Stump size and resprouting ability: responses to selective cutting in a sandy dry dipterocarp forest, central Cambodia

ITO Eriko[1,*] & TITH Bora[2]

[1] Hokkaido Research Center, Forestry and Forest Products Research Institute (FFPRI-HKD), 7 Hitsujigaoka, Toyohira, Sapporo, Hokkaido, 062-8516 Japan.

[2] Institute of Forest and Wildlife Research and Development (IRD), Forestry Administration, Street 1019, Phum Rongchak, Sankat Phnom Penh Thmei, Khan Sen Sok, Phnom Penh, Cambodia.

* Corresponding author. Email iter@ffpri.affrc.go.jp

Paper submitted 15 June 2020, revised manuscript accepted 25 August 2020.

មូលន័យសង្ខេប

ព័ត៌មានមូលដ្ឋានគ្រឹះនៃការដុះលូតលាស់ព្រៃឈើឡើងវិញគឺមានសារៈសំខាន់ណាស់ក្នុងការផ្តល់នូវគោលការណ៍ណែនាំសម្រាប់ការប្រើប្រាស់ព្រៃឈើប្រកបដោយនិរន្តរភាព។ នៅក្នុងលក្ខខណ្ឌនេះ លទ្ធភាពនៃការដុះពន្លកឡើងវិញរបស់ដើមឈើគឺជាលក្ខណៈសំខាន់នៃប្រភេទជាក់លាក់ណាមួយក្នុងការបន្សាំទៅនឹងធម្មជាតិ និងផលរំខានពីសកម្មភាពមនុស្ស។ នៅក្នុងការសិក្សាស្រាវជ្រាវនេះ យើងផ្តោតទៅលើលទ្ធភាពដុះពន្លកឡើងវិញរបស់ប្រភេទដើមឈើមួយប្រភេទដែលត្រូវបានគេកាប់ជាទូទៅគឺប្រភេទដើមឈើត្បែង (*Dipterocarpus obtusifolius*) នៅក្នុងអំបូរ Dipterocarpaceae ស្ថិតនៅភូមិភាគកណ្តាលនៃប្រទេសកម្ពុជា។ គោលបំណងនៃការសិក្សាស្រាវជ្រាវរបស់យើងគឺធ្វើការពិនិត្យលើការប្រើប្រាស់ព្រៃឈើប្រកបដោយនិរន្តរភាពដែលស្ថិតនៅទីតាំងព្រៃឈើជ្រុះស្លឹក តំបន់ដីខ្សាច់ (sandy dry dipterocarp) ដែលភាគច្រើនកាន់កាប់ និងសំបូរទៅដោយប្រភេទឈើត្បែង។ ក្នុងគោលបំណងនេះ យើងបានត្រួតពិនិត្យលើទំហំគល់ដើមឈើ ដែលបង្ហាញអំពីលទ្ធភាពដុះពន្លកឡើងវិញរបស់ប្រភេទឈើនៅក្នុងទីតាំងសិក្សា។ ទំហំគល់ឈើត្រូវបានប្រើប្រាស់សម្រាប់ព្យាករអំពីវត្តមាន ឬអវត្តមាននៃការដុះពន្លកឡើងវិញរបស់ប្រភេទឈើ ហើយវាកើតឡើងច្រើនសម្រាប់ដើមឈើដែលមានទំហំដើមតូច។ ទំហំដើមឈើអតិបរមាត្រូវបានគេប្រើប្រាស់ធ្វើជាអុស(មានអង្កត់ផ្ចិត ៣០ស.ម) គឺវាមានទំហំធំពេកក្នុងការរំពឹងឱ្យវាដុះពន្លកឡើងវិញ។ យើងក៏បានវិភាគអំពីប្រជាសាស្ត្ររបស់ដើមឈើដែលមានអង្កត់ផ្ចិត(នៅកម្ពស់ដើមទ្រូង) ធំជាង ៥.០ ស.ម ដោយយោងទៅតាមការរាប់ដើមឈើក្នុងរយៈពេល១៦ឆ្នាំ(២០០៣-២០១៩) នៅតំបន់សិក្សានេះ។ អត្រាដំណុះកូនឈើឡើងវិញមានកម្រិតខ្ពស់ក្នុងអំឡុងឆ្នាំ២០១៤-២០១៩ ដែលនេះហាក់បីដូចជាបណ្តាលមកពីស្តុកឬបណ្តុំនៃក្រុមដើមឈើមិនទាន់ពេញវ័យ(juvenile trees) មានចំនួនច្រើន តែមិនមែនមកពីការដុះពន្លកកូនឈើឡើងវិញបន្ទាប់ពីព្រឹត្តិការណ៍កាប់បំផ្លាញឈើនោះទេ។ លើសពីនេះ នាពេលអនាគតឆាប់ៗនេះ យើងនឹងមិនមានការរំពឹងថានឹងអាចប្រមូលគ្រាប់ពូជឈើក្នុងបរិមាណច្រើនបានទេ ដោយសារដើមត្បែងធំៗដែលអាចផលិតគ្រាប់ពូជបាន សឹងតែទាំងអស់ត្រូវបានគេកាប់ដើមធ្វើអុសដុត។ លទ្ធផលនៃការសិក្សារបស់យើងអាចបញ្ជាក់ថា ការដកហូតយកឈើធ្វើអុសដុតអាចជាកត្តាគំរាមកំហែងខ្ពស់បំផុតក្នុងការប្រើប្រាស់ព្រៃឈើជ្រុះស្លឹកតំបន់ដីខ្សាច់ ដែលស្ថិតក្នុងតំបន់សិក្សានេះ។

CITATION: Ito E. & Tith B. (2020) Stump size and resprouting ability: responses to selective cutting in a sandy dry dipterocarp forest, central Cambodia. *Cambodian Journal of Natural History*, **2020**, 34–41.

Abstract

Basic information on forest regeneration is necessary to provide guidelines for sustainable forest use. In this context, the resprouting ability of trees is an important species-specific character for adaptation to natural and anthropogenic disturbances. In this study, we focused on resprouting ability of a commonly logged tree species, *Dipterocarpus obtusifolius* (Dipterocarpaceae) in central Cambodia. Our aim was to examine the sustainability of forest use in a sandy dry dipterocarp forest i.e., an open forest community dominated by *D. obtusifolius*. For this purpose, we determined the stump sizes showing resprouting ability for species in the study forest. Stump size significantly predicted the presence/absence of resprouting and this was much more common in smaller stems. The maximum tree size used for fuel wood (30 cm in diameter) was too large to expect resprouting. We also analysed the demography of trees with diameters at breast height > 5 cm based on a 16-year chronological tree census (2003–2019) in the study forest. The relatively high recruitment rate during 2014‒2019 was likely achieved by a stock of juvenile trees and not by resprouting caused by tree-cutting events. Moreover, a large supply of seeds cannot be expected in the near future because almost all reproductive *D. obtusifolius* trees have been logged for firewood. Our results suggest that fuel wood extraction may be the greatest threat to sustainable use of sandy dry dipterocarp forests in our study region.

Keywords Conservation, *Dipterocarpus obtusifolius*, forest degradation, fuel wood, resprouting ability, selective cutting, sustainable management.

Introduction

The resprouting ability of trees is an important species-specific character for adaptation to natural disturbances (Bellingham & Sparrow, 2000). Various studies in tropical forests have examined this ability in response to hurricanes (Bellingham *et al*., 1994; Zimmerman *et al*., 1994; Jimenez-Rodríguez *et al*., 2018), fire (Paciorek *et al*., 2000; Mlambo & Mapaure, 2006; Lawes *et al*., 2011; Nguyen *et al*., 2019), and slash-and-burn agriculture (Miller & Kauffman, 1998). From the perspective of conservation, information on resprouting ability is fundamental to practical applications.

Human population growth is currently causing deforestation pressure in Cambodia. The country has attracted the attention of the REDD+ programme (i.e., reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries) because it is regarded as a "hot spot" for deforestation and forest degradation (FAO, 2010; FAO, 2020). As a result, quantitative studies have been conducted on the sustainability of forest use in Cambodia e.g., on wood fuel consumption (Top *et al*., 2004a) and the gain-loss approach quantifying carbon gains from annual increases and losses in biomass caused by natural and anthropogenic processes (Sasaki, 2006; Sasaki *et al*., 2013, 2016; Kiyono *et al*., 2017).

Basic information on forest stands and their regeneration is necessary to provide guidelines for sustainable forest use in Cambodia (Ito *et al*., 2016). Such information must be presented for individual forest types, appropriately stratified by degradation processes. In this study, we focused on resprouting ability of a commonly logged tree species, *Dipterocarpus obtusifolius* Teijsm. ex Miq. (Dipterocarpaceae). Our aim was to examine the sustainability of forest use in an open forest community dominated by *D. obtusifolius*, referred to as sandy dry dipterocarp forest. For this purpose, we determined the stump size showing resprouting ability for tree species in a sandy dry dipterocarp forest in central Cambodia.

Methods

Our study was conducted in Kampong Thom Province (12.8°N, 105.5°E; elevation: 70 m). The climate of the area is seasonally tropical, and the months from November through April are dry. Mean annual temperature is 27 °C and annual rainfall (mean ± SD) is 1542 ± 248 mm (2000–2010; NIS, 2012). Our study sites were located on extensive quaternary sedimentary rock. The soils present are classified as acrisols, but have albic and arenic features that suggest a closer relationship with arenosols (Toriyama *et al*., 2007a).

Our study forest was a sandy dry dipterocarp forest (Ito *et al*., 2017). Sandy dry dipterocarp forests are characterised by a strong dominance of *Dipterocarpus obtusifolius* (Dipterocarpaceae; Khmer: "Tbeng"), which favour sandy or gravelly soils or laterites (Smitinand *et al*., 1980). This forest type has been variously referred to as "forêt claire à *Dipterocarpus obtusifolius*" (Vidal, 1960), *D. obtusifolius* on sand or grey soil ("à *D. obtusifolius*, sur sable ou terre grise"; Rollet, 1972), *D. obtusifolius* community (Baltzer *et al*., 2001), and *D. obtusifolius* stand type (Hiramatsu *et al*., 2007). Sandy dry dipterocarp forests are most characteristic of areas east of the Mekong River in Cambodia in sites with thin sandy soils over laterites (Rundel, 1999). In Kampong Thom Province, northeast of Tonle Sap Lake, they often occur as scattered forest patches among evergreen forests in sites with deep sandy soils that are subject to seasonal flooding (Hiramatsu *et al*., 2007).

The Cambodian Forestry Administration has classified national forest cover into four major types: evergreen, semi-evergreen, deciduous, plus a mixture of other forms such as forest re-growth, inundated forests, stunted forests, mangrove forests and forest plantations (Forestry Administration, 2011). Deciduous forests comprising dry mixed deciduous forests and dry dipterocarp forests are predominant in Cambodia and account for 24.7% of its land area (Forestry Administration, 2011). Dry dipterocarp forests are characterized by a dominance by a small number of deciduous species of Dipterocarpaceae, such as *D. intricatus*, *D. tuberculatus*, *Shorea obtusa* and *S. siamensis* (Rundel, 1999). They have also been subdivided into four forms, each with different combinations of soil type and dominant dipterocarp species (Rollet, 1972). Although our sandy dry dipterocarp study forest is classified as one form of dry dipterocarp forest among deciduous forests, it has not shown clear deciduousness, only displaying irregular and incomplete leaf shedding of component tree species (Ito *et al*., 2007). For example, the leaf longevity of *D. obtusifolius* in the forest often exceeds one year (E. Ito & Tith B., unpublished data) and never results in a leafless crown.

Sandy dry dipterocarp forests often exhibit low species richness (Hiramatsu *et al*., 2007; Ito *et al*., 2017), annual growth rates and carbon increments (Ito *et al*., 2017). They have open structures with 40–70% canopy cover (Rundel, 1999; Hiramatsu *et al*., 2007; Forestry Administration, 2011), are associated with ground fires (Rundel, 1999; Hiramatsu *et al*., 2007), have nutrient-poor sandy soils (Rollet, 1972; Toriyama *et al*., 2007a,b) and experience seasonal flooding and drought conditions (Rollet, 1972; Rundel, 1999; Baltzer *et al*., 2001; Araki *et al*., 2007). *Dipterocarpus obtusifolius* predominates and is an ecologically plastic and stress tolerant species (Rundel, 1999). It is also fire resistant in having the ability to resprout after fire like other deciduous dipterocarps (*D. tuberculatus*, *S. obtusa* and *S. siamensis*) (Nguyen *et al*., 2019).

We established a permanent sample plot (30 × 80 m) to investigate stand structure and dynamics in sandy dry dipterocarp forest at the study site in 2003 (Hiramatsu *et al*., 2007; Ito *et al*., 2017). Field surveys were conducted in 2003, 2008, 2009, 2010, 2011, and 2012 (pre-logging) and in 2014 and 2019 (post-logging) to investigate tree growth and demography. Based on a 2012 census undertaken before illegal logging occurred at the site, the tree density and basal area of stems with a diameter at breast height (DBH) ≥5 cm were 408 stems ha^{-1} and 12.3 m^2 ha^{-1}, respectively (Ito *et al*., 2017). The plot had one dominant dipterocarp species, *D. obtusifolius* (accounting for 50% of stand basal area and 60% of stand tree number), which was associated with *Gluta laccifera* (Pierre) Ding Hou (Anacardiaceae, 35% and 6%, respectively) (Hiramatsu *et al*., 2007). The forest lacked auxiliary deciduous species such as *D. tuberculatus*, *S. obtusa*, *S. siamensis*, *Pterocarpus macrocarpus* (Fabaceae) and *Xylia xylocarpa* (Fabaceae), which usually occur together in dry dipterocarp or deciduous dipterocarp forests (Royal Forest Department, 1962; Hiramatsu *et al*., 2007; Tani *et al*., 2007; Pin *et al*., 2013). Edaphic limitations are potential factors limiting species richness (Hiramatsu *et al*., 2007) and the ground surface was waterlogged several times in the middle of the rainy season in 2005 (August through September, Araki *et al*., 2007). The ground vegetation includes *Xyris complanata* R.Br. (Xyridaceae) and insectivorous plants (*Drosera* sp., Droseraceae and *Nepenthes* sp., Nepenthaceae), which suggest low-nutrient edaphic conditions (Hiramatsu *et al*., 2007).

We investigated the resprouting ability of individual trees that had suffered illegal cutting in and around the permanent sample plot. To this end, the heights and diameters of the remaining stumps were measured in December 2019. Diameter was measured at the upper surface of the stumps. We recorded the presence/absence of resprouting stems on the stumps, the number of resprouting stems, and the place where each resprouting stem emerged (basal sprouting from the ground around the stump or sprouting from the upper side of the stump). Individuals of *D. obtusifolius* whose main stems were broken by the toppling of other trees were also investigated.

A nominal logistic regression model was used to generate prediction equations for the relationship between stump size and presence/absence of resprouting using a dataset of all tree species and a dataset for *D. obtusifolius* only. One-way ANOVA was used to test for differences in the height or diameter of resprouting on logged stumps for *D. obtusifolius*. Tukey HSD tests were used to distinguish differences in the place of resprouting. Statistical analysis was conducted using *JMP* statistical software vers. 10.0 (SAS Institute Inc., Cary, NC, USA). The threshold for significance applied in all tests was $P < 0.05$.

Results

During the chronological tree census (2003–2019), a total of 47 tree individuals were cut or had their stems broken by anthropogenic activities (Table 1). Illegal tree cutting within the plot progressed in stages, as follows.

During 2003–2012, there were no cutting events in our study plot. The site sometimes experienced fire, but no tree (>5 cm DBH) died as a result. Logging occurred during the 2012–2014 census. Stumps were found on 8 February 2014 and we estimate that these were cut between December 2013 and January 2014 due to the freshness of the logged stumps and because logging in the study area usually takes place during the dry season. Relatively large individuals of *D. obtusifolius* and *G. laccifera* (>38 cm DBH) were cut, probably for their timber (Table 1). Small trunks (<26 cm DBH) were also cut and discarded on site (Table 1). These may have been felled for fuel or used to test chainsaw performance. Further details on tree cutting during this period are reported by Ito *et al*. (2017). During the 2014–2019 census, the remaining large individuals of *D. obtusifolius* and *G. laccifera* were completely cut (Table 1). Most small trees were also cut during this period. On 28 February 2019, we found that the smaller trees had been gathered in one location at the site and estimate that these were cut between December 2018 and February 2019.

We investigated the resprouting ability of 47 trees. These comprised 45 trees that had been logged and two *D. obtusifolius* with broken stems (Table 1). Most of the investigated trees were *D. obtusifolius* (*n*=36) and the remaining species are shown in Table 1. Resprouting was observed in 15 trees in total (Table 1), most of which were also *D. obtusifolius* (*n*=13). The remaining two individuals were *Calophyllum calaba* var. *bracteatum* (Calophyllaceae) and *Parinari anamensis* (Chrysobalanaceae). Resprouting occurred in trees ranging from 4.8 to 26.9 cm in stump diameter (Fig. 1). Stump size significantly predicted the presence/absence of resprouting in all trees investigated (*P*=0.0006) and *D. obtusifolius* (*P*=0.0228). Among 26 individuals of *D. obtusifolius* that had a stump diameter less than 26.9 cm, 42.3% showed resprouting ability. Nominal logistic regression models indicated that >50% of the *D. obtusifolius* stumps with a diameter less than 16.1 cm also retained resprouting ability (Fig. 2).

The median number of resprouts per tree was two, and there was no clear trend for smaller stumps to generate a greater number of sprouts. The highest number of sprouts on a single stump was 24, followed by 13. Dominant–inferior relationships were clear among the resprouts however, with only one or two resprouts being vigorous. Basal sprouting was found in eight trees, and stem sprouting was found in four trees. One exceptional individual had a single vigorous resprout which occurred on a stem and a total of 12 small resprouts which occurred on the base.

There was a significant difference in the height of logged stumps with basal sprouting and those with stem sprouting for *D. obtusifolius* (ANOVA, *P*=0.0043, Fig. 3), but no significant difference was found in stump diameter between the two. The addition of the explanatory

Table 1 Selective tree cutting during 2012–2014 and 2014–2019 in the permanent sample plot in central Cambodia. Numerical values in square brackets represent resprouting trees. Stem diameter (cm) is given as mean and range in parentheses.

Tree species (Family)	Cutting period				Total
	2012–2014		2014–2019		*n*
	n	Stem diameter	*n*	Stem diameter	
Dipterocarpus obtusifolius Teijsm. ex Miq. (Dipterocarpaceae)	6 [3]	23.8 (11.4–42.3) [16.5 (11.4–26.0)]	30 [10]	25.4 (7.6–55.5) [20.9 (4.8–26.9)]	36 [13]
Gluta laccifera (Pierre) Ding Hou (Anacardiaceae)	3 [0]	57.4 (54.3–61.8) [—]	2 [0]	65.1 (63.3–66.8) [—]	5 [0]
Calophyllum calaba L. var. *bracteatum* (Wight) P.F. Stevens (Calophyllaceae)	1 [1]	9.5 [9.5]	0 [0]	— [—]	1 [1]
Parinari anamensis Hance (Chrysobalanaceae)	1 [1]	4.9 [4.9]	3 [0]	26.7 (7.2–46.0) [—]	4 [1]
Syzygium oblatum (Roxb.) Wall. ex A.M. Cowan & Cowan (Myrtaceae)	0 [0]	— [—]	1 [0]	31.2 [—]	1 [0]
Total	11 [5]		36 [10]		47 [15]

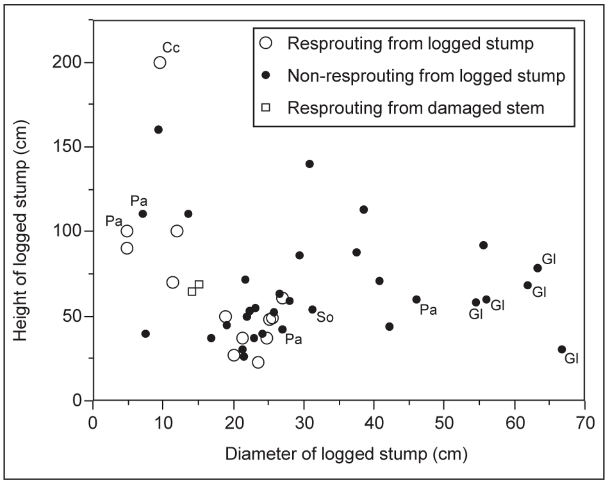

Fig. 1 Relationship between diameter and height of logged stumps. Abbreviations indicate the presence/absence of resprouting stems. Species other than *Dipterocarpus obtusifolius* are Gl=*Gluta laccifera*, C=*Calophyllum calaba* var. *bracteatum,* Pa=*Parinari anamensis*, So=*Syzygium oblatum*.

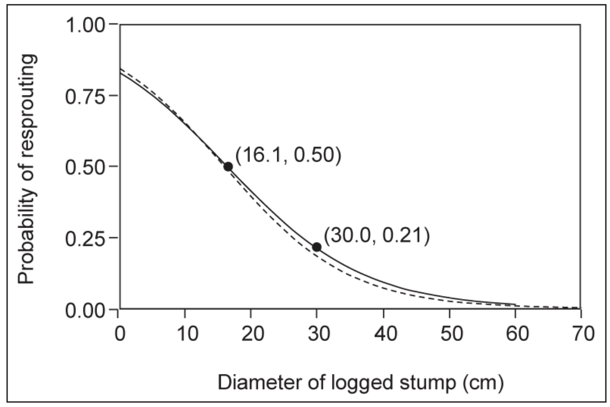

Fig. 2 Estimated probability of resprouting according to the stump diameter using nominal logistic regression. Dashed and straight lines indicate estimates for all species and *D. obtusifolius*, respectively.

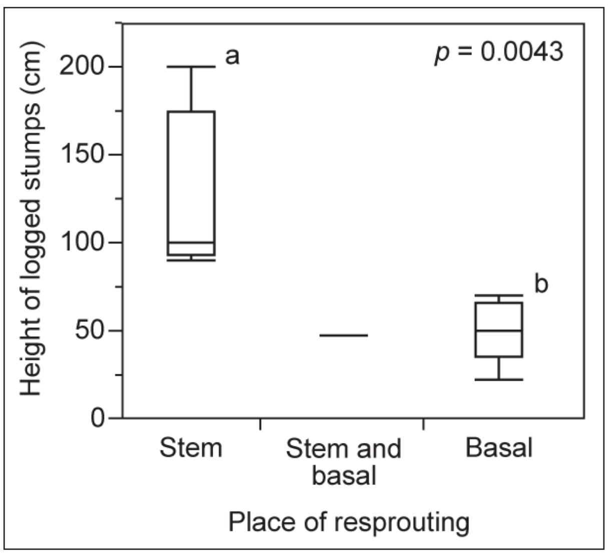

Fig. 3 Height of logged stumps by location of resprouting stem of *Dipterocarpus obtusifolius*. Data are presented as box-and-whisker plots (median, 25% and 75% quartiles, range). Columns labelled with different letters differ significantly.

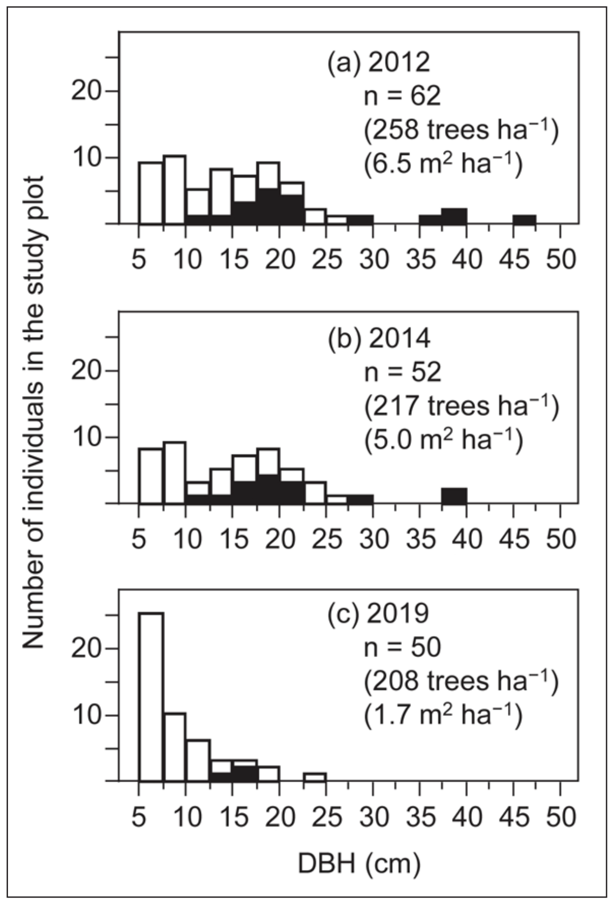

Fig. 4 Frequency distribution of DBH of *Dipterocarpus obtusifolius* in study plot: A) 2012 pre-logging census; B) 2014 post-timber logging census; C) 2019 post-firewood logging census. Black and white columns indicate individuals with confirmed and unconfirmed flowering and/or fruiting, respectively, prior to the 2009 census.

factors of stump height and interaction of stump size and height did not significantly improve the nominal logistic regression models predicting the presence/absence of resprouting.

The distribution of diameters for *D. obtusifolius* shifted markedly during our censuses (Fig. 4). What began as a relatively flat distribution (Figs. 4A, 4B) changed to an

L-shaped distribution (Fig. 4c). Tree density and basal area also decreased greatly, from 258 trees ha^{-1} and 6.5 $m^2 ha^{-1}$ during the 2012 census to 208 trees ha^{-1} and 1.7 $m^2 ha^{-1}$ during the 2019 census (Fig. 4).

Recruitment of *D. obtusifolius* occurred during the 2014–2019 censuses at a rate of 29 trees per plot. This was clearly greater than the recruitment of six trees per plot in the 11 years covered by the 2003–2014 censuses. Of the 29 recruitments observed in 2014–2019, only five were derived from resprouting.

Discussion

Following the selective logging recorded during our 2014 census (Ito *et al*., 2017), considerable cutting of small-diameter trees occurred during the 2014–2019 censuses (Table 1). The former was possibly for timber, whereas the latter was probably for firewood. *Dipterocarpus obtusifolius* is preferred for fuel wood (Top *et al*., 2004b; San *et al*., 2012) and was targeted among the smaller trees. These were also gathered in one location, presumably to dry and lighten the wood prior to transport.

Consistent with previous studies in continental Southeast Asia (Baker *et al*., 2009) and a meta-analysis of literature (Vesk, 2006), we found that resprouting was much more common in smaller stems (Figs. 1,2). Although sandy dry dipterocarp forest is often affected by fires (Rundel, 1999; Hiramatsu *et al*., 2007), the maximum diameter of resprouting stumps in our study was 26.9 cm (Fig. 1), whereas Baker *et al*. (2009) documented resprouting after fire in trees whose diameters ranged from 1 to 50 cm. Top *et al*. (2004b) reported that the maximum diameter of trees used for fuel wood in our study area was 30 cm and our data suggests that the probability of *D. obtusifolius* resprouting at this diameter is 21% (Fig. 2). However, caution is required here because we were not able to directly confirm resprouting for stumps with diameters greater than 26.9 cm (Fig. 1). In addition, the height of logged stumps did not influence the presence/absence of resprouting (Fig. 3). This suggests that resprouting ability may not be enhanced by managing felling heights.

Sist *et al*. (2003) recommended a procedure for setting cutting limits based on tree DBH during the reproduction stage of target species. In the case of *D. obtusifolius*, DBH at 50% and 90% of tree reproduction have been estimated as 18.8 cm (95% CI=16.2–23.9 cm) and 27.1 cm (95% CI=22.7–42.5 cm) respectively (Ito *et al*., 2016). Official guidelines state a cutting limit of 45 cm DBH for *D. obtusifolius* (MAFF, 2005). If logging at our study site adhered to these guidelines, a reproductive tree population could have persisted in the forest. However, given that trees cut during the 2014–2019 censuses averaged 21.5 cm DBH, it is likely that the size criterion for fuelwood cutting was too low to meet the recommendation of Sist *et al*. (2003). For instance, substantial densities of reproductive trees were recorded during the 2009 census in our study plots (83 stems ha^{-1}; Ito *et al*., 2017), but almost all reproductive trees were subsequently logged by 2019 (Fig. 4c) and the remainder were relatively small (ca. 16 cm in diameter; see also Fig. 4c). As such, a large supply of seeds cannot be expected in the near future and if further cutting were to occur before the current population of young trees begin reproduction, regeneration from seedlings would be very difficult.

A relatively high recruitment rate was observed during 2014–2019. This was likely due to a stock of juvenile trees with diameters less than 5 cm rather than resprouting caused by tree-cutting. Only 1–2 stems typically sprout from a logged stump and some small-diameter trees did not show resprouting ability (Fig. 1, 2). As a consequence, it is likely too optimistic to expect that resprouting could compensate for clear-cutting and thereby regenerate the forest. Top *et al*. (2004b) suggested that agricultural expansion may be the main cause of deforestation in Kampong Thom Province, rather than fuel wood extraction. However, the scattered sandy dry dipterocarp forests in the province are not a high priority for agricultural development because they are established on seasonally flooded and low-nutrient lands (Toriyama *et al*., 2007a). As such, fuel wood extraction may pose the largest threat to sustainable use of sandy dry dipterocarp forests in the province.

Acknowledgements

The authors are deeply indebted to H.E. Dr Ty Sokhun (Secretary of State, Ministry of Agriculture, Forestry & Fisheries [MAFF]), H.E. Dr Chheng Kimsun (formerly Head of Forestry Administration, MAFF), and to Dr Sokh Heng (Director, Institute of Forest and Wildlife Research and Development, MAFF) for permission to use permanent sample plot data and undertake field research. This paper reports results obtained by the emergency project to promote REDD action supported by the Forestry Agency, Japan. Field measurements were conducted as part of the programme funded by KAKENHI (20770021 & 18K06437) and the "Research Revolution 2002 Project" of MEXT Japan, the Global Environment Research Fund (B-072, B-0802), the global environment research coordination system supported by MOE Japan, and the "Estimation and Simulation of Carbon Stock Change of Tropical Forests in Asia (2011–2014)" supported by MAFF Japan.

References

Araki M., Toriyama J., Ohta S., Kanzaki M., Ito E., Tith B., Pol S., Lim S., Khorn S., Pith P. & Det S. (2007) Soil moisture conditions in four types of forests in Kampong Thom, Cambodia. In *Forest Environments in the Mekong River Basin* (eds Sawada H., Araki M., N.A. Chappell, J.V. LaFrankie & Shimizu A.), pp. 254–262. Springer, Tokyo, Japan.

Baker, P.J., Bunyavejchewin, S. & Robinson, A.P. (2009) The impacts of large-scale, low-intensity fires on the forests of continental South-east Asia. *International Journal of Wildland Fire*, **17**, 782–792.

Baltzer, M.C., Nguyen T.D. & Shore, R.G. (2001) *Towards a Vision for Biodiversity Conservation in the Forests of the Lower Mekong Ecoregion Complex*. WWF Indochina/WWF US, Hanoi and Washington DC, USA.

Bellingham, P., Tanner, E. & Healey, J. (1994) Sprouting of trees in Jamaican montane forests, after a hurricane. *Journal of Ecology*, **82**, 747–758.

Bellingham, P.J. & Sparrow, A.D. (2000) Resprouting as a life history strategy in woody plant communities. OIKOS, 89, 409-416.

[FAO] Food and Agriculture Organisation of the United Nations (2010) *Global Forest Resources Assessment 2010*. Http://www.fao.org/forestry/fra/fra2010/en/ [Accessed 1 August 2020].

[FAO] Food and Agriculture Organisation of the United Nations (2020) *The State of the World's Forests 2020*. Http://www.fao.org/documents/card/en/c/ca8642en [Accessed 1 August 2020].

Forestry Administration (2011) *Cambodia Forest Cover 2010*. ITTO-PD493/07 Rev.1(F). Forestry Administration, Phnom Penh, Cambodia.

Hiramatsu R., Kanzaki M., Toriyama J., Kaneko T., Okuda Y., Ohta S., Khorn S., Pith P., Lim S., Pol S., Ito E. & Araki M. (2007) Open woodland patch and the isolated stand of *Melaleuca cajuputi* in an evergreen forest of Kampong Thom, Cambodia: a transect study along a micro-topography gradient. In *Forest Environments in the Mekong River Basin* (eds Sawada H., Araki M., Chappell, N.A., LaFrankie, J.V. & Shimizu A.), pp. 216–224. Springer, Tokyo, Japan.

Ito E., Khorn S., Lim S., Pol S., Tith B., Pith P., Tani A., Kanzaki M., Ohta S., Kaneko T., Okuda Y. & Araki M. (2007) Comparison of the leaf area index (LAI) of two types of dipterocarp forest on the west bank of the Mekong River, Cambodia. In *Forest Environments in the Mekong River Basin* (eds Sawada H., Araki M., N.A. Chappell, J.V. LaFrankie & Shimizu A.), pp. 208–215. Springer, Tokyo, Japan.

Ito E., Chann S., Tith B., Keth S., Ly C., Op P., Furuya N. & Monda Y. (2016) Reproductive size thresholds of dipterocarps in Cambodian dry forests. *Cambodian Journal of Natural History*, **2016**, 98–101.

Ito E., Furuya N., Toriyama J., Ohnuki Y., Kiyono Y., Araki M., Sokh H., Chann S., Khorn S., Samreth V., So T., Tith B., Keth S., Ly C., Op P., Monda Y. & Kanzaki M. (2017) Stand carbon dynamics in a dry Cambodian dipterocarp forest with seasonally flooded sandy soils. *Cambodian Journal of Natural History*, **2017**, 109–127.

Jimenez-Rodríguez, D.L., Alvarez-Añorve, M.Y., Pineda-Cortes, M., Flores-Puerto, J.I., Benítez-Malvido, J., Oyama K. & Avila-Cabadilla, L.D. (2018) Structural and functional traits predict short term response of tropical dry forests to a high intensity hurricane. *Forest Ecology and Management*, **426**, 101–114.

Kiyono Y., Ito E., Monda Y., Toriyama J., Saito H., Furuya N., Sum T., Tith B., Keth N., Keth S., Ly C., Op P., Chann S. & Sokh H. (2017) Above-ground biomass gain of tropical seasonal forests in Cambodia estimated by the gain–loss method. *TROPICS*. DOI 10.3759/tropics.MS15-2.

Lawes, M.J., Richards, A., Dathe, J. & Midgley, J.J. (2011) Bark thickness determines fire resistance of selected tree species from fire-prone tropical savanna in north Australia. *Plant Ecology*, **212**, 2057–2069.

[MAFF] Ministry of Agriculture, Forestry and Fisheries (2005) Prakas No. #89, Forbidding harvest timber and non-timber forest products. MAFF, Phnom Penh, Cambodia [in Khmer].

Miller, P. & Kauffman, J. (1998) Seedling and sprout response to slash-and-burn agriculture in a tropical deciduous forest. *Biotropica*, **30**, 538–546.

Mlambo, D. & Mapaure, I. (2006) Post-fire resprouting of *Colophospermum mopane* saplings in a southern African savanna. *Journal of Tropical Ecology*, **22**, 231–234.

[NIS] National Institute of Statistics (2012) *Statistical Yearbook of Cambodia 2011*. National Institute of Statistics, Ministry of Planning, Phnom Penh, Cambodia.

Nguyen T.T., Murphy, B.P. & Baker, P.J. (2019) The existence of a fire-mediated tree-recruitment bottleneck in an Asian savanna. *Journal of Biogeography*, **46**, 745–756.

Paciorek, C.J., Condit, R., Hubbell, S.P. & Foster, R.B. (2000) The demographics of resprouting in tree and shrub species of a moist tropical forest. *Journal of Ecology*, **88**, 765–777.

Pin C., Phan C., Prum S. & Gray, T.N.E. (2013) Structure and composition of deciduous dipterocarp forest in the Eastern Plains Landscape, Cambodia. *Cambodian Journal of Natural History*, **2013**, 27–34.

Rollet, B. (1972) La vegetation du Cambodge. *Bois et Forets des Tropiques*, **145**, 23–3. [in French].

Royal Forest Department (1962) *Types of forest of Thailand*. No. R 44. Royal Forest Department, Bangkok, Thailand.

Rundel, P.W. (1999) Forest Habitats and Flora in Lao PDR, Cambodia, and Vietnam. WWF Indochina Programme, Hanoi, Vietnam.

San V., Spoann V., Ly D. & Chheng N.V. (2012) Fuelwood consumption patterns in Chumriey mountain, Kampong Chhnang province, Cambodia. *Energy*, **44**, 335–346.

Sasaki N. (2006) Carbon emissions due to land-use change and logging in Cambodia: a modeling approach. *Journal of Forest Research*, **11**, 397–403.

Sasaki N., Abe I., Khun V., Chan S., Ninomiya H. & Chheng K. (2013) Reducing carbon emissions through improved forest management in Cambodia. *Low Carbon Economy*, **4**, 55.

Sasaki N., Chheng K., Mizoue N., Abe I. & Lowe A.J. (2016) Forest reference emission level and carbon sequestration in

Cambodia. *Global Ecology and Conservation*, **7**, 82–96.

Sist, P., Fimbel, R., Sheil, D., Nasi, R. & Chevallier, M.H. (2003) Towards sustainable management of mixed dipterocarp forests of South-east Asia: moving beyond minimum diameter cutting limits. *Environmental Conservation*, **30**, 364–374.

Smitinand, T., Santisuk, T. & Phengklai, C. (1980) The manual of Dipterocarpaceae of mainland South East Asia. *Thai Forest Bulletin (Botany)*, **12**, 1–133.

Tani A., Ito E., Kanzaki M., Ohta S., Khorn S., Pith P., Tith B., Pol S. & Lim S. (2007) Principal forest types of three regions of Cambodia: Kampong Thom, Kratie, and Mondolkiri. In *Forest Environments in the Mekong River Basin* (eds Sawada H., Araki M., N.A. Chappell, J.V. LaFrankie & Shimizu A.), pp. 195–207. Springer, Tokyo, Japan.

Top N., Mizoue N. & Kai S. (2004a) Estimating forest biomass increment based on permanent sample plots in relation to woodfuel consumption: a case study in Kampong Thom Province, Cambodia. *Journal of Forest Research*, **9**, 117–123.

Top N., Mizoue N., Kai S. & Nakao T. (2004b) Variation in woodfuel consumption patterns in response to forest availability in Kampong Thom Province, Cambodia. *Biomass and Bioenergy*, **27**, 57–68.

Toriyama J., Ohta S., Araki M., Ito E., Kanzaki M., Khorn S., Pith P., Lim S. & Pol S. (2007a) Acrisols and adjacent soils under four different forest types in central Cambodia. *Pedologist*, **51**, 35–49.

Toriyama J., Ohta S., Araki M., Kanzaki M., Khorn S., Pith P., Lim S. & Pol S. (2007b) Soils under different forest types in the dry evergreen forest zone of Cambodia: morphology, physicochemical properties and classification. In *Forest Environments in the Mekong River Basin* (eds Sawada H., Araki M., N.A. Chappell, J.V. LaFrankie & Shimizu A.), pp. 241–253. Springer, Tokyo, Japan.

Vesk, P.A. (2006) Plant size and resprouting ability: trading tolerance and avoidance of damage? *Journal of Ecology*, **94**, 1027–1034.

Vidal, J.E. (1960) Les forêts du Laos. *Bois et Forêts des Tropiques*, 70, 5–21.

Zimmerman, J.K., Everham, E.M., Waide, R.B., Lodge, D.J., Taylor, C.M. & Brokaw, N.V. (1994) Responses of tree species to hurricane winds in subtropical wet forest in Puerto Rico: implications for tropical tree life histories. *Journal of Ecology*, **82**, 911–922.

