Carbon stock of peat soils in mangrove forest in Peam Krasaop Wildlife Sanctuary, Koh Kong Province, southwestern Cambodia

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មូលន័យសង្ខេប

មានការយល់ដឹងតិចតួចណាស់ពីតំបន់ដីមោក (Peatland) នៅកម្ពុជា។ តំបន់ដីមោកដែនជម្រកសត្វព្រៃពាមក្រសោបក្នុងខេត្តកោះកុងត្រូវបានរកឃើញក្នុងឆ្នាំ២០១៤ ដែលគ្របដណ្តប់ដី៤៩៧៦ហិចតា (គិតទាំង៣៨ហិចតានៅក្រៅដែនជម្រក) នៃព្រៃកោងកាងតំបន់ឆ្នេរ។ ក្រៅពីមុខងារជាទីជម្រក និងរក្សាគុណភាពទឹក ដីមោកក៏ជាអាងស្តុកកាបូនដ៏សំខាន់ ហើយដើរតួយ៉ាងសំខាន់ក្នុងការប្រែប្រួលអាកាសធាតុ។ ការកំណត់ពីបរិមាណកាបូនស្តុកក្នុងដីមោកនៅដែនជម្រកសត្វព្រៃពាមក្រសោបបានផ្តល់ជាចំណេះដឹងដ៏មានតម្លៃដើម្បីឈានដល់ការយល់ដឹងពីលទ្ធភាពផ្ទុកកាបូនក្នុងតំបន់ដីមោកកម្ពុជា។ យើងបានប៉ាន់ប្រមាណពីបរិមាណកាបូនស្តុកក្នុងតំបន់ដីមោកក្នុងព្រៃកោងកាងនៃដែនជម្រក។ សំណាកដីមោកត្រូវបានប្រមូល និងវិភាគ។ ចំណុះកាបូនក្នុងដីមោកគឺចន្លោះ១៩,៦ ទៅ ២២,៩% និងមានដង់ស៊ីតេមាឌ ០,៣៤៧ក្រ/សម^{៣}។ ផ្អែកលើការសិក្សានេះ និងការសិក្សាពីមុនៗ ជម្រៅជាមធ្យមនៃស្រទាប់ដីមោកគឺ ១១០សម និងមានមាឌសរុបគឺប្រហែល ៥,៨៣ x ១០^{៧}ម^{៣}។ យើងប៉ាន់ប្រមាណថាមានកាបូនប្រហែល៤,៤៧ x ១០^{៦}មក្រ ដែលស្តុកក្នុងដីមោកនៃដែនជម្រកសត្វព្រៃពាមក្រសោប។

Abstract

Very little is known about peatlands in Cambodia. The peatland in Peam Krasaop Wildlife Sanctuary (PKWS), Koh Kong Province, was discovered in 2014 and covers 4,976 ha (including 38 ha outside the sanctuary) in a coastal mangrove forest. In addition to their functions as habitats and maintaining water quality, peatlands are significant carbon sinks and therefore play important roles in mitigating climate change. Determining the size of the carbon stock in peat in PKWS is consequently valuable for understanding the sequestration capacity of Cambodian peatlands. We estimated the amount of carbon stock of peat soils in the mangrove forest of the sanctuary. Peat cores were collected and analysed. The carbon content of the peat was between 19.6 and 22.9%, and its bulk density was 0.347 g/cm^3. Based on our work and previous studies, the average depth of the peat layer is 110 cm and the total peat volume is about 5.83 × 107 m^3. We consequently estimate that approximately 4.47 × 10^6 Mg of carbon is stored in the peatlands of PKWS.

Keywords

Bulk density, carbon stock, mangrove, organic carbon content, peat soil, wetlands.

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Introduction

Wetland environments are abundant in Cambodia, covering 30% of the country (Kol, 2003; Mak, 2015). Peatlands, a type of wetland ecosystem characterized by accumulated organic matter (Parish *et al.*, 2008), have not been well studied in Cambodia and mangrove peatlands in particular have been neglected (Donato *et al.*, 2011).

Peat is a soil type dominated by decomposing plant materials, and contains more than 18% and 30% of organic carbon and organic matter respectively (Agus *et al.*, 2011). Peat is formed from decomposing plant materials under saturated conditions (Parish *et al.*, 2008), as dead vegetation layers on top of the soil. Benefits provided by peatlands include climate regulation—in the form of carbon sequestration—and other ecosystem services (Parish *et al.*, 2008). The latter include the roles peatlands play in the hydrological cycle by removing nutrients and sequestering large volumes of water and provision of habitat to diverse animal and plant species.

Peatlands cover around 3% (400×10^6 ha) of the global land area and occur in most areas of the world (Strack, 2008). Most are found in the boreal and temperate zones (3.57×10^8 ha: Page *et al.*, 2010), but tropical and subtropical zones are also important peatland regions, because of the high rates of plant production and high rainfall which reduces rates of decay (Parish *et al.*, 2008). Peatlands cover around 2.5×10^7 ha in Southeast Asia, almost 60% of peatlands within the Tropics. More than 70% of these occur in Indonesia. Malaysia, Brunei, and Thailand also have significant peatland areas, while smaller areas are found in Vietnam, the Philippines, Cambodia, Laos, Myanmar, and Singapore (ASEAN Secretariat, 2014).

The world's peatlands contain a carbon pool of about 550 Gt, which is twice that of above-ground forest biomass (Parish *et al.*, 2008). As a consequence, these play a major role in regulating climate through carbon dioxide storage, but also as a source of methane, another greenhouse gas (GHG). Loss of carbon storage caused by peatland fires or inappropriate management practices can lead to GHG emissions which contribute to climate change. When peat is exposed to oxygen, it oxidizes and releases carbon dioxide into the atmosphere. Climate change also affects the GHG cycle of peatlands by transforming their carbon sinks into sources of carbon emissions due to changes in temperature and rainfall, whereas their carbon content remains constant if they are protected and water levels remain unchanged. For instance, climate change is currently predicted to severely degrade 60% of Canadian peatlands and further contribute to global warming by releasing carbon dioxide and methane into the atmosphere (Tarnocai, 2006).

Degradation of peatlands is commonplace despite their many documented benefits, with human activities having a significant impact. A major cause of peatland degradation is their conversion to agricultural land by draining or burning, with over 12% (3×10^6 ha) of peatlands having being converted in Southeast Asia (ASEAN Secretariat & GEC, 2011). In the absence of disturbance, peatlands continuously accumulate carbon by storing slowly-decaying plant materials in the anaerobic peat layer. Because carbon sequestration in peatlands plays an important role in climate regulation, restoration of peatland is among the most cost-effective ways to mitigate climate change (Bain *et al.*, 2011).

The objective of our study was to estimate the amount of carbon stored in the coastal mangrove peatland in Peam Krasaop Wildlife Sanctuary, Koh Kong Province, southwestern Cambodia.

Methods

Study site

Peam Krasaop Wildlife Sanctuary (PKWS) is a protected area established by Royal Decree in 1993. It includes 23,750 ha of coastal mangrove in Koh Kong Province (Fig. 1), although the sanctuary area is larger (25,897 ha) according to an official map approved in 2003 (An *et al.*, 2009). Part of PKWS lies within the boundary of the Koh Kapik and Associated Islets Ramsar Site, which was designated as a result of supporting a significant mangrove ecosystem (criteria 1), endangered and rare species (criteria 2), and providing a site for feeding, breeding, and nursery grounds for fish and shellfish species (criteria 8) (Srey, 2012). The main tree species at the site are *Lumnitzera racemosa*, *Excoecaria agallocha*, *Rhizophora apiculata*, *R. mucronata*, *Brugueira gymnorrhiza*, *Melaleuca cajuputi*, *Heritiera littoralis*, *Xylocarpus granatum*, *L. littorea*, *Ceriops tagal*, *Avicennia alba*, *Scyphiphora hydrophyllacea*, *Glochidion littorale*, *Phoenix paludosa*, *Nypa fruticans*, *Acrostichum speciosum*, and *Pandanus* sp. (Lo *et al.*, 2014).

In 2014, as part of the ASEAN SEApeat project, activities were undertaken to assess peatlands in Cambodia. Based on satellite images, it was determined that PKWS had a high likelihood of containing peat (Lo *et al.*, 2014). Following interpretation of satellite imagery, on-site assessments were conducted to verify the presence of peat. Our study was conducted in 2016 within the mangrove peatland in PKWS. Prior to fieldwork, peat depth measurements from 22 peat cores and a map of the peatland were obtained from the SEApeat project. The mangrove peat layers ranged from 44–200 cm, with an

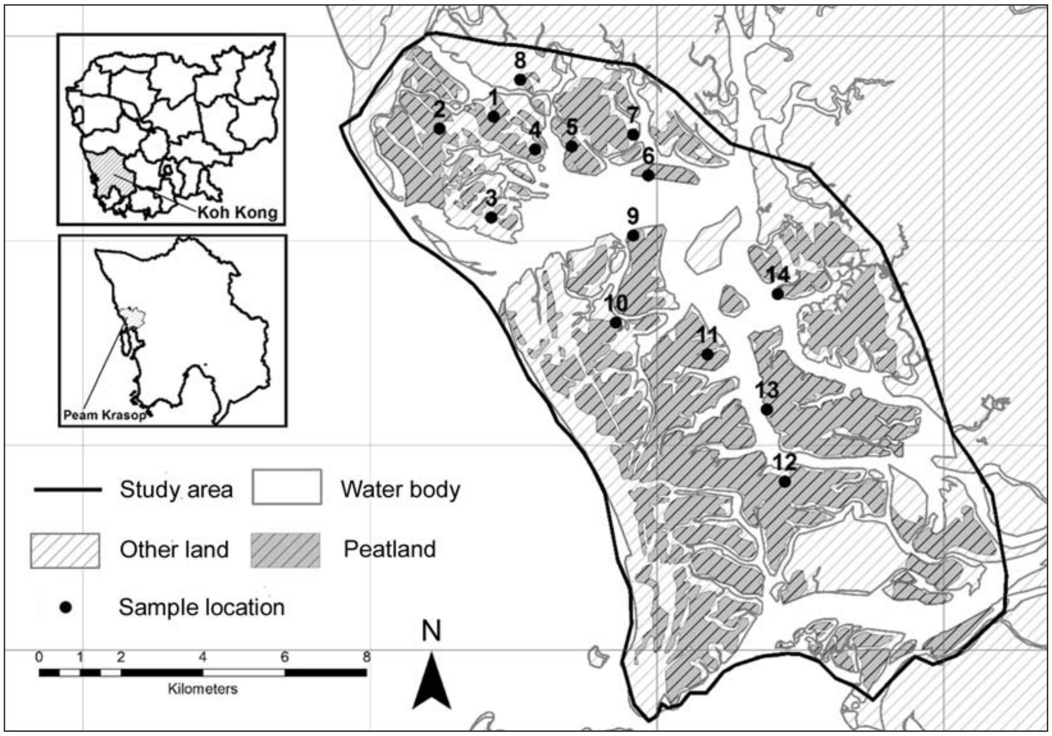

Fig. 1 Location of Peam Krasaop Wildlife Sanctuary and study samples.

average depth of 115 cm, and a total of 4,976 ha of the area were estimated to be peatland (Lo *et al.*, 2014).

Sampling methods

To select sampling locations, maps were created by transferring polygon outlines of areas of peatland identified in PKWS by Lo *et al.* (2014) into ArcGIS software and overlaying these with images from GoogleEarth. Because the characteristics of peat across PKWS were expected to be similar to Lo *et al.* (2014), it was assumed 14 peat cores would be sufficient to estimate its carbon stock. These were collected in PKWS on 23–24 January 2016.

A soil auger (made by Eijkelkamp, the Netherlands) was used to collect the 14 core samples. The volume of the soil auger (half-cylinder) was 1,410 cm^3 (height = 100 cm, radius = 3 cm). The depth of the peat layer was measured in each core. Each core was divided into 25 cm vertical sections. From each vertical core section, 5 cm samples were cut to produce 46 samples, these representing the length of each core at 25 cm intervals. Each of the 46 samples was analysed for bulk density and organic carbon. An additional 14 samples of the top layer of peat (1–25 cm) were collected using a soil ring (height = 4 cm, radius = 2.1 cm, volume = 55.4 cm^3) constructed by the authors from a stainless steel pipe, with a thickness of 1 mm. A GPS was used to record the locations of samples.

Samples were wrapped in aluminium foil, placed in individual plastic bags labelled with their respective locations, and packed into an ice box for transport. These were stored at 4°C for three days prior to analyses for bulk density and organic carbon content.

Bulk density

The volume of the soil sample was calculated from the diameter of the auger and soil ring. Peat sample bulk density (BD) was determined using the gravimetric method (Agus *et al.*, 2011). To determine dry mass, samples were dried at 105°C for six hours and weighed, and this process was repeated up to four times until constant mass was achieved. BD was defined as the dry weight of soil per unit volume. This was calculated as $BD = M_s/V_t$, where BD was bulk density (g/cm^3), M_s was the mass of the dry peat soil (g), and V_t was the volume of the soil sample (cm^3).

Peat depth and area

The depth of the peat layer was defined as the length of peat cores obtained in the field. The area of peatland in PKWS was digitized from the SEApeat project map into

71 polygons using ArcGIS, which was used to calculate the area of each polygon. The locations for our peat depth data were also included in ArcGIS, and the depth of each polygon was estimated as the product of its area and respective peat depth. Because of the limited number of samples, peat depths were assigned to each polygon as follows: 1) If a single core sample had been taken in the polygon, the value for that core was used; 2) If more than one core sample was taken, the mean of these was used; and 3) If no core sample was available for the area, the value of the nearest similar area with a known depth was used. Similarity was determined subjectively, based on vegetation cover and contiguousness.

Organic carbon content

Total organic carbon (TOC) was measured by loss on ignition at 550°C (Agus *et al.*, 2011). Two grams of each sample were dried at 105°C for 15 minutes, then weighed. To obtain a dry mass value (M_{dry}), this process was repeated until mass did not change between drying cycles. The dry samples were then transferred into a combustion oven at 550°C for four hours (Santisteban *et al.*, 2004; the method was modified according to Agus *et al.*, 2011, reducing the combustion time from six hours). The samples were cooled in a desiccator and their mass recorded as ash mass (M_{ash}). TOC was calculated as TOC = (M_{dry} – M_{ash}/ M_{dry}) / 1.724, where TOC was total organic carbon (g/g), M_{ash} was ash mass (g), M_{dry} was dry mass (g) and 1.724 was the conversion factor for organic matter to organic carbon (Agus *et al.*, 2011).

Carbon stock

The total carbon stock of the PKWS peatland was calculated as C_{stock} = A x D x BD x TOC, where C_{stock} was carbon stock (Mg), D was average peat depth (m), BD was average bulk density (Mg/m^3), TOC was organic carbon content (Mg/Mg), and A was the peatland area (m^2) (Weissert *et al.*, 2013).

Results

Bulk density

Bulk density values for core sections obtained from soil ring samples were on average 26% lower than auger samples taken at the same depth, at 0.347 (n=14, SD=0.11) and 0.436 (n=14, SD=0.14) g/cm^3 respectively (Table 1). However, this difference was only significant at p=0.037 due to high variance within the data. The value obtained from the soil ring is used in subsequent calculations because this sampling method is less disruptive than the auger (see Discussion). There was no significant difference between bulk densities and depth (p=0.309) and there was no consistent trend in BD variation with depth, some cores having increased BD at greater depth, some decreased BD, and others similar BD (Fig. 2).

Peat depth and volume

Combining data from Lo *et al.* (2014) with our study, the average depth of the peat layer was estimated as 1.10 m (n=35, SD=0.41) (Fig. 3). The total area of the peatland in PKWS was estimated at 4,938 ha (exluding 38 ha of peatland outside the sanctuary). Using these data, the total volume of peatland within PKWS is estimated to be approximately 5.83×10^7 m^3 (Table 2).

Organic carbon content

Organic matter values for the peat soils in PKWS ranged from 33.8–40.2%. The organic carbon content of peat by depth is shown in Table 2 and averaged 22.2% overall. There were no significant difference in organic carbon content with depth (p>0.05).

Carbon stock

The carbon stock of peatland in PKWS was estimated to be 4.47×10^6 Mg (Table 1). As BD and carbon content did not vary significantly with depth, we conclude that there is no significant difference in carbon stock with depth.

Discussion

Bulk density

The bulk density (BD) of peat in PKWS appears to be typical of mangrove systems. Previous reviews indicate that the BD of mangrove peat in Indo-Pacific oceanic and

Table 1 Bulk density values for core sections from soil ring samples (surface samples only) and auger samples (25 cm subsections of each core).

Sampling depth	n	Mean BD (g/cm^3)	SD
Soil ring	14	0.347	0.118
1 to 25 cm	14	0.436	0.149
25 to 50 cm	14	0.398	0.086
50 to 75 cm	9	0.410	0.121
75 to 100 cm	6	0.446	0.085
>100 cm	3	0.338	0.045

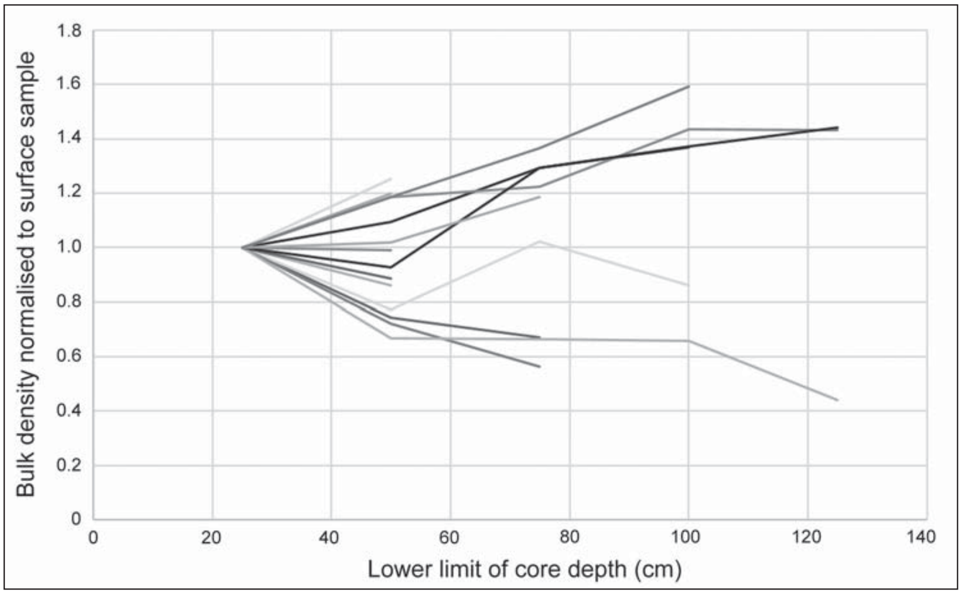

Fig. 2 Normalized bulk density of core sections from Peam Krasaop Wildlife Sanctuary. Each line represents one core.

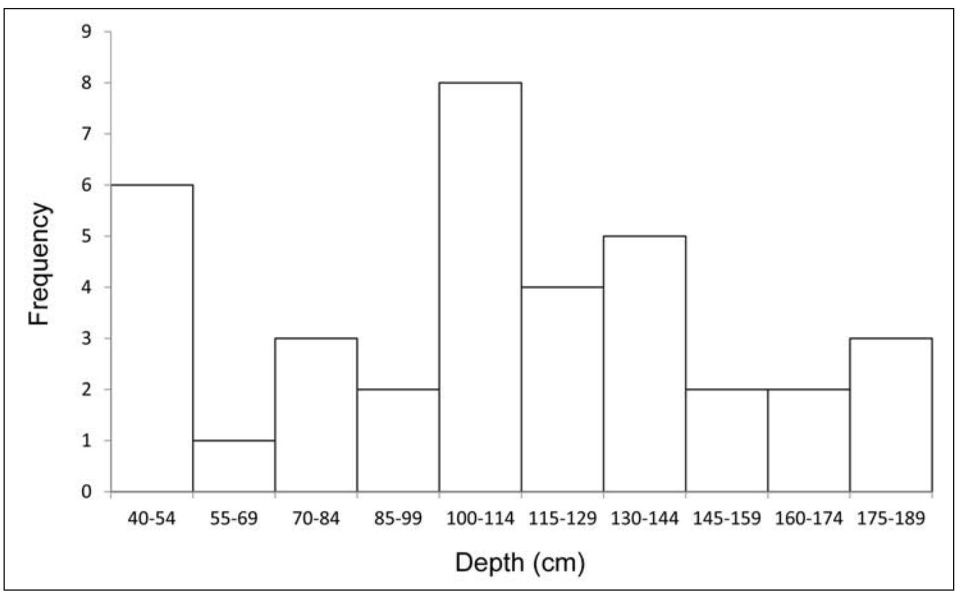

Fig. 3 Frequency of peat layer depths (n=36) at 15 cm intervals at Peam Krasaop Wildlife Sanctuary.

Table 2 Carbon stock in different peat layers at Peam Krasaop Wildlife Sanctuary.

Depth (cm)	n	Area (m^2)	Volume (m^3)	Bulk density (Mg/m^3)	Organic matter (Mg/Mg)	Carbon content (Mg/Mg)	Carbon stock (Mg)
1 to 25	14	4.94×10^7	1.23×10^7	0.347	0.387	0.224	9.62×10^5
25 to 50	14	4.94×10^7	1.22×10^7	0.347	0.402	0.233	9.89×10^5
50 to 75	9	4.46×10^7	1.11×10^7	0.347	0.372	0.216	8.32×10^5
75 to 100	6	4.42×10^7	1.04×10^7	0.347	0.338	0.196	7.07×10^5
>100 cm	3	4.03×10^7	1.23×10^7	0.347	0.394	0.229	9.76×10^5
	Total		**5.84×10^7**				**4.47×10^6**

estuarine systems ranges from 0.35 to 0.55 g/cm^3 (Donato *et al.*, 2011). The BD of peat in U Minh Ha National Park (Vietnam) ranges from 0.19 to 0.26 g/cm^3 with an average of 0.23 g/cm^3 (Quoi, 2010), compared to 0.347 g/cm^3 in PKWS. According to Andriesse (1988), the BD of peat soil ranges from 0.05 g/cm^3 in very fibric (i.e. containing undecomposed plant fibres) soils to around 0.5 g/cm^3 in well-decomposed materials. The high BD of mangrove peat in PKWS thus suggests it mainly comprises well-decomposed material, with only some areas including fibric peat. Based on our observations, the presence of plant roots within the well-decomposed peat of some of our samples came from live mangrove trees growing in the area (Fig. 4).

The BD of samples taken with our soil ring were more accurate than samples taken using the auger, which tends to distort soil cores. Agus *et al.* (2011) recommend using a soil ring to sample peat soil for BD analysis. It was not possible to use a soil ring for deeper layers of peat in PKWS due to the presence of mangrove root structures and overlaying water. Peat cores taken to estimate the depth of the peat layer using the auger were consequently less than optimal for the purposes of calculating BD. The mean BD of auger samples in the 1–25 cm peat layer was 0.436 g/cm^3, 26% higher than the value of samples obtained with the soil ring. We suspect that distortion occurred because the auger compressed the soil cores when rotated to obtain samples.

Peat depth

Peat layer depths in tropical areas range from 0.5 m to >10 m (ASEAN Secretariat, 2014), although estuarine peat is typically 3 m thick (Donato *et al.*, 2011). As such, the peat layer in PKWS is relatively thin with an average of 1.1 m, which is similar to values in oceanic systems (Donato *et al.*, 2011). This may be due to the young age of mangrove forests in situ and their close proximity to open water, which may hinder formation of peat layers due to the disruptive nature of tides.

Organic carbon content

The organic carbon content of peat ranges from 18–58% when measured using the 'loss on ignition' (LOI) method (Agus *et al.*, 2011), although Donato *et al.* (2011) obtained values of 7.9% and 14.6% for estuarine and oceanic systems respectively. Our values of 33.8–40.2% for PKWS are somewhat lower than those for U Minh Ha National Park in Vietnam (53.4–54.0%: Quoi, 2010). The higher values at the latter site may be due to its greater distance from the shoreline, and therefore reduced tidal influences compared to PKWS which is located in an estuary. Tides can affect accumulation rates of soil organic carbon due to regular water movement disturbing and washing away decomposing material, and depositing mineral sediments. Water movement and mixing may also increase oxygenation of organic material and reduce accumulation rates by increasing aerobic mineralization (Alongi, 2009).

Carbon stock

The carbon stock of peatlands in PKWS is 904 Mg/ha, which is typical of estuarine (1,074 Mg/ha) and marine (990 Mg/ha) mangroves (Donato *et al.*, 2011). In contrast, because peat thickness varies at U Minh Ha, this affects the amount of carbon stored per area. For instance, where peat layers reach a depth of 70 cm, carbon content is about 814 Mg/ha and where these reach 120 cm, carbon content is about 1,480 Mg/ha (Quoi, 2010).

Carbon storage in peat

Peatlands sequester more carbon per area than terrestrial ecosystems (Parish *et al.*, 2008). According to Toriyama *et al.* (2011), soil carbon stocks range from 56.9–108 Mg/ha in evergreen forest soils and 34.9–53.2 Mg/ha in deciduous forest soils in Cambodia. In addition, the carbon stock of forest soils in the Mondulkiri and Kompong Thom provinces was at most 114 Mg/ha (Toriyama *et al.*, 2012). As mangrove peatlands store almost an order of magnitude more carbon per area (904 Mg/ha in this study, Fig. 5), this strengthens the case for prioritizing conservation of mangrove peatlands.

The total carbon stock of peat soils in PKWS is 4.47 x 10^6 Mg, approximately 0.15 % of the total carbon stored in Cambodia's terrestrial ecosystems (2.97 x 10^9 Mg) and about 0.007 % of the total carbon storage in Southeast Asian peatlands (58 Gt: Strack, 2008). Given the organic carbon to carbon dioxide emission factor of 3.67 (Agus *et al.*, 2011), the PKWS peatlands could release 1.64 x 10^7 Mg of carbon dioxide emissions if burnt or otherwise destroyed.

Soil carbon estimation

Carbon density can be calculated from soil bulk density as a low cost option for estimating carbon stocks in tropical peat (Warren *et al.*, 2012). To test the applicability of the regression equation developed by Warren *et al.* (2012) to PKWS, we calculated the theoretical carbon density and compared it with the value obtained from the LOI method. The former gave a value more than twice the latter, i.e. it over-estimated the amount of carbon in the peat by a factor of 2.2. However, Warren *et al.* (2012) recommend that the equation be used only for soils with

Fig. 4 A peat core showing living roots from Peam Krasaop Wildlife Sanctuary.

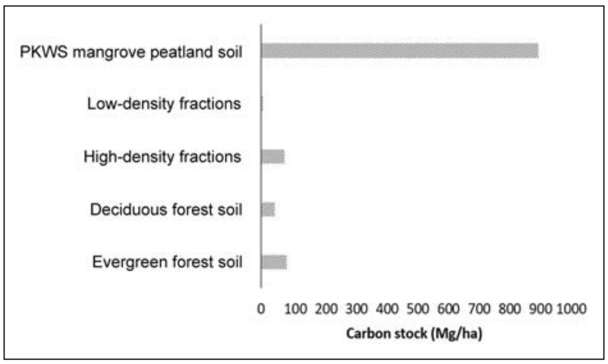

Fig. 5 Comparison of carbon stocks in Peam Krasaop Wildlife Sanctuary and forest soils (latter data taken from Toriyama *et al.*, 2011; 2012).

>40% carbon content. As this is higher than the organic content of peatlands in PKWS (33.8–40.2%), the linear relationship between BD and carbon density may not hold true due to physical properties of the soil affecting carbon content in low organic peat (Warren *et al.*, 2012). In fact, BD and carbon density were negatively correlated in our samples.

Conclusions

The carbon stock of peat soils has received little attention in Cambodia to date. Our study adds to knowledge of tropical peatlands, highlights their importance, and can contribute to improving awareness of the value of peatlands with implications for their management and conservation. Sand mining, drainage, and deforestation in peatlands is likely to impact these ecosystems and release their sequestered carbon into the atmosphere.

Our study can also inform further research in PKWS. In highlighting the importance of peatland and mangrove preservation, our results can support national climate change mitigation strategies and provide a basis for improving estimates of the potential of peatlands as carbon sinks in Southeast Asia.

Further work is required to characterize the peatlands of PKWS in detail. In particular, peat depths at the site should be validated because of the limited number of samples in our study. Further assessment of carbon for carbon credit programmes is also warranted to generate funds for conservation of PKWS through initiatives such as the Reduced Emissions from Deforestation and Degradation scheme. Other newly discovered peatlands in Cambodia, such as the Botum Sakor peatland, Koh Kong Province (Quoi *et al.*, 2015) should also be characterized to understand their function, identify possible threats, and develop effective management practices.

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