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Supplementary Materials for Sasaki and Yoshimoto

1. Forests in Cambodia

The Cambodian government defines forests for the United Nations Convention on Climate Change (UNFCCC) as land having forest canopy cover of 10% and tree height of 5 m and estimated that forests covered 10.9 million ha or 59.1% of the country's total land area in 2006 (Technical Working Group on Forestry and Environment, 2007) declining from 11.3 million ha in 2002. Total forest cover is comprised of deciduous forest (43.2%), evergreen forest (33.8%), semi-evergreen or mixed forest (12.5%), and mangrove and freshwater-flooded forests (8.9%). Wood shrubland, bamboo, and forest plantations cover only a small proportion of the total forest area (Fig. SM1). Because deforestation and uncontrolled logging continue, many important tree species in Cambodia have been placed on the International Union for Conservation of Nature (IUCN) Red List (So, 2004). In addition to these important tree species, Cambodia's forests are also home to a unique but critically endangered species of Kouprey or wild cow (*Bos sauveli*).

By law, commercial logging is allowed only in evergreen, mixed, and deciduous forests. Because of their ecological, social, and environmental importance, mangrove and freshwater-flooded forests were designated as protected areas by Royal Decree in 1993, along with an additional 3.1 million ha of forests. As of 2010, this protection was still in effect. At present, there are 16 forest concessions covering a total of 3.4 million. The remainder is for unspecified purposes, such as for population resettlement and for plantations of rubber, teak, oil palm, *eucalyptus* or *acacia*, and other industrial crops. A selective felling cycle of 25 years is allowed in Cambodia. In response to illegal logging (67% of all harvested timber as reported by DAI [1998]), the lack of technical capability, and the suggestions of the international community, logging operations in Cambodia were temporarily suspended in 2002, and this suspension remains in effect today. However, as a result of the lack of proper ownership rights to protect the suspended forest concessions coupled with an increase in unregulated land concessions granted for industrial crop plantations (MAFF, 2010), land clearing and anarchic land encroachments have been reported across the country (Ty, 2005).

Prior to the late 1980s, Cambodian forests were fully stocked with highly commercial timber species (in terms of tree species composition, stem density, and stand volume) because of inaccessibility as a result of prolonged decades of civil wars, landmines, and the total lack of rural security. Coincident with the logging ban in Thailand and the withdrawal of Vietnamese troops from Cambodia in 1989, logging by all Cambodian fighting factions intensified along the borders with Thailand, Laos, and Vietnam. Since the 1991 Paris Peace Accord ending the civil wars in Cambodia, internationally supported industrial logging activities began, and almost all of the highly valued forests were logged intensively at highly unsustainable logging rates (World Bank, 2006). Cambodian forests are owned by the government's Forestry Administration (FA), and the FA grants concession rights to logging companies through public bidding. The FA also recognizes prescribed access and use rights of local and indigenous communities (FA, 2006). About 92% of the Cambodian population lives in rural areas and depends on fuel wood from forests for daily cooking and warmth; this makes forests an important resource for sustainable development in Cambodia. The success of future REDD-plus agreements in Cambodia as well as in other developing countries depends on taking into account the needs of the rural population.

Due to its high stocks of commercial and valuable timber species compared to mixed and deciduous forests (Kim Phat et al. 2000, 2002a, 2002b), a large area of evergreen forest has been logged legally and illegally over the last three decades. Such unsustainable logging has caused rapid degradation, and in the worse case, the loss of evergreen forest to industrial crop plantations.

This report has been prepared as supplemental material to the published article. In this supplemental report we describe the forest inventory data, data analysis, and results for use in the main article.

Fig. SM1 – Location of forests and the study site in Sandan District, Cambodia

2. Data Processing

2.1. Forest Inventory Data

With the support of the Food and Agriculture Organization of the United Nations (FAO), the Department of Forestry and Wildlife (later renamed to the Forestry Administration) conducted the first national forest inventory in 1996 to assess forest resources in Cambodia (DFW and FAO, 1996). A cluster inventory system was employed covering an area of evergreen forest of 162,121.8 ha in Sandan district of Kampong Thom province (between 12°11'23"–13°26'52"N and 104°12'49"–105°44'20"E) (Fig. SM1).

Clusters were systematically located on 4 × 4 km grid lines, and a total of 23 clusters were successfully inventoried. Each cluster contains nine plots (Fig. SM2), in each of which trees with diameter at breast height (DBH) of 5.0–9.9 cm, 10–29.9 cm, and ≥30 cm were measured in subplot sizes of 10 × 10, 20 × 20, and 60 × 20 m, respectively (Table SM1). Basal area and volume for each tree were calculated by the FA with the assistance of the FAO (DWF and FAO, 1996). About 54.2% of all counted trees were identified in 23 families, and the rest (45.8%) were not identified or were unknown. On average, stem density and stand volume were estimated to be 1105.6 trees ha^{-1} (standard error [SE] 53.8) and 235.4 m^3 ha^{-1} (SE 17.5), respectively (Table SM2). We revisited these data and classified all trees to five tree grades according to their wood durability and utilization, as required by Sub-Decree 050 of the Cambodian Ministry of Agriculture, Forestry, and Fisheries (MAFF, 1986) for the purpose of timber royalty collection. These tree grades include luxury (GLT), first (G1T), second (G2T), third (G3T), and out of (OGT) grades. OGT indicates unidentified species of trees not on the official list of Cambodian tree species. All known tree species in each grade are given in Table SM3.

Table SM1 – Tree recording procedure in each sample plot

Subplot		DBH of measured trees
Dimension (m)	Area (ha)	(cm)
10 × 10	0.01	5.0–9.9
20 × 20	0.04	10.0–29.9
60 × 20	0.12	Greater than 30

Note: there are 9 plots of 60 x 20 m per cluster

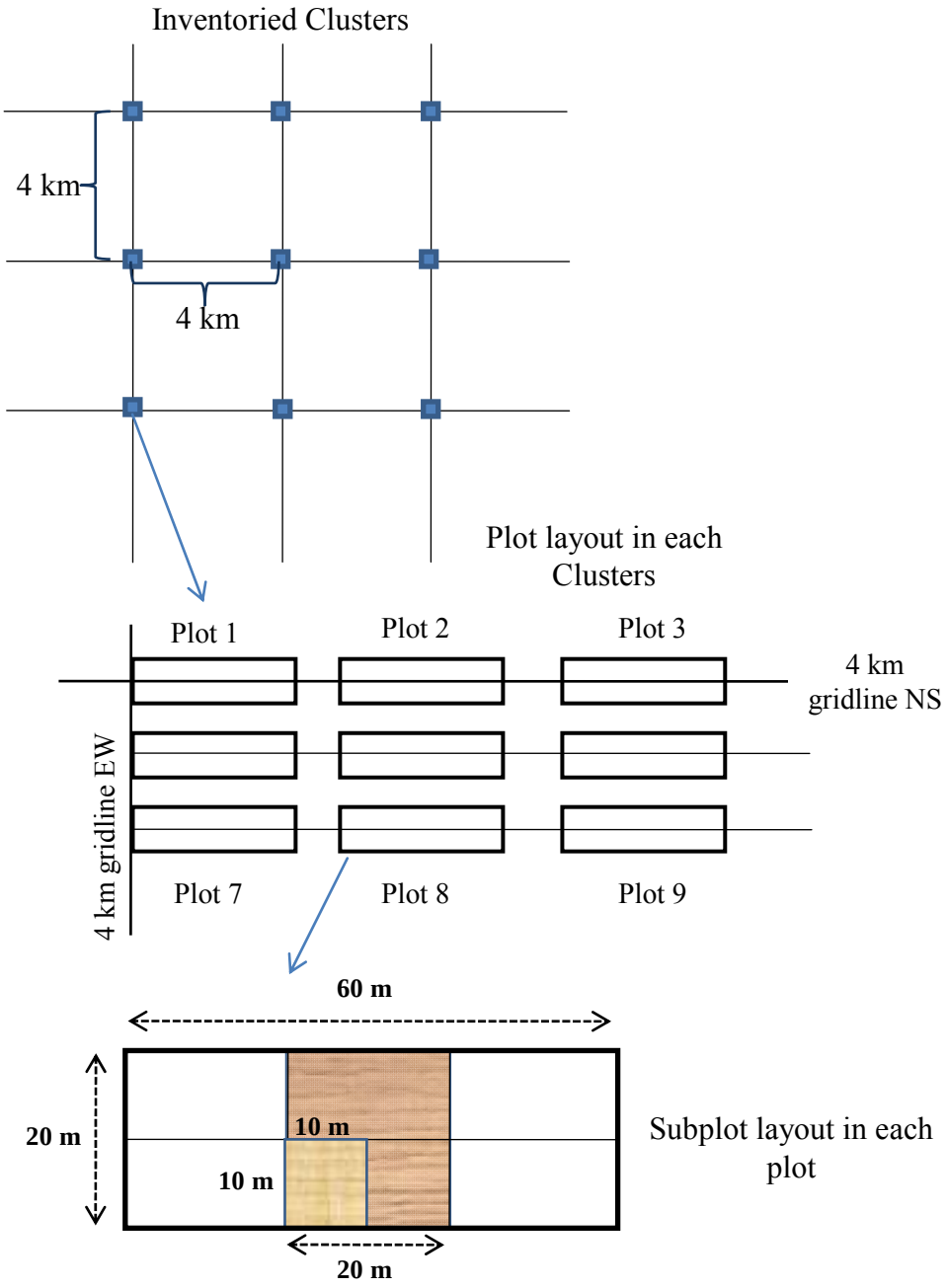

Fig. SM2 – Cluster, plot, and subplot layouts

152 Table SM2 – Average stem density and stand volume by families in an evergreen forest
153 in the Sandan District

Tree Family	5 cm≤DBH<45 cm				DBH≥45 cm				Total (DBH≥5 cm)			
	Density		Volume		Density		Volume		Density		Volume	
	trees	%	m3	%	trees	%	m3	%	trees	%	m3	%
Unknown species	498.7	46.4	34.2	35.2	7.6	24.3	25.2	18.2	506.4	45.8	59.4	25.2
Dipterocarpaceae	179.5	16.7	22.3	23.0	14.6	46.5	85.9	62.0	194.1	17.6	108.2	46.0
Myrtaceae	136.6	12.7	13.5	13.9	1.8	5.7	4.0	2.9	138.4	12.5	17.6	7.5
Ebenaceae	88.2	8.2	3.3	3.4	0.1	0.3	0.2	0.1	88.3	8.0	3.4	1.5
Euphorbiaceae	47.8	4.4	3.6	3.7	0.5	1.7	0.9	0.6	48.3	4.4	4.5	1.9
Caesalpinaceae	22.7	2.1	3.9	4.1	1.9	6.1	6.3	4.6	24.5	2.2	10.2	4.3
Clusiaceae	14.4	1.3	2.0	2.1	0.5	1.6	1.0	0.7	14.8	1.3	3.0	1.3
Meliaceae	12.7	1.2	0.7	0.7	0.0	0.0	0.0	0.0	12.7	1.1	0.7	0.3
Lauraceae	11.6	1.1	1.3	1.4	0.0	0.0	0.0	0.0	11.6	1.0	1.3	0.6
Rosaceae	10.9	1.0	3.0	3.1	2.1	6.8	6.8	4.9	13.0	1.2	9.8	4.1
Rhizophoraceae	10.2	0.9	1.5	1.5	0.0	0.1	0.1	0.1	10.2	0.9	1.6	0.7
Crypteroniaceae	8.7	0.8	2.8	2.9	0.5	1.6	1.4	1.0	9.2	0.8	4.2	1.8
Sapotaceae	7.4	0.7	1.6	1.6	0.7	2.3	2.1	1.5	8.2	0.7	3.6	1.5
Sterculiaceae	5.8	0.5	1.3	1.3	0.7	2.3	4.2	3.0	6.6	0.6	5.5	2.3
Hypericaceae	5.7	0.5	0.6	0.7	0.0	0.0	0.0	0.0	5.7	0.5	0.6	0.3
Fagaceae	3.2	0.3	0.2	0.2	0.0	0.0	0.0	0.0	3.2	0.3	0.2	0.1
Anacardiaceae	3.1	0.3	0.3	0.3	0.0	0.0	0.0	0.0	3.1	0.3	0.3	0.1
Lythraceae	2.6	0.2	0.3	0.3	0.1	0.3	0.2	0.1	2.7	0.2	0.4	0.2
Moraceae	1.6	0.2	0.3	0.3	0.0	0.1	0.1	0.1	1.7	0.2	0.4	0.2
Mimosaceae	1.4	0.1	0.1	0.1	0.0	0.0	0.0	0.0	1.4	0.1	0.1	0.0
Ochanaceae	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0
Verbenaceae	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0
Combretaceae	0.3	0.0	0.2	0.2	0.1	0.2	0.2	0.1	0.4	0.0	0.3	0.1
Anonaceae	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0
Total	1074.3	100.0	96.9	100.0	31.4	100.0	138.6	100.0	1105.6	100.0	235.4	100.0
Standard Error (from all clusters)									53.8		17.5	

154 Modified from Kim Phat et al. (2000); DBH, diameter breast height.

155

156 2.2. Mean Density, Basal Area, and Volume

157 We used the following equation to obtain the average values per hectare for stem
158 density, basal area, and stand volume for all trees in five grades by DBH classes:

159 $$\overline{X}_{ij} = \sum_{j=1}^{3} \frac{\sum_{i=1}^{n} X_{ij}}{subplot_k \times 9 \times 23} \quad , \qquad (1)$$

160 where $\overline{X}_{ij}$ is the average stem density (trees ha^{-1}), basal area (m^2 ha^{-1}), or stand
161 volume (m^3 ha^{-1}) of all tree species in grade *i* (GLT, G1T, G2, G3T, or OGT) of DBH
162 class *j* (5.0–9.9, 10–29.9, or ≥30 cm) of subplot *k* (0.01, 0.04, or 0.12 ha); X_{ij} is the

number of trees, basal area, or stand volume of all counted trees in a subplot corresponding to DBH class *j* in all 23 clusters.

2.3. Tree Grades and Timber Royalty

Cambodia classifies tree species into five grades as mentioned above. Only in exceptional cases where unavoidable felling is required, such as for the safety of forest road construction, other logging operations, or for necessary scientific research, may GLT trees be cut, provided that prior permission from the FA is obtained. Timber royalty is the payment made by logging companies (forest concessionaires) to the Cambodian government (owner of forest resources) for the right to harvest and is generally based on a unit rate of commercial timber harvested. Currently, Cambodia uses fixed rates for timber royalties that vary from \$20.0 m^{-3} for OGT to \$60 m^{-3} for G1T and to \$210 m^{-3} for GLT (Table SM3).

Table SM3 – Tree grades and timber royalty rates in Cambodia

Category of WP	Major Species	Royalty (US\$ m^{-3})
Luxury Grade (GLT)	*Albizzia lebbek, Cassia garretiana, Cassia siamealpinées, Dalbergia bariensis, Dalbergia cochinchinensis, Dasymachalon lamentaceum, Diospyros bejaudi, Diospyros helferi, Diosyros* sp., *Disoxylon Loureiri, Fagraea fragrans Melanorrhea laccifera, Pahudia cochinchinensis, Pterocarpus pedatus*	112–210.00
Grade I (G1T)	*Afzelie bijuga, Artocarpus sempervirens, Ceriops roxburghiana, Chukrasia tabularis, Crudia chrysantha, Dialium cochinchinensis, Hopea ferrea, Hopea helfera, Hopea odorata, Hopea recopei, Lagerstroemia* sp., *Litsea veng, Manikora Alexandra, Mesua ferrea, Peltophorum dasyrachis, Peltophorum ferrugineum, Pentacme Siamensis, Shorea obtusa, Sindora cochinchinensis, Stereospermum cheloneoldes, Tarrietia javanica, Tectona grandis, Terminalia tomentosa, Vitex* sp., *Xylia dolabriformis*	60.00
Grade II (G2T)	*Adina cordifolia, Anisoptera glabra, Dacrydium élatum, Diptérocaprpus costatus, Diptérocarpus alatus, Diptérocarpus dyeri, Diptérocarpus intricatus, Diptérocarpus jourdainii, Diptérocarpus obtusifolius, Diptérocarpus tuberculatus, Hassia cuneata, Hopea pierre Payena elliptica, Pinus merkusii, Podocarpus cupnessina, Shorea hypochra, Shorea* sp., *Shorea thorelli, Shorea vulgaris, Toona febrifuga, Vatica astrotricha, Vatica philastreana*	40.00
Grade III (G3T)	*Aglaia gigantia, Albizzia thorelli, Aquilaria crasna, Artocarpus altilus, Callophyllum* sp., *Calophylium saigonensis, Carallia lucida, Cinnamonmum litsaefolium, Cratoxylon prunifolium, Cryptéronia pani culata, Eugenia* sp., *Garcinia schomburghiana, Gercinia ferrea, Homalium*	32.00

	annamensis, Hydnocarpus anthelmitica, Kayea engeniafolia, Knema coricisa, Mangifera indica, Melaleuca leucadendron, Parinarium annamensis, Sandoricum indicum, Sarcocephalus cordatus, Sterculia campanulata Swintonia Pierre, Termanlia chebula, Terminalia mucronata, Tetramels nudiflora, Tout palétuvier sauf Smé	
Out of Grade (OTG)	All unknown species (species not in the existing list)	20.00

Note: Royalty rates are based on Decision Number 100 of 27 February 1995, co-signed by the Ministry of Finance and Economics and the Ministry of Agriculture, Forestry, and Fisheries.

2.4. Converting Stand Volume to Carbon Stock

Total carbon stock (aboveground and belowground) can be calculated from stand volume, using Brown's (1997) equation as follows:

$$CS_{ij} = V_{ij} \times BEF \times WD \times C \times (1+\alpha) \quad , \qquad (2)$$

where CS_{ij} is the carbon stock of tree grade i in DBH class j (tonne C ha^{-1}), V_{ij} is the stand volume (m^3 ha^{-1}), BEF is the biomass expansion factor (BEF = 1.74 [Brown, 1997]), WD is the wood density (WD = 0.57 [Brown, 1997]), C is the carbon content in dry wood (C = 0.5), and α is the percentage of understory vegetation, woody vines, deadwood and debris, and root to the aboveground carbon. Because these proportions are not available for forests in Cambodia, assumptions are based on studies in other tropical forests. The proportion of understory vegetation (DBH <10 cm) was estimated to be about 5.0–5.3% (DeWalt and Chave, 2004; Nascimento and Laurance, 2002), woody vines to be 2.1% (Nascimento and Laurance, 2002), deadwood and debris to be 9% (Marklund and Scheone, 2006), and root to be 29% (Marklund and Scheone, 2006). For this study, we assumed values of 2% (because trees with DBH ≥5 cm were counted in this study), 2%, 9%, and 29%, respectively, giving α = 0.42 or 42%. Because of its high sensitivity to warming (Knorr et al., 2005), carbon in soils was not considered. Estimated carbon stocks by DBH classes and timber grades are given in Table SM4.

3. Results

Mature trees described in the following sections as well as in the main manuscript are

205 determined in accordance with the DBH minimum size for harvesting: all trees with
206 DBH greater than the DBH minimum size are considered to be mature trees, of which
207 30% are then available for harvest. Based on the tree list in Sub-Decree 050, all GLT
208 have a DBH minimum size of 45 cm (if harvesting is allowed). The average DBH
209 minimum size for 25 (G1T) and 23 (G2T) tree species in Sub-Decree 050 are 43.6 cm
210 and 45.4 cm, respectively. We therefore assumed a DBH minimum size of 45 cm for
211 both grades. The average DBH minimum size of 31 tree species for grade 3 trees listed
212 in Sub-Decree 050 is 37.6 cm. For this study, we assumed a DBH minimum size of 40
213 cm for both G3T and OGT.
214
215 On average 709.2 trees ha^{-1} were recorded with DBH of 5.0–9.9 cm (Fig. SM3). Trees
216 of GLT, G1T, G2T, G3T, and OGT accounted for 9.0, 5.6, 15.3, 17.4, and 52.8%,
217 respectively. On average 312.2 trees ha^{-1} with DBH between 10.0 and 29.9 cm were
218 recorded, of which the percentage of trees in the above grades were 4.1, 5.0, 24.2, 22.6,
219 and 44.2%, respectively. For trees with DBH ≥30 cm, 84.2 trees were recorded, of
220 which 1.0, 11.6, 34.9, 22.2, and 30.2% were in GLT, G1T, G2T, G3T, and OGT,
221 respectively. Of the averaged total of 1091.4 trees ha^{-1}, GLT, G1T, G2T, G3T, and OGT
222 accounted for 7.1, 5.8, 19.1, 19.2, and 48.9%, respectively (Fig. SM3). Of the total of
223 1,105.6 trees ha^{-1} recorded, there were 38.8 mature trees distributed at 0.2, 4.2, 15.3, 7.4,
224 and 11.7 tree ha^{-1} for each of the above grades.
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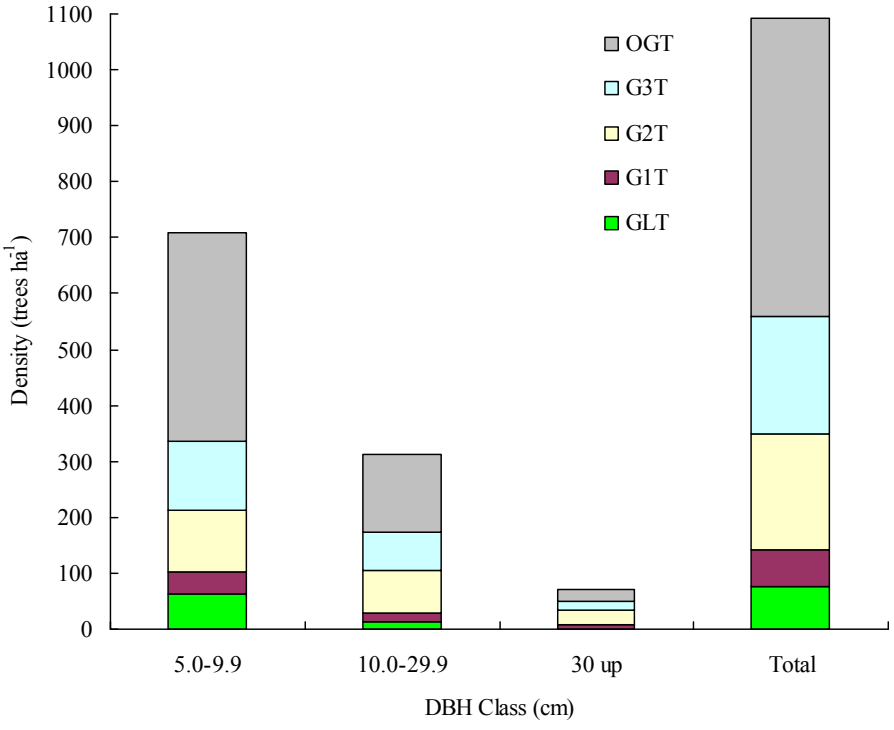
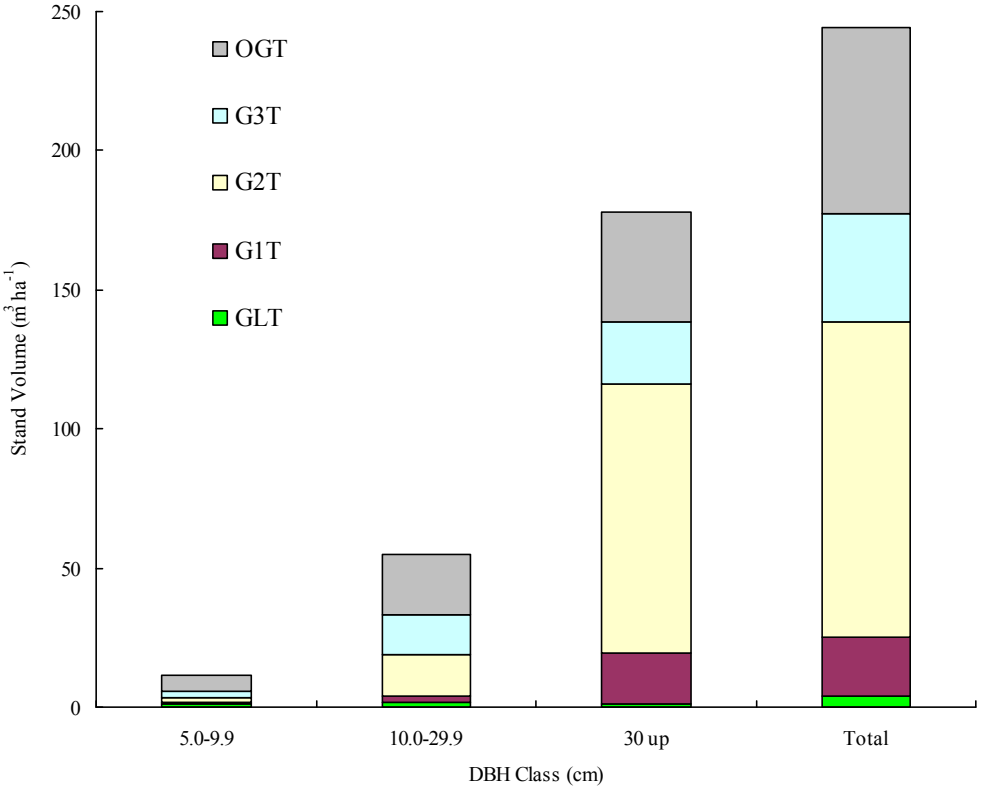


Fig. SM3 – Tree density distribution by tree grades and DBH classes

In terms of basal area, GLT, G1T, G2T, G3T, and OGT accounted for 8.6, 6.1, 16.2, 17.8, and 51.4% of the 2.7 m^2 ha^{-1} for trees with DBH between 5.0 and 9.9 cm; 2.9, 5.0, 26.3, 24.7, and 41.1% of the 7.6 m^2 ha^{-1} for trees with DBH between 10.0 and 29.9 cm; and 0.7, 10.5, 49.0, 15.0, and 24.8% of the 15.7 m^2 ha^{-1} for trees with DBH ≥30 cm. In total, the average basal area was 22.3 m^2 ha^{-1}, of which mature trees composed 49.1%.

The total average stand volume was 244.5 m^3 ha^{-1}, distributed as 4.8 (DBH class 5.0–9.9 cm), 22.6 (10.0–29.9 cm), and 72.7% (≥30 cm). Specifically, GLT, G1T, G2T, G3T, and OGT as follows: 1.0, 0.7, 1.9, 2.1, and 6.0, respectively, of the 11.7 m^3 ha^{-1} for 5.0–9.9 cm DBH; 1.5, 2.7, 14.7, 14.2, and 22.1, respectively, of the 55.2 m^3 ha^{-1} for 10.0–29.9 cm DBH; and 1.3, 18.2, 96.4, 22.5, and 39.2, respectively, of the 177.6 m^3 ha^{-1} for DBH ≥30 cm (Fig. SM4). The stand volume of mature trees accounted for 61.8% of the total stand volume.

Fig.



SM4 – Stand volume distribution by tree grades and DBH classes

252

253 Table SM4 – Aboveground and belowground carbon stocks by DBH classes and
254 tree grades
255

DBH (cm) Class Tree Grade	5–9.9	10–29.9	≥30	Total	Percentage (%)
GLT	0.7	1.0	0.9	2.6	1.5
G1T	0.5	1.9	12.8	15.3	8.9
G2T	1.3	10.3	67.9	79.6	46.2
G3T	1.5	10.0	15.8	27.3	15.8
OGT	4.2	15.6	27.6	47.4	27.5
Carbon Stock (t C ha^{-1})	8.2	38.9	125.1	172.2	100.0
Carbon Stock (t CO_2)	30.1	142.8	459.1	632.0	

256

257 According to Cambodia's Sub-Decree 050 on timber harvesting, 30–50% of the stand
258 volume of mature trees (except GLT) shall be harvested, depending on the proportion of
259 mature trees in the forests concerned. The forest inventory officer will decide the rate of
260 harvesting based on the proportion of harvestable (mature) trees in the concerned forests.
261 Due to illegal logging in the study site during the civil wars, some large trees must have
262 been logged, and we therefore assumed that 30% of mature stands are harvested on a
263 25-yr cutting cycle, which is consistent with the assumption of Kim et al. (2006) and
264 Sasaki (2006).

265

266 In order to calculate the taxes on exported wood products, i.e., sawn wood or veneer, we
267 estimated the proportion of harvested wood (HW) processed at the sawmills. Based on
268 several studies (Sist and Sridan, 1998; FAO, 2001; Holmes et al., 2002), about 20–40%
269 of HW is wasted due to skidding, trimming, and transporting, and therefore only about
270 60–80% is available at the sawmills for further processing. For this study, we assumed

that 30% of the HW is wood waste, and the remaining (termed as wood product or WP) 70% is further processed for end-use products (i.e., sawn wood or veneer). G1T and G2T are usually processed for veneer products at a conversion rate of 54% (Kim Phat, 1999), while the other grades are used for sawn wood at a conversion rate of 49% (Kim Phat, 1999).

Table SM5 – Estimated values for harvested wood (HW), sawn wood (SW), and veneer wood (VW) (m^3 ha^{-1})

Timber grades	Standing Volume of Mature Trees (MS)	HW (30% cut)	WP (=HW×0.70)	SW (=WP×0.54)	VW (=WP×0.49)
GLT	0.79	0.24	0.17	0.08	
G1T	14.5	4.35	3.05	–	1.64
G2T	87.47	26.24	18.37	–	9.92
G3T	16.4	4.92	3.44	1.69	–
OGT	31.88	9.56	6.69	3.28	–
Total	151.04	45.31	31.72	5.05	11.56

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