing the percentages of these areas every year. New road construction or mining in recently logged forests can be classified as non-forest, while previously cleared primary forest can show regrowth as secondary vegetation. The difficult terrain in the region makes robust collection of ground-control points challenging. Hence, we make the following suggestions: 1) dry summer season images are best to distinguish secondary and non-woody vegetation from primary forest, 2) a binary classification system of forest and non-forest, and 3) forest loss estimations within a completely forested region such that loss in later years can be detected using year-to-year image subtraction techniques. However, we hope our work is a step towards achieving accurate forest loss estimates for an under-explored, mountainous region with exceptional forests and biodiversity.

The key management measures to stop the illegal logging are 1) a complete ban on the use/sale and possession of mechanized chainsaws in the area. While prohibitory orders have been issued in the past by the district administration, these have not been enforced, 2) stopping the unregulated movement of hired labour from the neighbouring state into Arunachal Pradesh for their use in illegal logging and transportation activities, 3) a thorough on-ground survey of the areas affected along with official and transparent records of seizure and disposal of seized timber from inside the forest and from illegal timber depots 3) night patrolling by police/Forest Department staff on all possible movement routes to stop the movement of trucks carrying timber out of the state, 4) the establishment of regular forest and/or community monitoring patrols to check illegal felling within the RF and 5) a constant monitoring of the state of forest cover by an external agency to ensure that illegal logging has been stopped. In the long-term, for better governance, clarity in the use and ownership of forest land also needs to be addressed under the law given that some of the designated forest area is under settlements and multiple use areas by people.

Code Availability

The code for image classification publicly available on https://github.com/monsoonforest/deforestation/blob/master/randomForest-image-classification.

Data Availability

RapidEye and PlanetScope datasets are not openly available as Planet Labs is a commercial company. CS obtained the datasets through Planet Lab's Education and Research program upon application. The classified land-cover datasets can be made available upon request from the authors.

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Author contributions

AD and CS conceived the idea and the study; DP and AD provided field data; CS analysed the data; AD and CS wrote the paper with inputs from DP.

Conflict of Interest: The authors declare that they have no conflict of interest.

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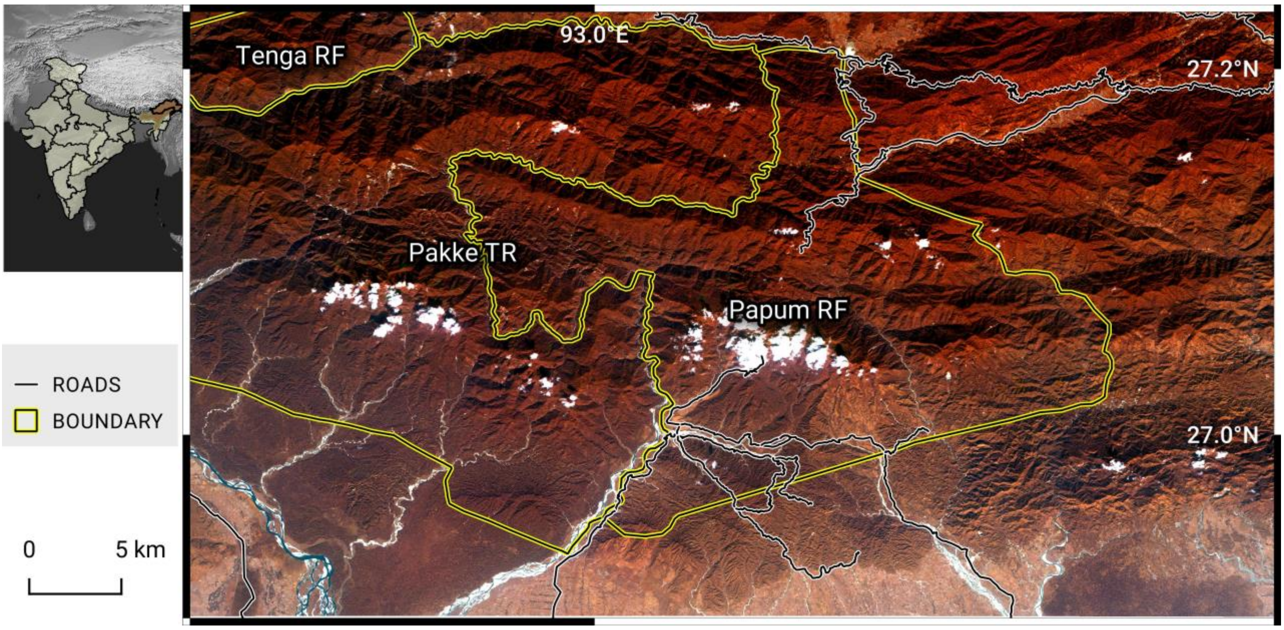
FIGURE CAPTIONS

Fig. 1 A November 2018, false-colour composite image (RapidEye bands 4,2,1) of the study area, showing Pakke TR, Tenga RF and Papum RF. The states of Assam and Arunachal Pradesh are coloured brown in the map of India. The border between Assam and Arunachal is also the lower boundaries of Pakke TR and Papum RF. Dark maroon areas indicate forests with high biomass, red shades are indicative of upland forests. Light shades of red, orange, brown are areas of agriculture, bamboo and other secondary vegetation. Whites are indicative of clouds, river beds and landslides. Blue depicts water. Notice the density of roads in the southwest of Papum RF.

Fig 2 (a) Area under forest cover from 2011 to 2019 within a 1 km buffer around the 29 hornbill nest sites. (b) Comparative chart of area of forest cover, logged-forest and non-forest between 2011 and 2019 from all hornbill nest sites within Papum RF.


Tenga RF
93.0°E
27.2°N
Pakke TR
Papum RF
27.0°N
ROADS
BOUNDARY
0
5 km

606 **Figure 1**

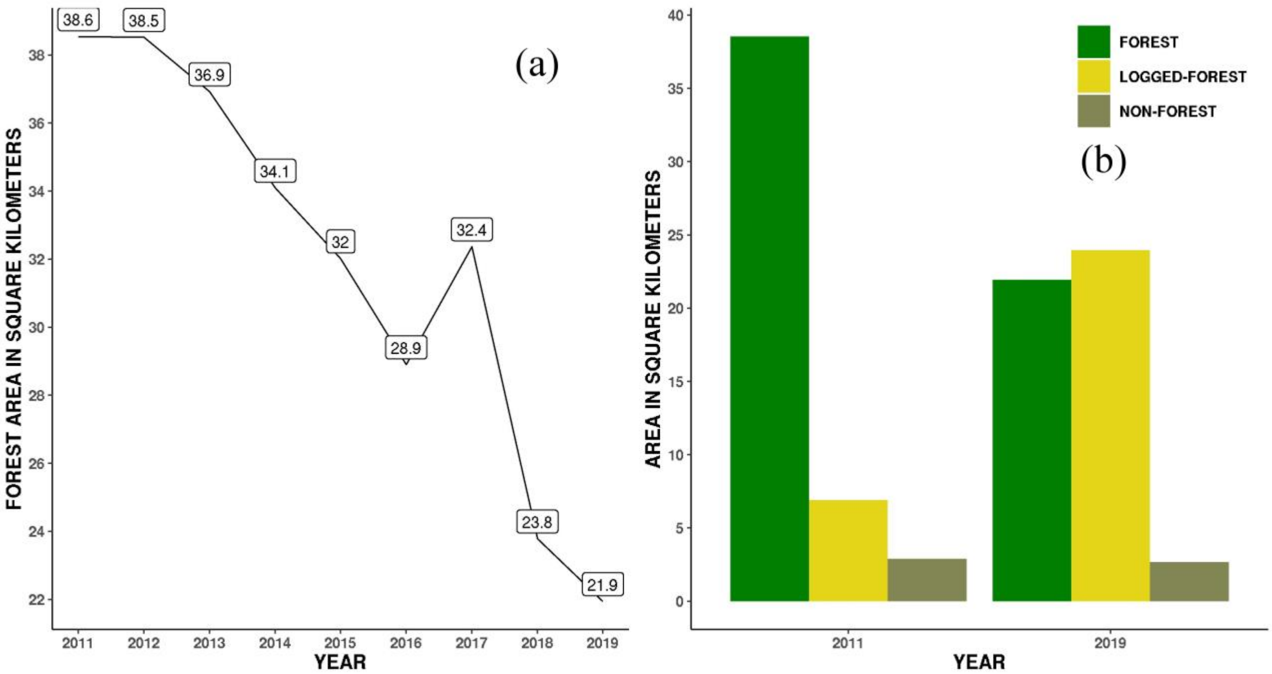


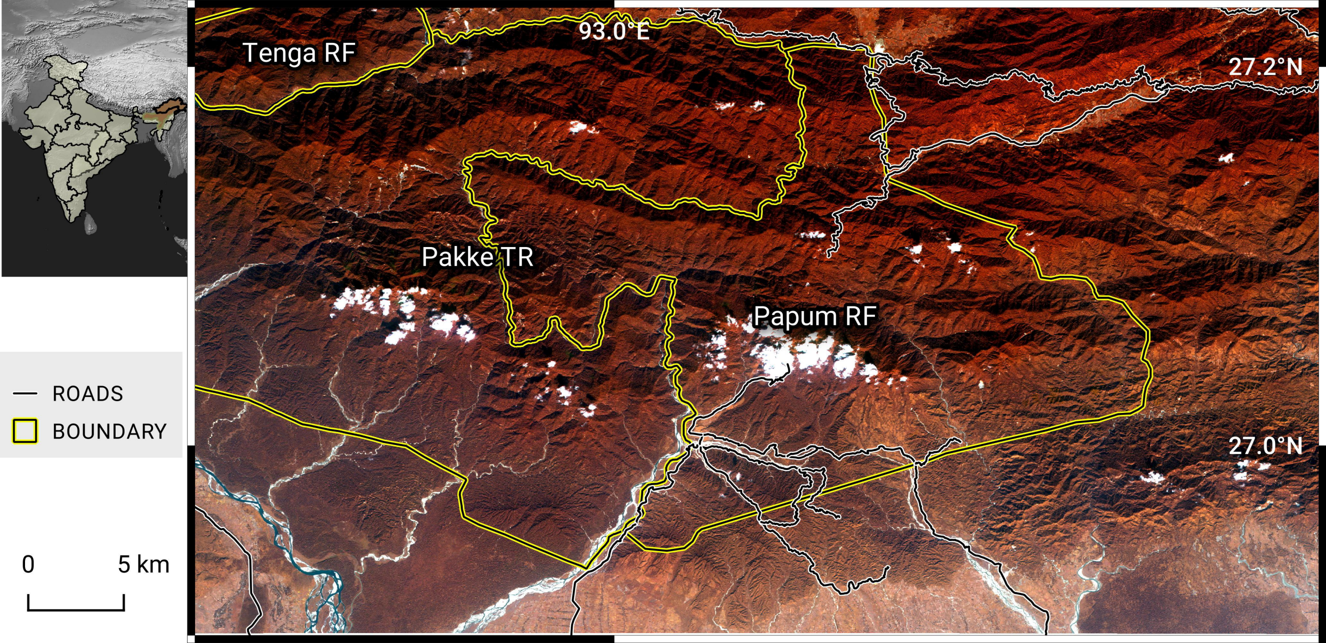
Figure 2

Table 1 Forest loss in the Papum Reserved Forest, Khellong Forest Division, Arunachal Pradesh quantified using RapidEye data for 2013, 2014, 2017. The total area of the Papum RF that was classified was 737 km^2. Numbers in parentheses indicate percentages. Cleared forest denotes..

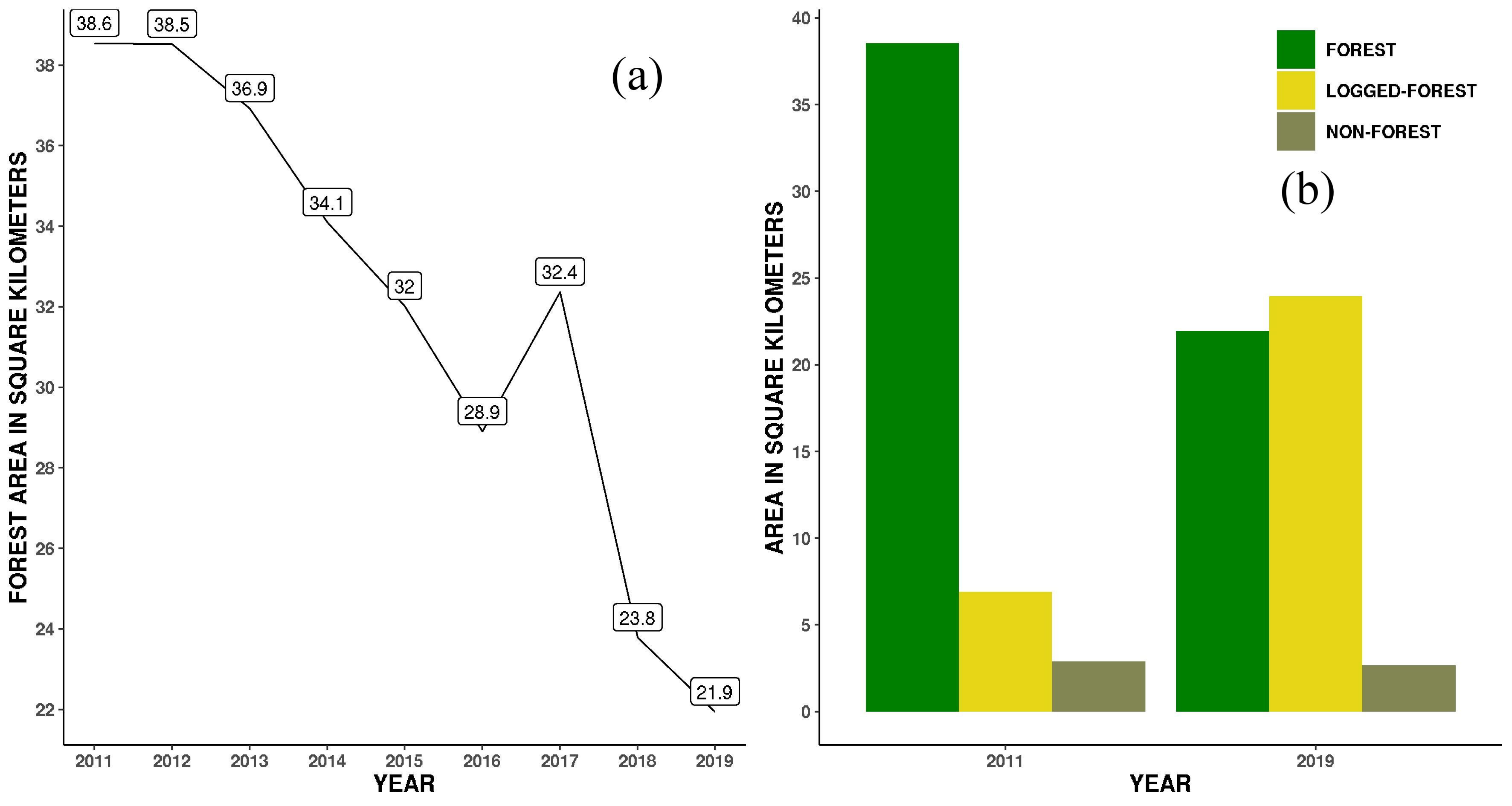
Year	Logged-forest in km^2 (%)	Forest in km^2 (%)	Non-forest in km^2 (%)
2013	128.8 (17.5)	593.8 (80.8)	14.3 (1.9)
2014	166 (22.5)	556.5 (75.5)	14.3 (1.9)
2017	156 (21.2)	561 (76.2)	19 (2.6)

Table 2 Forest loss around 29 hornbill nests in the Papum Reserved Forest, Khellong Forest Division, Arunachal Pradesh, north-east India; 2011 – 2019.

Year	**Forest area km^2**	**% Forest area**
2011	38.55	79.71
2012	38.52	79.66
2013	36.92	76.35
2014	34.09	70.49
2015	32.01	66.75
2016	28.90	59.50
2017	32.37	66.93
2018	23.78	48.95
2019	21.94	45.17

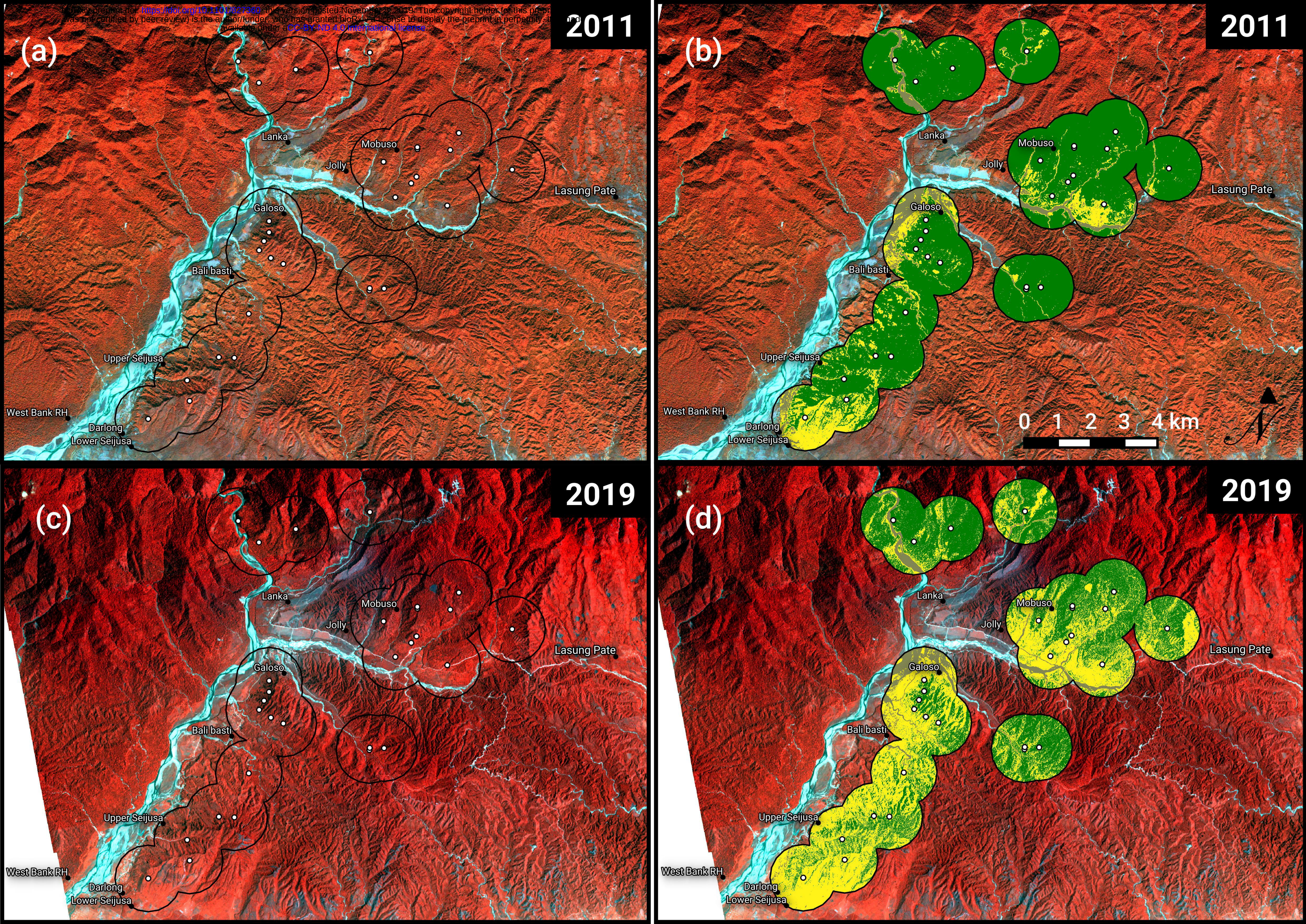


Tenga RF
93.0°E
27.2°N
Pakke TR
Papum RF
27.0°N
ROADS
BOUNDARY
0
5 km



(a)
FOREST AREA IN SQUARE KILOMETERS
YEAR
38.6
38.5
36.9
34.1
32
28.9
32.4
23.8
21.9
22
24
26
28
30
32
34
36
38
2011
2012
2013
2014
2015
2016
2017
2018
2019
(b)
AREA IN SQUARE KILOMETERS
YEAR
FOREST
LOGGED-FOREST
NON-FOREST
0
5
10
15
20
25
30
35
40
2011
2019


93.0°E
2013
27.2°N
27.0°N
93.0°E
2017
27.2°N
27.0°N
LAND-COVER
LOGGED-FOREST
FOREST
NON-FOREST
0
2.5
5
7.5
10 km


(a)
2011
(b)
2011
(c)
2019
(d)
2019
Lanka
Mobuso
Jolly
Lasung Pate
Galoso
Bali basti
Upper Seijusa
West Bank RH
Darlong
Lower Seijusa
0 1 2 3 4 km