Selective cutting of large-diameter trees in a lowland evergreen forest in central Cambodia

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មូលន័យសង្ខេប

រូបភាពថតលើផ្ទៃដីលំអិតពីរបៀប និងពេលវេលាដែលព្រៃឈើត្រូវបានសឹករិចរិលអាចផ្តល់ព័ត៌មានជាមូលដ្ឋានគ្រឹះសម្រាប់ការស្តារព្រៃឈើឡើងវិញនាពេលអនាគត។ ការកាប់ដើមឈើបែបជម្រើសដែលមានអង្កត់ផ្ចិតធំគឺជាដំណាក់កាលចាប់ផ្តើមនៃការរិចរិលព្រៃមានដើមឈើធំ។ យើងបានកត់ត្រាការកាប់ព្រៃឈើក្នុងតំបន់ទំនាបព្រៃស្រោងស្ងួតក្នុងខេត្តកំពង់ធំ ភាគកណ្តាលនៃប្រទេសកម្ពុជា។ ការចុះប្រមូលទិន្នន័យនៅទីវាលត្រូវបានធ្វើឡើងដើម្បីកត់ត្រាប្រភេទ និងទំហំដើមឈើដែលបានកាប់នៅកន្លែងបានកំណត់ដោយរូបភាពពីផ្កាយរណប។ ការប្រៀបធៀបរូបភាពផ្កាយរណប ALOS/PRISM ពីរដែលមានកម្រិតភាពច្បាស់ 2.5m ថតនៅខែវិច្ឆិកា ឆ្នាំ២០០៦ និងខែមីនា ឆ្នាំ២០០៨ បានបង្ហាញអោយឃើញថា ៥០១ ទីតាំងមានការបាត់បង់គំរបព្រៃយ៉ាងធំក្នុងទំហំផ្ទៃដីសិក្សា ១៤.៩៣ គម^{២}។ ការសិក្សារបស់យើងបានបង្ហាញថាទីតាំងចំនួន ១០១ ក្នុងចំណោម ១០៣ទីតាំងដែលបានត្រួតពិនិត្យឃើញថាមានការបាត់បង់ដើមឈើ ដោយមានភស្តុតាងនៃស្នាមកាប់ចំនួន៨៨ ទីតាំងក្នុងចំណោម ១០១ទីតាំង។ ដង់ស៊ីតេនៃការកាប់ឈើដែលបានប៉ាន់ប្រមាណពីឆ្នាំ២០០៦ ដល់ឆ្នាំ២០០៨ (ឧទាហរណ៍ ចំនួនពីររដូវប្រាំង) មានយ៉ាងតិច ២៨.៧ ដើម/គម^{២}។ ដើមឈើអំបូរឈើទាល (dipterocarps) ចំនួនពីរ ប្រភេទដែលបានកាប់គឺ *Dipterocarpus costatus* (ឈើទាលបង្គួយ) និង *Anisoptera costata* (ផ្ដៀក) មានអង្កត់ផ្ចិតជាមធ្យម ៨៤ សង់ទីម៉ែត្រ និងកម្ពស់ ១៣០ សង់ទីម៉ែត្រ។ ការកាប់បំផ្លាញធ្វើឡើងដោយក្រុមជាច្រើនដែលមានចម្ងាយ ១.៣ គីឡូម៉ែត្រពីផ្លូវធំ។ ព័ត៌មានដង់ស៊ីតេនៃការកាប់ និងទំហំដើមឈើដែលបានកាប់រួមចំណែកក្នុងការគណនាពីការសឹករិចរិលព្រៃឈើនៅប្រទេសកម្ពុជាកន្លងមក។

Abstract

Detailed ground-based records of how and when forests have been degraded can provide fundamental information for future restoration efforts. Selective cutting of large-diameter trees represents the initial stage of high-storage forest degradation. We recorded such cutting in a lowland, dry evergreen forest in Kampong Thom Province in central Cambodia. Field surveys were performed to record the species and sizes of cut trees in locations identified with satellite imagery. Comparison of two ALOS/PRISM satellite images with a 2.5m resolution taken in November 2006 and March 2008 revealed 501 sites with large canopy loss within a 14.93 km^2 study area. Our field surveys revealed that 101 of 103

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sites checked had experienced tree mortality, with mortality due to cutting evident at 88 of the 101 sites. The estimated cutting density from 2006 to 2008 (i.e., over two dry seasons) was at least 28.7 trees/km^2. The two species of dipterocarps cut, *Dipterocarpus costatus* (*chhoeuteal bankouy*) and *Anisoptera costata* (*phdiek*), had a median diameter of 84 cm at a height of 130 cm. The cutting was carried out by several groups within 1.3 km of the main road. This information on the cutting density and the size of the cut trees contributes to quantifying past forest degradation in Cambodia.

Keywords *Anisoptera costata*, conservation, crown gap, *Dipterocarpus costatus*, forest degradation, selective cutting.

Introduction

Deforestation and forest degradation in Cambodia are being addressed, but remain challenging. The causes of historical deforestation and forest degradation under different political regimes in Cambodia were summarized by Kim *et al*. (2005) and Tsujino *et al*. (2019). Until 2002, when a moratorium on logging was declared, the commercial forestry concession system introduced in 1993 formed the mainstay of forest management in Cambodia (Ty *et al*., 2009; Sasaki *et al*., 2013). Under the 2002 Forestry Law, commercial logging has been largely prohibited, except when plantations (for example, of rubber trees) are approved (Ty *et al*., 2011). Broadhead & Izquierdo (2010) observed that the logging moratorium resulted in the closure of mills and reductions in illegal logging, but also shifted the focus of illegal logging from commercial to small-scale operators, from few players to many, and from export to domestic markets. Deforestation between 2002 and 2010 (or 2016) was related to rapid population and economic growth nationally (Michinaka *et al*., 2013; Tsujino *et al*., 2019). In 2023, forest crimes continue, despite continued crackdowns by the authorities (Khmer Times, 2023).

Reliable forest statistics are essential when drafting guidelines for sustainable forest use. Detailed documentation of when and how forests have been subjected to anthropogenic disturbances, based on field surveys, is also important for improving forest management and planning forest restoration. Forest degradation due to illegal selective logging (hereafter cutting) has been recognized, but at least in the government report submitted in 2009, no information was available to assess forest degradation in Cambodia on a nationwide basis (Ty *et al*., 2009). Unsustainable fuel wood collection, one of the main drivers of forest degradation, has been well studied and its impacts quantified (Top *et al*., 2004a, 2004b, 2004c; San *et al*., 2012; Ito & Tith, 2020). However, there is somewhat less information on forest degradation caused by cutting of large-diameter trees for timber. A recent analysis of the impact of selective logging/cutting on forest ecosystems found that studies were biased geographically, with in Southeast Asia, including Cambodia, being poorly studied (Hari Poudyal *et al*., 2018). Langner *et al*. (2018) used differential indicators from satellite images to detect canopy disturbance due to selective logging in evergreen forests across Cambodia. In addition to using very high-resolution imagery, they conducted a field survey in Kampong Thom Province to confirm the accuracy of satellite detection. However, finer details regarding forest canopy disturbance due to selective logging have yet to be reported.

The purpose of our study was to document the early stages of forest degradation, starting from selective cutting in relatively well-preserved high-storage evergreen forests. For this purpose, we conducted a field survey to record the details of selective cutting of large-diameter trees that occurred under a logging moratorium in Kampong Thom Province, central Cambodia. The aspects of the cutting activity and site disturbance were documented by surveying areas of significant canopy loss in evergreen forests detected by comparing satellite images from two time periods.

Methods

Study site

Our study site was located in Sandan District, Kampong Thom Province (12°43'–12°48' N, 105°27'–105°30' E, thus about 8.75 by 6.25 km in area; Fig. 1). The seasonal tropical climate is governed by monsoons and November through April are dry. Mean annual temperature is 27°C and mean annual rainfall (± SD) is 1,542 (± 248) mm (2000–2010; NIS, 2012).

The study site was previously a concession forest. A license for the concession was issued in July 1995 to Grand Atlantic Timber International Co. Ltd., which was subsequently cancelled in June 2002 (World Bank, 2005a, 2005b; Kurashima *et al*., 2013). During our study period (2006–2009), the site existed as a cancelled concession forest. A circular area of land with a radius of about 10 km, including the study site, was designated as a protection forest. The date of its designation is unknown, but

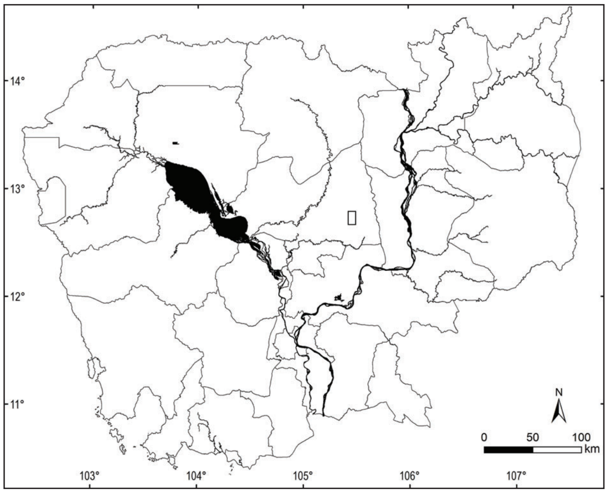

Fig. 1 Location of the study site (rectangle) in Cambodia.

the site was included on a 2008 map of forest land uses in Cambodia (Sasaki *et al*., 2013).

Forests at the study site are classified as lowland dry evergreen forest. Evergreen forests in Cambodia are categorized into four subtypes based on their elevation (lowland or sub-montane) and moist or dry climate, using the 2007 classification system of the Ministry of Environment (cited in Brun, 2013). As mentioned, this subdivision is based on elevation, with 650 m used as the boundary between lowland and sub-montane types, as well as other bioclimatic criteria that differentiate the humid coastal ranges (moist, annual precipitation ca. >2000 mm), lower-humidity inland forests (dry) and hinterlands (Brun, 2013). Lowland dry evergreen forest, one of the four evergreen forest subtypes, is included in dry evergreen forest in the classification system of the Cambodian Forestry Administration (FA, 2011). The distribution of evergreen forests in Cambodia and the environmental conditions associated with their classification are described by Ito *et al*. (2021).

Members of the Dipterocarpaceae typically dominate in lowland dry evergreen forest (Rundel, 1999; Tani *et al*., 2007; Ito *et al*., 2021). Two tall dipterocarp species, *Dipterocarpus costatus* C. F. Gaertn. (*chhoeuteal bankouy* in Khmer) and *Anisoptera costata* Korth. (*phdiek*), dominate the upper canopy layer of forests at the study site (Pooma, 2002). The study site features a sandy soil, Haplic Acrisol (Alumic, Profondic) (Toriyama *et al*., 2007, 2008), characteristic of gently undulating, sandy alluvial plains.

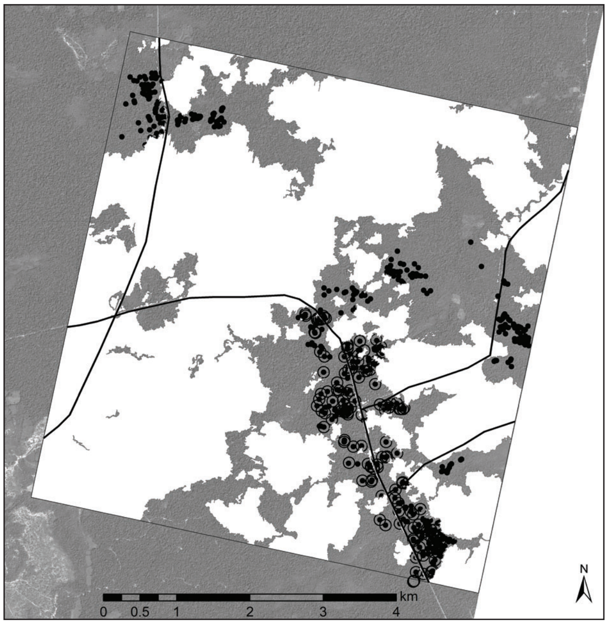

Fig. 2 The distributions of image-detected crown gaps and field-surveyed cutting sites. The closed black circles and the empty circles indicate crown gap sites detected on images and sites of tree mortality found during the field survey, respectively. Within the almost-square area of interest, the black lines indicate major roadways whereas the white areas indicate cloud-affected image areas that were not examined. The ALOS/PRISM images used for visual identification are shown in the background.

Detection of potential cutting sites by remote sensing

We obtained advanced land observing satellite panchromatic remote-sensing instrument stereo mapping (ALOS/PRISM) images (with a 2.5 m spatial resolution and a revisit cycle of 46 days) taken on 27 November 2006 and 1 May 2008, thus 1.25 years apart. The 2006 images include many clouds, whereas the 2008 images are clear. The total area explored was 14.93 km2, excluding the cloud-affected areas in the first image set. We employed object-based classification (Walter, 2004) to identify cutting of emergent trees with large crowns (>22.5 m in diameter, thus occupying 9 x 9 pixels on the ALOS/PRISM images). Selective cutting of such large trees can be identified via crown disappearance and the presence of large crown gaps. In the pre-felling images, the crowns of large-diameter trees fill the upper layer of the forest and the images are bright. After cutting, the canopy disappears and the images are dark. We performed principal component analysis (PCA) of both of the image sets to enhance the altered areas (Awaya & Tanaka, 2003) and identify the disappearance of large tree crowns. Large negative values of the second component indicated new crown gaps. In total, 501 potential cutting sites were visually identified (Fig. 2) and a subset of these was selected for field surveys.

Ground truthing survey

Our field survey was undertaken from 31 October 2008 to 4 November 2008, although preliminary surveys were also conducted on 31 August 2008 and 5 March and 30 November 2009. We visited potential cutting sites detected in ALOS/PRISM images. We recorded the location, size, tree-stump species, cause of death (cutting, natural mortality or collision with a felled tree) and the fall direction of felled trunks. Stump diameter was measured at breast height (1.3 m) (DBH) and for stumps <1.3 m in height, DBH was estimated using regression equations based on the maximum height and diameter and the diameter at ground level of the stump (Ito *et al*., 2010). Stump height was measured only when stumps were <1.3 m in height. For taller stumps, the height classes were estimated using photographs taken at 10 cm increments. The total area covered in the field was estimated from tracks recorded in a GPS 60CSx (Garmin, USA).

We also visually checked for cut trees or dead trees not detected on ALOS/PRISM images within 20 m on either side of paths taken between points of interest and investigations similar to those described above were undertaken when stumps were found. We estimated when such trees had been cut or had died, thus before or after the initial satellite imagery (before November 2006 or after December 2006 respectively) based on the freshness of a cut surface, the extent of resin exudation and the amount of bark on the sides of a stump. The conditions of stumps detected on ALOS/PRISM images were used as references for the decision criteria. The date of creation of industrial refuse left on stumps also served as a reference. Cutting largely occurred during the dry season (November to March), which was the agricultural off-season at that time. Therefore, stump ages were in one-year increments and thus (in our view) easy to determine. However, we concede that such judgments are subjective and therefore somewhat uncertain. Further, for trees cut during the 2007–2008 dry season, it was near-impossible to determine whether cutting occurred between the initial and final imagery (between December 2006 and February 2008) or after the final imagery (post-March 2008). All statistical analyses employed JMP software v10.0 (SAS Institute Inc., USA).

Results

Observations at sites of crown gaps

Our field surveys covered 0.34 km^2 and we visited 103 sites of crown gaps observed on images and confirmed that 101 were of these genuine gaps; trees had died. The trees were healthy at the remaining two sites. Of the 101 dead trees, 87.1% (*n*=88) had been cut, 9.9% (*n*=10) had died of natural causes and 3.0% (*n*=3) had died as a result of collision with a felled tree. In one location where a tree had died of natural causes, a large tree had not died, but a clump of smaller trees had. Thus, the percentage of large-diameter trees cut relative to the number of crown gaps on images was 88/103 (85.4%). We therefore estimate that 428 of the 501 canopy gaps detected in images of the 14.93 km^2 study area reflected cutting, with a cutting density per unit area from 2006 to 2008 (during two dry seasons) of at least 28.7 trees/km^2. Since our satellite imagery did not detect all crown gaps, this will naturally be an underestimate.

Spatial distribution of putative cutting sites

It was evident that the crown gaps (or cutting sites) were intense in small areas near main roads (Fig. 2) and many were within 50 m of a main road (Fig. 3a). As noted above, 85.4% of the crown gaps identified in satellite imagery were estimated to be sites where large-diameter trees were cut. The number of these sites decreased as the distance from a main road increased and cutting generally ceased at 1.2–1.3 km (Fig. 3a). The detection density (as in the number of detections divided by the area analysed: Fig. 3b) reduced less with distance from roads than the number of detections (Fig. 3c). The detection density within 50 m of a main road was 100 sites/km^2, whereas the average for other classes (>50 m & ≤1.3 km) was 30.8 sites/km^2. This detection density was multiplied by the percentage of large-diameter trees cut relative to the number of crown gaps on images (85.4%) to give an estimated cutting density of 85.4 trees/km^2 within 50 m of a main road and 26.3 trees/km^2 for >50 m and ≤1.3 km from a main road.

Species and sizes of trees cut

We recorded 222 stumps of cut/naturally fallen trees during the field survey, which included the cloud-covered area of the satellite images. Of these, 191 were cut trees, five had been killed by adjacent cutting and 26 had died naturally. We identified 190 of the cut trees to species in the field and found 113 (59.5%) were *D. costatus* and 56 (29.5%) were *A. costata*.

The DBH frequencies of the dipterocarps cut are shown in Fig. 4. Their medians and interquartile ranges were 84.0 cm and 75.7–97.7 cm. Mean ± SD DBH (range) were 86.4 ± 16.2 (56.0–131.7) cm and 90.1 ± 17.2 (55.6–150.6) cm for *D. costatus* and *A. costata*, respectively. Both species were cut before November 2006 (white histograms: Fig. 4a, 4b) or after December 2006 (black histograms: Fig. 4a, 4b). The size frequency distribution

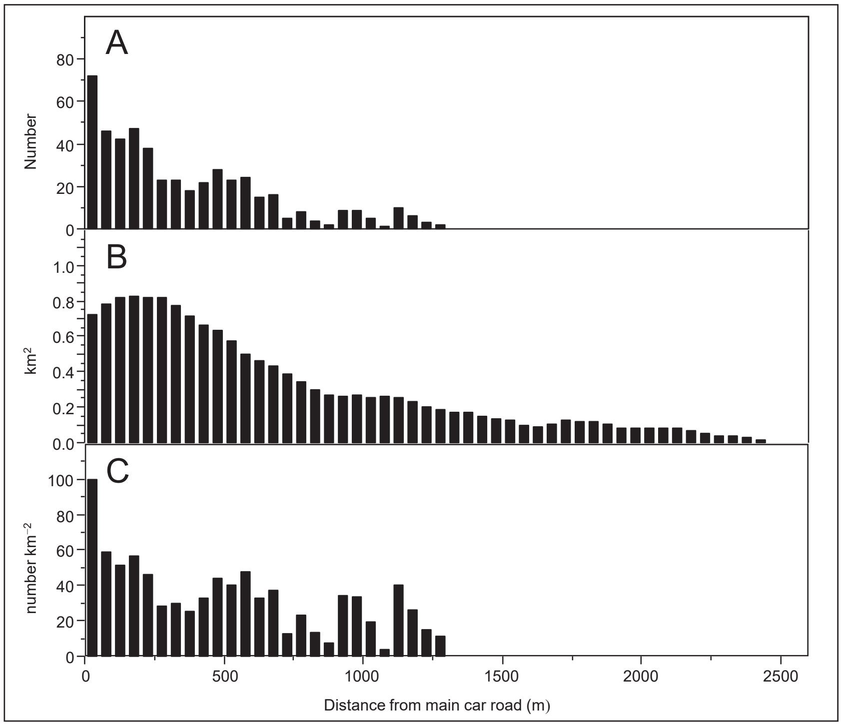

Fig. 3 Frequency distributions by linear distance from a main road. A) Number of crown gap sites evident on images, B) Analysis area, omitting areas hidden by clouds, C) Detection density.

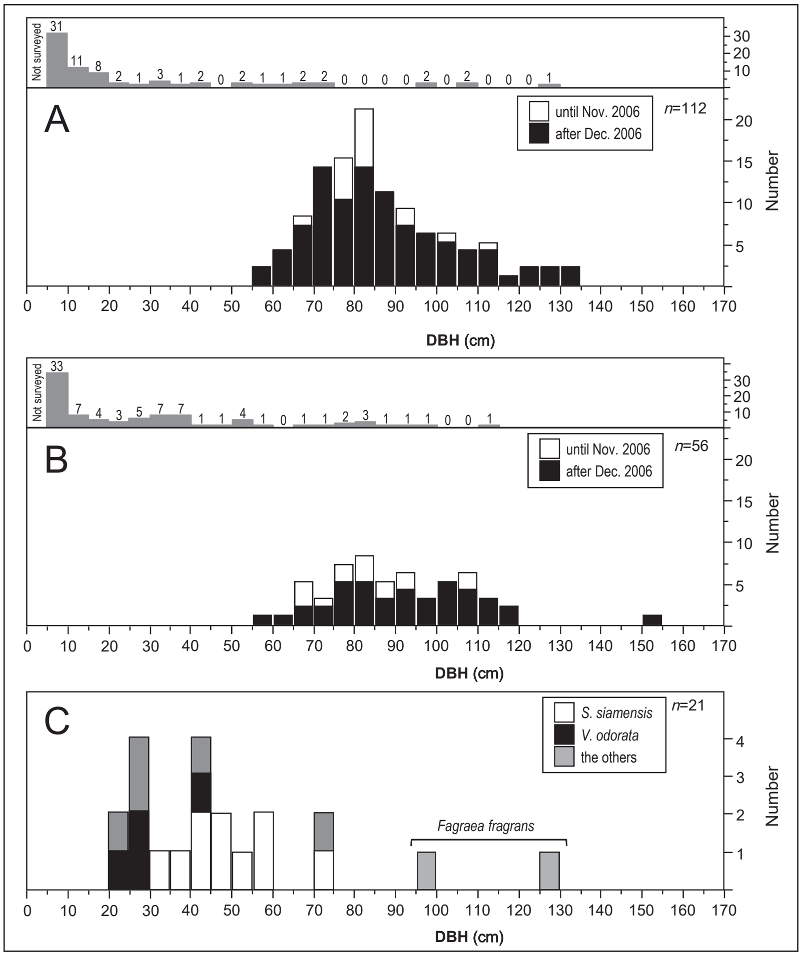

Fig. 4 Frequency distributions of diameter at breast height (DBH) for trees cut: A) *Dipterocarpus costatus*, B) *Anisoptera costata*, C) Other species. In A and B, the white and black columns are data obtained before and after the initial imaging (before November 2006 and after December 2006) respectively. The gray bars at the top of the figure show the frequency distribution of DBH for each species population from a tree census in the surrounding area, with numbers above the columns indicating the number of confirmed individuals (Ito *et al.*, 2023). In C, the white and black columns refer to *Sindora siamensis* and *Vatica odorata*, respectively. A DBH datum was missing for one stump of *D. costatus*.

of both tree species obtained from tree censuses of the surrounding area is also shown elsewhere (Fig. 4a, 4b: Ito *et al*., 2023).

Other species cut (*n*=21) included *Sindora siamensis* Teysm. ex Miq. (Fabaceae, *ko koh*, *n*=10), *Vatica odorata* (Griff.) Symington (Dipterocarpaceae, *chromas*, *n*=4), *Fagraea fragrans* Roxb. (Loganiaceae, *tatrao*, *n*=2), among others. Such species commonly had smaller DBHs, apart from *F. fragrans* (Fig. 4c). Most of the *S. siamensis* stumps were old (before November 2006), although a few were more recent.

Naturally dead trees

As noted above, 26 trees that had died naturally were found during the ground survey, including three *D. costatus* and eight *A. costata*. Mean DBH ± SDs (ranges) of trees that died naturally were 118.3 ± 14.6 (77.0–163.0) cm and 86.3 ± 8.9 (54.1–133.8) cm for *D. costatus* and *A. costata* respectively. Nominal logistic analysis was used to predict whether mortality was anthropogenic or natural using tree species as the predictor variable. This revealed significantly higher natural mortality of *A. costata* (χ2=6.94, *p*=0.014, *df*=1, *n*=180) than other species (odds ratio 5.53, *p*=0.0084).

The other 15 trees that died naturally included *Lophopetalum duperreanum* Pierre (Celastraceae, *proloup*, *n*=3), *Vatica odorata* (Dipterocarpaceae, *chromas*, *n*=2), *Tristaniopsis merguensis* (Griff.) Paul G.Wilson & J.T.Waterh. (Myrtaceae, *mdenh meas*, *n*=2), *Madhuca* sp. (Sapotaceae, *srokum*, *n*=2), Anacardiaceae (*n*=1), and unknown species (*n*=5). The mean DBH ± SD (range) of the trees that had died naturally was 51.9 ± 18.8 (15.0–76.0) cm (*n*=14, with 1 missing datum).

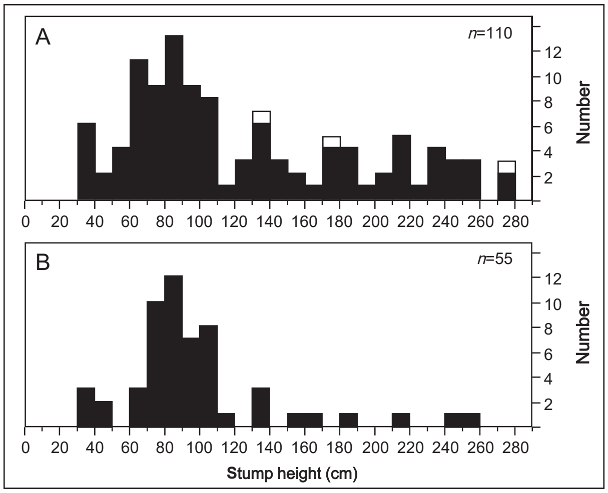

Fig. 5 Frequency distributions of the stump heights of A) *Dipterocarpus costatus*, B) *Anisoptera costata*. The white columns in A indicate that the figures are underestimates.

Cutting and processing operations and ground disturbance in the site

Chainsaws were used for cutting. Most stumps were cut between 60–110 cm in height, with a value of approximately 80 cm most frequent for both dipterocarp species (Fig. 5). A significant number of trees were cut higher. Of trees cut higher than 120 cm, 42% were *D. costatus* and 16% *A. costata*. The former were often cut higher to avoid lower deep scars on burns made to collect resin (Fig. 6), although there were many cases where felled trees had burn scars. Neighbouring stumps were often of similar height (data not shown). Some trees were left to rot. We found at least seven such trees. Trees found to be hollow may be abandoned (Fig. 7).

Fig. 6 Stumps of *Dipterocarpus costatus* with burn scars created to collect resin. A) Lower cut position, B) Higher cut position.

Felled trees were sawn on site. Sometimes, the logs were removed after the bark had been removed with an axe (Fig. 8a, 8b) and sometimes, the timber was processed into planks (Fig. 8c). Chain saw chips were observed near stumps when the cuts were very fresh (Fig. 8d). Fine sawdust disappeared rapidly, whereas bark and wood remained (Fig. 8e). One to two years after cutting, only wood blocks and bark remained on the forest floor (Fig. 8f).

No road was sufficiently wide to admit large vehicles. Former sawmill sites were often converted to cutting roads (Fig. 9a), and surrounding juvenile trees cut, especially if the road was extensively used (Fig. 9b).

Fig. 7 A felled tree with hollows left to rot at the study site.

Discussion

Forest degradation due to loss of large-diameter trees from 2006 to 2008

Our study provides key information on forest degradation due to selective cutting in the study area from 2006 to 2008. The most fundamental figure in this study is the DBH frequencies for cut dipterocarps (Fig. 4). To quantify forest degradation in terms of its carbon emissions, it is necessary to estimate the amount of biomass loss over time in a given area, for which a combination of field inventories and remote sensing is necessary (Bustamante *et al*., 2016; Gao *et al*., 2020). Our ground-based information, combined with satellite imagery, contributes to quantifying forest degradation more reliably and suggests that a cutting density of 28.7 trees/km^2 occurred over two dry seasons in our study area.

Information on the sizes of trees cut also indicates the progression of forest degradation. Comparisons of the DBH frequencies of cut dipterocarps and natural population suggests that the loggers cut trees from the largest diameter class (Fig. 4a, 4b). There was no difference in tree size in terms of the time of cutting (before November 2006 or after December 2006). However, cut stumps with a DBH <65 cm were only found after December 2006, implying that large-diameter trees had been depleted and smaller individuals subsequently targeted.

Shifts in the species targeted for cutting may reflect the progression of forest degradation. We found that *D. costatus* and *A. costata* were primary targets for cutting (Fig. 4). Both species are straight dipterocarps which attain 30–35 m in height (Toyama *et al*., 2013) and are thus priority targets for cutting (Kim Phat *et al*., 2002). This situation persisted from at least November 2006 to November 2009 i.e., from the time the first image was acquired to the time the last ground survey was conducted. This indicates that forest degradation in the study area was at a stage where the most useful large-diameter tree species were selectively cut, which likely corresponds to an initial stage of forest degradation. Aside from the two dipterocarp species, stumps of *S. siamensis* were most commonly found. Most of these were old (before November 2006), but some stumps were more recent, implying that the species might have been targeted anew. Although the number of observations is small (*n*=10), these records likely reflect changes in the species selected as the primary targets were depleted. Excessive selective logging often results in different vegetation, which is a typical sign of forest degradation (Thompson *et al*., 2013).

The amount of wastage in forest harvesting processes and its impact on carbon sequestration potential has been little addressed in studies on the influence of selective logging (Hari Poudyal *et al*., 2018). We quantified stump height and DBH for trees cut at our study site. Stump heights varied considerably (Fig. 5), possibly due to cutting practices and tree species (see below). Tree stumps are the main component of deadwood mass, one of the four carbon pools (above-ground and below-ground biomass, deadwood and litter) (Kiyono *et al*., 2010, 2011, 2017, 2018). These data provide baseline information for considering greenhouse gas emissions under REDD+ (Reducing Emissions from Deforestation and forest Degradation) projects.

Identifying crown gaps is a standard method for detecting forest degradation (Mitchell *et al*., 2017). The resolution of our ALOS/PRISM images (2.5 m) was sufficient to detect emergent tree crown gaps ca. 30 m in diameter. As such, archived ALOS/PRISM images may be effective to detect the early stages of former forest

Fig. 8 Processing of harvested trees and forest-floor remnants. A) Bark stripped off by an axe on the forest floor (1 November 2008), B) Logs on main road (31 August 2008), C) Lumber milled into boards (5 March 2009), D) Fine sawdust after chainsaw use at a recent cutting site (26 June 2018), E) Over time, fine sawdust disappears and bark becomes more prominent (5 March 2009), F) Wood blocks and bark at one to two years after cutting (1 November 2008).

degradation due to selective cutting in Cambodian evergreen forests. While earlier satellite images have certain quality limitations, these data are nonetheless valuable. However, this is the maximum density of large-diameter tree loss that could be estimated. To apply the coefficient for converting crown gap density to cutting density we obtained (85.4%) to other areas, the assumption that natural mortality of large-diameter trees is comparable to the study site would have to be met. Integrated assessment of forest degradation across an entire region requires regionally robust and consistent approaches, and locally developed approaches that assess degradation levels in small target areas on a case-by-case basis are considered inadequate (Miettinen *et al.*, 2014). As information on forest degradation due to selective logging is scarce for Cambodia (Hari Poudyal *et al*., 2018) however, it is also necessary to continue to build on findings obtained from locally developed approaches.

Cutting operations under the logging moratorium

Under the logging moratorium, illegal logging (cutting) operations shifted from commercial to small-scale operators, from few players to many, and from export to domestic markets (Broadhead & Izquierdo, 2010). Our observations in this study support this view. The most frequent cutting height was approximately 80 cm, implying that the operator was standing on the ground when using the chainsaw. However, a significant number of trees were cut higher (Fig. 5) and sometimes over 2 m. Neighbouring stumps were often of similar height (data not shown), implying that different cutting teams favoured particular heights. *Dipterocarpus costatus* was often cut higher to avoid lower deep scars on burns made to collect resin (Fig. 6), although there were many cases where trees felled had burn scars. This variation can be explained by the practices of individual cutting groups (personal communications from local residents). This suggests that cuttings in this area during our study period may have been carried out by several groups with different cutting practices, although the reasons underlying the choice of felling height remain unclear.

The development of roads is a key factor in promoting forest degradation (Walker *et al*., 2013; Lapola *et al*., 2023). Tree cutting, particularly of tall trees, is often intense near main roads. We found intensive cutting of large-diameter trees in small areas near main roads (Fig. 2). Cutting intensity, as indicated by crown gaps, was extremely high within 50 m of the main road (Fig. 3c) where there, all large trees would have been cut (85.4 trees/km^2). Conversely, the number of crown gaps decreased as the distance from a main road increased and generally ceased by 1.2–1.3 km (Fig. 3a). This finding is consistent with cases reported in Borneo, where logging activity can extend up to 1 km or more in flat terrain (Bryan *et al*., 2013). This could imply that the labour required for transporting cut timber offsite on the flatlands was similar. However, reductions in our detection density in terms of the distance from roads were lower (Fig. 3c). Thus, cutting intensity was relatively uniform within the reaches of the cutting groups, where a significant number of (though not all) large trees were cut (26.3 trees/km^2). Former forest degradation could be more reliably assessed using information on the road network, logging equipment and transportation machinery at a given point in time, and our study provides the basic information for this purpose.

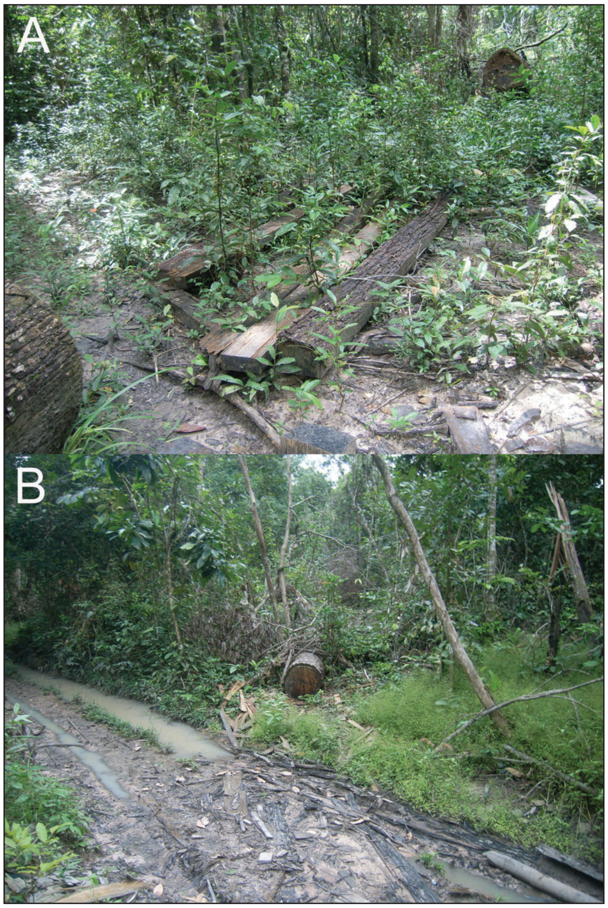

Fig. 9 Cutting roads at study site. A) Former sawmill access roads converted to cutting road, B) Felled juvenile trees adjacent to heavily-used cutting road.

Some cutting teams lacked the ability to foresee decay (Fig. 7) and many valuable trees and genetic resources were wasted as a result. This suggests that the rapid entry of unskilled small-scale operators into cutting may have resulted in unsustainable selective cutting. A cultural shift from timber mining to successful common-pool resource management has been proposed to halt poor logging practices (Putz *et al*., 2000; Zimmerman & Kormos, 2012). Deforestation in Cambodia after 2002 has been linked to population growth, gross agricultural production and large-scale plantation development (Michinaka *et al*., 2013). The relatively high cutting pressure evident at our study site from 2007 to 2009 was probably attributable to a population boom after the civil war and availability of chainsaws. It would have been considerably more difficult to foster a sustainable culture, for example, consensus on sustainable forest management, under rapid development pressure.

It has been noted that unauthorized logging may have led to the export of illegal timber (GIATOC, 2021). Kim *et al*. (2006) assumed that all individuals of *D. costatus* and *A. costata*, the two main forest resource species in Cambodia, were processed into veneer wood, although the exact percentages of processing uses was unknown. Use of dipterocarp trees for construction and plywood manufacturing has also been reported (Barney, 2005; GIATOC, 2021). The demand for wood for domestic housing construction in Cambodia, related to war and population growth, has been substantial (Kim *et al*., 2005), even into the 2000s (Broadhead & Izquierdo, 2010). According to local informants, the large-diameter tree cutting observed in our study area was for house construction. If true, alternative sources of timber supply are needed to halt the practice (Ty *et al*., 2011) and development of a stable and affordable supply of sustainable building materials would contribute to relieving the pressure on local forest resources.

Implications for forest conservation and restoration

Our detection density for crown gaps provides an important value for forest restoration: 100 sites km^{-2} in the closest class to a main road (Fig. 3c). Our field survey confirmed the mortality of individual trees in almost all (98%, 101/103) of the crown gaps detected. Since the selective cutting was exploitative, this estimate can be considered the natural population density of large-diameter dipterocarp trees in the study area. This figure would be useful for future restoration efforts in indicating the structure and biomass of the former forest.

The size of naturally dead trees of *A. costata* (86.3 ± 8.9 (54.1–133.8) cm) appeared to be smaller than those of *D. costatus* (118.3 ± 14.6 (77.0–163.0) cm), although the size distribution in the natural population did not differ greatly (Fig. 4a, 4b). Additionally, the quantity of naturally dead stumps of *A. costata* was significant. The reason for this is unknown, but it could have been a situation where natural mortality of *A. costata* was evident. Many tropical forest studies have shown that mortality rates in logged and unlogged forests are similar, except for the high mortality rate of trees damaged during logging (Sist & Nguyen-The, 2002; Yamada *et al*., 2013; Stas *et al*., 2023). However, disturbance-sensitive species, even in the absence of incidental damage during logging, may decline as a result of exposure of residual trees to constraining conditions such as increased wind stress or windthrow (Figueira *et al*., 2008; Garcia-Florez *et al*., 2017). Should *A. costata* be a disturbance-sensitive species, it could experience increased mortality due to surrounding forest degradation. In this case, it should be given special consideration in efforts to conserve local tree populations.

In conclusion, our study characterises the early stages of forest degradation in lowland evergreen forests due to intensive cutting of large-diameter dipterocarp trees. Under the logging moratorium, cutting activity was performed by several groups with different logging practices and covered an area up to about 1.3 km from the main road. The information we provide can help quantify forest degradation and is valuable for the REDD+ framework and forest restoration efforts. Steady accumulation of current and past insights on many aspects of forest information is essential to improve forest management in Cambodia.

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