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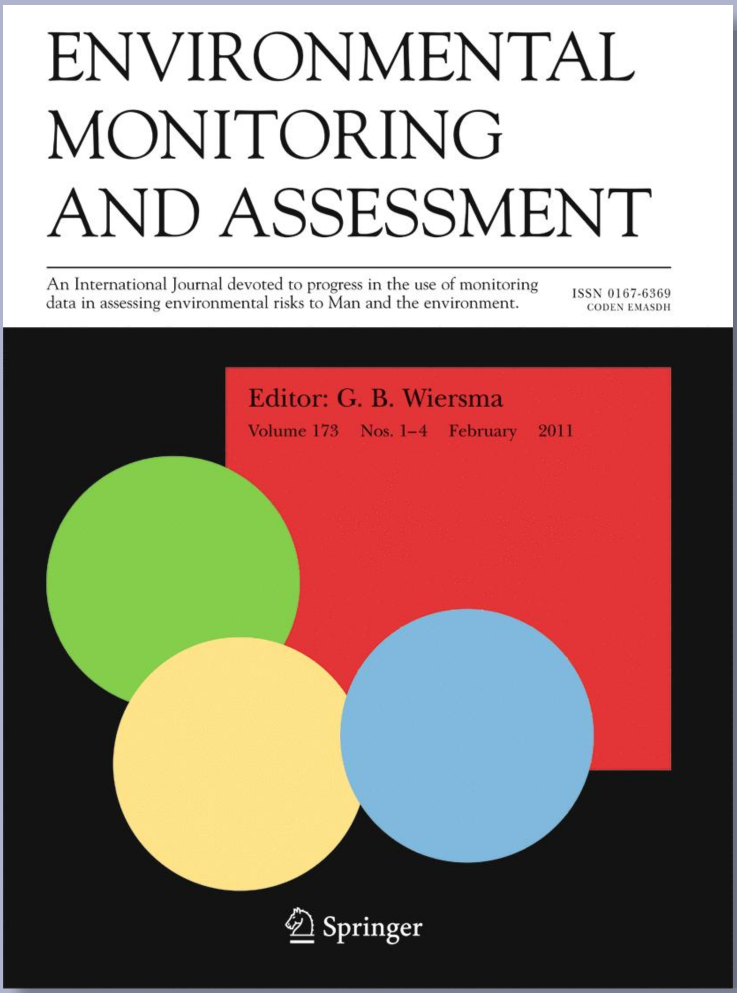

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Co-assessment of biomass and soil organic carbon stocks in a future reservoir area located in Southeast Asia

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Abstract An assessment of the organic carbon stock present in living or dead vegetation and in the soil on the 450 km^2 of the future Nam Theun 2 hydroelectric reservoir in Lao People's Democratic Republic was made. Nine land cover types were defined on the studied area: dense, medium, light, degraded, and riparian forests; agricultural soil; swamps; water; and others (roads, construction sites, and so on). Their geographical distribution was assessed by remote sensing using two 2008 SPOT 5 images. The area is mainly covered by dense and light forests (59%), while agricultural soil and swamps account for 11% and 2%, respectively. For each of these cover types, except water, organic carbon density was measured in the five pools defined by the Intergovernmental Panel on Climate Change: aboveground biomass, litter, deadwood, belowground biomass, and soil organic carbon. The area-weighted mean carbon densities for these pools were estimated at 45.4, 2.0, 2.2, 3.4, and 62.2 tC/ha, respectively, i.e., a total of about 115 ± 15 tC/ha for a soil thickness of 30 cm, corresponding to a total flooded organic carbon stock of 5.1 ± 0.7 MtC. This value is much lower than the carbon density for some South American reservoirs for example where total organic carbon stocks range from 251 to 326 tC/ha. It can be mainly explained by (1) the higher biomass density of South American tropical primary rainforest than of forests in this study and (2) the high proportion of areas with low carbon density, such as agricultural or slash-and-burn zones, in the studied area.

Keywords Aboveground and belowground biomass · Subtropical reservoir · Remote sensing · Nam Theun 2 reservoir

Introduction

Since the 1990s, tropical reservoirs have been identified as being potentially significant greenhouse gas (GHG) producers (gross emissions), producing mainly carbon dioxide and methane (Saint Louis et al. 2000; Tremblay et al. 2004; Giles 2006). However, the true net GHG "footprint" of these reservoirs is still the subject of much debate

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(Galy-Lacaux et al. 1997; Rosa and dos Santos 2000; Delmas et al. 2005; Fearnside 2005; Dos Santos et al. 2006; Harvey 2006). Uncertainties and variability (Dos Santos et al. 2006) in the data collected are one of the chief reasons behind this scientific debate on the issue of net GHG emissions by tropical reservoirs. Uncertainties particularly concern the extent of the initial organic carbon stock in the area prior to the impoundment. A precise estimation of this parameter is very important since most of the GHG produced in reservoirs during the first years originate from the decomposition of the flooded initial organic carbon stock contained in both biomass and soils (Giles 2006). In tropical countries, this phenomenon is all the more significant since the biomass is often abundant (FAO 2006).

So far, tropical and subtropical reservoirs studied have been almost exclusively located in primary tropical rainforests in South America (Fearnside 1995, 1997; Rosa et al. 2003; Delmas et al. 2005). For these projects, initial organic carbon density (amount of carbon per surface unit) was estimated based on the literature (Abril et al. 2005) compiled in large databases on carbon in vegetation (Olson et al. 1983; FAO 2006) and soils (Zinke et al. 1984; FAO 2006). In other tropical and subtropical areas covering a panel of biomes (forests, swamps, agricultural soils…), such as in Southeast Asia, the quantification of organic carbon stock may be more delicate because of the heterogeneity of the soil coverage, which is not an issue in homogeneous and small areas where only one cover type is present. Except this special situation, the assessment of organic carbon stock requires two stages: (1) the mapping of each biome area and (2) the estimation of carbon density for each biome. For the first step, the most cost-effective and efficient method is remote sensing. The different types of sensors have proven to be satisfactory for many ecological applications, such as mapping land cover into broad classes, estimating biomass and structure (Lefsky et al. 2002; Dong et al. 2003; Drake et al. 2002, 2003; Broadbent et al. 2008; Anaya et al. 2009), primary vegetation production (Goetz et al. 1999), the extent of burnt forests (Kaufman et al. 1990), soil moisture (Njoku and Entekhabi 1996), and even soil organic carbon (SOC) content where measurement taking is not impeded by vegetation (Gomez et al. 2008). However, given the high geographical variability of responses for the same vegetation conditions, calibration with local field observations is almost always required (Lefsky et al. 2002; Dong et al. 2003; Drake et al. 2003; Anaya et al. 2009). As regards the second stage, in Southeast Asia (including Cambodia, Laos, Myanmar, Thailand, Vietnam, Malaysia, Brunei, East Timor, Indonesia, Malaysia, the Philippines, and Singapore), some estimations of organic carbon density per biome type can be found in the literature for either vegetation (Yamakura et al. 1986; Brown et al. 1989; Shanmughavel et al. 2001; Brearley et al. 2004) or soils (Batjes 1996; Noordwijk et al. 1997; Roder et al. 1997; Rumpel et al. 2006). However, studies combining both, for a given area, are very scarce and limited to forested zones (Brown et al. 1993); or else, they are only based on country-scale assessments (FAO 2006). The main conclusion that can be drawn from these data is the high variability in organic carbon density between biomes in a given area and even between regions for a given biome.

This variability can be explained by difference in environmental conditions or human activities and also by uncertainties surrounding currently available estimates. Most of these uncertainties arise from (Blais et al. 2005) (1) the data-processing approach with sometimes the integration of an environmental variable controlling vegetation distribution like rainfall or temperature, (2) the relatively small amount of available data in comparison with the large areas on which extrapolations are made, (3) the biased spatial coverage, with some regions being overrepresented (e.g., forests), and (4) poor reliability of data and the use of inappropriate methodologies. All these drawbacks preclude a priori an accurate bibliography-based estimation of the organic carbon stock in a precise and poorly studied zone with a high vegetation diversity.

A new hydroelectric reservoir, the Nam Theun 2 (NT2) reservoir, was set up in Lao People's Democratic Republic (PDR) in the Nam Theun River catchment area. Monitoring and modeling programs have been implemented in order to assess current water quality and GHG emissions and to predict short- and long-term changes in these parameters. In order to preclude uncertainty and debate, an up-to-date and accurate quantification of the total organic carbon stock present either in living and dead vegetation or in the soil on the entire preimpoundment reservoir area is needed. A few former data are available (Prosser 1997; NTPC 2005) but focused only on land use and forest biomass. No local data on soil carbon exist. Moreover, in the meantime, anthropogenic activities (deforestation, construction works) have impacted the land use patterns on the reservoir area. The first aim of this study was thus to assess this land cover breakdown by remote sensing analysis just before the impoundment and to discuss the anthropogenic-induced changes. Secondly, based on this new mapping, the main objective of this study was the estimation of the total organic carbon stock present on the studied area and its distribution between the aboveground and belowground stocks and between the refractory and the more easily degradable fractions. These values are of the utmost scientific importance as regards the relevance to remove or burn the aboveground biomass before impoundment in order to reduce the potential GHG emissions, especially methane, consecutive to the degradation of this biomass.

Materials and methods

Study system

The study system, located on the Nakai Plateau (Khammouane Province) in Lao PDR, is defined by the outline of the future Nam Theun 2

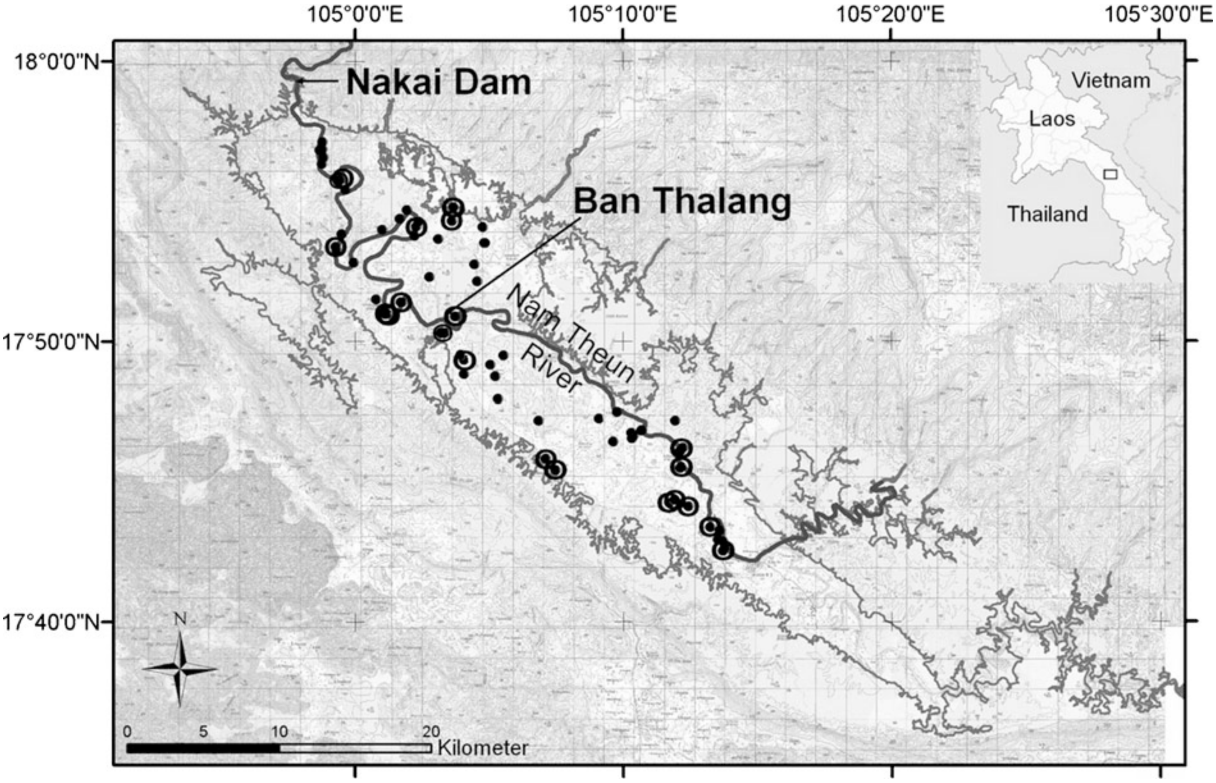

Fig. 1 Location map of the study area defined by the highest water level of the future reservoir (*gray line* = 538 m asl). *Black circles* indicate the sampling points for soil organic carbon analysis; *open circles* show the sampling points for biomass assessment

hydroelectric reservoir at its full water supply level. It represents a surface area of about 450 km^2 (Fig. 1), located between 510 and 538 m above sea level (NTPC 2005). The Nakai Plateau is drained by the Nam Theun River, which has a total catchment area of 4,013 km^2 and a mean annual discharge of 238 m^3/s (NTPC 2005). According to the Intergovernmental Panel on Climate Change (IPCC) definition, the climate is moist tropical (IPCC 2003) with wet, dry cold, and dry warm seasons. Mean annual rainfall on the plateau is estimated at about 2,400 mm, mainly distributed between May and September (88%; NTPC 2005).

The bedrock mainly consists of fine- to medium-grained micaceous, quartzose red–brown, and gray sandstones and brown–red to brown mudstone and siltstone (Lower Cretaceous). In the very center of the area lies the youngest basement geologic formation (Mid Cretaceous to Tertiary), composed of evaporite rocks, chiefly halite and gypsum (United Nations 1990; NTPC 2005). In the central area upstream of Ban Thalang (Fig. 1), late Tertiary alluvial deposits lie in a 38 × 6 km band. The river meanders through this area, and soils are composed of soft to very stiff, silty clays and loams. Right along the river, more recent alluvium material, consisting of fine to coarse sands, can be found. There is another zone containing deposits downstream of Ban Thalang. In this area, soil horizons contain more sand and are sandy loams (NTPC 2005).

Definition and mapping of the various cover types

During previous field investigations, the studied area was qualitatively divided into homogeneous zones regarding land use (forestry, agriculture, wetlands, and construction sites), vegetation density, and the composition of the forested areas. From this initial analysis, nine cover types were defined (Table 1): dense forest (D), medium forest (M), light forest (L), degraded forest (DG), riparian forest (R), agricultural soils (AG), swamps (S), water (W), and "others" (O). This latter type corresponds to roads, villages, construction sites, etc…

Remote sensing analysis was done using two SPOT 5 images (10 m-resolution, four bands: green, red, near infrared, and short-wavelength infrared, orthorectified) covering the whole study area. Images were collected during the dry season, in January and April 2008, the distinction between annual and perennial vegetation being easier during this season. The analysis of the vegetation evolution from January to April was carried out on zones present on both images; the impacts in terms of discrimination capability between the different classes remain limited. The satellite images were processed using Overland Thematic Processor (Poilvé and Houdry 2007). This software implements a model-based approach to directly generate biophysical maps from the digital number image data (Verhoef and Bach 2003).

Table 1 List and description of cover types on the study area

Cover type	Code	Content
Dense forest	D	Natural dense primary and natural modified forest with few small pockets of dry evergreen forest but mainly mixed deciduous and broadleaf forests
Medium forest	M	Regenerated forest with a regular cover. Intermediary area between dense and light forests
Light forest	L	Forest (mixed deciduous, broadleaf, and pine forests) with a low tree density (regeneration), young or sparse on an herbaceous stratum; bamboos
Degraded forest	DG	Slash-and-burn areas with or without grass; unstocked forest, tree stratum in poor environmental conditions (frequent inundation, etc.…)
Riparian forest	R	Bamboo forest along the river and around some ponds
Agricultural soil	A	Agricultural parcels, pastures, grass zones near water (ponds and river), glades with very low vegetation, paddy fields
Swamps	S	Swamp area with the presence of water or very humid; zones with aquatic vegetation
Water	W	Rivers, ponds…
Others	O	Roads, construction sites, villages…

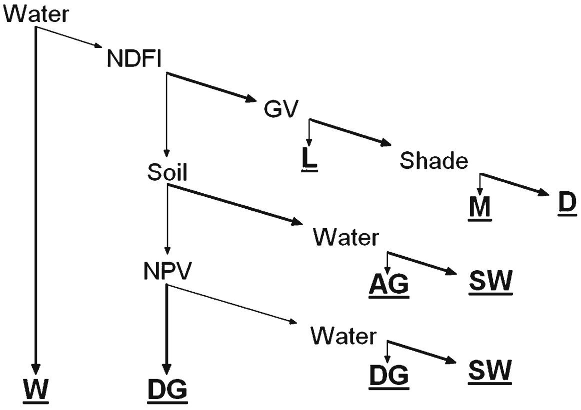

Fig. 2 Decision tree used for the classification of each pixel in a predefined cover type: dense (*D*), medium (*M*), light (*L*), degraded (*DG*), and riparian (*R*) forests; agricultural soil (*AG*); swamps (*SW*); and water (*W*). Criteria used were fractions of nonphotosynthetic vegetation (*NPV*), green vegetation (*GV*), soil, water, canopy shadow factor (*CSH*), and the normalized difference fraction index (*NDFI*). *Thick arrows* give the direction when measured values exceeded fraction thresholds

The embedded core models are LOWTRAN for the atmospheric radiative transfer (Kneisys et al. 1995) and SAIL/PROSPECT for the canopy reflectance modeling (Verhoef 1984; Jacquemoud and Baret 1990). The biophysical outputs that were primarily used are the parameters that describe the pixel composition: green vegetation cover (GV), nonphotosynthetic vegetation cover (NPV), soil, and water. In addition, another parameter, the canopy shadow factor (CSH), characterizes the surface shading due to canopy roughness. All these parameters were used individually and combined to produce the normalized difference fraction index (NDFI), an index that proved most useful in providing a direct scale of degradation for forest canopies (Souza et al. 2005). Each pixel was then classified according to the decision tree presented in Fig. 2.

Thresholds were defined at each decision node to correspond to the vegetation conditions on the date of image acquisition. An aggregation process was then needed to reduce background noise by assigning a minimal area for each object while aiming for the formation of homogeneous objects. For the riparian forest, it was impossible to find a reliable determination key—the forest was thus identified based on location criteria only and according to field observations, i.e., 20 m on each river bank. In addition, slash-and-burn areas could not be distinguished from degraded forest because of the vegetation regrowth. An error matrix was calculated from 60-field reference points to estimate the accuracy of the cover mapping (Fig. 1).

Estimation of the organic carbon stock in each cover type

In its Good Practice Guidance for Land Use, Land-Use Change and Forestry, the IPCC provides a definition of the different pools to consider for an exhaustive assessment of the organic carbon stock in a terrestrial ecosystem (IPCC 2003). This definition (Table 2) is used throughout this study.

Table 2 Definitions for terrestrial organic carbon pools used in the Good Practice Guidance for Land use, Land-Use Change and Forestry of the IPCC (2003)

Pools		Description
Living biomass	AGB	All living biomass above the soil including stem, branches, bark, lianas, saplings, seedlings, and foliage
	BGB	All living biomass of live roots. Fine roots of less than 2 mm diameter are excluded because these often cannot be distinguished empirically from soil organic matter or litter
Dead organic matter	Deadwood	Includes all nonliving woody biomass not contained in the litter, either standing or lying on the ground or in the soil
	Litter	Carbon in all nonliving biomass with a diameter less than the minimum diameter chosen by the country for lying dead, in various states of decomposition above the mineral or organic soil
Soils	SOM	SOM is mainly composed of SOC, including fine roots, in mineral and organic soils (including peat) to a specified depth chosen by the country. The default soil thickness of 30 cm advocated by the IPCC (2003) was used

Table 3 Carbon stock quantification methodology according to the carbon pool defined in Table 2

Carbon pool		Carbon stock measurement methods		
		Quadrate size (m)	Replicates/ cover type	Carbon estimation procedure
AGB	Large trees ($\text{dbh}^{a} > 10$ cm)	5 × 5 or 10 × 10	3	dbh were measured for all trees[b], and biomass estimation was made using the allometric equation given by the IPCC (2003) for moist tropical hardwood: AGB dry matter (kg/tree) $= \exp[-2.289 + 2.649 \times \ln(\text{dbh}) - 0.021 \times (\ln(\text{dbh})^2]$. Carbon density was then calculated according to the IPCC by applying a factor of 0.5 on dry biomass (IPCC 2003)
	Small trees ($3 < \text{dbh} < 10$ cm)			
	Lianas			dbh were measured for all lianas, and the biomass estimation was made using the allometric equation given by Gehring et al. (2004) for moist tropical forest: AGB dry matter (kg/liana) $= \exp[-7.114 + 2.276 \times \ln(\text{dbh})]$. Carbon density was then calculated according to the same previous IPCC recommendations
	Bamboos			An allometric equation was developed on site (from nine bamboos per size class, $8 < \text{dbh} < 12$ cm, $r^2 = 0.99$) and used to estimate the total biomass: AGB dry matter (kg/bamboo) $= \exp[-0.5517 + 2.0514 \times \ln(\text{dbh})]$. Carbon density was then calculated according to the same previous IPCC recommendations
	Seedlings and saplings ($\text{dbh} < 3$ cm)	5 × 5		Vegetation was quantitatively collected and weighted on site. AGB wet matter results were converted into dry matter[c], and carbon density was then calculated according to the same previous IPCC recommendations
BGB		5 × 5 or 10 × 10		Calculated with the roots to shoots ratio estimated for tropical dry forest at 24% (IPCC 2003). The ratio was directly applied to AGB carbon density
Deadwood		5 × 5		Deadwood and litter were quantitatively collected and weighted[c] on site. Carbon density was then calculated according to the same previous IPCC recommendations
Litter		1 × 1		Carbon density was then calculated according to the IPCC by applying a factor of 0.37 on dry biomass (IPCC 2003)
Soil organic matter		–	9	Soil bulk density was measured by weighting a surface core sample (diameter 8 cm, height 9.5 cm) before and after oven drying (three replicates per cover type). Soil samples were taken at 0-, 20-, 50-, and 100-cm depths, and organic carbon concentrations were measured with the method of Gaudette et al. (1974). Default soil thickness used for carbon density calculation was 30 cm as advocated by the IPCC (2003) to estimate GHG emissions resulting from land use and land use changes

[a] dbh (diameter at breast height): diameter at 1.5 m aboveground level

[b] The size of the quadrate and the number of replicates (three per cover type) were too low to be representative of the true tree density (Chave et al. 2004). Data were taken from the only extensive study on logging activities on the same area carried out in 1994 (Prosser 1997). In nonlogged zones, values estimated for large (dbh > 20 cm) tree density were 78, 66, 63, and 18 trees per hectare for dense, medium, light and degraded forests, respectively, while an average value of 678 trees per hectare was given for small trees. The assumption is made that the measured distribution of the tree sizes was correct and that the tree density per vegetation type has not changed since 1994

[c] Conversion of wet to dry biomass has been done using unpublished results on the same vegetation type in Laos. The mass loss of vegetation component during sun drying has been estimated at about 60% for seedlings, saplings, foliage, and litter

The measurement methodology depends on the carbon pool considered. These quantification methods are summarized in Table 3. For each of the following cover types: D, M, L, DG, R, AG, and S, nine sampling points were randomly chosen for SOC analysis and three quadrates of different sizes for aboveground biomass (AGB), belowground biomass (BGB), deadwood, and litter quantification (Fig. 1). For the cover types W and O, no sampling has been done. For the first one, the aboveground and belowground carbon density was fixed at 0 tC/ha. For type O, the aboveground carbon density was 0 tC/ha (all the aboveground vegetation was removed), and an average value between D, M, L, DG, and AG was taken for belowground density. This is probably a conservative estimate since a proportion carbon was removed from soils during construction.

The field campaign was carried out between 16 March and 9 April 2008 at the end of the dry season, just before the beginning of the reservoir impoundment.

For belowground organic carbon stock, included in BGB and soil organic matter (SOM), the IPCC recommends using a soil thickness of 30 cm. However, the methodology used to quantify BGB (Table 3) implies that all tree roots were measured. It is therefore necessary to evaluate the fraction of the BGB in the uppermost 30 cm. According to Jackson et al. (1996) or Schenk and Jackson (2002), fine and large roots in the uppermost 30 cm represent about 60–70% of the total root biomass. Fine root density was measured on site (sieving at 2 mm and weighting on a 1 × 1-m quadrate), and large root biomass in the superficial soil layer was then estimated by subtraction.

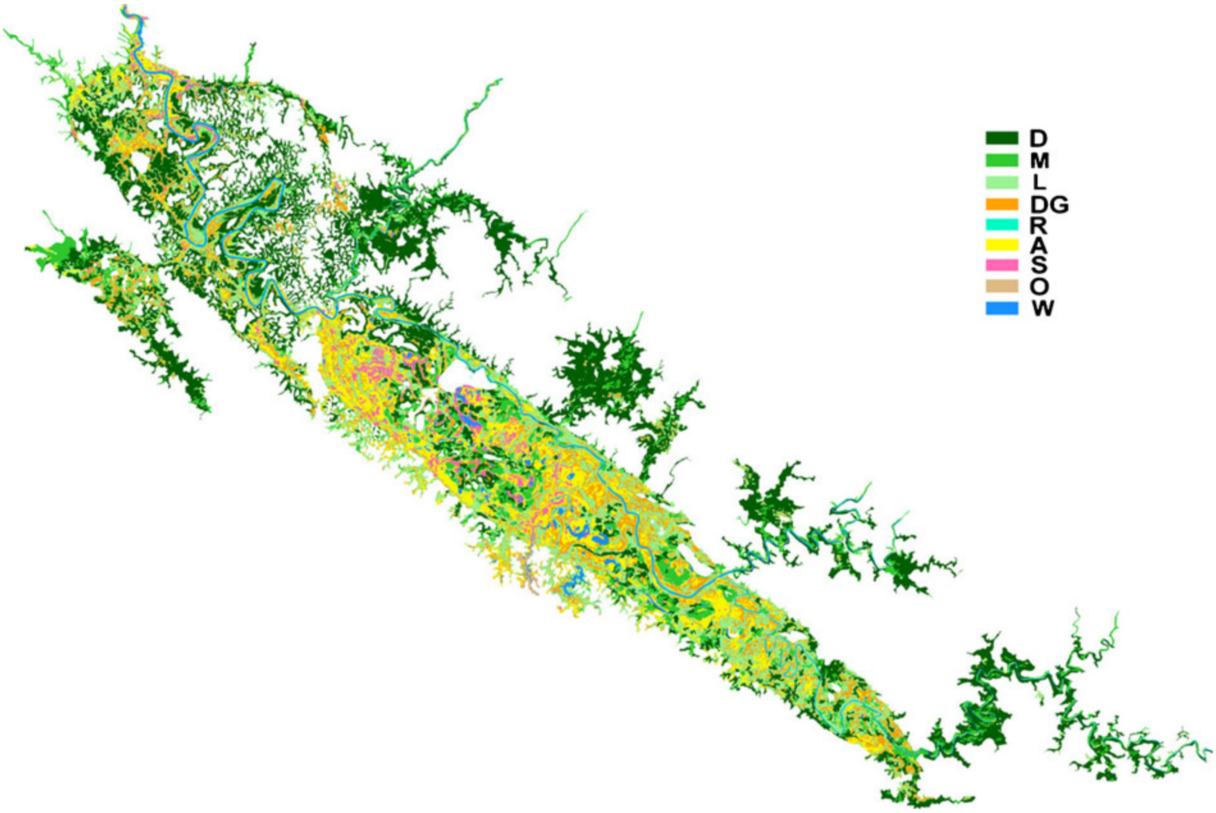

Fig. 3 Distribution map of the various cover types on the reservoir area situated below 538 m above sea level (many islands are present in the western part of the reservoir; dense [*D*], medium [*M*], light [*L*], degraded [*DG*], and riparian [*R*] forests; agricultural soil [*A*]; swamps [*S*]; water [*W*]; and "others" [*O*])

The distinction between the refractory fraction and the easily degradable fraction is not straightforward. The organic carbon decomposition rate depends on vegetation composition and environmental conditions (Coûteaux et al. 1995). Biomass with a high cellulose content is likely to decompose relatively rapidly, while the fraction with a high lignin content is rather refractory to decomposition (Coûteaux et al. 1995). Therefore, the easily degradable fraction can be defined as seedlings, saplings, lianas, litter, bamboos, and foliage. This definition is somewhat arbitrarily and relative since degradation rates depend on the environmental conditions. For instance, in anoxic conditions prevailing at the bottom of most tropical reservoirs, the degradation rate is lower than in aerobic conditions (Guérin et al. 2008). The foliage biomass was estimated with allometric equations measured in Malaysian forests (Kato et al. 1978; Osada et al. 2003): for a diameter at breast height (dbh) ranging from 3 to 50 cm, the percentage of leaf biomass as compared to total tree mass was comprised between 11% and 1.6%. We considered that the refractory fraction comprises deadwood and living stems and branches. No distinction was made for BGB and SOC.

Table 5 Distribution (area) of cover types in the reservoir area at full supply level (538 m above sea level) in April 2008

Cover type	Total	
	km^2	%
Dense forest	154.5	34.6
Medium forest	45.2	10.1
Light forest	110.9	24.8
Degraded forest	51.8	11.6
Riparian forest	4.0	0.9
Agricultural soil	48.7	10.9
Swamps	10.5	2.4
Water	15.3	3.4
Others (road, villages. . . .)	5.3	1.2
Total	446	100

Results and discussion

Land use distribution in the reservoir area

The vegetation distribution on the NT2 reservoir area is presented in Fig. 3, and the associated error matrix is shown in Table 4.

The overall accuracy of the classification is 73.3%, but not all the cover types were sorted out with the same precision. Dense forest was very well singled out, while medium forest was more difficult to isolate as such. This latter often appeared as more or less narrow fringes between dense and light forests. The fraction of agricultural soils classified as degraded forests corresponds to slash-and-burn areas.

The extent and the aspect of wetlands vary throughout the year. During dry season, when the SPOT 5 images were taken, swamps are partly drained and may look like agricultural zones. It explains why about one third of the swamp reference field points were classified as degraded forest and agricultural soils. This limitation implies that only the minimal swamps area was observed (Fig. 3): at the end of the dry season, swamps represents only 2.4% (Table 5) of the total area. The maximal extent of swamps, at the end of the wet season, has been roughly estimated at 7% with the topographic map of the area (RDP Lao-SGE 1985) on which they are represented.

Table 4 Error matrix for the nine cover types (dense [D], medium [M], light [L], degraded [DG], riparian [R] forests, agricultural soil [A], swamps [S], water [W], and "others" [O])

Map derived from field data	Map derived from image classification								
	D	M	L	DG	R	A	S	W	O
D	1.00								
M	0.50	0.13	0.38						
L			0.88			0.13			
DG				0.80		0.10			0.10
R					1.00				
A	0.22					0.78			
S				0.22		0.11	0.56		0.11

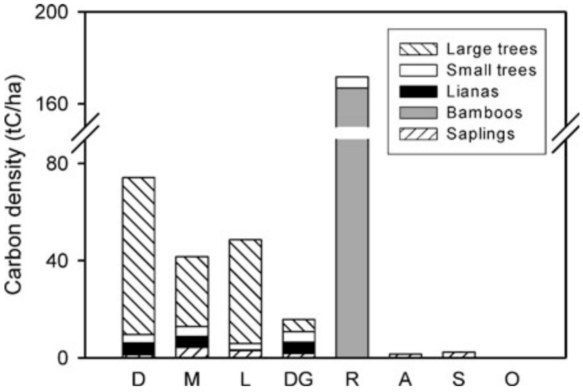

Fig. 4 Aboveground biomass composition (expressed in carbon density) for the various reservoir cover types: dense (*D*), medium (*M*), light (*L*), degraded (*DG*), and riparian (*R*) forests; agricultural soil (*A*); swamps (*S*); and "others" (*O*)

Most of the reservoir consists of forests: dense, medium, and light forests cover 69.5% of the total reservoir area. Forests are not homogeneously distributed: they cover about 84% of the zones downstream of Ban Thalang (Fig. 1) and along the tributaries and only 54% for the rest of the study area. Agricultural soils, degraded forests (including slash-and-burn areas), and swamps are mainly present in the southeast part of the reservoir.

Organic carbon density in the different pools

Aboveground biomass

The composition of the AGB for the various cover types is shown in Fig. 4. Dense, medium, and light forests have a total AGB of 74, 42, and 49 tC/ha, respectively. The AGB essentially consists of large and small trees. Table 6 presents some AGB data, mainly for forests (degraded forests not being considered), for several Southeast Asian countries. Comparison of AGB published data is relatively complex due to differences in the methodologies used and data quality (FAO 2001). The main possible sources of confusion are (1) the biomass unit (wet biomass, dry biomass, or carbon), (2) the minimal tree stem diameter, (3) whether or not understory biomass is taken into consideration and, (4) the age of the estimations. For instance, Brown et al. (1993) explain the dissimilarity between their results and those of the Food and Agriculture Organization of the United Nations (FAO; Table 6) by continued degradation of the forest due to population increase in the intervening period (data used by Brown et al. dates from 1980) as well as by differences in methods. The same reasons can explain the lower forest AGB densities measured in this study (42–74 tC/ha) as compared to those found for Lao PDR forests by Brown et al. in the 1980s (137 tC/ha) or by the FAO in 2005 (73 tC/ha; Brown et al. 1993; FAO 2006). Actually a few years of intense logging reduced locally the AGB density in the forests on the NT2 reservoir area. Moreover, global estimations of Lao forest AGB encompass primary, mainly evergreen, forests that account for about 9% of the total Lao forests (FAO 2006). AGB densities in these ecosystems are generally very high as confirmed by values in Table 6 for Cambodia, Indonesia, or Myanmar. Such primary and dense forests were virtually absent in the studied area, and it may also explain why FAO estimates are about 20% higher. At the regional scale, forests with low biomass carbon densities are generally located in continental countries (India, Laos, Thailand, and so on), while forests with high biomass densities are present in the islands of Borneo and New Guinea (Brown et al. 1993).

AGB in degraded forests of the NT2 area has been estimated at 15 tC/ha. The FAO also provides an estimate of AGB of the "other wooded lands" of 39 tC/ha (FAO 2006). The FAO definition of "other wooded lands" corresponds more or less to degraded forests. However, in this study, contrary to the FAO definition, this forest type also includes slash-and-burn areas in which the forest has been totally removed. That is probably why AGB in degraded forests in the NT2 reservoir area is lower than FAO estimations.

The highest AGB was measured in the riparian forest (167 tC/ha) due to the high density of bamboos. In tropical Amazonian rainforests where bamboo is dominant, as in open forests, bamboo biomass represents no more than 5% of the total AGB (Torezan and Silveira 2000). In Ethiopia, for bamboo forests, some studies give an AGB density of 55 tC/ha (Embaye et al. 2005) or 121 tC/ha (27–249 tC/ha) for a 20-year-old

Table 6 Aboveground biomass and soil organic carbon values in Southeast Asia

Country	Vegetation type (climate)	AGB (tC/ha)	SOC (tC/ha)	Comments	Reference
Cambodia	Dense forest (moist)	148		Only trees with a dbh above 10 cm	Brown 1997
	Semidense forest (moist)	185			
	Secondary forest (moist)	95			
	Open forest (moist)	80			
	Open forest (dry)	35			
	Well to poorly stocked forest (moist)	50–78			
	Deciduous forest (moist)	60			
	All forests (national)	153	129	Only trees with a dbh above 10 cm. Soil layer 1 m	Brown et al. 1993
	All forests (national)	91		FAO definitions for AGB	FAO 2006
Indonesia	Old secondary rainforest (wet)	132		Only trees with a dbh above 10 cm	Brearley et al. 2004
	Primary evergreen (wet)	178			
	Evergreen rainforest (wet)	255		Only trees with a dbh above 4.5 cm	Yamakura et al. 1986
	All forests (national)	162	183	Only trees with a dbh above 10 cm. Soil layer 1 m	Brown et al. 1993
	All forests (national)	50		FAO definitions for AGB	FAO 2006
Lao PDR	Evergreen + mixed deciduous + broadleaf forests (moist)	59–102		Measurement in the same area as in this study	Prosser 1997
		42–74	58–69	FAO definitions for AGB. Soil layer 0.3 m	This study
	National other wooded land (60% forest + 40% unstocked forest)	39		FAO definitions for "other wooded land" and for AGB	FAO 2004, 2006
	Agricultural soil (moist)		95	Soil layer 0.3 m	This study
	Swamps		102		
	All forests (national)	137	136	Only trees with a dbh above 10 cm. Soil layer 1 m	Brown et al. 1993
	All forests (national)	73		FAO definitions for AGB	FAO 2006
Myanmar	Evergreen	30–100		Only trees with a dbh above 10 cm	Brown 1997
	Mixed deciduous	23–68			
	Indaing forest	5–33			
	All forests (national)	120	136	Only trees with a dbh above 10 cm. Soil layer 1 m	Brown et al. 1993
	All forests (national)	79		FAO definitions for AGB	FAO 2006
Thailand	All forests (national)	94	128	Only trees with a dbh above 10 cm. Soil layer 1 m	Brown et al. 1993
	All forests (national)	39		FAO definitions for AGB	FAO 2006
Vietnam	All forests (national)	132	134	Only trees with a dbh above 10 cm. Soil layer 1 m	Brown et al. 1993
	All forests (national)	73	48	FAO definitions for AGB. Soil layer 0.3 m	FAO 2006
Southeast Asia	Forest in lowland (moist)	117–162	133–187	Only trees with a dbh above 10 cm. Soil layer 1 m	Brown et al. 1993
	Forest in lowland (seasonal)	94–88	121–142		
	Forest in lowland (dry)	38	121		
	Forest in montane (moist)	115–152	135–114		
	Forest in montane (seasonal)	83	125		
	All forests (national)	99–162	126–178		
	All forests (national)		68	Soil layer 0.3 m	FAO 2006

Table 6 (continued)

Country	Vegetation type (climate)	AGB (tC/ha)	SOC (tC/ha)	Comments	Reference
Asia	Tropical dry forest		251	Soil layer 1 m	Olson and Watts 1982; Post et al. 1982; Olson et al. 1983; Zinke et al. 1984
	Tropical moist forest		66		
	Tropical wet forest		97		
	Tropical savannah		48–69		
	Marsh and swampwoods		110		
	All ecosystems		113		
	All forests (national)		66	Soil layer 0.3 m	FAO 2006

plantation in Kerala (Kumar et al. 2005). In the riparian forest along the Nam Theun River, the bamboo density was high (166 tC/ha), with large clumps several meters in diameter. This value is comparable to AGB density measured for cultivated bamboo growing in particularly good conditions (Kumar et al. 2005). The growth of bamboos in the NT2 riparian forest was probably not so fast, and high measured bamboo AGB is likely to be a consequence of an unadapted sampling strategy (Table 3). However, the effect of this potential overestimation is limited since the riparian forest only represents 0.9% of the total studied area (Table 5).

For nonforested cover types, AGB is very low: 0.6 and 2.4 tC/ha for agricultural soils and swamps, respectively. This can be easily explained by the extreme scarcity of trees or bamboos.

Litter and deadwood

Litter and deadwood represent a relatively small fraction of the total carbon pool (Fig. 5). Litter density is relatively homogeneous in the different forest types, comprising between 2.5 and 3.0 tC/ha for medium and light forests, respectively. This value is similar to the FAO estimation (2006) for Lao PDR: 2 tC/ha. In dense, medium, and light forests, deadwood density varies between 1.8 and 4.3 tC/ha, while the highest value was found in the degraded forest. These values were lower than those given by the FAO: 10 tC/ha.

Belowground biomass

Except for the riparian forest, in which BGB is mainly composed of bamboo rhizomes, accounting for 41 tC/ha, the highest BGB densities were measured in dense, medium, and light forests (Fig. 5). The value for dense forests is close to that given by the FAO (2006) for Lao PDR: 20 tC/ha. In its Good Practice Guidance for Land Use, Land-Use Change and Forestry, the IPCC recommends using a soil thickness of 30 cm for quantifying organic carbon stock likely to be converted into GHG (IPCC 2003). Thus, rather than total BGB, only the fraction, in the superficial layer, must be taken into account. BGB in the uppermost 30 cm has been estimated at 4.9, 1.3, 4.1, and 1.5 tC/ha for dense, medium, light, and degraded forests, respectively. The average value over the whole studied area was 3.4 ± 5.2 tC/ha. For bamboos, almost the entire rhizome develops in the uppermost 30 cm.

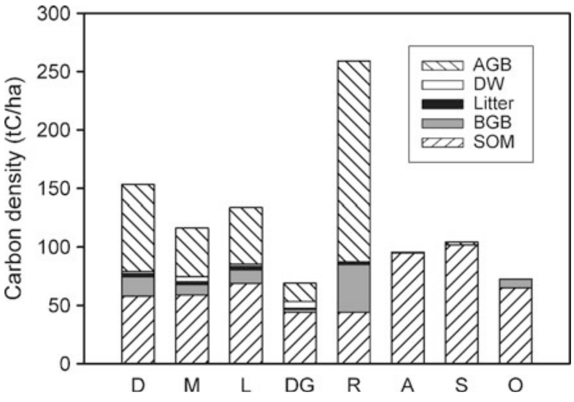

Fig. 5 Distribution of the total organic carbon density among the various carbon pools: aboveground biomass (*AGB*), deadwood (*DW*), belowground biomass (*BGB*), and soil organic matter (*SOM*) and for the different reservoir cover types: dense (*D*), medium (*M*), light (*L*), degraded (*DG*), and riparian (*R*) forests; agricultural soil (*A*); swamps (*S*); and "others" (*O*)

Soil organic matter

Vertical profiles of organic carbon content are presented in Fig. 6 for the various soil types (excluding the "other" type). A decrease in SOC with a depth is observed except for the riparian forest soil (constant carbon concentration). This decrease can be well approximated by the following exponential equation:

$$\text{Organic carbon concentration (\%)} = y_0 + a\,\mathrm{e}^{b\cdot\text{depth (centimeters)}} \qquad (1)$$

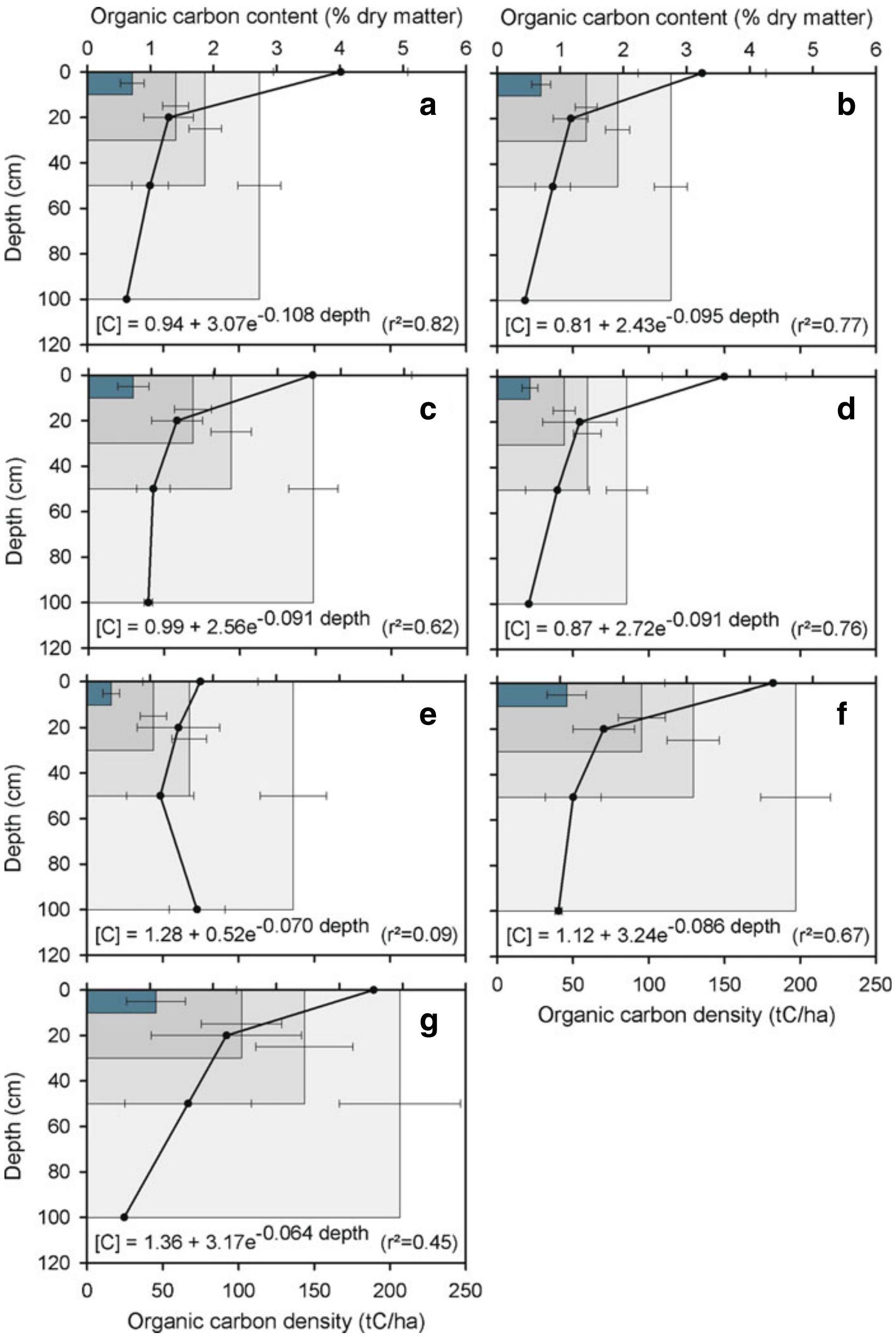

Fig. 6 Mean SOC content (% dry matter) profiles in the reservoir (*black circles*) and mean SOC density (tC/ha) in the reservoir for four soil thicknesses (*gray bars* 0–10, 0–30, 0–50, and 0–100 cm) for the various cover types (dense [**a**], medium [**b**], light [**c**], degraded [**d**], and riparian [**e**] forests; agricultural soil [**f**]; and swamps [**g**]). The exponential equations approximating the decrease in SOC content with depth are also given. *Error bars* for SOC content and density represent ±1 standard deviation ($n = 9$ for SOC content, and for SOC density, standard deviation calculations were made with $n = 9$ SOC values and $n = 3$ bulk density values)

Parameters y_o, a, and b are given in Fig. 6 for the various cover types. From SOC content and measured soil bulk density, the SOC density, expressed in tC/ha, has been calculated for four soil strata: 0–10, 0–30, 0–50, and 0–100 cm (Fig. 6).

The vertical profile of SOC content in riparian forest soil was particular with the lowest concentration in surface (1.80%) and the highest at a 1-m depth (1.74%). As previously stated, this profile is not adequately described by the exponential function (very low regression coefficient). It implies that processes resulting in carbon vertical distribution were particular for this kind of soil. It is probable that organic carbon originates from the river water percolating in the whole soil layer (1 m) rather that the decomposition of biomass in the superficial soil layer.

The differences between parameters of Eq. 1 for dense, medium, light, and degraded forest soils were tested with an analysis of variance (ANOVA; one-way ANOVA). No significant differences were observed ($p < 0.05$) between the parameters, implying a similarity in the vertical pattern in SOC content for all the forest soils (except riparian forest). The corresponding SOC densities were 58, 59, 69, and 44 tC/ha for dense, medium, light, and degraded forests, respectively. SOC density in forests of some Southeast Asian countries is presented in Table 6. As for AGB, SOC density data comparison is not straightforward because of differences in methodology, especially with regard to the soil thickness considered. In Table 6, only densities given by the FAO are calculated for a thickness of 30 cm, and the value for Southeast Asian forest is 68 tC/ha, which is in good agreement with results in the NT2 forest soils. In most of the publications, a soil thickness of 1 m is used to calculate SOC densities (Table 6). Using this definition, SOC densities in studied forest soils comprised between 85 tC/ha (degraded forest) and 149 tC/ha (light forest). These values are in the same range as those published by Olson and Watts (1982) and Olson et al. (1983) for Asian forests (66–97 tC/ha) or Brown et al. (1993) for Lao forests (136 tC/ha; Table 6).

SOC density was highest in agricultural soil and swamps: 95 and 102 tC/ha, respectively (Fig. 5). This is the result of both a higher soil bulk density (in average 20% as compared to forest soils) and a higher SOC content, especially for swamps in which SOC accumulates and decomposes very slowly. High SOC densities in swamps, bogs, and peatlands have already been reported (Zinke et al. 1984) in North America and Asia (Table 6). The higher bulk density in agricultural soil may be explained by the firming of the soil consecutive to human activities such as rice cultivation or cattle grazing.

Average organic carbon stock in the reservoir area

Considering the distribution of the various cover types (Table 5), the average aboveground organic carbon stock (including AGB, deadwood, and litter) is about 50 ± 13 tC/ha (Fig. 7a, Table 7). Large

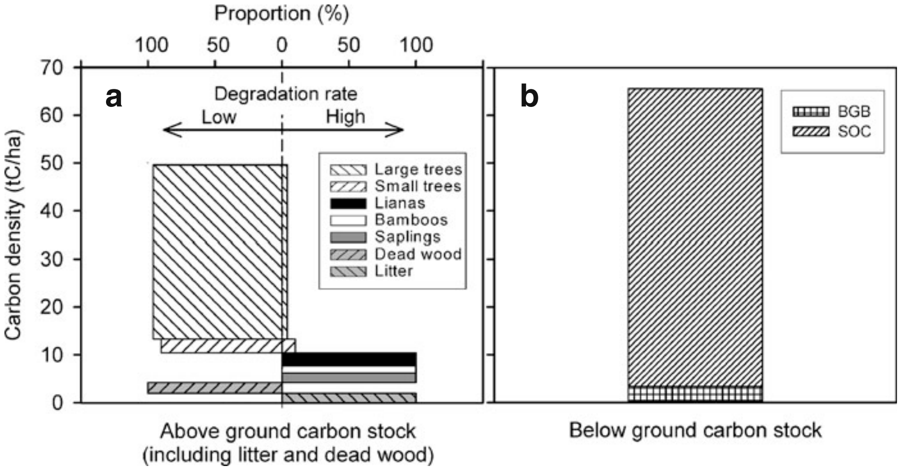

Fig. 7 Aboveground (**a**) and belowground (**b**) organic carbon stocks in the reservoir area. For each pool of the above ground carbon stock (including deadwood and litter), an indicative distinction is made between fractions with low and high degradation rate (between 0% and 100%, top scale)

Table 7 Distribution of the organic carbon density (tC/ha) and quantity on the whole reservoir area (MtC) among the various carbon pools

Carbon pool		Density (tC/ha)	Quantity (MtC)
Aboveground biomass	Large trees[a]	36.3 ± 13.1 (1.4 ± 0.5)	1.62 ± 0.58
	Small trees[a]	2.9 ± 1.4 (0.3 ± 0.1)	0.13 ± 0.06
	Lianas	2.7 ± 1.8	0.12 ± 0.08
	Bamboos	1.5 ± 0.7	0.08 ± 0.03
	Saplings, seedlings	2.0 ± 0.7	0.09 ± 0.03
Deadwood		2.2 ± 1.1	0.10 ± 0.05
Litter		2.0 ± 0.7	0.09 ± 0.05
Belowground biomass (0–30 cm depth)		3.4 ± 5.2	0.15 ± 0.23
Soil organic matter		62.2 ± 5.0	2.75 ± 0.23
Total carbon stock		115 ± 15	5.12 ± 0.68

[a] Numbers in parentheses represent the easily degradable fraction (tentative values)

trees are dominant, accounting for 73% of the total density. Other carbon pools have a relatively similar carbon quantity, ranging between 1.5 and 2.9 tC/ha. The small contribution of bamboos can be explained by the limited extent of the riparian forest (Table 5).

The proportion of aboveground carbon stock with low and high degradation rates is indicated in Fig. 7. For large and small trees, respectively, 1.4 and 0.3 tC/ha are considered to have a high degradation rate. The total density of easily degradable biomass is estimated to be 10 ± 2 tC/ha, corresponding to 20% of the total aboveground carbon stock. This value is only an order of magnitude and probably overestimated since the distinction between the two pools is not so simple. For instance, a fraction of the saplings, the lianas, or the litter is probably composed of refractory compounds.

The average belowground organic carbon stock (SOM + BGB) in the uppermost 30 cm is about 66 ± 7 tC/ha (Fig. 7b, Table 7). Roots larger than 2 mm account for only 5% of the total carbon density. Ninety-five percent of the carbon stock is therefore made up of SOC, including fine roots (<2 mm). SOC density depends on the soil thickness considered. Figure 6 shows the mean reservoir SOC concentration and the associated density for various soil thicknesses. Values are 31, 62, 84, and 93 tC/ha for the following soil layers: 0–10, 0–30, 0–50, and 0–100 cm. The distinction between refractory and easily degradable organic matter is more difficult to determine than for aboveground carbon stock except for large roots that have a low decomposition rate. For SOM, no conclusion can be drawn because it is a mixture of many compounds having different degradation rates (cellulose, lignin, humic and fulvic acids, etc.). Moreover, the composition of SOM and thus its degradation rate changes with the depth. Further investigation is needed to assess it.

The average organic carbon density (aboveground and belowground) in the NT2 reservoir area is 115 ± 15 tC/ha. This corresponds to a total carbon stock of 5.1 ± 0.7 MtC, 2.2 for AGB, litter, and deadwood and 2.9 for BGB and SOC.

The Nam Theun 2 reservoir: organic carbon stock and management

The decomposition of the flooded organic carbon stock after reservoir impoundment leads to the production and emission of GHGs, mainly CO_2 and CH_4 depending on local environmental conditions such as hydrodynamics, water quality, temperature, bacteriology, etc.... Reviews on processes affecting production and fate of GHGs in reservoirs can be found in Tremblay et al. (2005). To a first approximation, the ratio between flooded organic carbon and installed production gives an indication of the possible impact of the project. This ratio and other characteristics are presented for some tropical reservoirs in Table 8. South American reservoirs have a carbon stock ranging from 251 to 326 tC/ha leading to ratios comprised between 15 and 304 kgC/W. These values are higher than for the NT2 and Nam Leuk reservoirs (4.77 and 4.17 kgC/W, respectively).

The Petit Saut reservoir has a high biomass/capacity ratio (86.1 kgC/W), and GHG gross emissions have been estimated at 42.3 $MtCO_{2eq}$ over a 100-year timescale (Delmas et al. 2001). The same estimation has been made for the NT2

Table 8 Ratio of flooded organic carbon stock to installed power capacity for several tropical reservoirs

Reservoir	Country	Area (km^2)	Installed capacity (MW)	Total organic carbon stock (tC/ha)	Total flooded biomass (MtC)	Ratio flooded biomass: installed capacity (kgC/W)
Balbina	Brazil	2,346[a]	250[a]	326[d]	76	304
Samuel	Brazil	560[a]	217[a]	275[d]	15	69.1
Curuá-Una	Brazil	72[b]	40[b]	319[d]	2.3	57.5
Tucuruí	Brazil	2,430[a]	3,960[a]	251[d]	61	15.4
Petit-Saut	French Guyana	365[c]	115[c]	270–289[c,e,f]	9.9	86.1
Buyo[g]	Ivory Coast	895	220	270	24	109
Taabo[g]	Ivory Coast	69	220	160	1.1	5.00
Nam Leuk	Lao PDR	13	60	196[h]	0.25	4.17
Nam Theun 2	Lao PDR	450	1,070	115[i]	5.1	4.77

[a] Rosa and dos Santos 2000
[b] Fearnside 2005
[c] Delmas et al. 2005
[d] Fearnside (1995) for aboveground biomass, deadwood, and litter and FAO (2006) for soil organic carbon stock in the uppermost 30 cm
[e] A soil thickness of 40 cm was considered for Petit Saut in Delmas et al. 2005
[f] Guérin et al. 2008
[g] Richard et al. 2005
[h] Unpublish data for aboveground biomass, deadwood, and litter and this study for soil organic carbon stock in the uppermost 30 cm. The biomass has been partly removed (burnt) before the impoundment
[i] This study

reservoir assuming that GHG emissions are equal to those for the Petit Saut reservoir multiplied by the ratio between organic carbon content in the two reservoirs (Delmas et al. 2001). Predictions are estimated between 21 and 34 $MtCO_{2eq}$, over a 100-year timescale (NTPC 2005).

One way to mitigate these emissions would have been to remove organic carbon before impoundment. Unless the first 30 cm of soil be removed, which is not realistic, the only approach would be to remove AGB through burning. The burning of the vegetation has a positive effect if one considers that the organic carbon is mineralized in CO_2 instead of other GHGs with higher global warming potential (GWP; IPCC 2007). This statement is not correct since the combustion of the vegetation is also responsible for the emission of CO, CH_4, and N_2O. The production rate of these GHG during forest fires, as well as their respective GWPs, is given in Table 9. For the Petit Saut reservoir, the combination of all trace gas emissions following forest burning yields emissions of 15.2 and 30.4 MtCO2eq for burning efficiencies of 50% and 100%, respectively (Delmas et al. 2001). This range of burning efficiencies corresponds to the extreme values for

Table 9 Emission factors for forest fires and global warming potential (over a 100-year timescale) of the GHG produced (Delmas et al. 2001; IPCC 2003)

	CO_2	CO	CH_4	N_2O	Total
Emission factor (g/kg dry matter combusted)	1,580	130	9	0.11	
Global warming potential[a]	1	3	21	290	
GHG produced for a burning efficiency of 50% (2.1 Mt dry biomass; $MtCO_{2eq}$)[b]	3.4	0.9	0.4	0.07	4.8
GHG produced for a burning efficiency of 100% (4.3 Mt dry biomass; $MtCO_{2eq}$)[b]	6.9	1.7	0.8	0.14	9.6

GHG emissions due to the combustion of 50% and 100% of the aboveground carbon stock of the NT2 reservoir are also in given in equivalent CO_2
[a] We used the same GWP values as Delmas et al. (2001) did in their estimation of GHG emission of the NT2 reservoir. These values were updated in 2007 (IPCC 2007)
[b] Values taken in Table 7: aboveground carbon stock = 2.2 MtC = 4.4 Mt biomass (dry matter)

tropical dry forests with a drying time longer than 6 months (IPCC 2003). With this initial burning, Delmas et al. (2001) come up with a cumulated range of 38.1–53.3 $MtCO_{2eq}$ over a 100-year timescale, that is to say, between 90% and 126% of emissions without deforestation (42.3 MtCO2eq). For the NT2 reservoir, GHG emissions due to the combustion of the vegetation comprised between 4.8 and 9.6 $MtCO_{2eq}$ (Table 9). Total GHG emissions over a 100-year timescale with the initial burning have been estimated using the same approach as Delmas et al. (2001; previous paragraph) but by distinguishing the respective contributions of aboveground and belowground carbons in GHG production (Guérin et al. 2008). Cumulated GHG gross emissions with the initial vegetation burning are thus estimated between 98% and 110% of the gross emissions without biomass removal. This range is narrower than for Petit Saut probably because of the lower proportion of aboveground carbon stock (43% of the total carbon stock) in the NT2 reservoir than in the Petit Saut reservoir (57%).

It appears that the removal of the vegetation from the NT2 reservoir area would only have a very limited impact (positive or negative) on the cumulated GHG gross emissions over a 100-year timescale. However, several other parameters must be taken into account: (1) calculations must be done with net emissions that may be significantly lower than gross emissions: 14–43% of the gross emissions for the Petit Saut reservoir (Delmas et al. 2001); (2) many other environmental issues are induced by the vegetation burning (Levine 1991) such as the emission of aerosols or the release of high amounts of nutrients; (3) the biomass may regrow between vegetation clearance and impoundment; (4) direct CO_2 emissions are due to exploitation and transport of the biomass.

Conclusion

Precisely quantifying the organic carbon stock over several hundred square meters in tropical countries is both energy and time consuming, requires a combination of different techniques, and cannot be achieved without thorough filed measurements.

Organic carbon stocks in living and dead vegetations and soil were measured on the Nam Theun 2 reservoir area before the impoundment in eight cover types: dense, medium, light, degraded, and riparian forests; agricultural soils; swamps; and "others". The geographical distribution of these cover types was measured by remote sensing on two recent (2008) SPOT 5 images covering the 450 km^2 of the studied area. The aboveground organic carbon stock density, including large and small trees, lianas, understory, litter, and deadwood, has been estimated at 50 ± 13 tC/ha. Belowground organic carbon stock (soil organic matter and tree roots) density in the uppermost 30 cm of the NT2 reservoir area is estimated at 66 ± 7 tC/ha. This corresponds to a total organic carbon stock on the NT2 reservoir area of 5.1 ± 0.7 MtC (2.2 MtC for aboveground biomass, litter, and deadwood and 2.9 MtC for belowground biomass and soil organic carbon). The organic carbon stock is much lower than for other tropical reservoirs in South America or Africa.

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