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Interrill erosion in the sloping lands of northern Laos subjected to shifting cultivation

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Abstract

In this study our main objective was to quantify water interrill erosion in the sloping lands of Southeast Asia, one of the most bio-geochemically active regions of the world. Investigations were performed on a typical hillslope of Northern Laos subjected to slash and burn agriculture practiced as shifting cultivation. Situations with different periods of the shifting cultivation cycle (secondary forest, upland rice cultivation following a four-year fallow period and three-year continuous upland rice cultivation) and soil orders (Ultisols, Alfisols, Inceptisols) were selected. One metre square micro-plots were installed to quantify the soil material removed by either detachment of entire soil aggregate or aggregate destruction, and the detached material transported by thin sheet flow, the main mechanisms of interrill erosion. In addition, laboratory tests were carried out to quantify the aggregate destruction in the process of water erosion by slaking, dispersion and mechanical breakdown. The average runoff coefficient (*R*) evaluated throughout the 2002 rainy season was 30·1 per cent and the interrill erosion was 1413 g m^{-2} yr^{-1} for sediments and 68 g C m^{-2} yr^{-1} for soil organic carbon, which was relatively high. Among the mechanisms of interrill water erosion, aggregate destruction was low and mostly caused by mechanical breakdown due to raindrops, thus leading to the conclusion that detachment and further transport by the shallow runoff of macro-aggregates predominates. *R* ranged from 23·1 to 35·8 per cent. It decreased with the proportion of mosses on the soil surface and soil surface coverage, and increased with increasing proportion of structural crust, thus confirming previous results. Water erosion varied from 621 to 2433 g m^{-2} yr^{-1} for sediments and from 31 to 146 g C m^{-2} yr^{-1} for soil organic carbon, and significantly increased with increasing clay content of the surface horizon, probably due to the formation of easily detachable and transportable sand-size aggregates, and proportion of macro-aggregates not embedded in the soil matrix and prone to transport. In addition, water erosion decreased with increasing proportion of structural crusts, probably due to their higher hardness, and when cultivation follows a fallow period rather than after a long period of cultivation due to the greater occurrence of algae on the soil surface, which affords physical protection and greater aggregate stability through binding and gluing. This study based on simultaneous field and laboratory investigations allowed successful identification and quantification of the main erosion mechanisms and controlling factors of interrill erosion, which will give arguments to further set up optimal strategies for sustainable use of the sloping lands of Southeast Asia.

Keywords: **soil interrill erosion; runoff; soil crusting; shifting cultivation; sloping lands; Laos**

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Introduction

Soil erosion by rainfall and runoff is a natural and geologic phenomenon, one of the most important components of the global geochemical cycle. It shapes landscapes and participates in the displacement of soil fertility to sedimentation zones. Off-site consequences of increased water erosion include floods, decreases in groundwater recharges, eutrophication hazards, water pollution by heavy metals and pesticides, and sedimentation in valleys and reservoirs

(IGBP, 1995). Because it leads to the creation of fertile areas such as terraces or flood plains, soil water erosion can be beneficial to the environment.

The increase in the global demand for food and fresh water and the associated land use changes or misuses exacerbate water erosion, which nowadays is a major threat to the sustainability of the soil resource (IGBP, 1995). Current changes in climate have increased the risks of erosion of the soil resource and the consequences on soil fertility, water availability and biodiversity.

In the tropics, the extensive deforestation of natural forests for cultivation purposes has long been recognized as causing severe changes in the ecosystem (Ingram *et al*., 1996). One of the first consequences of deforestation, biomass burning and conversion of natural to agricultural ecosystems is the emission of carbon (C). Concomitant with such a rapid decrease is the compaction (e.g., the case of the Amazonian forest, Desjardins *et al*., 1994; Fearnside and Barbosa, 1998) and crusting of soils, with dramatic consequences on runoff generation and soil interrill erosion (e.g. in West Africa, Valentin *et al*., 2004). Although the impact of land use changes such as deforestation on the loss of forest ecosystem carbon or the compaction of soils in the tropics has been thoroughly investigated (IPCC, 2001), little is known about the consequences for soil interrill erosion. A decrease in the topsoil porosity where organic matter and nutrients concentrate leads to a decrease in infiltration (Husain *et al*., 2002), inducing more runoff, nutrient leaching and soil erosion. Regarding recent concerns about the increase in atmospheric CO_2 concentration, soil erosion may also be either a source of carbon, through the emission of CO_2 during the transport of eroded soil organic carbon (SOC), or a carbon sink, when SOC is buried in sediments (Lal, 2003).

The sloping lands of Southeast Asia are one of the most bio-geochemically active areas of the biosphere (Labat *et al*., 2004). In the region, the traditional agricultural practice is that of slash and burn agriculture practiced as shifting cultivation. It is a non-intensive practice without fertilizer inputs and mechanization shown to preserve the soil fertility in the long term through the improvement of both nutrient cycling and soil structure (Sanchez and Hailu, 1996). Due to increasing human pressure on the available land, the fallow duration, i.e. the time period between two successive clearing/ cropping phases at the same site, has gradually decreased from 10–15 years in the 1970s to two to five years nowadays (de Rouw *et al*., 2005), whereas ecological sustainability may require a minimum fallow period of 10 years (Sanchez and Hailu, 1996). This is expected to have direct consequences on the environment and especially on the downstream transfers of sediments and carbon (Sarin, 2001). Among the very few studies available, Gafur *et al*. (2003) in Bangladesh quantified soil erosion losses in catchments to vary between $0{\cdot}3\ \mathrm{kg\ m^{-2}\ yr^{-1}}$ under fallow and $1{\cdot}8\ \mathrm{kg\ m^{-2}\ yr^{-1}}$ under continuous cultivation. In the sloping lands of Northern Thailand, soil losses evaluated in cropped fields using 1 m × 1 m plots increased from 0·6 to $3{\cdot}3\ \mathrm{kg\ m^{-2}\ yr^{-1}}$ with decreasing slope gradient (Janeau *et al*., 2003). Although some information exists on soil water erosion in the tropics, there is still the need for quantitative information on soil interrill erosion, the mechanisms involved and the associated factors of control. This issue is crucial for the evaluation of the actual water, sediment or solute transfers within landscapes but also for the prediction of the impact of the expected changes on climate and/or land use management on the functioning of sloping lands ecosystems. In this study, our main objective is to evaluate soil interrill erosion in the sloping lands of Northern Laos for different soils and periods of the shifting cultivation cycle. One metre square micro-plots and laboratory tests were used simultaneously to quantify interrill erosion and to investigate the main mechanisms involved in the removal of soil material from the soil mass by detachment of entire soil aggregate or aggregate destruction, and the transport of the detached material by thin sheet flow.

Materials and Methods

Site

The study site is located within the mountainous areas of Northern Laos (Figure 1). It is a 100–150 m long hillslope (Figure 2) with altitudes above sea level from 505 m at the stream bank to 584 m at the hillslope summit. The average slope gradient of this classical convexo-concave hillslope is 46 per cent. The toeslope is a gently inclined surface of 10–15 per cent gradient followed by a concave footslope with a slightly greater slope gradient. The slope gradient increased to 40–50 per cent backslope, the steepest and most convex middle portion of the hillslope (Figure 2). This position is bounded upslope by a steep (60–70 per cent) and convex shoulder. The slope gradient decreases afterwards to 25 per cent near the summit.

Climate, geology and soils

Two distinct seasons characterize the study area: a wet season from April to October and a dry season from November to March. The 30-year average rainfall is 1403 mm and the mean annual temperature is 25 °C (MRC, 1997). Rain

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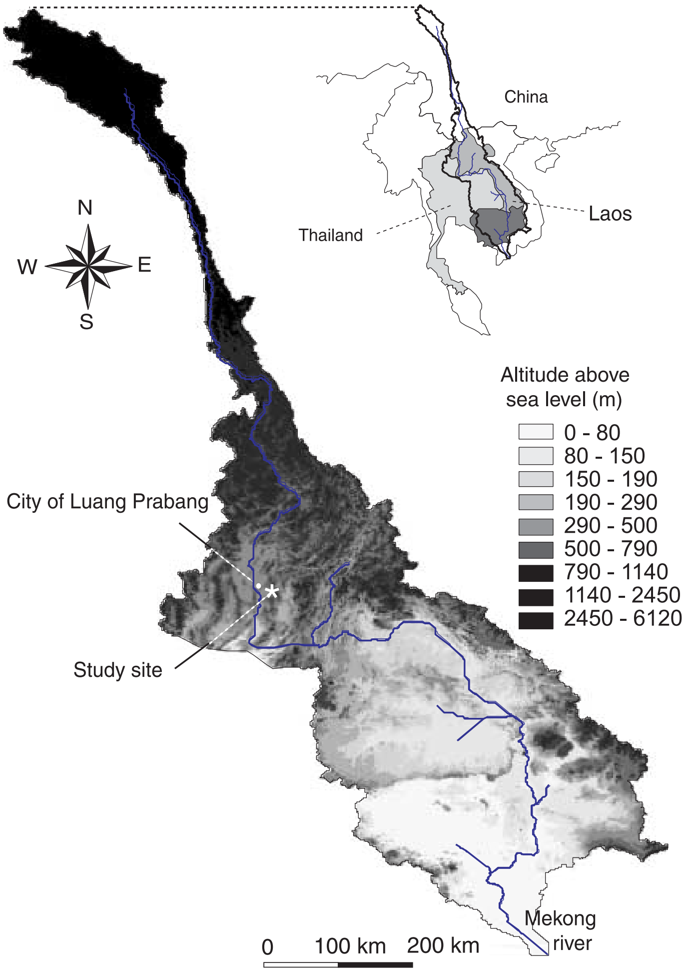

Figure 1. Location of the study site of northern Laos within the Mekong basin. This figure is available in colour online at www.interscience.wiley.com/journal/espl

exceeds evapotranspiration throughout the year except for November to April, the driest months. The study hillslope is typical of the region. Soil has formed within sedimentary rocks (argilites and siltstones) from Permian to Upper Carbonifer. They are distributed along slopes as follows: Entisols at the toeslope and footslope; Ultisols and Alfisols on the backslopes and Inceptisols at the shoulder and summit (Soil Survey Staff, 1999). Entisols developed within alluvial and/or colluvial materials were marked by fluvic properties and redoximorphic features. Surface organo-mineral horizons showed a clayey, dark-brown (10YR3/3) matrix with numerous dark yellowish brown (10YR4/3) spots. At depth, a higher proportion of stones and redoximorphic features characterized massive mineral horizons. Deep and clayey soils (Ultisols and Alfisols) are the most representative soils at the study hillslope. They exhibit a fragipan with clay films more than 1 mm thick and with a base saturation of less than 35 per cent in the case of Ultisols. Due to erosion, the fragipan frequently outcrops to the soil surface and disappears in the upslope direction.

Land use and land management

The hillslope is subjected to the typical slash and burn system of Southeast Asia characterized by a succession of cropping and fallow periods and practiced as shifting cultivation. Crops are mainly rice (*Oryza sativa*) and increasingly maize (*Zea mays*) or Job's tears (*Coix lacryma Jobi*). Fallows are grassy/woody fallows. At the study site, croplands are located on footslope and backslope positions whereas the toeslope is devoted to banana trees and/or legumes (Figure 2). A secondary forest covers the hillslope summit. The first management operation for rain-fed rice cultivation within the hillslope was slashing and burning of either the fallow or the crop residues. It occurred in March

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Figure 2. Picture of the study area on 15 July 2002. Landform type and land use pattern with from front to back rain-fed rice, banana trees (valley bottoms), natural fallow (slopes) and secondary forest (hillslope summits). The study hillslope is located on the left-hand side of the picture, in front.

and was followed by soil preparation for sowing. Tillage was manual (performed with a hoe) and shallow (0–2 cm). Crops were sown manually after the first rains of the rainy season (mid May) and are weeded up to the flowering stage.

Evaluation of soil surface features

Given their importance in runoff generation and soil crusting (e.g. Auzet *et al*., 2004), surface features have been characterized and visually quantified in the field using the method described by Janeau *et al*. (2003). The main surface types included free aggregates (AGR, i.e. not embedded in a crust), free gravel (ROCK), structural crust (STRUC), erosion crust and gravel crust, and plant residues as based on the classification of Valentin and Bresson (1992, 1997). In addition, percentages of colonization of crusts by mosses (MOS) or algae (AL) were noted (see, e.g., Malam Issa *et al*., 1999) as well as faunal constructions (worm casts, termite surface tunnels). Vegetation cover was also visually assessed distinguishing crop and weed. Evaluations were performed on each micro-plot throughout the rainy season using field descriptions and photograph interpretations.

Field evaluation of soil interrill erosion

The soil interrill erosion was assessed throughout the 2002 rainy season. Measurements of runoff, sediment and organic carbon (OC) losses were performed on 15 1 m × 1 m plots installed within the hillslope on similar geological substrates and aspects, but for situations differing by the soil type, the land use and the land use history (the succession of land use preceding the survey). Because it has been shown that in under similar conditions runoff and soil losses clearly decrease with slope angle (Janeau *et al*., 2003), all the plots were installed on the same slope gradient (45 per cent). Five combinations of soils, land use and land use history were investigated: (1) Ultisols under rain-fed rice cultivation after a four-year fallow period (UCF4); (2) Ultisols under three-year continuous cultivation of rain-fed rice (UCF0); (3) Alfisols under rain-fed rice after a four-year fallow (ACF4); (4) Inceptisols under rain-fed rice after a four-year fallow (ICF4) and (5) Inceptisols under secondary forest (IFo). For each situation, three micro-plot replicates were installed just after the burning operation. The metal borders surrounding the micro-plots were inserted in the soil to a depth of 0·1 m.

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The study site has been under a slash and burn system since 1960 with similar land use and land management but with periods of rain-fed rice cultivation alternating with longer periods of natural grassy/woody fallow. The preceding fallows of UCF4, ACF4 and ICF4 treatments were cut on 10 March. The residues were burned on 22 March and the fields were seeded on 15 May. The plots were weeded on 19 June and 1 and 27 August by shallow (2 cm) weeding using a hand hoe.

Field measurements were carried out from 15 May (the first rain of the season) to 3 November (the last rainfall event). After 5 June, measurements were considered as occurring under conditions of steady-state soil losses because no significant soil cracking or features of linear erosion were observed within the micro-plots. After each rainfall event, the runoff amount from each micro-plot replicate was measured. A runoff aliquot was oven-dried to estimate both sediment concentration and sediment discharge. During this study, a total of 525 samples were collected from 35 rainstorm events. Rainfall event characteristics such as rainfall amount and maximum or average rainfall intensity were estimated using an automatic rain gauge with a 6 min step.

The soil organic carbon (SOC) of eroded sediments was estimated using the Heanes wet oxidation technique (Heanes, 1984) based on the heat of reaction and dilution. The annual eroded SOCs from the micro-plots were estimated by determinations of the SOC content of sediments collected for a limited set of runoff events, including the main rainfall event of the season and four additional events randomly selected over the remaining 34 rain events. Because an evaluation of the SOC content of the sediment produced by all rainfall events was not possible, the mean SOC content of these five events was later used to compute the annual losses of SOC from the entire set of 35 runoff events. The general hypothesis of the study is that the SOC content of these five events randomly selected gives an accurate picture of the yearly SOC erosion.

Soil texture and bulk density of the 0–5 cm layer were evaluated at each micro-plot replicate at the end of the rainy season, just after the harvest of rain-fed rice. Bulk densities were estimated using three 250 ml cylinders per micro-plot. Soil texture was obtained from the classical sedimentation method on one sample per plot repetition. One sample per repetition was also used for SOC determination in the soil following a methodology described above.

Laboratory evaluation of aggregate destruction in the process of water erosion

The destruction of soil aggregates in the process of water erosion was evaluated following the Le Bissonnais laboratory test (Le Bissonnais, 1996). Soil aggregates of each treatment were collected from the 0–5 cm layer. From the bulk soil of the 0–5 cm layer collected just after the burning operation, aggregates 3–5 mm in size were obtained by dry sieving. The testing was based on a combination of three procedures, each corresponding to different wetting conditions and energy inputs due to the action of rainfall (respectively fast wetting, slow wetting and mechanical breakdown) representing as many desegregation mechanisms (respectively slaking, dispersion and mechanical breakdown). A complete description of these could be found in the work of Le Bissonnais (1996). The fast-wetting test consisted of the gentle immersion of dried aggregates in 50 ml de-ionized water. For slow wetting, dried aggregates are put on a filter paper and then wetted by capillarity on a suction table. For mechanical breakdown, aggregates are immersed in ethanol, placed in a flask with de-ionized water and afterwards rotated end-over-end 10 times. Subsequently, the size distribution of the aggregates subjected to these tests was evaluated. Weights of aggregates collected on each sieve were measured and expressed as the percentage of the sample dry mass. The aggregate stability was expressed by the mean weight diameter (MWD) calculated as follows: $\mathrm{MWD} = \Sigma(x_i \times w_i)/100$ with x the mean intersieve size and w_i the percentage of particles retained on each i sieve. The greater MWD is the more resistant to desegregation the soil is.

General statistics

Descriptive statistics for the erosion variables of runoff (R), sediment concentration (SC), soil interrill erosion (SL), soil organic carbon content (SOC) and eroded soil organic carbon (EOC) were computed from the 35 rainfall events. Statistics include minimum, maximum, median, average, standard deviation, coefficient of variation, skewness (which measures the deviation of the distribution from symmetry) and kurtosis (which measures the ‘peakedness’ of the distribution). A skewness different from zero reveals an asymmetrical distribution, whereas a kurtosis different from zero reveals either a more flat or a more peaked distribution than the normal one.

In addition, an ANOVA and a principal components analysis (PCA) were applied to the data to test the relationships between water, soil and soil organic carbon losses and some selected environmental variables. Classes for the other independent variables were the following: average rainfall intensity (<5 mm h^{-1}; [5–15]; [15–30]; >30 mm h^{-1}); maximum 6 min rainfall intensity (<25 mm h^{-1}; [25–50]; [50–75]; >75 mm h^{-1}); cumulative rainfall of the event (<25 mm;

Table I. Main soil characteristics (texture in five classes; organic carbon, OC; bulk density; OC stock) of the 0–5 cm layer for three replicates of the following five treatments: Ultisols cultivated under upland rice after a four-year fallow (UCF4); Ultisols under continuous cultivation (UCF0); Alfisols under upland rice after a four-year fallow (ACF4); Inceptisols under upland rice after a four-year fallow (ICF4) and (v) Inceptisols under secondary forest (Ifo)

	UCF4	**UCF0**	**ACF4**	**ICF4**	**IFo**	**Average**
Soil texture (g kg^{-1})						
Clay (<2 μm)	521	549	517	430	389	48
Fine silts (2–50 μm)	267	270	276	309	279	280
Coarse silts (20–50 μm)	89	75	82	80	73	80
Fine sands (50–200 μm)	63	42	58	60	67	58
Coarse sands (200–2000 μm)	60	63	66	120	192	100
Rock fragments (kg kg^{-1})	0·0	0·0	0·05	0·25	0·25	0·11
Organic C content (g C kg^{-1})	22·7	22·5	24·8	18·5	22·3	22·2
Bulk density (Mg m^{-3})	0·9	0·9	1·3	1·9	1·8	1·4
Organic C stock (g C m^{-2})	1032	1018	1457	1013	1087	1122

[25–50]; [50–75]; >75 mm); clay content of the 0–5 cm layer (<40 per cent; [40–50]; >50 per cent) and proportion of the soil surface covered by mosses or algae (<5 per cent; [5–10]; [10–15]; >15 per cent) and by free rock elements and aggregates (<2 per cent; [2–5]; [5–10]; >10 per cent). The principal components analysis converts the actual variables (in our case the erosion variables) into the so-called factors, or principal components (PCs), which are linear combinations of the actual variables, not correlated with each other (i.e. they are orthogonal) and together explaining the total variance of the data (Jambu, 1991). In this multivariate statistical tool the first and second factors often explain most of the variance and therefore most of the information contained in the data.

Results

Soil characteristics

Within the study hillslope, the average clay content of the 0–5 layer of soils was 48 per cent. Values varied from 39 per cent for Inceptisols to 55 per cent for Ultisols (Table I). Inceptisols exhibited the greater proportion of sands. On average, the bulk density of the 0–5 cm horizon was 1·4 Mg m^{-3} with values from 0·9 Mg m^{-3} for Ultisols to 1·9 Mg m^{-3} in the case of Inceptisols under cultivation. The average soil organic content (SOC) of the surface layer was 22·2 g C kg^{-1}. Lower contents (18 g C kg^{-1}) occurred in cultivated Inceptisols. A value of 25 g C kg^{-1} was observed in Alfisols. The average organic C stock computed for the 0–5 cm layers was 1122 g C m^{-2} with greater values (1457 g C m^{-2}) for Alfisols.

Rainfall characteristics over the 2002 rainy season

2002 was characterized by a total rainfall amount of 1651 mm, which is slightly higher than the 30-year average of 1403 mm. 2002 followed an exceptionally rainy year (2001) with a rainfall of 1737 mm (23 per cent more than the 30-year average). From 25 May to 25 October, 35 rain events of a total depth of 1023 mm produced runoff. The depth of rain events shows a minimum of 4·5 mm, a maximum of 162 mm and a median at 17 mm (Figure 3). The median 6 min rainfall intensity was 40 mm h^{-1} with a range of 5–135 mm h^{-1} (Figure 3). The strongest rain event occurred on 20 July (event number 24, Figure 3). It showed a total amount of 132 mm and a maximum 6 min intensity of 100 mm h^{-1}. Four other rainstorms with high volume and rainfall intensity occurred at the end of the rainy season, on 9 September (event number 32), 2 (33) and 6 (34) October and 3 November (35) (Figure 3).

Water, soil and carbon erosion

The average runoff amount computed over the 2002 rainy season from the 15 micro-plots (Table II) was 251 l m^{-2} yr^{-1}, yielding an average runoff coefficient, R, of 28 per cent. Average R ranged from 23·1 per cent on Ultisols under cultivation after a four-year fallow period (UCF4) to 35·8 per cent on Inceptisols under forest (IFo) (Table II). The significant environmental factors that explained R variance for the set of micro-plots were the average

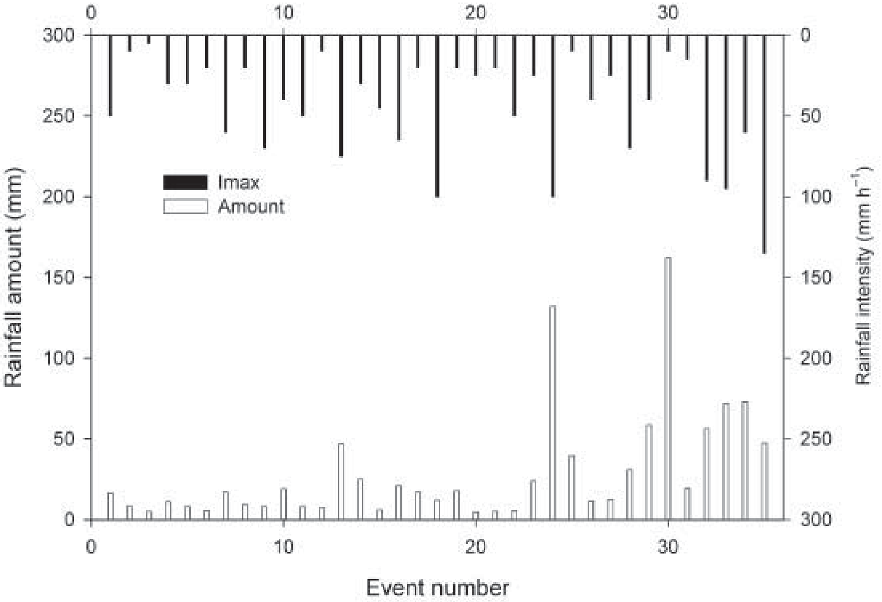

Figure 3. Total rainfall depth and maximum 6 min rainfall intensity for the 35 runoff events of 2002.

rainfall intensity ($F = 12$; $P < 0{\cdot}001$), the maximum rainfall intensity ($F = 8$; $P < 0{\cdot}001$); the clay content of the 0–5 cm layer ($F = 7$; $P = 0{\cdot}001$), the soil surface coverage ($F = 13$; $P < 0{\cdot}001$), the proportion of the soil surface covered by mosses ($F = 13$; $P < 0{\cdot}001$) and a structural crust ($F = 3$; $P < 0{\cdot}001$) on the soil surface. The second axis of the principal component analysis, which accounts for 34 per cent of the total data variance, shows a trend associated with runoff generation (R contribution to this axis of 0·96) (Figure 4). Because the proportion of the soil surface covered by a structural crust (Struc.) and the average rainfall intensity (Iav.) have positive coordinates on this axis, R increases as Struc. and Iav. increase. On the other hand, negative coordinates for proportion of mosses (Mos.), surface coverage (Cov.) and clay content (Clay) indicate that R decreases when Mos., Cov. and Clay increase.

The average sediment concentration (SC) in runoff varied between 2·7 g l^{-1} for ICF4 and 7·6 g l^{-1} for IFo. Maximum SC occurred for the rain event of 20 July (event number 24) with a replicate average of 57 g l^{-1} for IFo (Table II). The lowest SC during this event occurred on ACF4 and ICF4 with respectively 16 and 13 g l^{-1}. Ultisols show intermediary values with however greater SC under continuous cultivation than under cultivation with a preceding fallow period (Table II). In addition to being significantly correlated with the average and maximum rainfall intensity, SC correlated with the soil clay content, the duration of the cultivation period and the presence of crusts colonized or not by algae/mosses and of free aggregates and gravel fragments on the soil surface (Table III). From the third axis of the PCA with a trend associated with soil interrill erosion we learn that SC increases with increasing free aggregates and gravel fragment, clay content, cultivation duration and average rainfall intensity but decreases with increasing cumulative rainfall, soil surface coverage and presence of structural crusts (Figure 4).

Values of soil interrill erosion by water were much more variable, with values between 621 and 2433 g m^{-2} yr^{-1} for soil losses and between 31 and 146 g C m^{-2} yr^{-1} for eroded organic carbon (EOC) (Table II). Greater erosion was observed for Ultisols under continuous cultivation and on forested Inceptisols. Lower losses occurred at mid-slope position for both AFC4 and ICF4 treatments (Table II). From Table II we also learn that most of the losses (e.g. 1383 g m^{-2} of a yearly amount of 2114 g m^{-2} for sediment, Table II) occurred during a single rainfall event. On Ultisols, EOC was lower when cultivation followed a fallow period than under continuous cultivation (35 compared to 75 g C m^{-2} yr^{-1}). A greater proportion of yearly carbon losses during the 24th rainfall event occurred on continuous cultivation than after a fallow period (64 per cent for UCF0 compared to 19 per cent for UCF4).

The ANOVA revealed that soil and SOC losses from the micro-plots correlated with maximum rainfall intensity ($P < 0{\cdot}001$), rainfall amount ($P < 0{\cdot}001$), the proportion of structural crust and of crust colonized by algae ($P < 0{\cdot}001$) and the presence of free aggregates ($P < 0{\cdot}05$). From the second axis of the PCA, which explained 50·6 per cent of the variance and with a trend associated with soil losses (contribution to this axis of 0·60 for SL and 0·50 for EOC), we learn that soil interrill erosion increases as rainfall intensity, rainfall amount and duration of continuous cultivation increase, and decreases with increasing proportions of structural crust and algae.

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Table II. General statistics (minimum, min.; maximum, max.; median; average, av.; standard deviation, SD; skewness, skew; kurtosis, kurt., and coefficient of variation, CV) for runoff value (*R*), sediment concentration (SC) and soil losses (SL) measured on 1 m × 1 m interrill plots for the 35 rainfall events of 2002. Content of soil organic carbon (SOC) of eroded soil and eroded organic carbon (EOC). Five treatments were considered: Ultisols cultivated with upland rice after a four-year fallow (UCF4); Ultisols under continuous cultivation (UCF0); Alfisols with upland rice after a four-year fallow (ACF4); Inceptisols with upland rice after a four-year fallow (ICF4) and (v) Inceptisols under secondary forest (IFo). The general statistics on eroded organic carbon (EOC) were computed from five randomly selected events from the set of 35. The sum of EOC (sum*) was computed over the year 2002

		UCF4	UCF0	ACF4	ICF4	IFo
R amount (l m^{-2} yr^{-1})	Sum	202	223	278	244	310
R rate (%)	Min.	3·9	3·5	4·9	4·5	3·9
	Max.	72·7	73·1	81·3	71·6	98·0
	Median	21·6	25·3	34·9	29·8	33·2
	Av.	23·1	26·8	34·8	30·0	35·8
	SD	14·2	16·8	16·7	14·4	21·0
	Skew	0·9	0·6	0·5	0·3	0·8
	Kurt.	0·6	–0·3	0·3	–0·4	0·2
	CV	61·6	62·8	47·9	47·9	58·7
SC (g l^{-1})	Min.	0·2	0·3	0·1	0·0	1·5
	Max.	28·6	36·5	15·7	13·0	57·0
	Median	2·1	3·3	2·0	1·6	5·8
	Av.	4·0	6·0	2·8	2·7	7·6
	SD	4·7	7·4	2·8	3·0	6·7
	Skew	2·7	2·3	2·1	1·8	4·3
	Kurt.	9·1	5·2	5·4	3·1	27·6
	CV	116·5	123·7	102·8	108·3	88·6
SL (g m^{-2})	Min.	0·5	0·5	0·2	0·0	1·0
	Max.	563·1	1383·2	267·7	214·5	798·8
	Median	7·4	11·9	7·8	6·5	25·5
	Av.	28·1	61·3	26·5	17·7	70·6
	SD	76·0	248·9	50·1	28·9	126·5
	Skew	5·1	6·9	3·4	4·0	3·7
	Kurt.	29·1	51·6	11·6	21·8	14·8
	CV	270·8	406·3	189·3	163·1	178·9
(g m^{-2} yr^{-1})	sum	975	2114	924	621	2433
EOC (g C kg^{-1})	Min.	23·6	20·2	32·9	35·0	31·3
	Max.	42·3	49·2	49·2	49·3	49·5
	Median	32·1	33·7	41·1	42·4	36·8
	Av.	32·1	34·3	41·6	42·1	39·1
	SD	0·4	0·2	–0·2	–0·2	0·6
	Skew	0·6	–0·4	–1·3	–0·1	–1·1
	Kurt.	6·4	9·3	5·8	4·5	6·6
	CV	20·1	27·0	14·1	10·7	16·9
*E**		1·7	1·7	2·6	2·8	2·7
EOC (g C m^{-2})	Min.	0·0	0	0·0	0·0	0·0
	Max.	18·1	48·5	11·1	9·0	31·2
	Median	0·2	0·7	0·3	0·3	0·9
	Av.	0·9	0·4	1·1	0·7	2·7
	SD	2·4	2·0	2·1	1·2	4·9
	Skew	5·1	8·4	3·4	4·1	3·7
	Kurt.	29·1	6·9	11·6	21·7	14·9
	CV	270·9	52·1	189·3	163·1	180·1
(g C m^{-2} yr^{-1})	sum	31	75	59	32	146

* Enrichment factor from bulk soil.

Table III. Statistics ANOVA between the runoff, soil and organic carbon losses from the micro-plots as dependent variables and some independent variables. Fifteen micro-plot replicates and 35 rainfall events were considered

Independent variables†	df	Sum of squares	Mean squares	*F* value	*P*‡
Runoff					
Iav.	3	10 100	3 366	12·5	0·000***
Imax.	3	7 269	2 423	8·3	0·000***
Cum.	3	485	485	1·9	0·169
Clay	3	4 017	2 009	7·4	0·001*
Cult.	1	350	350	1·3	0·26
Cov.	3	6 823	2 274	7·9	0·000***
Mos.	3	4 257	4 257	13·5	0·000***
Al.	3	224	22	0·1	0·702
Struc.	3	1 100	304	3·3	0·000***
Agr.	3	118	118	3·8	0·051
Rock	3	634·8	212	1·4	0·263
MWD	3	2 865	1 432	4·8	0·009*
Sediment concentration					
Iav.	3	691	230	7·7	0·000***
Imax.	3	1 441	480	16·8	0·000***
Cum.	3	148	49	1·6	0·189
Clay	3	469	235	7·7	0·000***
Cult.	1	503	503	17·8	0·000***
Cov.	3	2 181	31	1·0	0·478
Mos.	3	554	79	2·6	0·012*
Al.	3	1 448	85	2·9	0·000***
Struc.	3	3 535	77	2·9	0·000***
Agr.	3	1 805	404	6·0	0·014*
Rock	3	1 260	630	21·9	0·000***
MWD	3	757·9	379	12·7	0·000***
Soil losses					
Iav.	3	29 800	9 932	0·5	0·644
Imax.	3	1 440 000	479 000	32·0	0·000***
Cum.	3	2 010 000	671 000	48·5	0·000***
Clay	3	3 674	1 837	0·1	0·902
Cult.	1	79 700	79 700	10·7	0·000***
Cov.	3	31 400	10 500	0·6	0·617
Mos.	3	9 498	9 498	0·5	0·482
Al.	3	45 200	45 200	14·9	0·000***
Struc.	3	133 000	37 226	10·7	0·000***
Agr.	3	4 173	1 173	4·2	0·042*
Rock	3	11 300	3 774	0·8	0·499
MWD	3	52 000	26 000	1·5	0·229
Eroded organic carbon					
Iav.	3	42	14	0·6	0·590
Imax.	3	1 910	637	35·3	0·000***
Cum.	3	2 571	857	51·1	0·000***
Clay	3	7	4	0·2	0·846
Cult.	1	76	76	11·7	0·000***
Cov.	3	15	5	0·2	0·875
Mos.	3	11	11	0·4	0·509
Al.	3	88	29	3·7	0·014*
Struc.	3	162	45	10·4	0·000***
Agr.	3	918	318	3·8	0·045*
Rock	3	15	5	0·8	0·477
MWD	3	93	47	2·2	0·115

† Iav., average rainfall intensity; Imax., maximum 6 min rainfall intensity; Cum., cumulative rainfall; Clay, clay content of the 0–5 cm layer; Cult., duration of the cultivation period; Cov., soil surface coverage by vegetation; proportion of the soil surface covered by mosses (Mos.). algae (Al.) and structural crust (Struc.).

‡ *, *** Significant at the 0·05 and 0·001 probability levels. respectively.

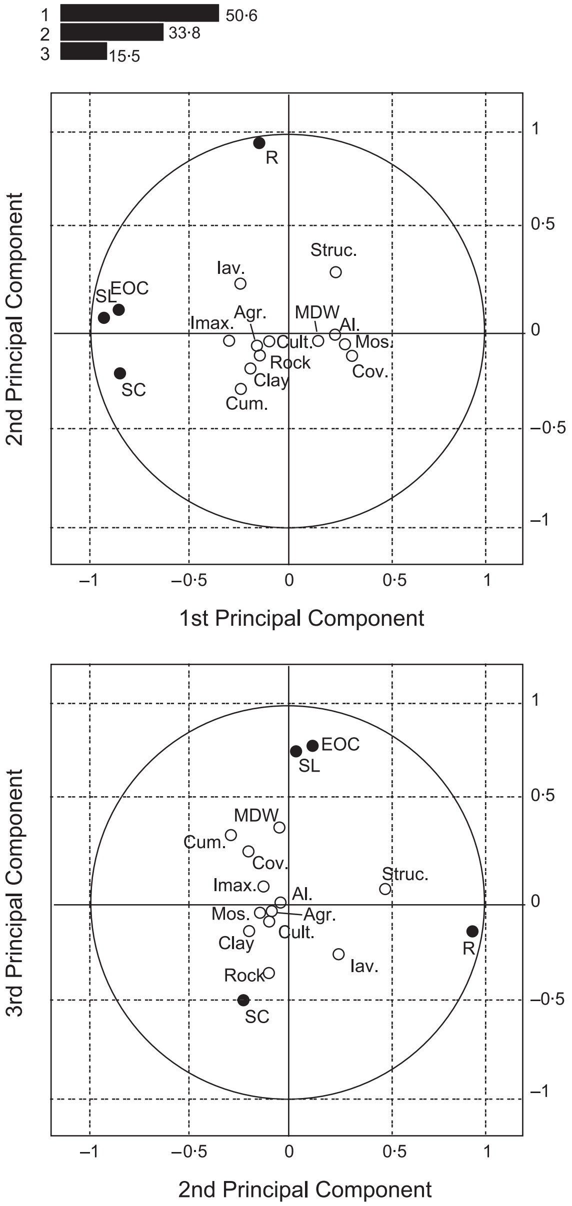

Figure 4. Principal component analysis (PCA) scattergram of 'factor scores' for erosion variables (runoff rate, *R*; sediment concentration, SC; eroded organic carbon, EOC) and environmental factors (average rainfall intensity; Imax., maximum 6 min rainfall intensity; Cum., cumulative rainfall; Clay, clay content of the 0–5 cm layer; Cult., duration of the cultivation period; LU, land use; Cov., soil surface coverage by vegetation; proportion of the soil surface covered by Mos., mosses, Al., algae, Struc., structural crust, and Rock, free rock elements). Percentage of the cumulative variance attributed to axes 1–3.

Table II finally indicates that the eroded soil material was enriched in soil organic carbon (SOC) compared with the bulk soil. The enrichment factor (E) was 2·3 on average with values from 1·7 on UCF4 and UCF0 to more than 2·5 for the other treatments. The organic content (EOC) of eroded sediments was over 40 g kg^{-1} for ACF4 and ICF4 but lower, about 30 g kg^{-1}, for UCF4 and UCF0.

Aggregate destruction in the process of water erosion

The mean weight diameter MWD of residual aggregates for each treatment is presented in Table IV. The average MWD between all test procedures varied from 2·46 mm for IFo to 3·27 mm for UCF4, the treatment exhibiting the

Table IV. Mean and standard deviation of the mean weight diameter MWD between three replicates of each treatment and for each stability test. Average MWD for the three tests. Five treatments were considered: UCF4 (Ultisols cultivated with rainfed rice after a four-year fallow); UCF0 (Ultisols under continuous cultivation of rainfed rice); ACF4 (Alfisols with rainfed rice after a four-year fallow); ICF4 (Inceptisols with rainfed rice after a four-year fallow) and IFo (Inceptisols with secondary forest)

	Slow wetting		**Fast wetting**		**Mechanical breakdown**		
	Av.	**SD**	**Av.**	**SD**	**Av.**	**SD**	**Average**
UCF4	3·29	0·04	3·39	0·04	3·13	0·03	3·27
UCF0	3·20	0·07	3·34	0·05	2·76	0·29	3·10
ACF4	3·20	0·17	3·38	0·03	2·98	0·32	3·19
ICF4	3·07	0·09	3·18	0·19	2·65	0·27	2·97
IFo	2·57	0·21	2·80	0·26	2·01	0·26	2·46

more resistant soil aggregates. MWD did not vary much between treatments for the test procedures of slow and fast wetting, except for IFo with lower aggregate stability. Greater differences between treatments occurred for the mechanical breakdown modality, with lower MWD for IFo (2·01), UCF0 (2·76) and ICF4 (2·65) and greater values for UCF4 (3·13) and ACF4 (2·98) (Table IV). Ultisols and Alfisols with a fallow period before cultivation were significantly more resistant to mechanical breakdown than the other treatments.

Discussion

This study revealed the relatively high soil interrill erosion of the sloping lands of Northern Laos with soil losses from 1 m × 1 m micro-plots between 0·6 and 2·4 kg m^{-2} yr^{-1}. This is of the same order as the previous estimations of the very few studies in the region and under similar slope and micro-plot conditions such as those in Northern Thailand obtained by Janeau *et al.* (2003) on bare soils with losses of between 0·6 and 3·3 kg m^{-2} yr^{-1}. Soil interrill erosion in Northern Laos could however be considered as relatively low, considering the steepness of the slope (45 per cent), particularly if compared with the other processes of erosion occurring in the sloping lands such as rill and tillage erosion. For example, at the same study site Chaplot *et al.* (2005) evaluated erosion rates by rill erosion over a 3 year period of 1·8 kg m^{-2} yr^{-1} and at the same site and under similar slope conditions Dupin *et al.* (2003) evaluated tillage erosion to be 0·1 kg m^{-2} per manual tillage pass. In Northern Thailand Turkelboom *et al.* (1997) evaluated this rate to range between 0·8 and 5 kg m^{-2}.

The laboratory tests revealed that aggregate destruction is mainly mechanical, i.e. due to the kinetic energy of raindrops. The other aggregate destruction mechanisms of slaking caused by an increased air compression, swelling tensions or physico-chemical dispersion that predominate under loamy conditions (Le Bissonnais and Arrouays, 1996) were shown here to be of the second order. Moreover, the tests revealed the high stability of soil aggregates according to the standards of Le Bissonnais and Arrouays (1996). This is probably due to the high clay, iron and/or aluminium content as commonly found for tropical soils (Muller, 1977; Chauvel *et al.*, 1978).

These results on soil aggregate destruction and overall interrill erosion seem to produce an unexpected outcome. The paradox is that although soil aggregates were stable the interrilll erosion was high. Considering that soil detachment by raindrops is a precursor to interrill erosion (Sharma and Gupta, 1989) and thus the rate-determining mechanism of interrill erosion (Bradford *et al.*, 1987), what might explain the high interrill erosion levels measured in the sloping lands of Laos? The detachment and transport of entire soil aggregates (even with a relatively low susceptibility to breakdown) by raindrops and shallow runoff may be one possible explanation. This transport may occur in the suspended flow (Chaplot and Le Bissonnais, 2003) if the aggregates are small or by raindrop-induced saltation if larger (Kinnell, 2005). Such a hypothesis of erosion of entire aggregates was confirmed by our results and field observations showing a great proportion of aggregates in the eroded soil material and by the fact that high erosion rates occurred on clayey soils with stable aggregates (Chenu *et al.*, 2000) but sand sized and thus prone to detachment and transport. A second explanation for such a paradox is the detachment of soil material by an eroding agent other than falling raindrops. Among other eroding agents, biological activity that liberates on the soil surface easily transportable soil material could be cited. This hypothesis is supported by the significant correlation observed in this study between interrill erosion and proportion on the soil surface of free aggregates and gravels, mostly detached by the activity of termites and ants. However, this last hypothesis seems to be of the second order since the correlation coefficient between free aggregates and interrill erosion was significant at the 0·05 probability level only.

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Soils with low clay content generated more runoff due to weaker aggregates, thus leading to the formation of a surface crust of lower infiltration (Bresson and Boiffin, 1990). Although crusted surfaces that predominates after a fallow period induced more runoff, they lessened soil interrill erosion and carbon losses due to a lesser particle detachability associated with a higher hardness (see, e.g., Valentin, 1991). This crust may also protect the soil from further soil detachment due to a lower surface roughness and greater bulk density (Bresson and Boiffin, 1990). Alga or moss crusts did not affect soil infiltration because they colonize pre-existing abiotic crusts (see, e.g., Valentin *et al.*, 2004). However, as shown by Malam Issa *et al.* (2001), cyanobacteria may significantly decrease the overall soil interrill erosion because algae make the crusts more cohesive and because the presence below the superficial crusts of filaments and residual organic matter tightly binds soil particles, thus explaining the greater aggregate resistance to mechanical breakdown of soils colonized by algae and mosses during a preceding fallow period. Water erosion increased with the proportion of structural crust, probably due to greater runoff and thus detachment and transport possibilities by for instance rain-impacted flow (Kinnell, 2005).

Finally, a surprising result was the large soil interrill erosion under forested Inceptisols. This may be due to a combination between a low clay content of the surface horizon, the greater kinetic energy of raindrops due to leaf drip, and the presence of soils almost bare due to frequent bushfires (nearly every year) of the under-storey.

Conclusions

Our main objective in this study of the sloping land of Southeast Asia was to evaluate soil interrill erosion for different soils and periods of the shifting cultivation cycle. Soil interrill erosion was evaluated using field 1 m × 1 m micro-plots and laboratory experiments to account for both actions of raindrops and shallow runoff on detachment and transport of soil material. Three main conclusions can be drawn from this study.

First, although soil aggregates are resistant, considerable amounts of soil and soil organic carbon are detached and transported by interrill erosion. This apparent contradiction may be explained by the detachment and transport by water erosion of entire macro-aggregates. Macro-aggregates acting as sand grains were shown to be mainly detached by falling raindrops and secondarily by the activity of the soil macro-fauna enhancing the liberation on the soil surface of easily transportable soil material.

Second, although weaker aggregates induce the formation of structural crusts these do not result in greater soil interrill erosion. On the contrary, crusts lessened soil interrill erosion. This was probably due to a higher hardness of crusts and by the development during the preceding fallow period of algae and mosses that lessened soil detachment by providing a physical protection and lowered mechanical desegregation due to the biological gluing or binding of soil aggregates.

Favoring the development and the conservation of such features on the soil surface would significantly limit soil detachment and overall interrill erosion. To meet this challenge, adequate land use management and practices would have to be defined. Among them, the presence of a fallow period within the shifting cultivation cycle associated with no tillage practices during cultivation should be promoted.

The third conclusion is that the simultaneous field and laboratory investigations of soil interrill erosion for different soils and land use allowed successful identification and quantification of the main mechanisms and controlling factors of soil interrill erosion. In particular, field micro-plots informed on detachment by falling raindrops and transport capacity of thin sheet flow, the two main mechanisms of soil interrill erosion, whereas laboratory tests, despite being inadequate to predict the overall erosion, informed on the level of aggregate destruction and the involved mechanisms.

Moreover, further research studies should be conducted on the combination between field and laboratory experiments to improve the mechanism identification and discrimination between the relative impacts of the processes and mechanisms involved in water erosion. To extrapolate these results to other areas of Southeast Asia, additional investigations should also be performed on a wider range of environmental situations (different fallow durations, land management . . .) and on modelling issues to predict soil erosion over landscapes (see, e.g., Kirkby, 2002; Lane and Chandler, 2003).

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