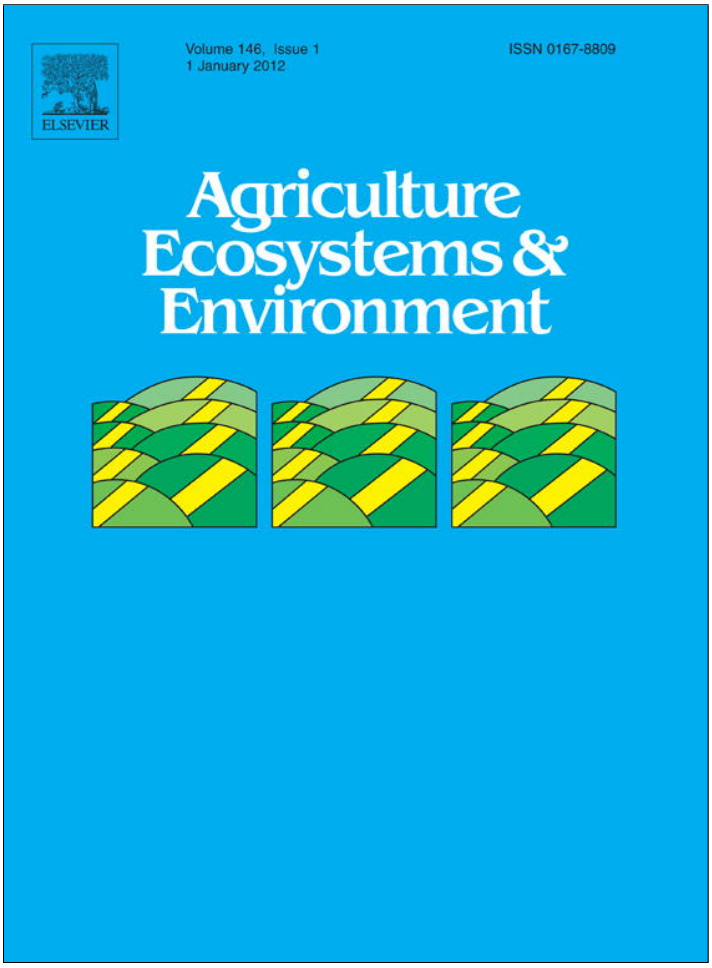
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Long-term soil carbon loss and accumulation in a catchment following the conversion of forest to arable land in northern Laos

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ABSTRACT

Quantifying the magnitude of soil organic carbon loss linked to the conversion of forest to arable land in tropical environments requires long-term estimates of soil redistribution trends within the catchment. In order to assess the cumulative soil carbon loss that occurred since deforestation and cropping started in 1967, a multidisciplinary study was carried out in a small catchment (67 ha) with a swamp area in its middle part, characterized by steep slopes under shifting cultivation of upland rice, typical for northern Laos's landscapes. Using ^{137}Cs and total organic carbon (TOC) inventories, it was possible to estimate a soil TOC depletion rate of 0.039 kgC m^{-2} yr^{-1} in 42 years (1963–2005), corresponding to *ca.* 21% of its initial content in the top 10 cm. Because farmers preferred clearing more fertile soils located downhill and leave forest on poorer soils on the crests, the redistribution of ^{137}Cs and TOC along slopes of the catchment was mainly controlled by the topographic position of soils and the cultivation frequency. Estimates of soil TOC accumulation in wetlands with δ^{13}C measurements and sediment volumes by electrical resistivity tomography showed that TOC accumulation rates were linked to land use change since the 1960s with three successive periods corresponding to undisturbed forest, deforestation-first rice crop and rice-fallow rotations. Forest clearing triggered a higher soil TOC delivery to the swamp (19.6 ± 5.5 kgC ha^{-1} yr^{-1}) over 8 years (1967–1975) than the former undisturbed forest (8.5 ± 1.8 kgC ha^{-1} yr^{-1}) and crop-fallow rotations over 30 years (1975–2005, 6.4 ± 4.8 kgC ha^{-1} yr^{-1}). Due to the small size of the area covered by the swamp, only a limited fraction of eroded soil organic carbon (*ca.* 7 wt.%) was stored in wetlands of the catchment. Mineralization apparently played a key role for soil TOC depletion since first forest clearing.

1. Introduction

Agriculture is encroaching rapidly on tropical mountains due to demographic and economic pressures that accelerate deforestation. Such disruption causes soil loss along catchment slopes (Valentin et al., 2008), landslides and sediment transfer to lakes and impoundments (Downing et al., 2008; Thothong et al., 2011) resulting in widespread land degradation (Sidle et al., 2006). Soil organic carbon depletion linked to erosion is of major importance in agricultural catchments as it reduces soil stability and productivity (Murty et al., 2002; Quinton et al., 2010) at unprecedented scales and rates in Southeast Asia (Ludwig et al., 1996; Seidenberg et al., 2002; Wezel et al., 2002). Moreover, eroded carbon, once in the river network and subject to mineralization, may contribute to greenhouse gas emissions (Lal, 2003). Soil erosion studies conducted from plot to hill slope scales are frequently used to assess soil organic carbon detachment and transport by overland flow (*e.g.*, Bellanger et al., 2004) but it remains difficult to upscale these results to the catchment level because they are often subject to threshold effects (Lugo and Brown, 1993; Turkelboom et al., 2008), involve different processes (*e.g.*, Poesen et al., 1996) and do not account for deposition along slopes and valley bottoms (Chaplot and Poesen, 2012). The catchment unit appears to be an appropriate scale because it integrates topography and other land characteristics as well as how cultivation responds to them. Moreover, this unit is often repeated in the landscape and may be used for out scaling. In Southeast Asia smallholders who practice shifting cultivation clear the forest predominantly on sloping land. Although slash-and-burn

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causes temporary deforestation during the cropping period it also allows the regrowth of secondary forest. With abundance of land, farmers typically only cultivate a part of the catchment alternating with long term fallowing (Roder, 2001). As pressure on arable land increases, the fallow period is shortened and an increasing surface of the remaining forest is cut. Replacing forest by fields on steep slopes without the use of external inputs to compensate nutrient export, results in a decline in land productivity that is associated with decreasing soil organic levels (Kendawang et al., 2005), degraded soil fertility (Brand and Pfund, 1998) and increasing labour demand to control weed invasion, which in turn, urges the farmers to adopt alternative land uses (Roder, 2001; Saito et al., 2008).

At the landscape or catchment level, the ongoing conversion of large tracks of mature forest to arable land triggers long-term soil organic carbon depletion (Arrouays et al., 1995) that may take centuries to decades, *i.e.*, 125 years in Madagascar (Brand and Pfund, 1998), 100 years in Northern Thailand (Zinke et al., 1978), 60 years in Vietnam (Wezel et al., 2002) or 45 years in Laos (Seidenberg et al., 2002). Fallout radionuclides such as ^{137}Cs (half life of 30.2 years) and ^{210}Pb$_{xs}$ (half life of 22.3 years) provide tools for the assessment of soil particles redistribution in agricultural catchments at pluri-decennial scales (Ritchie and McHenry, 1990; Van Oost et al., 2003). The period of ^{137}Cs fallout between 1954 and 1976, with a maximum delivery rate in 1963 (UNSCEAR, 1969), coincides with the last maximum extension of the forest cover in Southeast Asia. The following years progressive to near-complete deforestation corresponded to a period of reduced or zero ^{137}Cs-fallout. For instance, 73% of Laos surface was covered by mature forest in the 1960s and a reduction to 40–47% occurred in the 1990s (MAF, 1999; Soderak, 1999). Most of the ^{137}Cs and ^{210}Pb$_{xs}$ reaching land surface is tightly bound to fine size soil particles that can be detached by rainfall and exported in suspended loads (*e.g.*, He and Walling, 1996). Depletion of ^{137}Cs and ^{210}Pb$_{xs}$ from catchment's slopes is thus associated with soil particles redistribution. In contrast, enrichment in ^{137}Cs takes place in areas of soil particle accumulation as in floodplains (Owens et al., 1999). Furthermore, soil organic carbon erosion and deposition trends can also be assessed from measurements of their residual activity (*e.g.*, Ritchie and McCarty, 2003; Huon et al., 2006; Van Oost et al., 2007; Wei et al., 2008).

In this study a multidisciplinary approach based on history records of land use and vegetation, ^{137}Cs and ^{210}Pb$_{xs}$ inventories, soil and sediment TOC (total organic carbon) concentration and stable carbon isotopes measurements and electrical resistivity tomography field prospection was carried out in a cultivated catchment, typical for northern Laos to: (i) determine the cumulative loss of soil organic carbon that occurred since shifting cultivation started during the 1960s, (ii) assess whether environmental parameters (*i.e.*, topographic position and slope) and cultivation frequency were linked or not to soil organic carbon depletion after forest clearing and, (iii) estimate the capacity of wetlands to trap and store soil-derived organic matter within the catchment.

2. Study area

2.1. Biophysical environment

The Houay Pano catchment (67 ha), located 10 km south of Luang Prabang in northern Laos (19°51′00″N–19°51′45″N, 102°09′50″E–102°10′20″E, Fig. 1), belongs to the MSEC (Managing Soil Erosion Consortium) network (Valentin et al., 2008). Climate is characterized by summer monsoon. Approximately 77% of total rainfall occurs between May and October, with a maximum supply in July and August (Ribolzi et al., 2008). Mean annual air temperature and precipitation in the Houay Pano catchment were 25.3 °C and 1403 mm, respectively (Valentin et al., 2008). The main stream is perennial with an average base flow of 0.4 ± 0.1 L s^{-1} that may exceed 150 L s^{-1} after important storms (Ribolzi et al., 2008). In its upper part, water flows through a swamp (0.19 ha) draining 32.5 ha, fed by a permanent groundwater sheet. Although temporary flood deposits can be found along the narrow stream banks, the swamp represents the only long-term sediment accumulation zone within the catchment.

With altitudes between 425 m and 718 m above sea level, the catchment is characterized by steep slopes, ranging 3–150% and averaging 61%. The geological basement of Houay Pano is composed of lower Indonisian series (shales, greywackes, pelites and sandstones, VKL, 1971), overlaid by Carboniferous to Permian limestones that only outcrop in the extreme NE upper part of the catchment. Deep (>2 m) to moderately deep (>0.5 m) and mainly loamy clay Alfisols (UNESCO, 1974) dominate the catchment with: (i) moderately fertile Alfisols, quoted type 1 (51–58% clay content in the 0–35 cm layers, Chaplot et al., 2009) for 48% of catchment surface (MSEC, 1999) and, (ii) slightly more acidic – lower base saturation Alfisols, quoted type 2 (47–60% clay content in the 0–35 cm layers, Chaplot et al., 2009) for 33% of catchment surface (MSEC, 1999). Shallow (<0.5 m) mainly clayey Inceptisols (27–48% clay content in the 0–35 cm layers) located along crests and ridges occupy the remaining catchment surface (MSEC, 1999). Kaolinite and illite are the major soil clay minerals down slope whereas kaolinite, interstratified with vermiculite–chlorite–smectite layers, predominates upslope.

2.2. Vegetation and agriculture

The original vegetation is lowland forest with bamboo, the name "Houay Pano" means "valley of bamboo sprouts". Away from stream and groundwater access the majority of species are at least partly deciduous during the dry season. In this study "primary" and "high" forest refer to floristically similar sites that were never used for shifting cultivation as far as records can be established. Primary forest differs from high forest by its unique ground flora but was only encountered in sample sites of the Nam Khan valley, adjacent to the studied catchment. The Houay Pano catchment is part of the village land of Ban Lak Sip (2476 ha, 503 inhabitants, 2003 census). About 90% are Khamou (or Kmhmu) farmers, traditional shifting cultivators. Due to the government resettlement policy applied since 1976, population density increased from 19 to 55 inhabitants per km^2 while a forest protection policy applied since 1994 reduced the area for shifting cultivation to 136 ha (Lestrelin et al., 2005). The village comprises 95 households with 2–7 plots of land per family. Twenty-six households have 1–2 plots in the Houay Pano catchment. The shifting cultivation practices of the Khamou are well documented (Suksavang and Preisig, 1997; Izikowitz, 2001; de Rouw et al., 2005). A single crop of upland rice (*Oryza savita* L.) is followed by a fallow period of 2–5 years in Houay Pano and 20–30 years in the Nam Khan valley. The cash crops, maize (*Zea mays* L.) and Job's tears (*Coix lacryma-jobi* L.), are sometimes planted the second year as a follow up for rice. No tillage is carried out except, if necessary, superficial scraping for weed control with a small curved hoe (Dupin et al., 2009). Isolated fields are rare and block-wise slashing of the forest is the rule. In Houay Pano remnants of high forest over poor quality soils, covered 8.9 ha in 2005. Teak and banana plantations accounted for 9.7 ha. The remaining land is used for shifting cultivation, in a typical mosaic of bush fallow and fields (Fig. 1).

The swamp is colonized by 2–4 m high Napier grass (*Pennisetum purpureum* Schumach.), a C$_4$-photosynthetic pathway plant (leaf δ^{13}C = −12‰, this study) introduced in Houay Pano for horse feeding in the 1960s. Remnants of the original 1-m high wild Taro (*Colocasia esculenta* L., Schott), a C$_3$-photosynthetic pathway plant

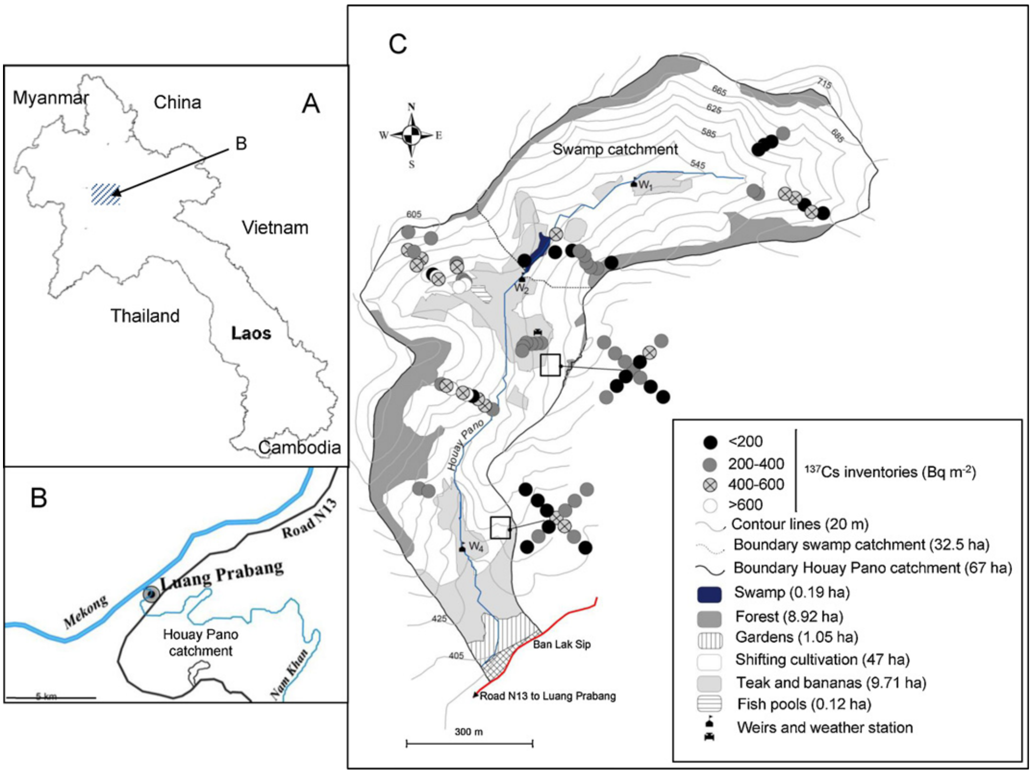

Fig. 1. Study area: (A) location of Laos in SE Asia, (B) location of the Houay Pano catchment and the Nam Khan river, (C) Houay Pano catchment (67 ha, solid line) with land use in 2005 and location of the 81 soil sampling sites. Topsoil 30-cm ^{137}Cs inventories are reported for each site. Cross-like sample distributions are out of scale (location: 1.41 m, 7.07 m and 17.7 m from the central position along the diagonals).

(*e.g.*, δ^{13}C = −27‰; Chikaraishi and Naraoka, 2003), are found at the inlet. In contrast to wild Taro, a plant producing few leaves and no litter, Napier grass forms dense masses of litter and, hence, gives much more obstruction to stream flow and favour sediment retention during the rainy season. Similar swamps were found in 2011 near the abandoned Hmong village of Pagnakhalouang in the Nam Khan valley.

3. Material and methods

3.1. Electrical resistivity tomography measurements

Sediment volumes in the swamp were estimated following 4 successive steps presented in Table 1. A field survey based on electrical resistivity tomography (ERT) was carried out within a rectangular area of 0.41 ha, comprising 14 profiles crossing the swamp every 5 m and one perpendicular profile along the main course of the stream. The surface of the swamp in the surveyed area was 0.12 ha. The inlet (215 m^2) and the outlet (250 m^2) areas, not included in the study area, represented 28% of swamp extension.

Along each profile, 72 stakes made of stainless steel (electrodes) were stuck in the soil with a constant spacing of 1 m and connected to the resistivity meter. Resistivity measurements were made along each profile using quadrupoles $P_1C_1C_2P_2$ arranged in a reciprocal Wenner–Schlumberger configuration. Such array, well suited for multi-channel recording system, provides convenient data coverage and relevant signal/noise ratio for subsurface electrical imaging (Dahlin and Zhou, 2004). A smooth blocky estimation of the actual ground resistivity variations from surface down to 7 m depth was calculated with the inversion software. The width of the blocks (1 m) was homogeneous and corresponded to unit inter-electrode spacing. The height of the first layer of blocs (0.5 m) was equal to the median depth of investigation of the smallest quadrupoles used (Roy and Apparrao, 1971) and was increased by 10% for each of the following layers to offset the decrease of the sensitivity function of the array (Mc Gillivray and Oldenburg, 1990). The calculated vertical profiles of resistivity variations hence had a stair shape with 9 fixed steps of increasing height towards depth. Based on the principles of suppression and equivalence (Kunetz, 1966), a simpler vertical model with the same 1D apparent resistivity response than the stair shape model but with only 3 or 4 layers was then calculated every 2 m along the 15 surveyed profiles using an approach similar to the 1D laterally constraint inversion methods (Auken et al., 2005). This method allowed more accurate estimates of the interface depths of the different layers identified in the swamp. The volume of each layer was finally estimated using a kriging interpolator of thickness variations within the surveyed area of the swamp and was extrapolated following the features observed along the profiles closest to the inlet and the outlet, respectively.

3.2. Soil and sediment sampling

Between 2000 and 2005, 81 soil profiles were cored down to 30 cm with 10 cm depth increments using a soil corer with a 4.3 cm × 4.7 cm internal section (Fig. 1). At each sampling point local slope, topographic position, vegetation type and land use were determined. Fifty-five samples were collected along 50–200 m long topographic transects and two sets of 13 soil cores were collected following a cross-like pattern. The later comprises one central soil core and 12 other cores, located on the two diagonals crossing at the central point. The purpose of this procedure was to check short-distance heterogeneity by comparing mean values using an increasing number of samples (n = 5, 9 and 13) covering an increasing distance. Additional samples were collected outside the Houay Pano catchment on Khamou land with similar soils, slopes, elevation, and original forest cover, but where the pressure on arable land

Table 1
Instruments and softwares used for the estimation of sediment volumes in the swamp.

Steps of estimation	Instrument/software	Manufacturer/country	Reference
1. Field data acquisition	Multi-channel Resistivity meter: SYSCAL Pro 72	Iris Instruments/France	Griffiths and Barker (1993)
2. Calculation of the ground resistivity blocky model	3D resistivity data inversion Software: RES3DINV v.2.16	Geotomo Software/Malaysia	Loke and Barker (1996)
3. Calculation of the simplified layered model	1D resistivity processing Software: X21PI v.2	Moscow State University/Russia	Bobachev et al. (1995)
4. Estimation of sediment volume	3D surface mapping	Golden Software Inc./USA	

was less important. In Nok Pit (5 km from Houay Pano) and Houay Khot (25 km from Houay Pano) similar sampling was carried out under bamboo forest. In the Nam Khan valley (100–150 km from Houay Pano) fallows over 20 years old (n = 6) with neighbouring primary forest (n = 4), and upland rice plots after 20 years of fallow (n = 1) were sampled in Don Njung, Phak Vong, Siphonthong, and Souane Mone.

In the swamp pits were dug at the inlet, outlet and central part at the end of the rainy season in October 2005 (Fig. 1). Surface vegetation was cut over 5-m^2 area. Undisturbed sediment samples were collected continuously, every 10 cm, down to 2 m using a large cylinder with a 785 cm^3 internal volume providing an overall set of 60 samples.

3.3. Soil and sediment analyses

Bulk densities were determined for all soil and sediment samples by collecting undisturbed cores and oven-drying the samples at 105 °C for 48 h. Samples were sieved to 2 mm in order to remove coarse vegetation debris and stones, followed by gentle aggregate breakdown using a hand mortar for ^{137}Cs and ^{210}Pb activity measurements. Additional grinding to very fine powder (<200 μm) was carried out for total organic carbon (TOC) and δ^{13}C analyses. After removal of organic matter by H_2O_2 and hexametaphosphate dispersion, grain size fractionation (5 texture classes) was performed by repetitive pipetting of clay then loam fractions followed by sieving of coarser residues (Pansu and Gautheyrou, 2003), on a selection of 12 soil samples collected along topographic sequences and for all sediment samples collected in the swamp. The former set served to determine the binding level of ^{137}Cs and $^{210}Pb_{xs}$ to specific texture classes.

The ^{137}Cs and $^{210}Pb_{xs}$ activities were measured for all soil and sediment samples using sub-sample aliquots placed in tightly closed plastic boxes and submitted to 24 h γ-counting. ^{137}Cs and ^{210}Pb were determined at 662 keV and 46.5 keV, respectively. All measurements were carried out by γ-spectrometry (8000 channels, low background) using coaxial HP Ge and N-type detectors facilities available at the LSCE. Efficiencies and backgrounds were periodically controlled with International Atomic Energy Agency (IAEA) sediment and soil standards. In contrast to ^{137}Cs released in the atmosphere by nuclear bomb testing and nuclear power plant damages, ^{210}Pb is produced continuously by radioactive decay in rock and soils of the ^{238}U decay series and of gaseous ^{222}Rn, the later being released to the atmosphere through the decay of ^{226}Ra. Unsupported or excess ^{210}Pb, quoted as $^{210}Pb_{xs}$, corresponds to the fallout fraction of ^{210}Pb produced by atmospheric ^{222}Rn. Excess $^{210}Pb_{xs}$ was calculated by subtracting the supported activity determined with two ^{238}U daughters, ^{214}Pb (average counts at 295.2 keV and 351.9 keV) and ^{214}Bi (609.3 keV), from the total ^{210}Pb activity (Le Cloarec et al., 2007). The instrumental precision on ^{137}Cs and ^{210}Pb measurements typically represented 5–10% of sample activity with respect to its counting time (Evrard et al., 2010). ^{137}Cs and $^{210}Pb_{xs}$ were measured in Bq kg^{-1} of soil and converted into Bq m^{-2} using dry soil bulk densities to calculate soil inventories on the same sample aliquots. The ^{137}Cs inventories were corrected to year 2005 to account for radioactive decay of samples collected before 2005 using a half-life of 30.17 years.

During the period of maximum ^{137}Cs fallout in southeast Asia between 1954 and 1976 (UNSCEAR, 1969; Ritchie and McHenry, 1990) precipitation reached a mean of 1139 ± 225 mm in the Houay Pano with an excursion to 1564 mm in 1963 (Bricquet et al., 2003). Using precipitation data, an average ^{137}Cs reference value of 615 ± 20 Bq m^{-2} could be derived using the outputs of two modelled rainfall-derived ^{137}Cs fallout for 1963 (Walling and He, 2001; Hien et al., 2002) and ^{137}Cs inventories for assumed undisturbed soils (Huon et al., 2006). This value corresponds to the residual fallout activity in 2005 (*ca.* 1600 Bq m^{-2} before radioactive decay).

Total organic carbon (TOC) and ^{13}C/^{12}C isotope ratios were measured on the same aliquot of finely grounded sample by EA-IRMS (Carlo-Erba NA-1500 NC Elemental Analyser on line with a dual inlets Sira 10 Fisons Isotope Ratio Mass Spectrometer) at UMR Bioemco. The carbon stable isotope abundances are reported as δ^{13}C in per mil (‰) relative to Pee Dee Belemnite (PDB) standard (Coplen et al., 1983). TOC concentrations are reported in mgC g^{-1} of dry sample (equivalent to wt.‰). Data reproducibility was checked by replicate analyses of samples and of a tyrosine standard (Girardin and Mariotti, 1991) during the course of this study. No additional treatment for carbonate removal was required because soil pH was always lower than 6 (Huon et al., 2002).

3.4. Historic land use

Key informants were farmers from five households who participated in the initial forest clearing of Houay Pano catchment and cultivated land in the catchment since. Social events and vegetation changes assisted in recovering cultivation years (Table 2). Details about the use of the swamp were also obtained. The results of interviews were checked against aerial photographs (1953, scale 1:40,000; 1982, 1:30,000), maps (1943, 1:100,000) and technical documents (SLU, 1998). Aerial photographs confirmed the blockwise clearing of forest in line with traditional Khamou farming (Suksavang and Preisig, 1997) meaning that the five farmers commonly joined in one big field.

Hence cultivation years could be crosschecked among the group, one farmer confirming the statements of another's. During field walks these farmers indicated on the slopes the locations of areas that were cultivated in the past, and again their statements could be verified one against another. But exact locations of old fields were assessed using our own observations. In many cases permanent gullies separates fields from fallow land (Valentin et al., 2005). Other borders were assessed using the height and abundance of tree stumps. In high forest most trees are slashed at a convenient height of about 80 cm. Surviving trees resprout during fallowing. In the next cultivation cycle, instead of cutting all the resprouting stems individually, tree stems are cut well below 80 cm. Hence, every time a plot is recultivated, stumps become shorter and less abundant. On the slopes of Houay Pano catchment blocks of contrasting tree stump populations could thus be mapped indicating ancient field limits, particularly those cleared in 1967–1983 showing lowest densities of resprouting trees and shrubs, all with very

Table 2
History of land use in the Houay Pano catchment and well-remembered incidences used in the interviews with the farmers of Ban Lak Sip.

Period	Vegetation, farming, major events
Before 1967	High forest with bamboo[a] and patches of disturbed forest
1960	Hmong farmer's arrival, Napier grass[b] planted on swamp border
1962	Massive bamboo flowering and die-off
1966	Population increase, nearby hamlet joins Ban Lak Sip
1967–1983	Clearing of high forest
1967	First time Khamou cultivate in Houay Pano
1969	Population increase, nearby hamlet joins Ban Lak Sip
1972	Second time Khamou cultivate in Houay Pano
1973	War refugees arrive in Ban Lak Sip
1974	Hmong flee after communist take-over, Napier no longer harvested
1975	Official founding of Ban Lak Sip, 40 families (11 cultivate in Houay Pano)
1976	Resettlement policy application
1978	Massive bamboo flowering and die-off
1980	New weed Mimosa[c] arrives
1982	Third time Khamou cultivate in Houay Pano
1984–2005	Rotations of shifting cultivation, crop diversity
1986	First teak plantation
1989	Bamboo flowering and die-off
1991	First banana plantation
1993	Wild Taro[d] harvested for pig feed. Napier covers the swamp
1994	Land allocation policy application
1996	First large-scale cultivation of maize and Jobs' tears[e]
1998	First survey of the MSEC programme

[a] *Phyllostachys* sp.
[b] *Pennisetum purpureum* Schumach.
[c] *Mimosa diplotricha* C.Wright ex Sauv. var. diplotricha
[d] *Colocasia esculenta* (L.) Schott
[e] *Coix lacryma-jobi* L.

short stems, and areas cleared between 1995 and 2005 carrying many woody stems of 30–80 cm height. The monitoring of land use in Houay Pano became much easier after 1994, following the permanently allocation of land to 26 households, and after 1998, when the MSEC programme started using GIS and ArcView for the mapping of annual land use.

3.5. Statistical analysis

Simple linear regression analysis was used to identify relationships between the independent variables: topographic position, local slope, period of high forest clearing, total number of crop-fallow rotations, and the dependent variables: measured ^{137}Cs activity, TOC concentration. Correlations between factors were also calculated. Stepwise linear regression was used to identify the best predictors for TOC content. With this procedure, independent variables can be added individually to the model at each step of the regression and therefore changes in the correlation coefficient can be evaluated. Only parameters statistically significant at the $P < 0.05$ level were retained.

4. Results

4.1. Land use history

Three periods occur in the Houay Pano land use history (Table 2). Prior to 1967 the catchment was covered by high forest with patches of disturbed forest visible on the 1943 topographic map and 1953 aerial photographs. Disturbed areas are possibly related to incidental cultivation or result from bamboo die-off. Farmers explain the relatively late forest clearing of Houay Pano compared to other village land by the presence of bamboo (*Phyllostachys* sp.) in Houay Pano that commonly indicates soils of lower quality (Pravongviengkham, 1998) but also provides income. Approximately 24% of the catchment surface was deforested for rice cropping in 1967 and another 20% in 1972. In both cases mostly Alfisols 1 were used. In 1982 farmers returned for the third time to Houay Pano where they cleared about 49% of the catchment comprising, both high forest, mainly on Alfisols 2, and secondary forest on Alfisols 1. Most of the high forest cover was removed the following years as confirmed by the 1985 topographic map (plate E-48-4, scale 1:100,000). In the third period (1984–2005), short rotations prevail, comprising one rice crop alternating with 3–8 years of fallow. Every year, some part of the catchment is under cropping, ranging from 10% to 40% of its surface. Meanwhile crop variety increases (Table 2) and fields encroach progressively into the remaining high forest on Alfisols 2 and Inceptisols.

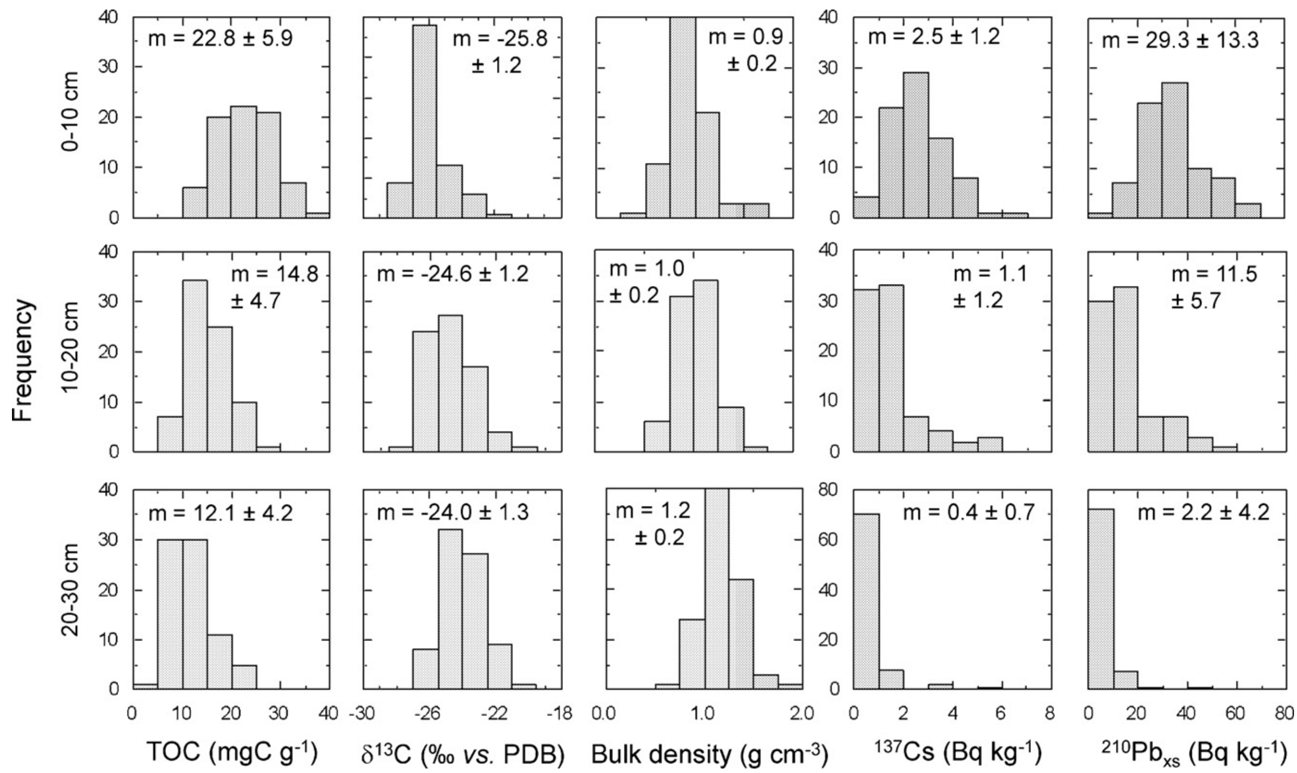

Fig. 2. Frequency histograms for TOC concentration, $\delta^{13}C$ values, bulk dry density, ^{137}Cs activity and $^{210}Pb_{xs}$ activity in soil samples of 81 profiles for three depth classes. Mean values $(m) \pm 1\sigma$ (standard deviation) are reported in each graph.

Table 3
Significant correlations between environmental and land use factors (Pearson's coefficient, $n = 81$, $^{*}P < 0.05$, $^{**}P < 0.001$).

	Topo[a]	Slope[b]	Clearing[c]	Crop[d]	^{137}Cs[e]	$TOC_{0-10\,cm}$[f]	$TOC_{0-30\,cm}$[g]
Topo	1						
Slope	–	1					
Clearing	−0.51**	–	1				
Crop	–	–	0.69**	1			
Cs	−0.35**	–	–	−0.26*	1		
$TOC_{0-10\,cm}$	−0.31**	0.24*	–	–	0.54**	1	
$TOC_{0-30\,cm}$	−0.43**	–	0.25*	–	0.61**	0.92**	1

[a] Topo = topographic position ranging from crest (100%) to valley bottom (0%).
[b] Slope = local slope in %.
[c] Clearing = period since high forest clearing ranging 38 yr (1967) to 0 yr (under forest in 2005).
[d] Crop = number of crop-fallow rotations.
[e] Cs = ^{137}Cs activity in Bq kg^{-1}.
[f] $TOC_{0-10\,cm}$ = TOC concentration in the 0–10 cm soil layer in mgC g^{-1}.
[g] $TOC_{0-30\,cm}$ = TOC concentration in the 0–30 cm soil layer in mgC g^{-1}.

The swamp remained under the original monospecific wild Taro vegetation up to 1960, when Hmong farmers planted Napier grass on its border. The Hmong did not cultivate in Houay Pano but used Napier for horse feeding. After their departure in 1974 Napier was no longer harvested. In the period 1975–1992 Napier slowly encroached into the Taro population, but without reaching the centre of the swamp, nor the inlet. Napier replaced wild Taro in the centre only in 1993 when Khamou started harvesting Taro leaves for pig food. Recognisable corms of wild Taro dating from 1993 or before were found in the sediments of the central pit.

4.2. Variability of radionuclide activities and TOC concentrations in soils

In all soil profiles, TOC concentrations and ^{137}Cs and $^{210}Pb_{xs}$ activities decreased with depth. Bulk soil density and soil organic matter δ^{13}C increased slightly but consistently, on average by 0.25 g cm^{-3} and 1.8‰, respectively (Fig. 2). Higher TOC concentrations in surface soil corresponded to higher levels in the deep layers. The isotopic composition of soil organic matter is depleted in ^{13}C, indicating the continuing dominance of C_3 plants in the catchment, apparently not influenced by the occasional and recent cultivation of maize and Job's tears (Table 2) and the local occurrence of C_4 weeds. Penetration of radionuclides in the soil rarely exceeded 30 cm with low to below-detection level activities at 20–30 cm soil depths (Fig. 2). In average 91 ± 7% of total ^{137}Cs activity was preferentially bound to fine soil particles with 65% to clay <2 μm and 26% to fine loam 2–20 μm size fractions. These results only slightly differed for $^{210}Pb_{xs}$ (84 ± 7%) with 50% and 34% for clay and fine loam particles, respectively.

The high variability of ^{137}Cs, $^{210}Pb_{xs}$ and TOC values was shown both for linear soil sampling along catchment slopes and from sampling following cross patterns (Fig. 1). In the latter, average ^{137}Cs inventories did not change if an increasing number of soils were taken into account, *i.e.*, 237 ± 95 Bq m^{-2} and 309 ± 181 Bq m^{-2} ($n = 5$), 268 ± 130 Bq m^{-2} and 277 ± 150 Bq m^{-2} ($n = 9$) and 277 ± 119 Bq m^{-2} and 229 ± 145 Bq m^{-2} ($n = 13$) for the two sampling areas. Equivalent conclusions can be drawn for $^{210}Pb_{xs}$.

4.3. Variability linked to land features and cultivation

In contrast to soil type that is not statistically linked to TOC and ^{137}Cs inventories, several correlations relate these contents to topographic position and land use factors (Table 3). Lower slope positions are correlated with higher ^{137}Cs and TOC contents and ^{137}Cs decreases with increasing cropping frequency. Lower slope positions were preferred for initial deforestation (higher TOC contents) and these sites have supported frequent cultivation (decreasing ^{137}Cs inventories). It is noteworthy that TOC does not decrease with 3–7 cultivation cycles but only after 8–9 rotations (Fig. 3) and that sites still under high forest in 2005 had low TOC contents (*ca.* 11 mgC g^{-1}).

The soil TOC concentration could be statistically predicted by two equations (Table 4). Cropping frequency and topographic position were relevant in predicting TOC in sites cultivated with annual crops between 3 and 7 times. In sites more frequently cultivated TOC can be predicted by cropping frequency, local slope, and period since first clearing.

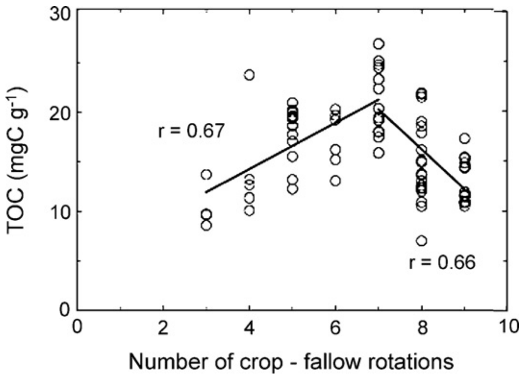

Fig. 3. Scatter plot of TOC content in the 0–30 cm soil layer *vs.* number of annual crop-fallow rotations. Pearson's correlation coefficients are reported in the graph.

4.4. Relationship between soil ^{137}Cs and TOC contents

A significant positive correlation is observed between the two-radionuclide inventories (Fig. 4A). Soil TOC concentrations are also linked to ^{137}Cs activities, in particular in the topsoil, suggesting that a common process controls their concomitant depletion (Fig. 4B).

The relationship holds for soil TOC and ^{137}Cs inventories of the top 30 cm soil layers (Fig. 4C) so that the reference inventory of 615 ± 20 Bq m^{-2} (residual 1963 ^{137}Cs fallout in 2005) corresponds to an initial soil TOC content of 6.3 ± 0.1 kgC m^{-2}. In other words the top 30 cm soil layers contained *ca.* 6.3 kgC m^{-2} at the time of maximum ^{137}Cs fallout in 1963. Soils sampled outside the catchment match this TOC-^{137}Cs empirical relationship, *e.g.*, Nok Pit with 3.6 kgC m^{-2} and 329.4 Bq m^{-2} for TOC and ^{137}Cs, in the top 30 cm of the soil, respectively. In turn, the TOC content of the top 30 cm soil layers is significantly correlated with its TOC concentration in the top 10 cm (Fig. 4D). Hence TOC depletion in the 0–30 cm soil layer to 74% of its initial stock since 1963 corresponds to a 21.4% decrease of TOC concentration in the top 10 cm, from 28.9 to 22.7 mgC g^{-1} (Fig. 4D), covering the period of high forest clearing and several cycles of shifting cultivation. Soil TOC concentration in the top 10 cm of primary forest sites in sparsely populated areas of the Nam Khan valley sometimes located only a few hundred meters away from cultivated land, averaged 27.2 ± 4.8 mgC g^{-1} ($n = 6$); a value close to the estimated topsoil content for the Houay Pano catchment before forest clearing in 1963.

4.5. ERT characterization of swamp deposits and sediment volume estimates

Blocky cross sections allow a clear identification of five different units with decreasing resistivity range (Table 5 and Fig. 5): (i) unit I located at the mouth of a gully in the upper part of the right bank of the swamp; (ii) unit II located downwards profile F both on the right and the left banks of the swamp; (iii) unit III with a

Table 4
Predictive equations for TOC in relation to cultivation frequency (stepwise regression procedure).

Variable	Predictive equation	*n*	*r*
$TOC_{0-30\,cm}$ after 2–7 crop-fallow rotations	$TOC_{0-30\,cm} = -0.668 + 0.379\,Crop + 0.009\,Topo$	44	0.76
$TOC_{0-30\,cm}$ after 8–9 crop-fallow rotations	$TOC_{0-30\,cm} = 0.3 - 0.12\,Topo + 0.13\,Slope + 0.031\,Clearing$	32	0.74

Explicative factors: Crop = number of rotations, Topo = topographic position, Slope = local slope, Clearing = period since high forest clearing

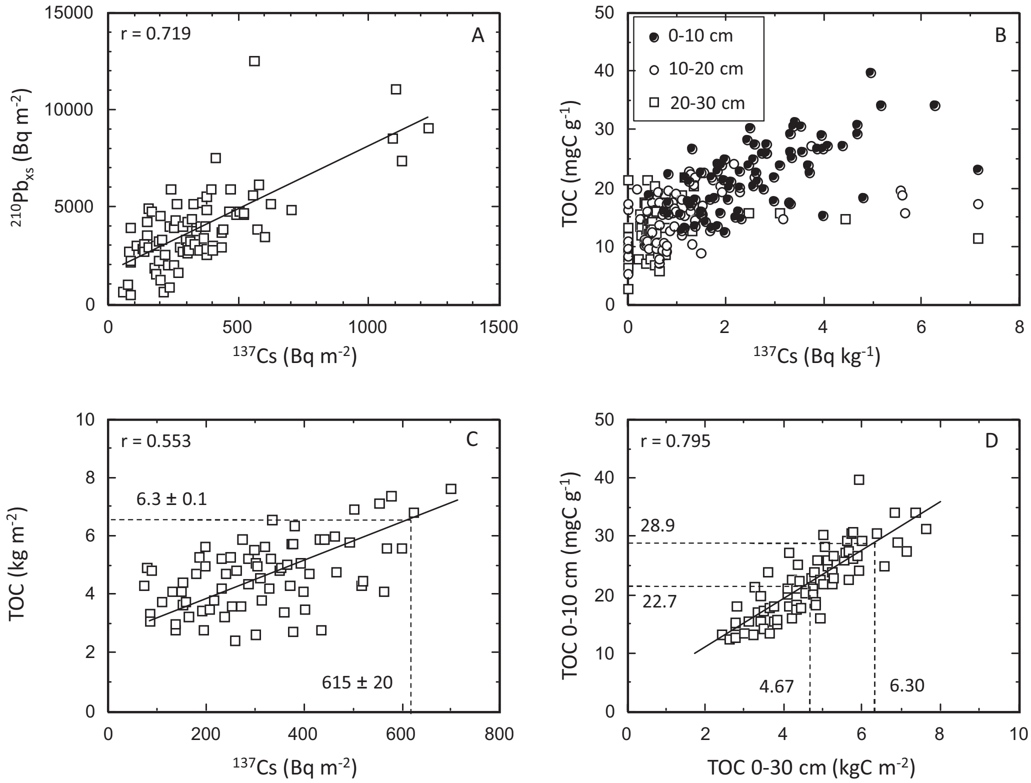

Fig. 4. Scatter plots of: (A) $^{210}Pb_{xs}$ *vs.* ^{137}Cs inventories in 0–30-cm topsoil layers, (B) TOC concentration *vs.* ^{137}Cs activity in the different soil depths, (C) TOC stocks *vs.* ^{137}Cs inventories in 0–30 cm topsoil layers and (D) TOC concentration in the 0–10 cm soil layer *vs.* TOC stock in the 0–30-cm soil layer. Pearson's correlation coefficients are reported for each plot. Remarkable values discussed in the text are also reported.

distribution at intermediate depths of the swamp, generally covered by more resistive material in the upper part of the swamp (units I or II), by less resistive material in the central part of the swamp (unit IV) and not covered by other material in the lower part of the swamp; (iv) unit IV located at shallow depths and overlaying unit III in the central part of the swamp and (v) unit V filling the basin and reflecting the downwards deepening of bedrock.

The bedrock and associated weathered materials with much higher resistivity are identified under the deposited materials. The geomorphic layout provides evidence that units I and II correspond to recent sediment accumulation conveyed in gullies – diffuse runoff along hill slopes and by landslides, respectively. In contrast units III–V involves trapping of stream sediment loads originating from the surrounding slopes.

Equivalent resistivity models (Fig. 6) are validated, as the calculated resistivities of the layers with unfixed interface depths are consistent with the range of resistivity values of the blocks with fixed heights. This approach was also validated by observations in the central pit C that showed a clear textural change at 95 cm depth with clayey materials overlaying sandy materials (see Section 4.6). For the closest resistivity vertical profile, the estimated depth of the interface between unit IV and III (Fig. 6) is consistent with respect to the depth of the textural change. Total thickness averaged 2.5 ± 1.6 m but reaches more than 4 m in a sub-basin of *ca.* 200 m^2 located in the middle part of the swamp (Fig. 7).

The calculation made over the surveyed area yielded a total sediment volume of 2960 m^3, not significantly different from a simple estimate obtained by multiplying the surface of the swamp within the surveyed area by the average sediment thickness (2.5 m × 1200 m^2 = 3000 m^3). Extrapolation of the average sediment thickness calculated for ERT profiles towards the inlet (2.1 m) and the outlet (2.6 m) allowed estimates of sediment volumes located outside by multiplying these average thicknesses by the surfaces of the excluded areas, *ca.* 450 m^3 and 580 m^3 for the inlet and the outlet of the swamp, respectively. Thus, the total volume of sediment trapped in the swamp can be estimated *ca.* 4000 m^3. As for total sediment volumes, calculation of the thicknesses of each unit provides estimates of the respective volumes of the 5 units identified in the surveyed area (Table 5).

Local colluviums (units I and II) represent 10% of total sediment volume in the central part. The remaining 90% are sediments supplied by soil erosion along upstream slopes of the catchment and direct stream supply. The superposition of unit V at the bottom, unit III at intermediate depth and unit IV at shallow depth in the central part of the swamp suggests the occurrence of three different periods of erosion, transport and deposition. However, the time frame that could be derived from ^{137}Cs and $^{210}Pb_{xs}$ sediment activities indicates that only units III and IV are directly connected to the present-day stream course and linked to sediment trapping in the swamp (see Section 4.6). Therefore, deeper (below 2 m-depth) and older sediments of unit V were not taken into account. The longitudinal cross section (Fig. 5) shows that unit III accounts for most of the sediment accumulation towards the inlet of the swamp and approximately half of the sediment accumulation towards its outlet. The remaining deposits towards the outlet corresponded to the deep unit V, overlying the bedrock. The extrapolation towards the inlet is supported by

Table 5
Characteristics and volumes of the sediment units identified by ERT measurements in the swamp.

Unit	Resistivity (Ω m)	Thickness (m)	Extrapolation towards inlet (215 m^2)	Surveyed area (1200 m^2)	Extrapolation towards outlet (250 m^2)	Total swamp (1665 m^2)
I	40–50	0.7 ± 0.3		100 m^3		100 m^3
II	30–40	1.0 ± 0.5		200 m^3		200 m^3
III	25–30	1.6 ± 0.8	450 m^3	900 m^3	165–265 m^3 [a]	1500–1600 m^3
IV	15–20	0.9 ± 0.4		600 m^3	25–125 m^3 [b]	600–700 m^3
V	10–15	3.0 ± 1.8		1200 m^3	290 m^3 [c]	1500 m^3
Total			450 m^3 [d]	3000 m^3	580 m^3	4000 m^3

[a] Approximately half of sediments volume in the area excluded towards outlet minus the minimum and the maximum possible volume of the hidden unit IV.
[b] Unit IV: minimum and maximum possible thicknesses multiplied by the surface of the area excluded towards outlet.
[c] Approximately half of sediment volumes in the area excluded towards outlet.
[d] Average thickness of sediments multiplied by surface of the excluded area.

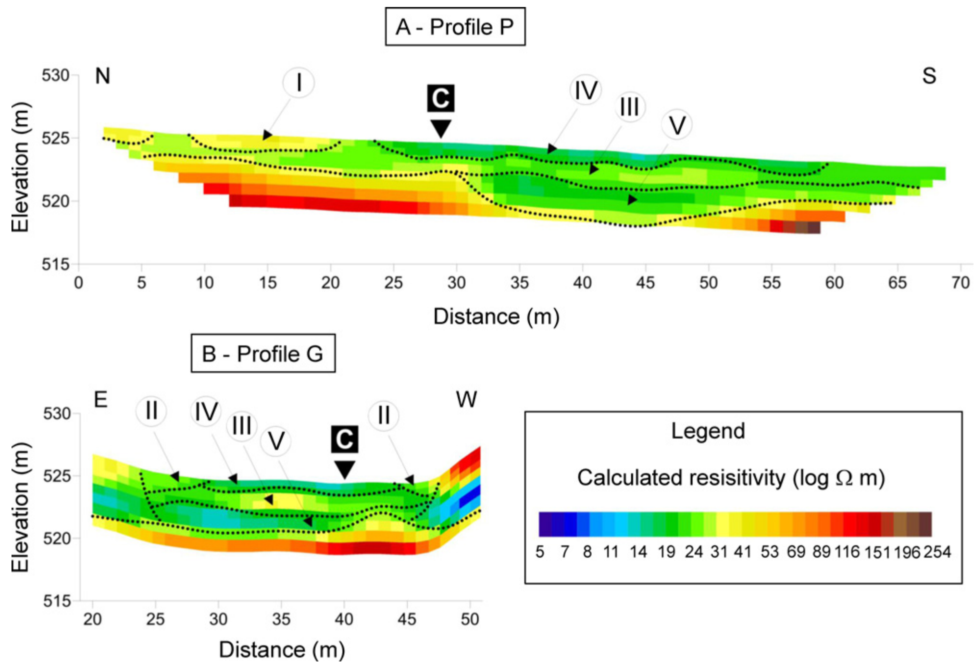

Fig. 5. Plots of North-South (A) and East-West (B) cross-sections of calculated resistivity in the swamp. Units I–II correspond to colluviums. Units III, IV and V are sediments of increasing age originating from soil erosion in the surrounding slopes. C is the location of the central pit.

observations for the inlet pit where no textural differentiation was observed (see Section 4.6). It is, therefore, likely that the total volume of sediments accumulated between the inlet of the swamp and the northern limit of the surveyed area corresponds to unit III. The extrapolation towards the outlet is not supported by observations at the outlet pit that shows a clear textural differentiation at 50 cm, indicating that unit IV was actually overlying unit III and was not detected by ERT. This is best explained by the resolution of the resistivity model set with a thickness of 0.5 m for the first layer. The topmost unit IV was only clearly detected in the central part of the swamp where its thickness exceeded 0.5 m. A "hidden" unit IV with a thickness lower than 0.5 m is assumed towards the outlet of the swamp. The volume of recent sediments accumulated between the southern limit of the surveyed area and the outlet can be estimated to half of the total accumulation (290 m^3). Part of this volume accounts for the "undetectable" unit IV, ranging 25–125 m^3, determined by multiplying the area of this part of the swamp by the lower and higher possible thicknesses, 0.1 m and 0.5 m, respectively. The volume of the underlying unit III towards the outlet is hence estimated ranging 165–265 m^3. These extrapolations allow estimates of the recent sediment volumes accumulated between the inlet and the outlet (Table 5).

4.6. Impact of the replacement of Taro by Napier on sediment trapping in the swamp

The replacement of wild Taro by Napier is shown by the superposition, in the central pit, of two distinct layers with different physical characteristics (Fig. 8D): (i) above 110 cm depth, sediments have low density (0.49–1.00 g cm^{-3}, Fig. 8E), high clay and fine loam contents (*ca.* 60–85 wt.%, Fig. 8D), low resistivity (15–20 Ω m, Unit IV, Table 5) and high TOC contents (Fig. 8B); (ii) below 110 cm depth, sediments display coarse textures (up to *ca.* 22 wt.% of coarse sands), low clay and fine loam content (*ca.* 34–59 wt.%, Fig. 8D, a high bulk density increasing to a maximum of 1.43 g cm^{-3}, Fig. 8E), higher resistivity (25–30 Ω m, Unit III, Table 5) and lower TOC contents (Fig. 8B).

The outlet, covered in 2005 by Napier, showed sediments in the top 30 cm resembling the fine textural superficial layers of the central swamp. In contrast, the inlet, covered in 2005 by wild Taro, contained sediments of rather uniform coarse texture and bulk density suggesting a continuous cover of wild Taro.

Because wild Taro and Napier have contrasted isotopic compositions the incorporation of organic matter derived from Napier may be fingerprinted by its $\delta^{13}C$

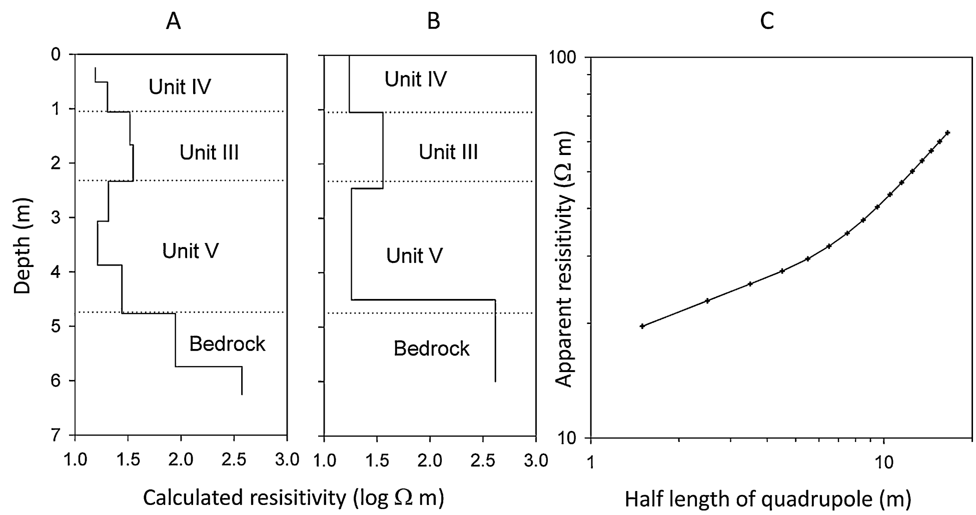

Fig. 6. Estimates of layer thickness with: (A) Resistivity model with fixed thickness of layers calculated with RES3DINV, (B) simplified equivalent resistivity model with 4 layers, (C) apparent resistivity curves of the initial and the simplified model (root mean square difference = 0.1%). This bi-log graph is shown with the usual convention for Vertical Electrical Soundings (VES).

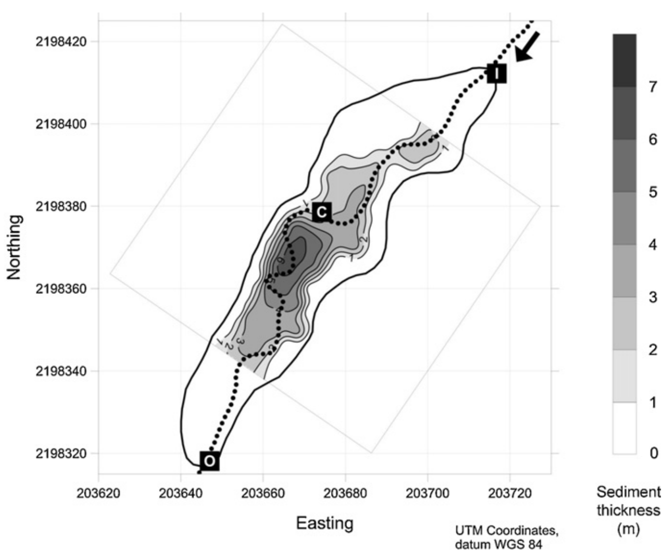

Fig. 7. Estimate of sediment thickness for the surveyed area of the swamp derived from ERT measurements. Iso-thickness lines are drawn each 1 m. Sampling pits are represented by black squares (I = inlet, C = centre, O = outlet).

value, also contrasting with that of soil derived particles (−25.8 ± 1.2‰, topsoil layer Fig. 2). The inlet composition (−26.2 ± 0.7‰, Fig. 8A) matches the composition of deep sediment layers below 160 cm in the central pit (−26.1 ± 0.5‰), providing evidence for the contribution of the wild Taro cover and for the input of soil derived organic matter. Above 160 cm in the central pit the composition of organic matter shifts toward ^{13}C-enriched compositions, up to −19.5‰ near surface (Fig. 8A). The spread of Napier from the border to the centre by successive stages of encroachment is reflected in the $\delta^{13}C$ value in the central pit (Fig. 8A). This trend reflects an increasing contribution of Napier to sedimentary organic matter. The combination of density, texture and $\delta^{13}C$ data allows estimates of sediment age in the central part of the swamp. The 150–160 cm depth sample is the deepest layer affected by Napier grass (Fig. 8A), therefore deposited after 1960, the year when Napier was first introduced. The deepest sample with fine texture deposits, at 100–110 cm depth, could be dated after 1975, because from that date on, Napier was no longer harvested and expanded in the swamp. It is worth noticing that, in contrast to dense Napier occupation, the contribution of wild Taro to the sedimentary organic pool should be much lower due to a low biomass.

4.7. *Sediment accumulation rates derived from ^{137}Cs and $^{210}Pb_{xs}$ activities*

The ^{137}Cs activity reached a maximum (4.2 ± 0.5 Bq kg^{-1}) in the 140–150 cm sediment depth interval in the centre of the swamp and at *ca.* 80 cm (3.9 ± 0.8 Bq kg^{-1}) in the inlet (Fig. 8C). These activities are likely to correspond to soil particles labelled by the peak ^{137}Cs fallout of 1963. Accordingly, 42 years should separate surface from these sediment layers, both sampled in 2005. This interpretation is supported by $^{210}Pb_{xs}$ measurements. With an average $^{210}Pb_{ex}$ of 12.6 ± 6.9 Bq kg^{-1} (mean 0–30 cm activity, see Section 4.2) deduced from catchment soil levels and assuming a regular and constant input of $^{10}Pb_{ex}$ by rainfall each year, the $^{210}Pb_{ex}$ activity should decrease to nearly 30% (3.5 ± 1.3 Bq kg^{-1}) of its initial value after 42 years. This value is closed to the $^{210}Pb_{ex}$ activity (5.5 ± 1.8 Bq kg^{-1}) recorded at the depth of the ^{137}Cs peak. No maximum fallout peak as for the centre was detected at the outlet, as sediments were most likely exported downstream by floods. It is only when Napier grass totally invaded the swamp (in 1993, Table 2) that, by enhanced reduction of stream velocity, accumulation of sediments could start for the outlet (top 30–40 cm, Fig. 8A and C).

The radionuclide activities decreased to below instrumental detection levels at different sediment depths, 190 cm, 110 cm and 40 cm, for ^{137}Cs at the centre, inlet and outlet of the swamp, respectively, and for $^{210}Pb_{xs}$ at 160 cm, 80 cm and 50 cm, at the centre, inlet and outlet of the swamp, respectively (Fig. 8C). The decrease to very low $^{210}Pb_{xs}$ activity in the 160–170 cm layer of the central pit, offers at least two explanations: either the deposition age is too old with respect to $^{210}Pb_{xs}$

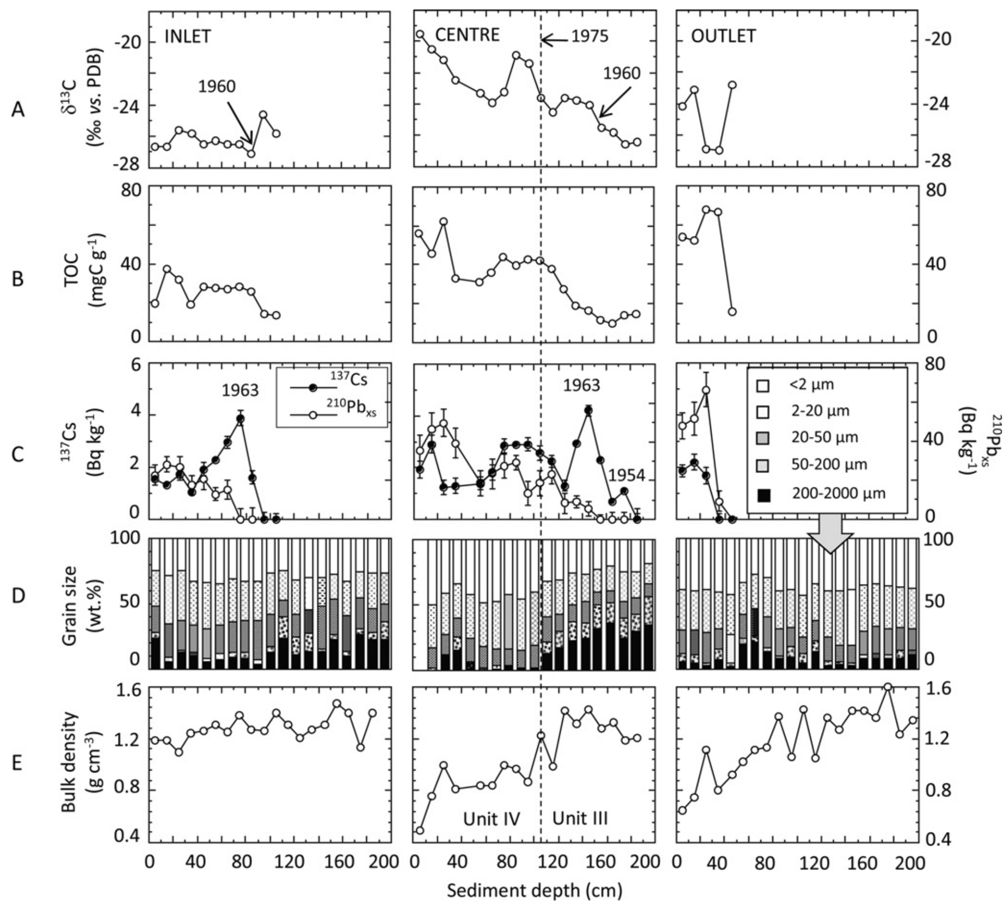

Fig. 8. Sediment composition at the inlet, the centre and the outlet of the swamp with: (A) $\delta^{13}C$-TOC, (B) TOC concentration, (C) ^{137}Cs and $^{210}Pb_{xs}$ activity, (D) texture and (E) dry bulk density. The remarkable boundary between units III and IV and estimated sediment ages, discussed in the text, are reported in the graph. Analytical uncertainties are reported for ^{137}Cs and $^{210}Pb_{xs}$ activity measurements.

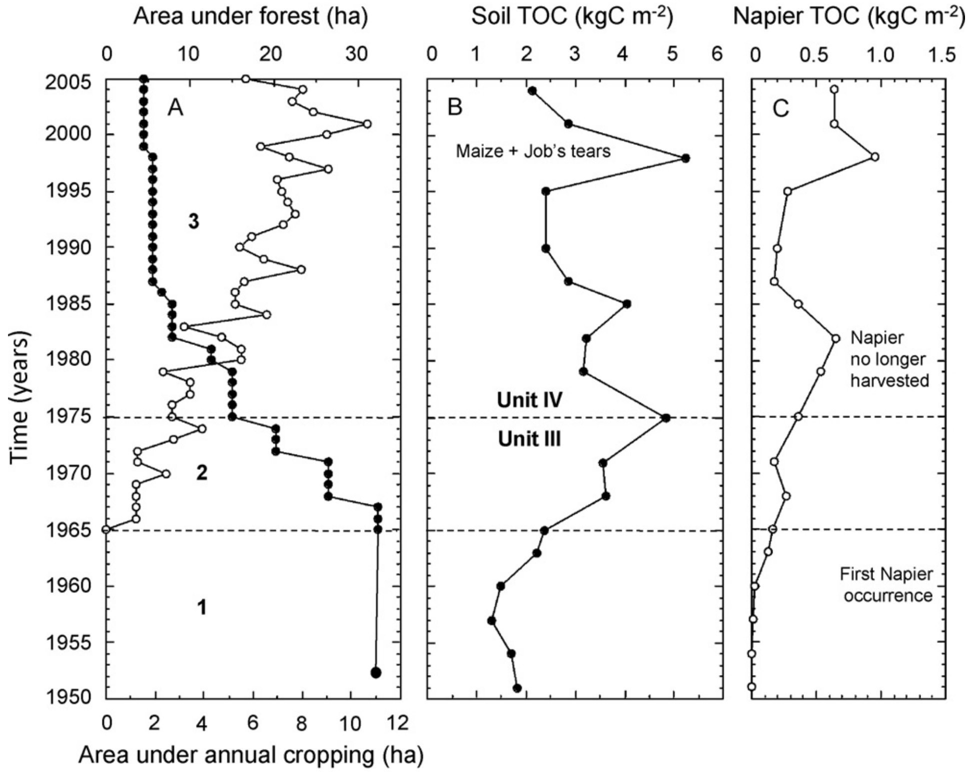

Fig. 9. Plots of annual evolution of forest in the upper part of the catchment and of TOC accumulation in sediments of the central pit of the swamp since the early 1950s with: (A) area under forest (closed circles) and area under annual cropping, expressed as moving averages over 5 years (open circles), (B) soil-derived TOC accumulation and (C) Napier grass-derived TOC accumulation. Remarkable boundaries (between units III and IV), periods (1–3) and events discussed in the text are reported in the graph.

decay and its radioactivity is no longer measurable or soil particles did not originate from the topsoil but from deeper soil horizons with no $^{210}Pb_{xs}$. The first assumption is supported by the residual ^{137}Cs activity (*ca.* 1.0 Bq kg^{-1}, Fig. 8C) determined for the same sample. Therefore the deposits are not older than 1954, year of the first measurable ^{137}Cs fallout (UNSCEAR, 1969). In contrast, it is when both ^{137}Cs and $^{210}Pb_{xs}$ activities are non-detectable in sediments, below 50 cm and 90 cm depths at the outlet and the inlet, respectively, than soil particle supply is older than 1954. Reconstruction of the time scale for sediment supply in the swamp is possible using the overall data. With a maximum ^{137}Cs fallout peak at 80 cm depth at the inlet of the swamp and assuming a constant deposition rate with wild Taro, the accumulation rate was 1.9 cm yr^{-1} (80 cm over 42 years). It is unlikely that uniform accumulation rates took place in the central pit (145 cm over 42 years) given that a faster rate is expected to have occurred in the top 110 cm due to Napier grass encroachment (high retention) and a lower rate in the deeper 35 cm under wild Taro (low retention). If we assume that the 110 cm sediment depth corresponds to 1975, the accumulation rate between 1975 and 2005 increases to *ca.* 3.7 cm yr^{-1} (110 cm over 30 years). Should we apply the 1.9 cm yr^{-1} rate determined for the inlet to the deeper layers (below 110 cm) of the central pit of the swamp then accumulation appears slightly underestimated for the bottom part of the profile. Introducing an intermediate rate of 3.3 cm yr^{-1} provides correct sediment ages for 1963 (maximum fallout, Fig. 8C), 1954 (first fallout, Fig. 8C) and 1960, the year stated by Houay Pano farmers for the first occurrence of Napier in the swamp (150 cm sediment depth, Fig. 8A).

4.8. Soil TOC accumulation in the swamp vs. erosion in the catchment

In order to achieve an estimate of soil TOC supply from catchment slopes stored in the swamp, the contribution of Napier grass-derived carbon must be separated from that of soil-derived carbon. This could be performed using the contrasted isotopic signature of both types of organic matter in an ideal two components mixing (Fig. 9B and C and Annexe 1). When plotted against estimated sediment ages derived from radionuclide activities and farming information, the calculated TOC contents provide a pattern for soil and Napier organic matter storage in the central part of the swamp since the early 1950s.

Three successive stages of soil organic matter delivery are observed: (1) a rather constant and moderate input before *ca.* 1967 (<2.0 kgC m^{-2} yr^{-1}) during the period of high forest cover; (2) a massive input in 1967–1975, related to forest clearing, progressively rising with increasing deforestation (up to a maximum of 4.85 kgC m^{-2}, Fig. 10) and, (3) a variable and moderate supply in the recent years (3.1 ± 1.0 kgC m^{-2} yr^{-1}) associated with shifting cultivation over most of the catchment.

The third period also corresponded to the progressive encroachment of Napier grass towards the centre of the swamp (Fig. 8). Hence the peak of soil-derived TOC accumulation in 1998 reflects both the high erosion rates and the high retention property of Napier grass. High erosion rates are associated with two trends: more area under annual cropping in a given year due to the shortening of the fallow period and to greater crop diversity. It is during this period that large-scale maize and Job's tears were planted (Table 2). These two crops generate much more erosion than rice and fallow, 14.3 Mg ha^{-1} yr^{-1} and 16.3 Mg ha^{-1} yr^{-1} *vs.* 5.7 Mg ha^{-1} yr^{-1} and 0.3 Mg ha^{-1} yr^{-1}, respectively (Valentin et al., 2008). Adding all TOC stocks, the soil carbon accumulation can be estimated at 51.3 kgC.m^{-2} in the central part of the swamp since the early 1950s (28.3 kgC m^{-2} for 1976–2005 and 22.9 kgC m^{-2} for 1951–1975). Napier grass only represented *ca.* 5.6 kgC m^{-2} (*ca.* 10%, Fig. 9B and C). Most striking is the TOC accumulation trend that remained proportional to the reduction of high forest area (Fig. 10).

Combining ERT volumes and TOC stocks it is possible to estimate sediment delivery to the swamp, 24–31 Mg yr^{-1} for the period after 1975 (Unit IV, Table 6)

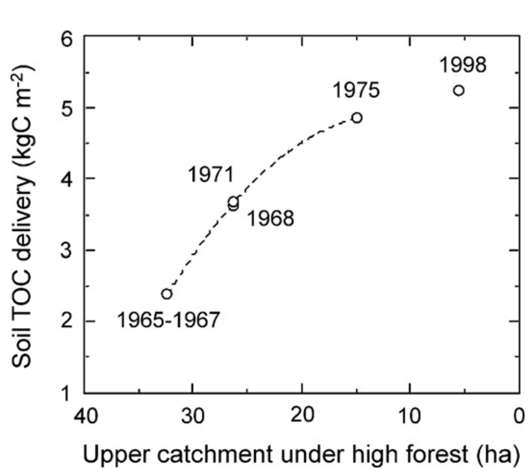

Fig. 10. Remaining high forest cover in the upper catchment *vs.* soil TOC delivery in the swamp during the period of high forest clearing. Corresponding years are reported in the graph.

Table 6
Estimated soil particles delivery to the swamp derived from TOC concentrations and ERT sediment volumes.

Unit	Time (yrs)	TOC stock (kgC m^{-2})	Volume[a] (m^3)	Surface[b] (m^2)	TOC[c] (kgC yr^{-1})	Soil TOC[d] (MgC yr^{-1})
IV	29 (1976–2005)	28.3	650	722	705	24–31
III	24 (1951–1975)	22.9	1550	969	925	32–40

[a] Median values in Table 5.
[b] Median volumes divided by average thickness in Table 5.
[c] Soil-derived TOC contribution calculated by multiplying TOC stock by surface and dividing by time.
[d] TOC content divided by average TOC concentration (26.1 ± 3.1 MgC g^{-1}) of sediment load at W_1 monitored between 2001 and 2005.

and 32–40 Mg yr^{-1} for the 1951–1975 period. Although these measurements are associated with important uncertainties linked to high spatial variability, the estimated delivery is consistent with sediment input–output monitored between 2001 and 2005 with upstream (W_1, Fig. 1) and downstream (W_2, Fig. 1) gauging weirs (28.6 Mg yr^{-1}, Table 7).

Using data in Table 6, soil TOC accumulation in the swamp can be estimated to 33 MgC for 42 years (since the ^{137}Cs fallout maximum of 1963). With an additional 10% of the total as Napier grass derived organic matter (*ca.* 3.6 MgC since 1963, Fig. 9), TOC storage in the swamp reached *ca.* 36 MgC. Accordingly, soil depletion along catchment slopes is only partly counterbalanced by organic matter accumulation and vegetation growth in the swamp. With an initial TOC content of 6.3 kgC m^{-2} for the topsoil 30 cm horizon in 1963 and an average "present-day" content of 4.67 kgC m^{-2}, conversion of high forest to arable land and cultivation induced a loss of nearly 1.63 kgC m^{-2} (*ca.* 26%, 0.039 kgC m^{-2} yr^{-1}). Scaling this value to the upper catchment surface (32.5 ha) provides *ca.* 530 MgC. Therefore, a TOC accumulation of *ca.* 36 MgC in swamp sediments only represented *ca.* 7% of soil carbon loss in the catchment since 1963.

5. Discussion

5.1. Causes for heterogeneous redistribution of ^{137}Cs along catchment's slopes

Soil particles redistribution rates can be estimated for cultivated soils from mass balance models that link the residual soil ^{137}Cs activity to the reference inventory, tillage dilution, soil particle size and time-variant ^{137}Cs fallout (*e.g.*, Walling and He, 2001). These models do not apply for our study. Slash and burn is essentially a no-till cultivation system as soil disturbance is limited to patchy hoeing and hand pulling for weed control that mainly concern the top first 3 cm of the soil. In Houay Pano such tillage spread since 1996 (Dupin et al., 2009). Short-distance relocation of ^{137}Cs and $^{210}Pb_{xs}$ bound soil particles along slopes and within the soil is the combined result of faunal activity, overland flow, local rill erosion (*e.g.*, Chaplot et al., 2007) and spot tillage. Hence, clear identification of accumulation and erosion gradients over short distances remains difficult. Moreover, rainfall simulation experiments showed that soil surfaces in the Houay Pano catchment can be rapidly transformed to crusted surfaces with micro-terraces on steep slopes, much more permeable and less erodible than for low slopes (Ribolzi et al., 2011). Such heterogeneity working at fine scales is also reflected in the high variability of soil surface features and runoffs measured within 1-m^2 neighbouring plots under natural rainfall (Patin et al., 2012) and by the high scatter of average ^{137}Cs inventories with increasing distance of this study. At catchment scale; however, two trends in ^{137}Cs activity redistribution were statistically highlighted (Table 3): an increase from crest to valley bottom and a decrease with the number of shifting cultivation cycles. They can be explained by downward ^{137}Cs bound soil particles redistribution by erosion during the cultivation years (Valentin et al., 2008).

5.2. Linking soil ^{137}Cs and TOC inventories in the catchment

Along steep slopes, correlative ^{137}Cs and TOC contents are usually interpreted as reflecting the impact of intense tillage erosion on soil organic matter (Li et al., 2006). Because ^{137}Cs is less bound to soil organic matter than to clay minerals (Livens and Baxter, 1988; Staunton and Roubaud, 1997), the positive correlation between soil TOC and ^{137}Cs inventories is not a direct link. This relationship must rather be interpreted as reflecting a common redistribution of ^{137}Cs- and TOC-bound soil particles (Garcia-Oliva et al., 1995; Ritchie and McCarty, 2003; Martinez et al., 2010). It is known that the breakdown of organic matter-rich topsoil aggregates reduces the TOC content of soils by releasing fine size mineral-bound organic matter (Feller and Beare, 1998) and light charcoal components (Rumpel et al., 2006) that are translocated down slope or exported by overland flow. However, as our ^{137}Cs measurements fingerprint soil TOC content, the correlation is based, for each site, on the remaining soil TOC content since radionuclide fallout. Therefore, besides soil erosion, other processes such as biomass burning after clearing, reduced input by fallow vegetation with respect to the former high forest, export of labile carbon fractions with dissolved loads and mineralization of soil organic matter also contributed to soil TOC depletion, either *in situ* or following soil particle's displacements along slopes. The depletion rate derived from our study, 39 gC m^{-2} yr^{-1} during 42 years, is high when compared catchment specific deliveries of 1.2 gC m^{-2} yr^{-1} in 2002 (Chaplot et al., 2005) or 0.85 gC m^{-2} yr^{-1} in 2003 (Chaplot and Poesen, 2012) previously measured for Houay Pano. During these two years only 2–3% of soil TOC annual loss was exported. Because of a limited storage area in the catchment, sediment delivery ratios were obviously much higher in the past, in particular during the critical period of forest clearing in 1965–1975 (Fig. 10). Shortening of the shifting cultivation cycle after 1984 apparently took place in a more steady state way and involved the removal of soil particles derived from cultivated soil horizons depleted in TOC with respect to soils formerly under forest cover. This reduced storage is confirmed by lower soil TOC input in the swamp (*ca.* 2 kgC m^{-2}, Fig. 9B) although Napier grass covered most of the area, thereby increasing as much soil-derived particles trapping and retention. Other *in situ* processes, in particular mineralization, should have also played a key role in regard to soil TOC depletion. Gregorich et al. (1998) reported 20–30% TOC losses by mineralization in North American

Table 7
Estimated soil derived particles delivery to the swamp deduced from measured sediment yields in weir W_1 upstream and weir W_2 downstream of swamp.

Weir of sub-catchment	Sediment delivery (Mg ha^{-1} yr^{-1})	Catchment area (ha)	Sediment input (Mg yr^{-1})	Sediment output (Mg yr^{-1})
W_1	1.56[a]	19.6	30.6	–
W_1–W_2	1.56[a]	12.7[b]	19.8	–
W_2	0.67[a]	32.5	–	21.8
Total sediment delivery to the swamp (Mg yr^{-1}): 30.6 + 19.8 – 21.8 = 28.6				

[a] Valentin et al. (2008).
[b] 32.5 – 19.6 – 0.19 = 12.7 ha with swamp area = 0.19 ha.

soils, mainly during the first years of cultivation. This proportion should be enhanced under tropical conditions due to higher soil temperature and biological activity. Our results are consistent with experiments carried out in Luang Prabang by Roder et al. (1997) in slash and burn fields with 6–8 year fallow prior to upland rice cultivation. In their study soil TOC depletion reached *ca.* 230 gC m^{-2} yr^{-1} for the top 25 cm layer after 4 years and only about 10–20% was attributed to burning and soil erosion (Roder et al., 1995a). Mineralization thus represented the major soil TOC depletion process, initiated under rice cropping and continued over the following two years of fallowing.

5.3. Soil TOC depletion in the shifting cultivation system

Plots in the Houay Pano catchment were cultivated on average 5.3 times over 42 years that is one year out of eight. Deforestation and cropping caused a loss of *ca.* 21.5% of the initial TOC content in the 0–10 cm topsoil (Fig. 4). TOC depletion down to 22.7 mgC g^{-1} in 2005 is consistent with shifting cultivation fields located near Houay Pano: 28.4 mgC g^{-1} in 1991 (Roder et al., 1995b) and 22.3 mgC g^{-1} in 1998 (MSEC, 1999). Historic records in Houay Pano demonstrated that sites deforested early were also the most frequently cultivated since. Cultivation without external inputs universally decreases TOC pools, however, in Houay Pano, higher TOC values after 7–8 rotations were measured compared to 3–5 rotations and to sites still under forest. This can only be explained by a higher initial TOC content. The effect of shifting cultivation on soil TOC depends on the initial organic matter level of the soil, *i.e.*, its equilibrium level (Nye and Greenland, 1960). When this level is high, the TOC recovery during fallowing could also be elevated. This would explain why, in Houay Pano, the frequently cultivated sites contain more carbon (Fig. 3). However, TOC levels in topsoil decrease after 8 rotations or more. In the Nam Khan hinterland the soil TOC content under primary forest was systematically below (27.2 mgC g^{-1}) that of cultivated sites (34.9 mgC g^{-1}) and the first soil survey in Houay Pano (MSEC, 1999) provided higher soil TOC for cultivated soils (averaging 22.3 mgC g^{-1}) than in the remaining forested sites (averaging 19.4 mgC g^{-1}). Khamou farmers thus made preferential choices for cultivation that include the initial TOC level of the forest. Saito et al. (2006) found that shifting cultivators in northern Laos first all seek black soils ("din dam" in Lao) for rice cultivation. Sites in Northern Thailand, subject to shifting cultivation for about 100 years, had all similar low TOC but, in forest, soil TOC was still lower (Zinke et al., 1978). Several studies in SE Asia assessed the influence of shifting cultivation on TOC by comparing cultivated soils with nearby uncultivated forest soils. The latter, called undisturbed, natural, high, mature, sacred or primary forest, served as control. Conclusions were that soil TOC is not or weakly affected by shifting cultivation because of similar TOC storage in cultivated and forested soils (Forsyth, 1994; Bech Bruun et al., 2006; Ziegler et al., 2007; de Neergaard et al., 2008; Aumtong et al., 2009). However, the assumption that the forest near the cultivated sites represents an earlier stage is unfounded when farmers prefer more fertile soils and leave forest on poorer sites. The TOC loss due to shifting cultivation is underestimated when the initial level of a cultivated site is unknown and a nearby forest site is chosen as control.

In this study both ^{137}Cs and TOC inventories increase with lower topographic positions indicating an uphill supply. In contrast, de Neergaard et al. (2008) in Sarawak and Aumtong et al. (2009) in Thailand did not find a significant effect of slope position on TOC in cultivated catchments, and concluded that erosion was not the overriding force. An alternative explanation is that farmers have depleted the richer lower slope sites until all slope positions reached the same level. In Vietnam, finding lower slope soils more depleted in TOC (10.5 mgC g^{-1}) than upper slope soils (12.2 mgC g^{-1}), Wezel et al. (2002) speculated that low TOC contents at lower slope positions were due to enhanced mineralization, crop export and frequent cultivation. Direct links between soil erosion and topographic position are confounded with historic farmer's preferences but erosion should still be considered as an important trigger.

5.4. Linking soil TOC accumulation rates in the swamp with land use change

Our study outlines three successive stages of soil TOC transfer from slopes to the swamp. A high and steady input of TOC of 8.5 ± 1.8 kgC ha^{-1} yr^{-1} is generated in the period during which the catchment is still under forest (Fig. 9). A bamboo dominated forest typically consists of densely packed culms with little understory protecting the soil. Vigiak et al. (2008) demonstrated in Houay Pano that not only bamboo poorly trapped sediments originating from uphill positions, but also generated *in situ* soil erosion contrarily to grass strips and banana stands. Similarly, Bamboo provided poor soil protection in Japan where stands were linked to landslides and gullies (Hiromasa et al., 2004) and in China where weeding and tillage of *Phyllostachus* sp. had a detrimental effect on soil TOC content (Xu et al., 2008). Moreover, bamboo in Houay Pano was subject to synchronous flowering followed by massive die-off, apparently once every 10–15 years causing disturbance and likely erosion. With deforestation *Phyllostachus* sp. largely disappeared. Soil TOC delivery increased to 19.6 ± 5.5 kgC ha^{-1} yr^{-1} in the period of high forest clearing and the cultivation of a single rice crop (Fig. 9). Few field data document such a process in tropical environments. Kotto-Same et al. (1997) reported, in Cameroon, that greatest losses in soil carbon stocks resulted from land preparation prior to first cultivation; thereafter soil TOC pools remained relatively constant throughout shifting cultivation as shown in our study. Evidence is shown by the "low" soil TOC transfer, averaging 6.5 ± 4.8 kgC ha^{-1} yr^{-1}, for the period following 1984 when the slopes were covered by alternating crops and fallows (Fig. 9). Monitoring suspended loads at the outlet of cultivated plots and sub-catchments showed that erosion was related to the cultivation years with very low or even no outputs during fallow periods (Valentin et al., 2008). Thus, once the initial forest has been largely removed, and averaging over cultivation and fallow years, annual soil particle supply remained rather low, only slightly above the values obtained before deforestation.

Wetlands, such as the swamp area in Houay Pano, are usually considered as capable of sequestrating high amounts of carbon due to the slow decay of organic matter under anaerobic conditions (Whiting and Chanton, 1993). Such areas play a key role for carbon storage within continental hydrosystems (Stallard, 1998; Van Oost et al., 2012). The extent of storage depends on the surface covered by wetlands, rather limited in the Houay Pano catchment. A fraction of soil and plant TOC accumulated in the swamp was likely lost by post-deposition mineralization. However, because the stream is perennial and the swamp is fed by a permanent water table, highly reducing conditions with O_2-depleted waters prevail all year long (Huon et al., 2008) and only slow mineralization rates could have taken place. Furthermore, the distribution of TOC content with sediment depth (Fig. 8B) does not correspond to a regular time-related decaying profile (*e.g.*, Gälman et al., 2008) but rather reflects the extent of soil and vegetation inputs. Association with iron hydroxides, abundant in soils of the catchment, may also enhance the preservation of TOC as shown in other sedimentary environments (Lalonde et al., 2012).

6. Conclusions

Coupling land use and vegetation history records, soil and sediment TOC content measurements and fallout ^{137}Cs–$^{210}Pb_{xs}$ inventories within the Houay Pano catchment in Laos led to several conclusions:

1) Using 1963, the year of maximum ^{137}Cs fallout in Southeast Asia, it was possible to link soil TOC redistribution and accumulation trends within the catchment since the onset of forest clearing and shifting cultivation in 1967 and estimate the soil TOC depletion rate on catchment's slopes averaging all topographic positions.
2) At catchment's scale, the present day soil ^{137}Cs activity decreased with topographic position and the number of shifting cultivation cycles whereas, soil TOC content only decreased after 8 crop-fallow rotations. Between 3 and 8 rotations, farmers' preferences for fertile soils counterbalanced soil TOC depletion. Direct comparison between cultivated and forested soils in the same area can be misleading, with an overestimation of TOC loss due to shifting cultivation.
3) Validated by sediment yield measurements at the inlet and the outlet of the swamp for the most recent years, maximum TOC accumulation was found during the period of forest clearing and first cropping (1967–1975). Due to the small area covered by the swamp, storage was rather limited. Mineralization of soil organic matter, either *in situ* or displaced along catchment's slopes, appeared to be the main soil TOC depletion process, at least for the past 30 years (1975–2005).

7. Annexe 1

Volume mixing of Napier grass and soil organic matter in the swamp may be described by the following mixing equation: $(V_1+V_2)\ \delta^{13}C = V_1\ \delta^{13}C_1 + V_2\ \delta^{13}C_2$ (1), where V_1 and V_2 are the volumes of Napier and soil organic matter, respectively, in a total sample volume V and $\delta^{13}C_1$, $\delta^{13}C_2$ and $\delta^{13}C$ the corresponding isotopic compositions. Volumes can be replaced in Eq. (1) by their mass to density ratios. Using d_1 and d_2, the bulk densities and M_1 and M_2, the masses of organic matter for each component it comes: $(M_1/d_1 + M_2/d_2)\ \delta^{13}C = M_1/d_1\ \delta^{13}C_1 + M_2/d_2\ \delta^{13}C_2$ (2). Given M, the total mass ($M = M_1 + M_2$) and f_1 (M_1/M) and f_2 (M_2/M), the mass fractions of Napier and soil organic matter, respectively, Eq. (2) can be rewritten by dividing both sides by M as: $(f_1/d_1 + f_2/d_2)\ \delta^{13}C = f_1/d_1\ \delta^{13}C_1 + f_2/d_2\ \delta^{13}C_2$ (3). Equation (3) can be solved for f_1: $f_1 = d_1\ (\delta^{13}C_2 - \delta^{13}C)/[d_2\ (\delta^{13}C - \delta^{13}C_1) + d_1\ (\delta^{13}C_2 - \delta^{13}C)]$ with $f_1 + f_2 = 1$, using dry bulk densities of 0.4 g cm^{-3} and 1.2 g cm^{-3} and $\delta^{13}C$ values of −12.0‰ and −26.2‰ for Napier and soil organic matter, respectively. The TOC storage of Napier and soil-derived organic matter in the swamp can thus be determined for each sample by multiplying their TOC contents by their respective mass fractions.

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