Runoff, soil and soil organic carbon losses within a small sloping-land catchment of Laos under shifting cultivation.

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Résumé

Dans la plupart des zones tropicales de moyenne montagne, l'usage traditionnel des terres consiste en la culture itinérante sur brûlis marquée par de courtes périodes de culture et des périodes plus longues de jachère. En raison de la pression humaine croissante sur les terres agricoles, la durée de la période de jachère de ces zones se trouve significativement raccourcie. Bien qu'une telle réduction ait des conséquences environnementales majeures sur l'érosion des sols et leur dégradation, un besoin de connaissances existe pour quantifier l'impact à l'échelle du bassin versant. L'objectif majeur de ce travail est d'évaluer le ruissellement, les pertes en sol et en carbone organique d'un bassin versant de moyenne montagne soumis à la culture itinérante sur brûlis. Un deuxième objectif est d'estimer l'impact de la période de jachère sur l'érosion hydrique des sols. L'étude fut conduite dans les zones accidentées du nord du Laos au sein d'un bassin versant agricole de 0,6 ha. Les pertes en sol et en carbone furent évaluées après chaque évènement pluvieux naturel de la saison 2002 à l'exutoire du bassin versant et sur des placettes de $1m^2$ (sous riz pluvial cultivé sans mécanisation et différant par l'histoire culturale : 4 ans de jachère arbustive, RF4, et 3 ans de monoculture de riz, RF0). Pour mieux comprendre les différences d'érodibilité des sols, la stabilité structurale des agrégats des situations RF0 et RF4 a été testée selon 3 modalités : (1) humectation rapide ; (2) humectation lente ; (3) et désagrégation mécanique. La saison des pluies de 2002 fut marquée par 35 évènements pluvieux ayant un cumul de 1023-mm. Le cœfficient de ruissellement (R), les pertes en sol et en carbone furent significativement supérieurs sur $1m^2$ par rapport au bassin versant. R était de 20 % pour les deux modalités et de 2 % sur 0,6 ha. La quantité de sol érodé était de 431 g m^{-2} yr^{-1} sur 0,6 ha tandis qu'elle était de 975 et 2114 g m^{-2} yr^{-1} sur RF4 et RF0, respectivement. Parallèlement, la quantité de carbone érodé de 11.2 g C m^{-2} yr^{-1} à l'échelle du basin versant augmentait largement à 31.2 et 75.2 g C m^{-2} yr^{-1} sous RF4 et RF0. Ces résultats révèlent une réduction significative de l'érosion des sols après une période de jachère. Des données complémentaires sur la stabilité structurale des sols, l'usage des sols, leur caractéristiques de surface et leur couverture végétale ont montré que la plus faible érosion sur RF4 peut être due à une plus grande résistance du sol à la désagrégation liée à l'impact des gouttes de pluie. Le rôle bénéfique du « précédent jachère » pour l'imiter l'érosion hydriques des sols est ainsi démontré.

Mots clés : érosion, sol, carbone, jachère, bassin, Laos.

Abstract

In most sloping lands the main traditional agricultural practice consists of shifting cultivation marked by rotations between short cultivation periods and longer periods of fallow. Due to the increasing pressure on agricultural lands, the duration of the fallow period of the shifting cultivation cycle is being dramatically shortened in most developing countries. Although it is recognized that such a reduction in the shifting cultivation cycle is environmentally damaging in terms of water erosion and soil degradation, there is still a crucial need for quantitative data, at the catchment level especially. The main objective of this work was to evaluate runoff, soil and soil organic carbon (SOC) losses within a small sloping-land catchment of Laos submitted to shifting cultivation. A second objective was to assess the impact of the fallow period on water erosion. The study was conducted in the sloping lands of Northern Laos, within a small agricultural catchment of 0.6 ha. Soil and carbon (C) losses were evaluated for all events that produced runoff and erosion during the 2002 rainy season. Measurements were performed at the catchment outlet and on 1-m² microplots under upland rice cultivation with no mechanisation, and only differing by the land-use history: 4-year natural woody/grassy fallow period (RF4); 3-year continuous upland rice cultivation (RF0). In order to better understand the differences in soil and C erosion within the catchment, the structural stability of aggregates under RF0 and RF4 treatments was tested for three procedures reflecting different mechanisms of soil aggregate breakdown: (1) fast-wetting, (2) slow-wetting, and (3) mechanical breakdown. During the 2002 rainy season, 35 events resulting in 1023-mm total rainfall produced runoff and erosion. The runoff rate, soil and C losses at the microplot level were significantly higher than those at the catchment level. At the microplot level the mean runoff rate was 0.2 mm mm^{-1} for both treatments while at the catchment level it was less than 0.02 mm mm^{-1}. This was reflected in the soil and C losses. The amount of soil losses was 431 g m^{-2} yr^{-1} at the catchment level but 975 and 2114 g m^{-2} yr^{-1} at the microplot scale on RF4 and RF0, respectively. Similarly, eroded C was 11.2 g C m^{-2} yr^{-1} at the catchment level but 31.2 and 75.2 g C m^{-2} yr^{-1} at the microplot level on RF4 and RF0, respectively. Thus, the preceding fallow period significantly decreased the overall soil erosion but also the organic C erosion. The selective erosion of C also decreased after fallow since the C enrichment ratio in sediments was 1.4 on RF4 against 1.6 on RF0. Additional investigations on soil management, soil surface characteristics and coverage, and stability of soil aggregates revealed that the lower soil and C erosion on RF4 might be due to a greater aggregate resistance to mechanical breakdown caused by raindrops. These results demonstrate the importance of the fallow period in the limitation of the overall soil water erosion.

Key words: Soil erosion; Carbon erosion; Scale effect; Fallow; Structural stability; Sloping lands; Laos.

1. Introduction

An understanding of the impact of human activities on bio-geochemical cycling is fundamental to determine, for instance, the implications of changing soil properties on future yields and food security. The extent of human-induced soil degradation is so alarming that the acquisition of new scientific knowledge is of even greater importance. The effect of rapid changes in land-use on water and soil resources in the tropics caused by demographic, economic, political and/or cultural mutations is well documented. Changes in land-use patterns such as deforestation of natural forests and/or inappropriate use of terrestrial lands are considered as having notable effects on water supply, water quality, soil erosion and soil degradation (Ingram et al., 1996). One of the consequences of the conversion of the tropical rainforests to pastures or cultivation is a decrease of the porosity of the topsoil where organic matter and nutrients concentrate. This generally leads to a decrease in infiltration (Husain et al., 2002) inducing more runoff, nutrient leaching and erosion responsible for an important reduction of on-site fertility (i.e., soil degradation) as well as off-site consequences (flooding, decrease in groundwater recharge, eutrophization hazards, water pollution by heavy metals and pesticides, fill of valley bottoms or reservoirs). All these on- and off-site effects may dramatically jeopardize the future of natural ecosystems and the economic development of societies.

In sloping lands of the tropics, the main traditional agricultural practice consists of shifting cultivation. In shifting cultivation, the land management leads to successive periods of crop and fallow. This non-intensive practice is presumed to preserve the soil fertility in the long term (Sanchez and Hailu, 1996) due for instance to the improvement of nutrient cycling,

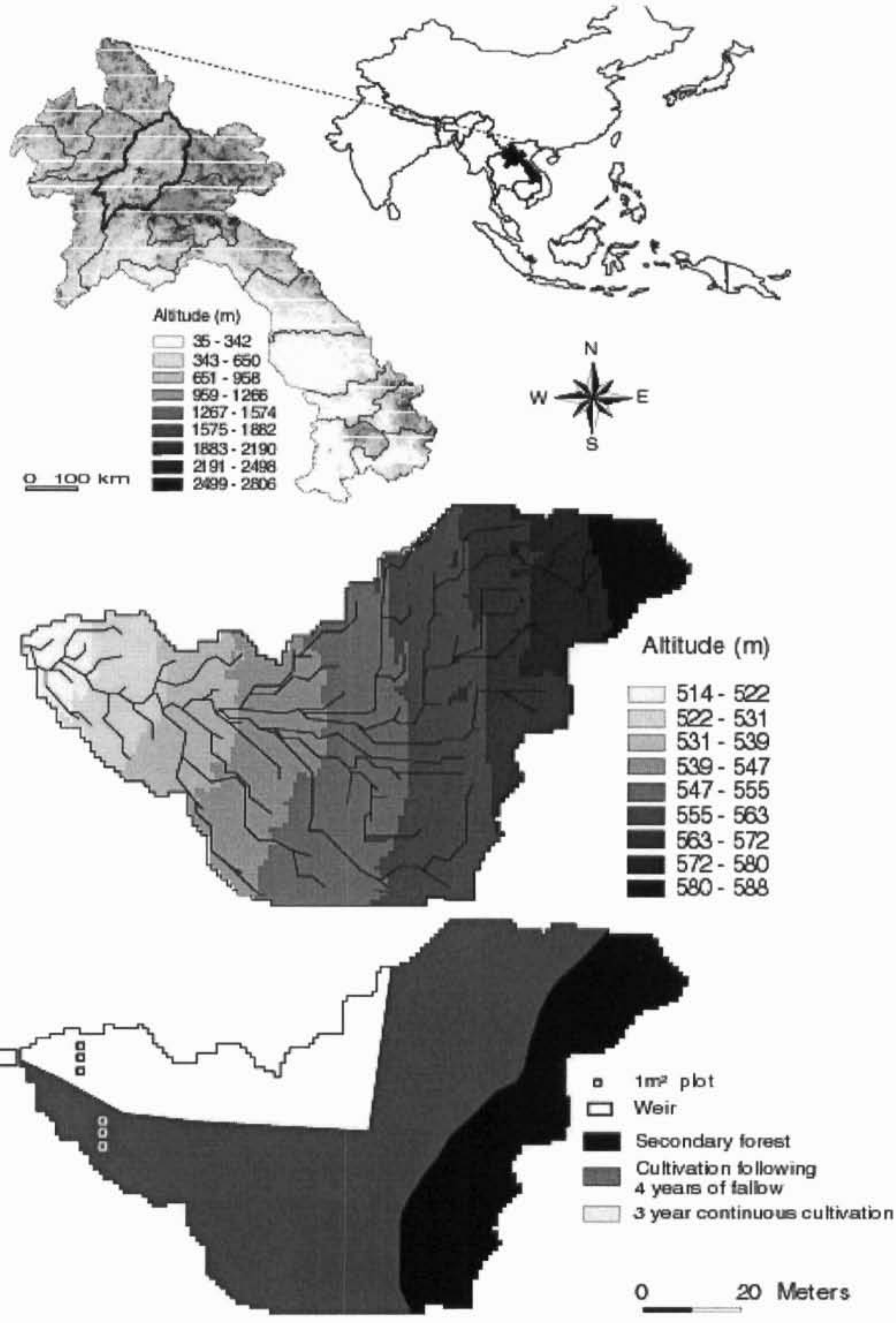

Figure 1a Location of the study catchment within the Luang Prabang province (Laos). Topographic conditions and estimated flow pathways from the digital elevation model with a 5-m mesh. Land-use type and history and position of microplots for the evaluation of runoff, sediment and carbon losses.

as shown in Northern Vietnam by Fagerstrom et al. (2002). Nowadays, in many sloping lands of the tropics, the shifting cultivation cycle (i.e., the time period between two successive clearing/cropping phases on the same site) is being shortened to 3-5 years whereas ecological sustainability may require a minimum fallow period of at least 10 years (Sanchez and Hailu, 1996). Such dramatic reduction or suppression of fallows may have direct consequences upon water erosion at the catchment level.

The direct impacts of fallow on the reduction of soil water erosion over catchments are well documented. Among available studies, Gafur et al. (2003) in Bangladesh indicated that the sediment loss from a catchment under fallow was about 0.3 kg m^{-2} yr^{-1}, that is, 6 times smaller than under cultivation. The median peak discharge under successive crops increased by a factor 7 and annual runoff increased by 16%. In Western Africa, results from runoff plots and lysimeters revealed C losses by erosion and leaching between 10 and 1900 kg C ha^{-1} yr^{-1}, depending on vegetal cover and annual rainfall (e.g., Roose and Barthès, 2001). In Cameroon, soil losses amounting to 0.12 kg m^{-2} yr^{-1} under fallow and 10.9 kg m^{-2} yr^{-1} under cultivation have been reported (Ambassa-Kiki and Nill, 1999). The reasons for lower erosion under fallow than under cultivation may be due to the decrease in detachment rate (reaching 64%, Mamo and Bubenzer, 2001) and the increase in infiltration (Husain et al., 2002).
But so far, there is still a need for quantitative data on the impact of the reduction of fallow duration on soil erodibility and C losses during the cropping period of the shifting cultivation cycle.

The main objective of this study was to evaluate runoff, soil and soil organic carbon (SOC) losses within a small sloping-land catchment of Laos under shifting cultivation. A second objective was to assess the impact of the fallow period on water erosion. The study was conducted in the mountainous areas of Northern Laos where shifting cultivation covers one third of agricultural land (Dufumier and Weigel, 1996). It involved simultaneous evaluations of water, sediment and C erosion at the outlet of a 0.6-ha catchment and on 1-m^2 microplots under upland rice cultivation following a 4-year fallow period (RF4) or under 3-year continuous upland rice cultivation (RF0). Measurements were compared to the soil aggregate stability (e.g., Le Bissonnais and Arrouays, 1997, and Barthès and Roose, 2002).

2. Materials and methods

Site

The study site, a 0.6-catchment, is located within a hillslope of northern Laos (Luang Prabang province). The average annual rainfall over the last thirty years is 1403 mm. The mean annual temperature is 25°C. Two distinct seasons characterize the study site: a wet season from April to October, and a dry season from November to March. The study hillslope is 170 m long with a convexo-concave shape (Figure 1). Altitudes range from 505 m in the streambed to 584 m at the summit. The mean slope gradient is 46%. At downslope position, average slope gradient is 30% with values from 5 to 33%. Values first increase in the upslope direction to reach a mean of 54% midslope and afterwards decrease to 25% at the summit. Within this hillslope, a permanent gully stretches out perpendicularly to the contour lines from the footslope to the midslope position. A weir constructed backslope this gully defines the catchment outlet (Figure 1). Field observations performed over the catchment indicated that

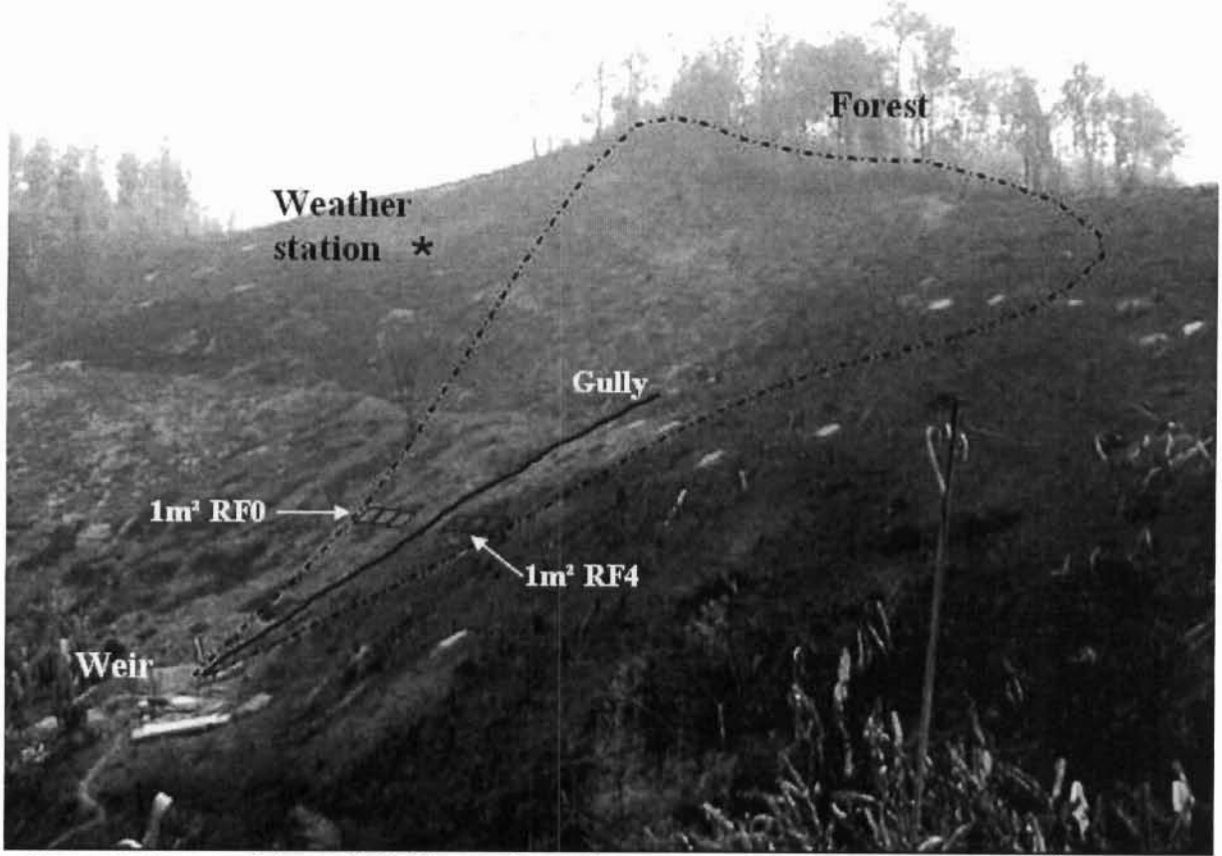

Figure 1. Picture of the study 0.6-ha catchment from the opposite hillslope on April 11th, after clear cut and burning. Position of the weather station, the weir at the outlet of the catchment and the three 1-m² microplot replicates under continuous cultivation (RF0) and under cultivation following a 4-year fallow (RF4).

the geological substratum is mainly constituted by argilites, siltstones and fine-grained sandstone from Permian to Upper Carbonifer. Soils developed from these bedrocks have a spatial distribution mainly controlled by the topography. Alfisols are the most representative soils within the catchments. They comprise all the surface area with crops. Alfisols are deep (from 2.5 to 4.5 m) clayey soils marked by a typical argillic B sub-surface horizon with clay films (thickness ≥ 1 mm). Due to erosion, this argillic horizon frequently outcrops at the soil surface. With increasing erosion rates, especially in the upslope direction, the argillic horizon disappears and soils become Inceptisols.

Land-use and land management

This catchment is representative of the slash and burn systems of South-east Asia without inputs. In particular it shows the effect of the gradual reduction of the fallow period from 10-15 years in the seventies to 2-5 years now, and the gradual encroachment of continuous cultivation on the whole catchment area (Figure 1 and 2). Land-use is predominantly composed at 80% of rotations between crops (mainly rice, *Oryza sativa*, and possibly maize, *Zea mays*, and Job's tear, *Coix lacryma Jobi*) and grassy/woody fallows. Forest is less than 20% of the whole catchment area. Upland rice and Job's tears are the most common crops. On hillslopes, crops are generally located at backslope and midslope positions whereas the slope summits are under forest and the bottomlands under tree plantations. The first management operation generally occurring from March to April consists in the burning of the land. The soil preparation for sowing consists in a manual and shallow tillage (0-2 cm) using a hoe. Afterwards the agricultural parcels are manually sowed and weeded throughout the growing season, until the harvest. The observations were carried out in 2002. Within this catchment, two contrasting land-use histories existed site by site with 4-year natural woody/grassy fallow period (RF4) and 3-year continuous upland rice cultivation (RF0). It was thus possible to evaluate the impact of the fallow period on the runoff, sediment and C losses since these two situations showed similar geological substrate (schist), slope angle (45%), slope position (backslope), orientation (West), soil type (Alfisols), land-use (upland rice) and land management. These two situations have been submitted to slash and burn at least since 1960 and to similar land-use and management with alternations between upland rice cultivation (2-3 years) and periods of natural fallow (5-6 years). The RF4 treatment was clear cut on March 10th. Both treatments were burned on March 22nd. Sowing occurred on May 15th. Each plot was weeded at the same time on June 19th, August 1st and 27th. For weeding, plots were shallowly tilled (0-2 cm) by the farmers with a hoe.

Evaluation of water erosion

During the 2002 rainy season, runoff rate and amount, sediment and C losses were measured both at the catchment outlet and on 1-m² plots. At the catchment outlet, a weir was constructed and automatic water level recorder and water sampler were installed for the estimation of water, sediment and C losses. For each land-use history, three bounded 1-m² microplots, each separated by two metres, were installed. Metal borders bounding the microplots were inserted in the soil to a depth of 0.1 m, just after the burning operation. Field measurements were carried out from May 15th, 2002, to November 3rd, 2002, the period during which rainfall occurred. After June 5th, measurements were considered to occur under conditions of steady-state soil loss because no significant soil cracking and rills were observed within the plots. For each rainfall event, rainfall characteristics such as rainfall amount and maximum or average rainfall intensity were estimated using an automatic raingauge with a 6-min step. After each rainfall event, the runoff amount from each microplot replicate was measured and an aliquot was collected and oven-dried to estimate sediment concentration and sediment discharge. In addition, soil surface features including crusting and soil surface coverage were evaluated visually every week. The soil surface roughness was quantified monthly using a laser device at each plot according to a 5-cm regular grid. A total of 210 samples were collected for 35 rainstorms.

Soil sampling and soil and sediment analyses

At the end of the rainy season and after the harvest of the rice, a soil profile was described for each treatment. The following parameters were measured: (i) the number, type (Soil Survey Staff, 1999) and thickness of horizons (including loose saprolite); (ii) the moist Munsell chroma and value; (iii) the structure and main features; (iv) texture; (v) bulk density; and (vi) organic C content. The bulk densities were estimated by the volumetric method using 250-ml volume cylinders. The measurement of organic C contents were performed following the wet oxidation techniques of Heanes (1984) using the reducing nature of soil organic matter to transform some dichromate ions added to samples to trivalent Cr^{3+} species. This method is directly derived from the original Walkley method where oxidisation of organic C is achieved using only heat of reaction and dilution. Because this Walkley method may underestimate organic C content (especially when high proportion of black C from slash and burn practices occurs) the Heanes technique, which involves a hot plate digestion stage, was selected for organic C determination. Before the determination of organic C, the samples were oven-dried at 105°C for 24 h and subsequently sieved at 2-mm. To estimate the annual eroded C at the catchment outlet and from the 1-m² plots, a determination of organic C content of sediments was performed for the main rainfall event of 2002 and for an additional set of four events randomly selected over the range of 35 events. The mean organic C content was afterwards used to compute the annual organic C losses.

Evaluation of the soil structural stability

The evaluation of the soil structural stability of RF0 and RF4 treatments was performed using soil aggregates collected on May 5th (before the rainy season and just after the burning of the crop or fallow residues) at a systematic location over the plot boundary. A large quantity of soil (around 5 kg) was collected from the 0-5 cm layer and aggregates 3-5 mm in size were obtained by dry sieving. These aggregates represented respectively 91% and 93% of the total soil weight for RF0 and RF4. Before measurements, the aggregates were oven-dried at 40°C during 24 hours. An evaluation of the C content of the soil samples was performed using the Heanes method (1984). The Le Bissonnais laboratory test (Le Bissonnais, 1996) is based on a combination of three treatments, each corresponding to different wetting conditions and energy inputs: fast-wetting, slow-wetting, and mechanical breakdown. The fast-wetting test consisted of the gentle immersion of 5-g sub-samples of dried aggregates in 50-ml deionized water. The second operation, 10 minutes later, consisted of the collection of the aggregates after the water had been removed by a pipette. For slow-wetting, a 5-g sub-sample of dried aggregates was put on a filter paper and then wetted by capillarity on a suction table at a pressure of 0.3 kPa. Residual aggregates were collected after 30 min. For mechanical breakdown, a 5-g sub-sample, immersed first in ethanol for 10 min, was placed in a flask with 50 ml of deionized water and made up to 250 ml with water and afterwards rotated end-over-end 10 times. After 30 min, the excess water plus the suspended particles were removed using a pipette. The residual material was finally collected. Subsequently, the size distribution of the aggregates was evaluated. To do so, aggregates were put on a 50-µm sieve immersed in ethanol and agitated five times. The fraction with a diameter lower than 50 µm was weighed after a 48-h oven-drying at 105°C. The remaining fraction was collected, oven-dried at 105°C for 48 h, and then submitted to dry-sieving through a column of six sieves with mesh sizes of 2, 1, 0.5, 0.2, 0.1 and 0.05-mm. 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: $MWD = \frac{\sum(x_i \times w_i)}{100}$ with x_i the mean intersieve size and w_i the percentage of particles left on each i sieve. Additional measurements of texture and organic C were performed for each plot on the 3-5 mm aggregates.

3. Results

The soil characteristics at the two treatments

The soil profiles of the two treatments showed a surface organo-mineral horizon with a thickness from 2 to 10-cm. The topsoil texture was clayey, clay proportion estimated from six replicates averaging 53% (Table 1). Few differences in topsoil texture existed between the two treatments. RF0 showed values ranging from 47 to 59% whereas differences between replicates were slightly lower for RF4 with a clay content from 53 to 57%. For both RF4 and RF0, fine silts represented 27% of total soil. Sands showed a mean account lower than 12%. On average, A horizons showed similar organic C contents and densities for the 0-5 cm layer. The mean organic C content from the three replicates was 22.5 g C kg^{-1} at RF0 and 22.7 g C kg^{-1} at RF4 (Table 1). No significant differences were observed between these two treatments for black C and mineral-bound C (data not presented). The mean bulk density was 0.93 in both cases with values ranging between 0.88 and 0.98. As a consequence, the mean organic C stocks computed for the 0-5 cm layers were around 1050 g C m^{-2} for both RF0 and RF4. Areas where A horizons were the thickest were marked by a homogeneous reddish brown matrix (5YR4/3) whereas some more reddish spots (5YR4/4) were observed within thinner parts. The structure was blocky sub-angular. Numerous fine, dead and non-deviated roots characterized the RF0, and medium to coarse roots were observed in the RF4 treatment. Just after sowing, a greater proportion of free aggregates on the soil surface was observed at RF4 than at RF0 (40% in average against 15%). In both cases, stable aggregates were

Table 1. Main soil characteristics (texture in five classes; organic C; bulk density; C stock) of the 0-5 cm layer for three replicates of the two treatments: continuous cultivation (RF0); cultivation following a 4-year fallow (RF4). Houay Pano catchment (Luang Prabang province, Laos).

	RF0				RF4			
	1	2	3	Mean	1	2	3	Mean
Soil texture (g kg^{-1})								
Clay (< 2 µm)	499	594	470	521	575	534	539	549
Fine silts (2-50 µm)	273	255	274	267	275	267	269	270
Coarse silts (20-50 µm)	94	66	107	89	57	85	84	75
Fine sands (50-200 µm)	62	50	76	63	42	43	42	42
Coarse sands (200-2000 µm)	72	35	73	60	51	71	66	63
Organic C content (g C kg^{-1})	24.3	15.3	28.1	22.5	21.8	24.3	21.9	22.7
Bulk density	0.98	0.88	0.92	0.93	0.91	0.97	0.91	0.93
Organic C stock (g C m^{-2})	1191	673	1293	1046	992	1179	996	1056

relatively coarse (6.5 mm in mean) but slightly coarser at RF0 than at RF4 (6.9 vs. 5.3 mm in average). Even after sowing, some crusted surface remained. RF4 showed 30% of crusted surface against 10% for RF0. In both cases, no particle sorting was observed. Additional soil surface observation indicated that the crust surface of RF4 was partly covered by algae (from 5 to 40% of the whole crust surface area) and occasionally by mosses (5% at a single replicate). At both treatments, punctual biological features remained after slash and burn on the soil surface. Stumps were on average 8 meters apart. Finally, some compacted earthworm casts embedded in the crust were observed at RF4. Such observations were not seen at RF0. The limits of the underlying mineral and clayey horizon were diffuse. This horizon showed a reddish matrix (5YR4/3) with numerous vertical and elongated browner spots, probably

Table 2. General statistics (minimum, Min.; maximum, Max.; average, Av.; standard deviation, SD) for runoff (R), sediment concentration (SC) and soil losses (SL) for the 35 rainfall events of 2002. Two treatments (continuous cultivation, RF0; cultivation following a 4-year fallow, RF4) and three replicates are considered for microplots. General statistics on eroded organic carbon (EOC) at the microplot and catchment levels computed from five randomly selected events, and total EOC computed over 2002. Houay-Pano catchment (Luang Prabang province. Laos).

	R rate mm mm^{-1}	R amount l m^{-2} yr^{-1}	SC g l^{-1}	SL g m^{-2}	EOC g C kg^{-1}	EOC g C m^{-2}
Catchment level						
Min.	0.001		0.1	1	17.4	0.0
Max.	0.062		133.0	116	32.3	3.1
Av.	0.017		25.1	12	26.1	0.3
SD.	0.018		29.6	27	5.6	1.2
Sum		17.2		431		11.2
RF0 microplots						
Min.	0.035		0.3	5	21.6	0.0
Max.	0.731		36.5	1383	44.7	48.5
Av.	0.218		9.4	60	35.6	2.2
SD.	0.168		7.4	249	12.3	16.2
Sum		223.1		2114		75.2
RF4 microplots						
Min.	0.039		0.2	5	31.3	0.0
Max.	0.727		28.6	422	33.0	18.6
Av.	0.197		4.8	28	32.1	0.9
SD.	0.142		4.7	76	0.8	9.8
Sum		202.1		975		31.2

resulting from the mixing of surface organo-mineral material by bioturbation. In both treatments, the sub-surface horizon with a blocky to columnar structure showed numerous clay films on both vertical and horizontal surfaces of peds but little porosity. Underlying horizons were reddish (10YR4/3) and red (5R4/6) to a depth of 1.5 m, becoming structureless at increasing depth.

The runoff, sediment and carbon losses during the 2002 rainy season

The 2002 rainy season, from May 25th to October 25th, was characterized by a total of 35 rainfall events with an amount of 1023 mm. Minimum and maximum rainfall amounts were 4.5 and 162 mm, respectively, with a median at 17 mm. These events showed a median maximum rainfall intensity in 6 min of 40 mm h^{-1} with values ranging between 5 and 135 mm h^{-1}. The most extreme event occurred on July 20th (Figure 2). It produced a total rainfall amount of 132 mm with a maximum intensity of 100 mm h^{-1} in 6 min. Four main rainfall events occurred towards the end of the growing cycle, on September 9th, October 2nd and 6th, and November 3rd, which ended the rainy season. Results of water, sediment and C losses for these 35 rainfall events are presented in Table 2 and Figures 3 to 5. At the catchment level, the mean annual runoff rate (R) was 0.017 mm mm^{-1}, with values for individual events ranging from 0.001 to 0.062 mm mm^{-1} (Table 2). During the five first events, the runoff coefficient was very low and only a slight increase of the cumulative amount occurred (Figure 2). No sediment and C erosion occurred during this period. Then, runoff and soil losses progressively increased up to event number 30 with the exception of event number 23. At the end of the rainy season, the total runoff amount was 17.2 l m^{-2} yr^{-1} and the total sediment losses were 431 g m^{-2} yr^{-1} (Figure 2). The events under study were characterized by a mean annual sediment concentration of 25.1 g l^{-1}, with a maximum value of 133 g l^{-1} on July 20th. The mean annual C concentration in sediments, computed from the 5 selected events, was 26.1 g C kg^{-1}, and the computed C losses were 11.2 g C m^{-2} yr^{-1}. On the microplots, mean annual runoff rates and total runoff amounts were slightly higher for RF0 than for RF4 (0.218 vs. 0.197 mm mm^{-1}, and 223 vs. 202 l m^{-2} yr^{-1}, respectively; Table 2 and Figure 3). However, mean sediment concentration was twice greater for RF0 than for RF4 (9.4 vs. 4.8 g l^{-1}, $p < 0.05$), and as a consequence, total soil losses were twice greater for RF0 than for RF4 (2.1 vs. 1.0 kg m^{-2} yr^{-1}, $p < 0.05$; Figure 4). Slightly greater mean sediment C content for RF0 than for RF4 (35.6 vs. 32.1 g C kg^{-1}) also resulted in twice greater total C losses for RF0 than for RF4 (75.2 vs. 31.2 g C m^{-2} yr^{-1}, $p < 0.05$). Thus fallow prior to cultivation reduced mean runoff and mean sediment C content by 10%, but reduced mean sediment concentration and total soil and C losses by 50-60%. The preceding fallow period significantly decreased not only the overall soil erosion but also the preferential erosion of C since the mean organic C enrichment ratio of sediments decreased from 1.6 (RF0) to 1.4 (RF4) as compared with the 0-5 cm soil layer, and from 1.7 (RF0) to 1.5 (RF4) as compared with the 0-10 cm soil layer (data not presented). In 2002 the amount of eroded C represented respectively 7.2 and 3.0% of organic C stocks for the 0-5 cm soil layer in RF0 and RF4. Over the period under study, no significant differences in soil surface coverage were observed between the two treatments (Figure 5).

The mean cumulative runoff and sediment losses at the two treatments studied during the rainy season are presented in Figures 4 and 5. At the very onset of the rainy season (from May 25th to June 6th) and under conditions of bare soil (soil surface coverage lower than 10% at both situations, Figure 5) and with low sized events, few differences existed between the two treatments. Differences became significant from the 10th event. Most of the erosion produced in 2002 occurred in the middle of the rainy season, especially during the most extreme event of July 20th. This event accounted for 65 and 43%, respectively, of the total annual soil losses on RF0 and RF4. In addition, during this major event for which the average soil surface coverage was 20% in both situations, greater soil erosion was observed on RF0 than on RF4 (Figure 4). Afterwards, the water erosion remained noticeable even with greater proportion of soil surface coverage, which increased from 20% on July 20th, 30% at mid August, 40% at mid September, and to 56% for RF0 and 72% for RF4 for the last rainfall event of November 3rd. The two treatments did not show significant differences in soil roughness (data not presented).

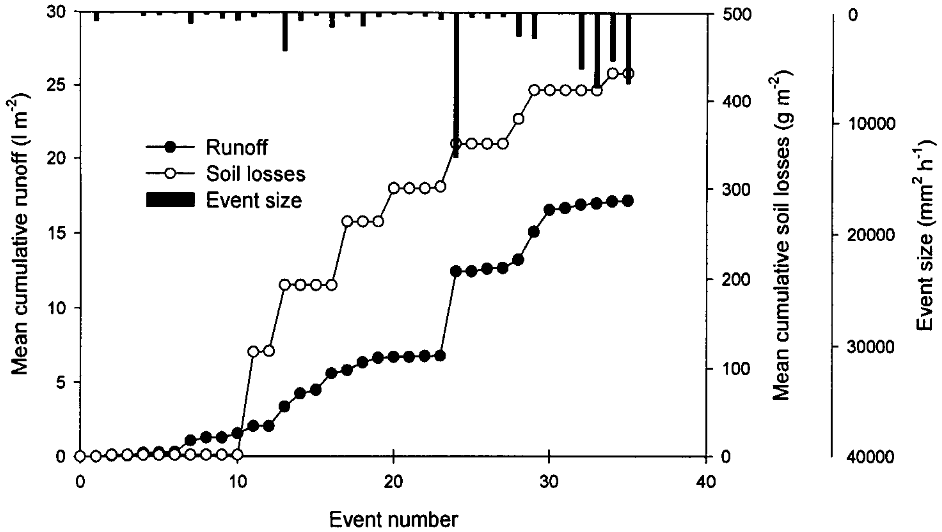

Figure 2. Mean cumulative runoff and soil losses at the 0.6-ha catchment outlet during the 2002 rainy season as a function of the rainfall event size.

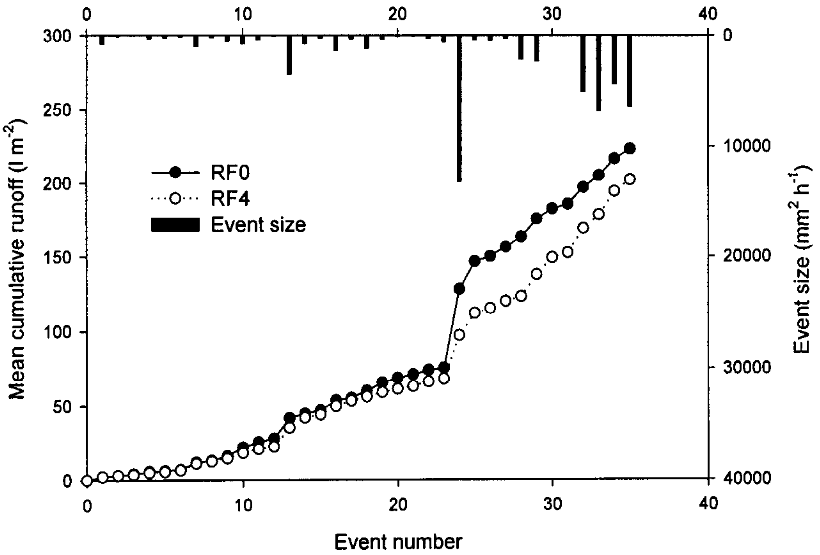

Figure 3. Mean cumulative runoff amount during the 2002 rainy season estimated from three 1-m² microplot replicates under continuous cultivation (RF0) and under cultivation following a 4-year fallow (RF4).

The evaluation of the soil structural stability

For each microplot replicate, the mean MWD and its standard deviation were computed from three laboratory replicates. The MWD for all replicates varied from 2.36 to 3.19 mm. This, according to Le Bissonnais and Arrouays (1997) working in temperate areas, is considered as being relatively high. Mean values were slightly higher for RF4 (3.13 mm) than for RF0 (2.94 mm). Greater and significant differences between treatments were observed for mechanical breakdown, in which greater disaggregation occurred for RF0. These results demonstrated that there was lower disaggregation susceptibility after four years of fallow than after continuous cultivation. Furthermore, they showed that this was due to the aggregate protection from raindrop impact provided by 4 years of fallow. However, fallow provided few benefits in these Alfisols in terms of the aggregate slaking caused by increased air compression, and the breakdown due to swelling tensions or physico-chemical dispersion.

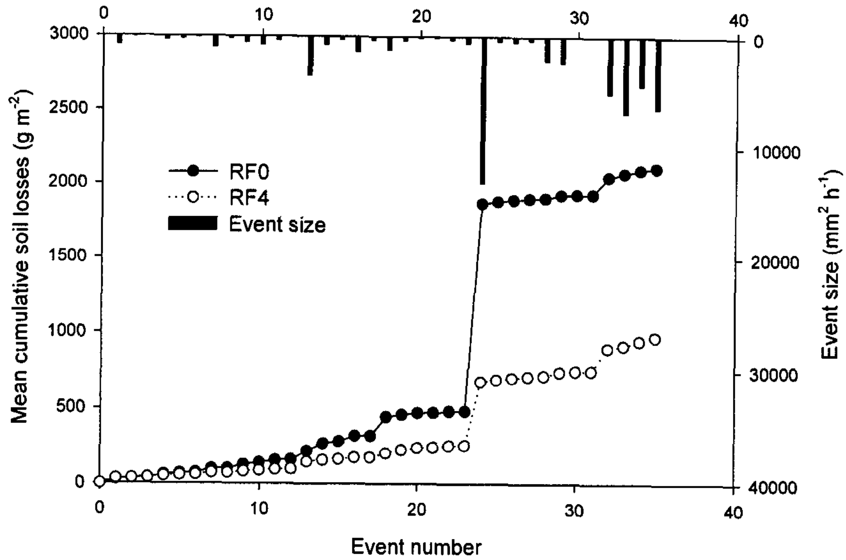

Figure 4. Mean cumulative sediment losses during the 2002 rainy season estimated from three 1-m² microplot replicates under continuous cultivation (RF0) and under cultivation following a 4-year fallow (RF4).

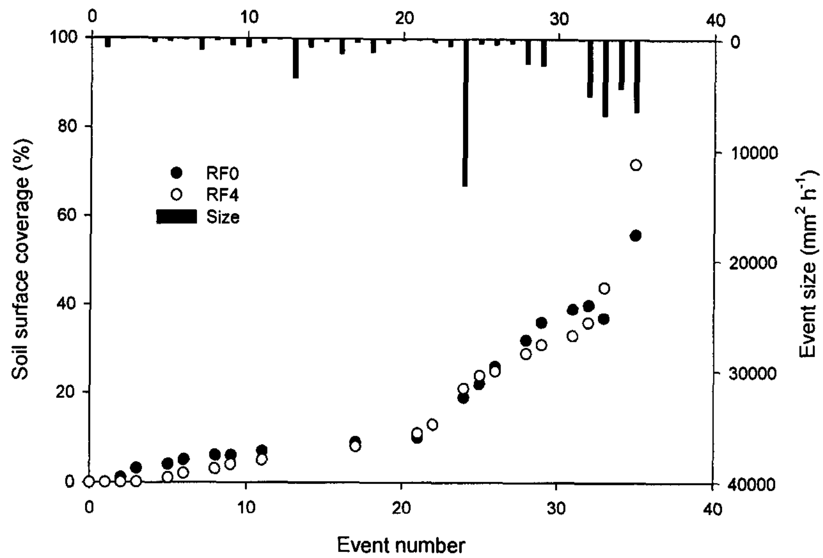

Figure 5. Soil surface coverage by vegetation including crop and weed under upland rice cultivation (RF0) and cultivation following a 4-year fallow (RF4). Mean of three field replicates.

4. Discussion

Within the catchment, a comparison between water erosion on plots differing only in the presence of a fallow period revealed a greater erosion under continuous cultivation than under cultivation following a fallow period. The preceding fallow period decreased the total yearly runoff amounts by 10% only while it reduced the total soil erosion by 50%. Such differences between plots showing similar soil characteristics and properties, topographic conditions, orientation and soil surface coverage mainly occurred during the strongest event of the rainy season. Afterwards, runoff was surprisingly greater for RF4 than for RF0, but this did not result in greater soil erosion in RF4 than in RF0. Further investigations should be performed to understand such a temporal behaviour. The lower soil erodibility after a fallow period may first be explained by a greater resistance of the soil aggregates to mechanical breakdown. Such a greater resistance was as well not explained by differences in soil structure, clay and soil C content of aggregates as previously observed (Le Bissonnais and

Singer, 1993; Le Bissonnais and Arrouays, 1997; Chenu et al., 2000; Malam Issa et al., 2001). No differences existed between RF0 and RF4 situations regarding the soil C content and stock, though the RF4 situation was expected to have greater C content and stock due to enhanced possibilities of physical C sequestration under fallow (Feller and Beare, 1997; Larré-Larrouy et al., 2004). One possible explanation for the greater aggregate resistance after fallow may come from the increased binding and gluing of aggregates or the organic C quality (Chenu et al. 2000; Malam Issa et al., 2001). This should be further investigated. Among the other possible explanations for the lower soil erodibility after a fallow period, the greater proportion of algae and mosses observed on the soil surface could be cited. These biological features may afford physically protection to the soil. Such an hypothesis seems plausible since differences in water erosion mainly occurred during the first half of the rainy season and especially during its strongest event when algae and mosses were present on the soil surface, and no differences occurred between the two treatments in the second half of the rainy season after the removal of these biological features by the rainfall. But further investigations need to be performed to establish a direct relation between the fallow period, such soil surface features and the overall water erosion. Finally, these results indicated that the stability of topsoil aggregates seems therefore to be a valuable predictor of water, sediment and C losses from water erosion, confirming previous investigations performed for instance by Barthès et al. (2000) using plots installed in Benin, Cameroon and Mexico under different climate (400- to 1600-mm annual rainfall), soil type (sandy clay loam Nitosol, loamy sand Ferralsol, loamy Regosol), and management (from savanna to long-duration mouldboard ploughing).

5. Conclusion

This study allowed the quantification of runoff, soil and SOC losses within a small sloping-land catchment of Laos submitted to shifting cultivation. In addition, some of the processes involved in inter-rill erosion were identified by using a combination of laboratory and field surveys. The major conclusion is that soil erosion and especially eroded C was relatively small at the small catchment level due to the high infiltration capabilities limiting the transport of sediments. At this level, erosion was transport-limited. Although at the microplot level soil detachment and runoff production were high, this was not apparent at the catchment outlet, suggesting the existence of high infiltration at punctual locations: gullies and biological features such as roots and stumps remaining after slash and burn. Furthermore, these biological features provide habitats, nutrients for a range of living organisms, potentiating infiltration pathways. Thus fallow periods reduce soil erosion by both limiting the detachment capacity and increasing infiltration at punctual locations.

The second conclusion is that a fallow period within a shifting cultivation cycle affords protection from soil erosion, locally, at the microplot level, by limiting soil detachment due to raindrop impact through a possibly greater aggregate stability and soil protection by biological features such as algae and mosses.

Finally, it is apparent that further investigations are necessary in order to first confirm these results and second to define an optimal duration of the fallow period, depending for instance on the soil conditions. Even though these results allow to quantify soil erosion of clayey tropical soils on sloping lands, further researches are needed to better understand the processes and mechanisms involved in their erosion by water and to take more appropriate decisions for land management.

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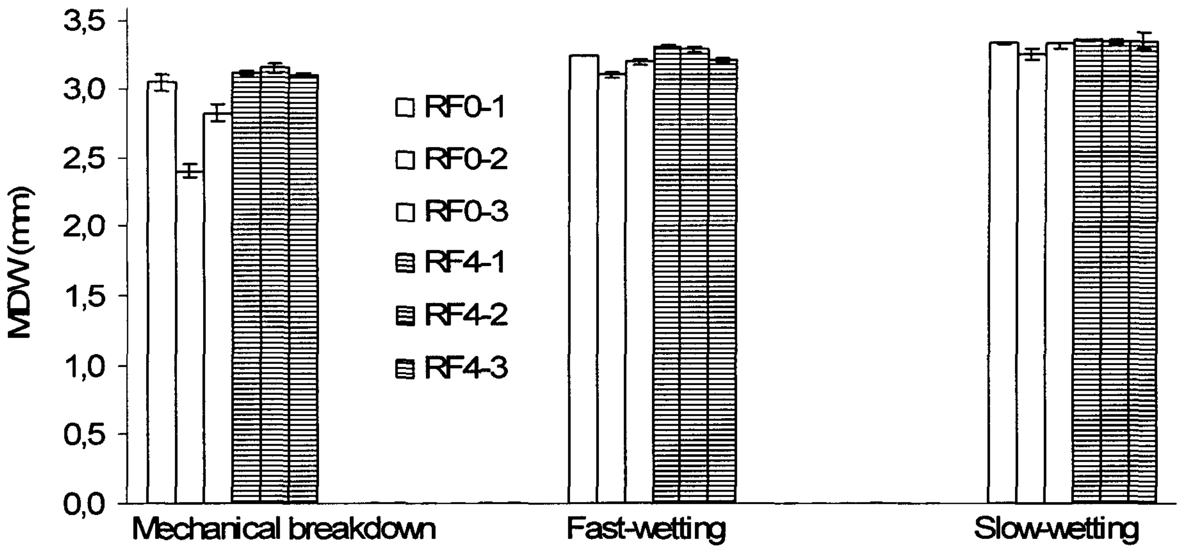

Figure 6. Mean weight diameter (MWD) of stable aggregates in 0-5 cm soil samples under continuous cultivation (RF0) and cultivation following a 4-year fallow (RF4) including three field replicates (1. 2. 3); the aggregation test included three treatments (mechanical breakdown, fast- and slow-wetting) and was carried out on three laboratory replicates for each sample (mean and standard deviation).

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