How Shifting Cultivation Limits Runoff, Sediment and Carbon Losses on Sloping Land

by Vincent Chaplot

Due to increasing land pressure in northern Laos, the duration of the traditional fallow period in shifting cultivation is being dramatically shortened. This reduction is environmentally damaging in terms of water erosion and soil degradation. The main objective of this study was to evaluate the effect of different fallow periods on the runoff, sediment and carbon losses within a small sloping catchment. A second objective was to assess the mechanisms involved in the erosion of clayed soils. Longer fallow periods decreased not only overall soil erosion but also carbon erosion, due to a greater resistance to the mechanical breakdown caused by raindrops. These results demonstrate the importance of the fallow period in the limitation of soil water erosion: if shifting cultivation in the uplands is replaced by continuous agriculture, environmental damage will increase.

The effect of rapid changes in land use on water and soil resources in the tropics caused by demographic, economic, political and/or cultural shifts is well documented. In sloping lands in the tropics, the main traditional agricultural practice consists of shifting cultivation, with successive periods of crop and fallow. This non-intensive practice is presumed to preserve soil fertility in the long term (Sanchez and Hailu 1996), for instance due to the improvement of nutrient cycling as shown in northern Vietnam by Fagerstrom et al. (2002). Nowadays, in many tropical sloping lands, the shifting cultivation cycle (i.e. the time period between two successive clearings/croppings on the same site) is being shortened to three to five years, whereas ecological sustainability may require a minimum fallow period of at least ten 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) indicated that in Bangladesh the sediment loss from a catchment under fallow was about six times smaller than under cultivation. 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).

However, there is still a need for quantitative data on the impact of the reduction of fallow duration on soil and carbon losses during the cropping period of the shifting cultivation cycle. The main objective of this study was to evaluate the effect of different fallow periods on the runoff, sediment and carbon losses within a small sloping catchment. A second objective was to assess the mechanisms involved in soil erosion variations of clayed soils by testing the structural stability of aggregates (e.g. Le Bissonnais and Arrouays 1996; Barthès and Roose 2002).

The study was conducted in 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 carbon erosion on 1m² microplots with a short-range variability of environmental factors, and at the outlet of a 0.6 ha catchment. Measurements of field erosion were performed on microplots under cultivation following a four-year fallow period (F4) and under continuous cultivation (F0). In addition, soil aggregate stability was evaluated at the laboratory.

The results are expected to increase knowledge on controlling processes and factors of water erosion, and to assist decisions on land management and land use planning. Furthermore, these results will allow the calibration of the vegetation factor in predictive models of water erosion such as the USLE or USLE-M (Wishmeier and Smith 1978; Kinnell 2001).

Materials and Methods

The study site, a 0.6 ha catchment, is located in Luang Prabang province. The average annual rainfall over the last thirty years was 1,403 mm. The mean annual temperature was 25°C. Two distinct seasons characterise the study site: a wet season from April to October and a dry season from November to March. Altitudes over the catchment, estimated from a 5 m digital elevation model (DEM) generated using a theodolite, ranged from 514 to 588 m. A permanent central gully stretches out from the catchment outlet to the first third of the hillslope.

Dramatic reduction or suppression of fallows may have direct consequences upon water erosion at the catchment level

The catchment is representative of the slash-and-burn without inputs systems of southeast Asia. In particular it shows the effect of the gradual reduction of the fallow period from ten to fifteen years in the 1970s to five to two years now, as well as the gradual encroachment of continuous cultivation on the whole catchment area. Land use is predominantly rotating land (80%) supporting shifting cultivation. Forest is less than 20% of the whole catchment area. Upland rice (*oryza*) and Job's tears (*Coix lacryma Jobi*) 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.

Site Description

Runoff, sediment and carbon losses were measured during the 2002 rainy season at the catchment outlet and on 1m² plots under a three-year continuous monoculture and under cultivation following a four-year fallow (F0 and F4 respectively).

Field measurements were carried out from May 15th, 2002 to November 3rd, 2002. 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. At the catchment outlet, a weir was constructed for the estimation of runoff. Automatic samplers were installed for sediment collection and thus for the estimation of sediment and carbon losses. It was possible to minimise variations in environmental factors (e.g. soil types, geology, topography) by selecting a single catchment where two contrasting fallow durations existed. Thus, runoff, soil, and carbon losses were monitored using three bounded 1 m^2 microplots per land-use history. Microplots were located downslope of the catchment on Alfisols. Their mean slope gradient was 45%. Two metres separated each microplot. The F4 treatment was clear cut on March 10th. Metal borders bounding the microplots were inserted in the soil to a depth of 0.1 m, just after the burning operation of 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 shallow tilled by the farmers. Soil surface features and roughness were quantified visually and using a laser at each plot according to a 5 cm regular grid.

For each rainfall event, characteristics such as rainfall amount, maximum or average rainfall intensity were estimated using an automatic raingauge with a 6-min step. After each rainfall event, the total runoff from each microplot replicate was measured and an aliquot was collected and oven dried to estimate sediment concentration and sediment discharge. A total of 210 samples were collected from 35 rainstorms.

In order to estimate carbon erosion at the catchment outlet and from the plots, additional determination of organic carbon (OC) content of sediments was performed for the main rainfall event of 2002 and an additional set of four events randomly selected over the range of 35 events. Measurement was performed following the wet oxidation techniques of Heanes (1984).

Evaluation of Soil Structural Stability

Evaluation of the soil structural stability of F0 and F4 treatments used soil aggregates collected before the rainy season in the vicinity of the microplots. Tests were performed in the laboratory following Le Bissonnais (1996). Soil samples were first collected in the field on May 5th, just after the burning of the crop or fallow residues. 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 sieving and then oven-dried at 40°C for 24 hours. The carbon content of the soil samples was evaluated using the Heanes method.

In addition to this 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 (including thickness of loose saprolite) of horizons; (ii) the moist Munsell chroma and value; (iii) the structure and main features. Additional measurements of texture, bulk densities and OC were performed for each plot from samples collected in the 0-5 cm layer at the onset of the study at a systematic location over the plot boundary. The bulk densities were estimated by the volumetric method using 250 ml volume cylinders (Anderson and Ingram 1993).

Runoff, Sediment and Carbon Losses

The 2002 rainy season, from May 25th to October 25th, produced a total rainfall amount of 1,651 mm. During this period runoff occurred at 35 events, with a total rainfall amount of 1,023 mm. Minimum and maximum rainfall amounts were 4.5 and 162 mm respectively, with a median of 17 mm. At the catchment level, the mean runoff coefficient (R) was 0.5% with values ranging from 0 to 5.7%. During the five first events, the runoff coefficient was very low and only a slight increase of the cumulative amount occurred. No sediment and carbon erosion occurred during this period. Then runoff and sediment erosion greatly increased up to event number 30 with the exception of event number 23. At the end of the rainy season, the cumulative runoff was 17 l m^{-2} and the cumulative sediment losses were 0.431 kg m^{-2}.

Sediment and carbon losses were significantly greater under continuous cultivation than on cultivation following a four-year fallow

On the microplots, the mean runoff coefficient was 25% and sediment and carbon losses were 0.045 kg m^{-2} and 34 g m^{-2} respectively. Runoff varied only slightly between the two studied fallow periods but sediment and carbon losses were significantly greater under continuous cultivation (F0) than on cultivation following a four-year fallow (F4). Fallow prior to cultivation reduced the total sediment erosion by 54%, the total carbon losses by 52%, and the mean sediment concentration and runoff by 34% and 14% respectively. The average sediment loss was more than double on F0 than on F4. The eroded sediments showed significantly higher OC content than the initial soil material. In 2002 the computed yearly eroded carbon was 46 g m^{-2} under F0 and 22 g m^{-2} under F4. These amounts represented 4.3% for F0 and 2.1% for F4 among the 0-5 cm soil layer stocks.

At the very onset of the rainy season (from May 25th to June 6th) and under conditions of bare soil and with low sized events, few differences existed between the two treatments. Differences became perceptible from the tenth 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 37% of the total annual soil losses on F0 and F4 respectively. In addition, during this major event greater soil erosion was observed on F0 than on F4.

Soil Stability

For each microplot replicate, the 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 (1996) working in Mediterranean and temperate areas, is considered relatively high. Mean values were slightly higher for F4 (3.13 mm) than for F0 (2.94 mm). Greater and significant differences between treatments were observed for mechanical break-down in which greater disaggregation occurred for F0. In addition and surprisingly, F4 produced a significantly greater proportion of particles with diameter <2 mm whereas F0 generated >2 mm aggregates. These results demonstrated that there was a 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 four years of fallow. However, fallow provided few benefits in these Alfisols in terms of the aggregate slaking caused by increased air compression or the breakdown due to swelling tensions or physico-chemical dispersion.

Discussion

The study's main objective was to evaluate soil water erosion within a small agricultural catchment of northern Laos showing different durations of the fallow period. Results at the catchment level revealed very low runoff coefficient (<1%) and moderate soil losses (0.4 kg m^{-2}) if compared with studies performed at similar scales and/or comparable environmental conditions. Gafur et al (2003) indicated that runoff from 1 ha catchments was about 20% in Bangladesh. Sediment losses in catchments under cultivation were about 1.8 kg m^{-2} y^{-1}. In Cameroon, soil losses at the small catchment scale were of 10.9 kg m^{-2} under cultivation (Ambassa-Kiki et al. 1999). The lower water erosion in northern Laos may be explained by the high infiltration possibilities in Alfisols. These infiltration possibilities may occur along slopes in local depressions or as a result of biological features such as tree stumps, root networks and macropores etc. In addition, a high infiltration level may occur within the central gully as observed by Bryan and Poesen (1989). Such a high infiltration may reduce the transport of sediment by limiting the efficiency of detachment and transport processes as proposed by Kinnel (2000) or Chaplot and Le Bissonnais (2003). Carbon losses of 11 g m^{-2} were slightly lower than those evaluated by Gregorich et al. (1998), at 13 to 49 g m^{-2}.

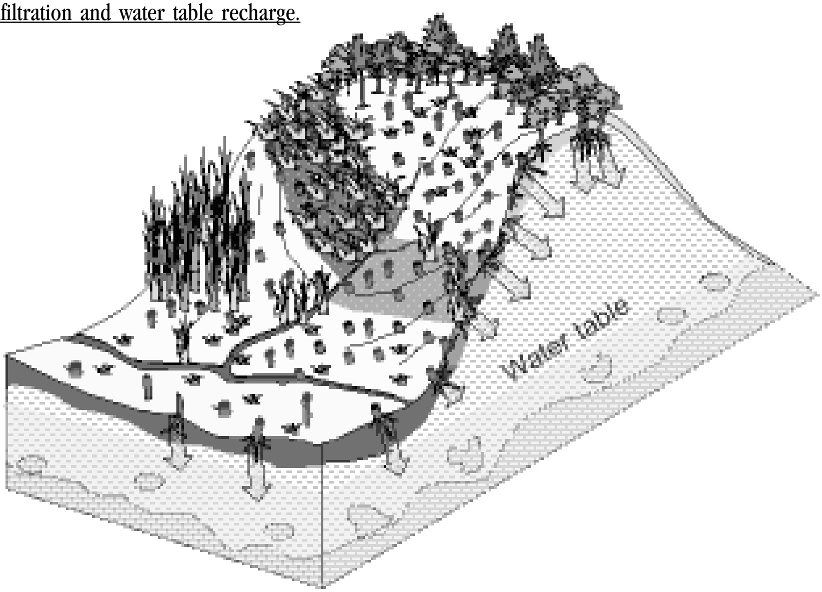
A fallow period limits soil detachment due to raindrop impact and by enhancing infiltration possibilities

At the microplot level, runoff and erosion were much higher, confirming greater infiltration and sedimentation possibilities at the catchment level as shown by Le Bissonnais et al (1998). The runoff was on average fifty times greater and the sediment and carbon loads were seven and three times greater on the microplots than at the catchment level. Within the catchment, a comparison between water erosion on plots differing only in the duration of the fallow periods revealed a greater erosion under continuous cultivation than under cultivation following a fallow period. Such a better soil protection from mechanical break-down after a long fallow period could not be directly explained by differences in the soil structure, the clay and soil carbon content of aggregates (Le Bissonnais and Singer 1993). Additional results on the stability of aggregates confirmed the overall high resistance to disaggregation of the study Alfisols. Although the two treatments with or without fallow prior to cultivation showed very stable aggregates (MWD = 2.94 and 3.13 mm, respectively), the soil aggregates from the long fallow period exhibited a greater resistance to mechanical break-down. However, although the soil aggregates were classified as very stable, soil losses were high in comparison with existing studies under temperate conditions (0.1 to 0.20 kg m^{-2} for total sediments, Chaplot and Le Bissonnais 2003) or under similar tropical conditions (0.6 to 3.3 kg m^{-2}, Janeau et al. 2003).

Conclusion

This study allowed the identification of some of the processes involved in inter-rill erosion by using a combination of laboratory and field surveys. The major conclusion is that a fallow period within a shifting cultivation cycle affords protection from soil erosion, locally, at the microplot level, by limiting the soil detachment due to raindrop impact, and at the catchment level by enhancing infiltration possibilities.

Figure 1. Modelled hydrologic functioning of a sloping-land catchment under shifting cultivation. Contribution of biological features such as roots, stumps remaining after slash-and-burn to water infiltration and water table recharge.



At the small catchment level, soil erosion was relatively low due to the high infiltration capabilities limiting the transport of sediments. At this level, erosion was transport-limited. Although soil detachment and runoff production were high at the microplot level, they were not apparent at the catchment outlet, demonstrating the existence of high infiltration at punctual locations: gullies and biological features such as roots and stumps remaining after slash-and-burn (Figure 1). Furthermore, these biological features provide habitats and nutrients for a range of living organisms, so creating infiltration pathways. Thus, fallow periods reduce soil erosion by both limiting the detachment capacity and increasing infiltration at punctual locations. The fallow period not only limits the overall soil water erosion but also increases soil fertility in the long term (Sanchez and Hailu 1996) due to, for instance, the improvement of nutrient recycling as shown in Northern Vietnam by Fagerstrom et al. (2002).

When farming sloping land, shifting cultivation is thus much more sustainable than continuous cultivation. This fact questions the logic of eliminating shifting cultivation on the basis limiting environmental damage. If shifting cultivation in the uplands is permanently replaced by continuous agriculture, environmental damage will rapidly and greatly increase since punctual features with high infiltration possibilities, such as roots, stumps and associated biological activity remaining after slash-and-burn, will all disappear. Runoff, instead of infiltrating soils, will flow down and off the hillslopes, producing more and more erosion and flooding. Finally, it is apparent that further investigations are necessary in order to establish an optimal duration of the fallow period, for instance as a function of the soil conditions. Such improved understanding will allow better soil erosion modelling, and help with taking more appropriate decisions on the management of clayey tropical soils on sloping land.

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Juth Pakai

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