Soil Erosion under Land Use Change from Three Catchments in Laos, Thailand and Vietnam

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Abstract: The systems often identified as “traditional” undergo rapid changes as a response to demographic, economic, political and cultural drivers. These transitional periods are often most critical for soil erosion. The on-site impacts of soil erosion reduce the soil chemical fertility through nutrient and organic depletion, and acid subsoil exposure. Erosion also damages the physical fertility by removing surface soil, reducing the soil depth and water holding capacity, and exposing gravel and rocks. These combined processes result in less productive soils, hence lower farm income. To obtain the initial crop yield prior to erosion, increased amounts of inputs are needed, which is most often beyond the economic capacity of the small holders. To study the impact of land use change upon erosion, concurrent case studies, as seen with a dynamic perspective, can compensate for long-term monitoring studies. This approach provides data, which can be used for prediction soil erosion based on global change scenarios. The main objective of this study was to assess the influence of the rapid change of cropping systems on water erosion from three small catchments in three countries of South-East Asia (Laos, Thailand, Vietnam), using a multidisciplinary approach. These three catchments were selected because of their similar biophysical components (very steep slopes on shales; Janeau *et al.*, submitted) and their land use intensification gradient. This investigation was conducted under the auspices the Management of Soil Erosion Consortium (MSEC) started in 1998 (Amado *et al.*, 2002). Water discharge and soil erosion were monitored during three years at the outlet of each catchment using weirs. These data were used to calibrate and validate the PCARES model (Predicting Catchment Runoff and Soil Erosion for Sustainability) in each cachment. This GIS-based model was developed in the Philippines for very steep slope conditions (Paningbatan, 2000). It is based on the concept developed by Rose & Freebairn (1985) and uses PCRaster, a GIS software designed to simulate overland flow and soil erosion for each erosive rainfall event. This model was run for the three study catchments using main scenarios for land-use change and climate. The first scenario for land-use was based on the most likely changes as based on the observed tendencies. The second scenario was based on the best bet options of land management. Climate change scenarios were essentially based on an increase of 20% and 40% of rainfall amount and mean intensity. Our results confirmed the very high sensibility of soil erosion to land use change as compared to climatic change. They also illustrated the dramatic hydrological changes (time-response and peak discharge).
Keywords: Global Change, catchment, soil erosion modeling

1 Introduction

Water availability, water quality and sediment delivery have become challenging issues for food supply, food security, human health and natural ecosystems. This is particularly true due to increasing preoccupations regarding to global changes involving climate and land-use. For instance, inappropriate land-use has long been recognized as one of the major cause water supply decrease, soil erosion and nutrient loss acceleration, particularly in areas of recent land cover changes such as tropical regions. Climate changes including variations of rainfall agressivity and annual amount may also induce more erosion. Beside to be responsible for an important reduction of in-site fertility, erosion also induces off-site consequences such as floodings, decrease of groundwater recharge; pollution by nutrients that increase the eutrophization hazards, heavy metals and pesticides; decrease of soil fertility and; fill of valley bottoms or reservoirs (IGBP, 1995). All these off-site effects may also dramatically jeopardize economic development of societies and future of natural ecosystems.

Despite the crucial need for a sound assessment of processes linked to global changes, available data remained scarce and based on a single process observed at a specific scale (e.g. soil loss from erosion plots). In the sloping land of South-East Asia, land-use changes are very rapid due to strong demographic, economic and politic pressures. In many locations, the pristine forest has been cleared for slash and burn cultivation or for more intensified systems based on the use of pesticides, fertilizers and machinery. At the onset of the rainy season, the tilled soil left bare tends to crust and generates runoff, which concentrates and favour gully erosion with on and off-site consequences.

Thus, there is actually a need to obtain at the watershed scale quantitative informations on the interaction between changes of land-use and climate, and water, nutrient and sediment fluxes that would help decision makers or planners to take appropriate decisions. This, in order to limit environmental consequences. To have direct and realistic estimations of erosion rates, studies could be performed in the field. However at the watershed scale studies conducted in the field would only consider few scenarios. This is due to methodological constraints impossible to avoid. If several scenarios are intended to be tested, field surveys would only be restricted to small bounded plots. Environmental modelling should be an interesting tool to test several scenarios at the watershed scale. Models may allow to better estimate sediment fluxes but also to better understand which processes are involved and how these processes interact. In this study we used a physically based model, the PCARES model (Predicting Catchment Runoff and Soil Erosion for Sustainability). It is GIS-based and rainfall-event model developed for very steep slope conditions (Paningbatan, 2000). PCARES is based on the concept developed by Rose & Freebairn (1985) and uses PCRaster, a GIS software designed to simulate continuously overland flow and soil erosion for each erosive rainfall event.

The objective of this study was to assess the influence of the rapid change of cropping systems on water erosion from three small catchments in three countries of South-East Asia (Laos, Thailand, Vietnam). These three catchments were selected because of their similar biophysical components (very steep slopes on shales; Janeau *et al.*, submitted) and their land-use intensification gradient. The Houay Pano catchment (60.2 ha; Lao PDR) is representative of the slash and burn systems, without inputs, submitted to a reduction of the fallow period, with invading *Chromolena odorata.* The Dong Cao catchment (59.5 ha; Vietnam) is representative of the transition between the systems with short fallow invaded by *Chromolena odorata* and *Imperata cylindrica* and the no-fallow systems with annual crops and small inputs. The Mae Yom catchment (79.5 ha; Thailand) is representative of the transition between the systems with intensive annual crops and high inputs, and the perennial fruit tree crops. Each of these catchment was equipped and monitored for water and sediment fluxes evaluation. Results for a 3 years period (1999 through 2001) were used to validate and calibrate the model. PCARES was afterwards run for scenarios of land-use change based on: (1) the an annual crop proportion of 20%, 60%, 80% and/or 100% of the catchment surface; (2) the generalisation of soil-conservation practices on annual crops. Three scenarios of climate change were simultaneously tested: (1) a decrease of 20% of previously selected rainfall event intensity; (2) an increase by 20% and 40%. Quantitative results on the effect of land-use and climate change are being presented and discussed. This investigation was conducted under the auspices of the Management of Soil Erosion Consortium (MSEC) started in 1998 (Magliano *et al.* 2002).

2 Sites description and data acquisition for model validation and calibration

The Houay Pano catchment (60.2 ha; Lao PDR) is representative of the slash and burn systems, without inputs, submitted to a reduction of the fallow period, with invading *Chromolena odorata.* The

Dong Cao catchment (59.5 ha; Vietnam) is representative of the transition between the systems with short fallow invaded by *Chromolena odorata* and *Imperata cylindrica* and the no-fallow systems with annual crops and small inputs. The Mae Yom catchment (79.5 ha; Thailand) is representative of the transition between the systems with intensive annual crops and high inputs, and the perennial fruit tree crops.

The study site in Laos (60.2 ha) is located in the Luang Prabang province at 10 km South of Luang Prabang city. It is a catchment of about 64 ha with UTM 1983 (zone 48) coordinates comprised between 203,245.14 to 204,679.65 and 2,197,318.4 to 2,198,825.04. It is representative of the slash and burn systems, without inputs, submitted to a reduction of the fallow period, with invading *Chromolena odorata*. The Mae Thang watershed (79.5ha, Thailand site) is located 550 km North of Bangkok. It is an area representative of the transition between the systems with intensive annual crops and high inputs, and the perennial fruit tree crops. Its UTM coordinates (zone 47) lies between 646,362.82 to 647,574.08 and 2,015,853.65 to 20,172,243.59. Finally, in Vietnam, the catchment of 59.5 ha shows UTM 1983 (zone 49) coordinates comprised between 548,932.74 to 550,207.07 and 2,317,502.75 to 2,318,365.24. This situation is representative of the transition between the systems with short fallow invaded by *Chromolena odorata* and *Imperata cylindrica* and the no-fallow systems with annual crops and small inputs.

In each of this sites, soil and land-use maps were established from field investigations. Soil maps were obtained from profile and auger hole description. Categories for land-use map were afterward regrouped in main groups as following: C (annual crops); Cp (crops with conservation practices); Fa (fallows or pastures); Fo (forest) and; O (orchards). Crops with conservation practices are mainly coffee and annual crops with tree associations. Topographic features of catchments have been derived from Digital elevation Models (DEM) with a 10-m mesh. DEMs from Thailand and Vietnam have been constructed by interpolation from digitized contour lines (with a 10 m interval) from 1/50 000 topographic maps. A more accurate DEMs have been established in Laos by interpolation from field spot heights using theodolithe. Spline Interpolations were performed to interpolate elevation data using the interpolation tool of Arc-View software (ESRI, 1994). Catchments were automatically delineated from DEMs and weirs location using Basins3 (EPA, 2000). Then, topographic characteristics were estimated from each DEM using Arc-View software (ESRI, 1997). Main characteristics (S surface; P, yearly precipitation amount; Pm, maximum monthly precipitation amount during the rainy season; r, a rainfall coefficient equal to Pm divided by the minimum monthly precipitation amount during the rainy season; S, slope gradient and Ssd, its standard deviation; C, proportion of annual crops, Fa, fallows or pastures,Cp, crops with conservation practices, O, orchards, and, forest, Fo) of each catchment are presented in Table 1.

Table 1 Statistics (mean, minimum, maximum, standard deviation) for each study catchment. S, the cachment surface; P, the yearly precipitation amount; (2) Pm, the maximum monthly precipitation amount during the rainy season; (3) r, a rainfall coefficient equal to Pm divided by the minimum monthly precipitation amount during the rainy season; (4) S, the slope gradient and Ssd, its standard deviation; the proportion of annual crops (C), fallow or pasture (Fa), crop with conservation practices (Cp), orchard (O) and, forest (Fo)

	S (ha)	P (mm)	Pm (mm)	r	S (degree)	Ssd	C %	Fa %	Cp %	O %	Fo %
Laos	60.2	1 402.0	275.0	0.16	28.0	11.0	9.1	52.7	0.0	12.2	26
Vietnam	59.5	2 035.0	671.8	0.13	25.0	9.0	28.0	22.0	20.0	30.0	0.0
Thailand	79.5	1 384.5	369.0	0.18	11.4	8.1	70.0	5.0	12.0	8.0	5.0

Each catchment was equipped by a weir with trap at its outlet and by manual rain gauges and automatic main weather station. Automatic water level recorders were then installed in the weirs. The location of these structures and equipments have been determined using GPS for watershed delineation and GIS analysis. Data collection and monitoring of water discharge and sediment loss wer performed from 1999 through 2001. Recorded water levels were transformed in discharges using pre-established calibration curves. Soil losses represented the sum of bedloads trapped in weirs and suspended sediment loads. Bed-loads were collected and evaluated after each storm event with significant erosion. In complement, water samples have been collected during storm events for sediment concentration evaluation and finally, suspended load estimation.

3 Model development

PCARES (Predicting Catchment Runoff and Soil Erosion for Sustainability, Pannigbatan, 2000) is a physical model that simulates runoff and soil erosion of a catchment during each erosive rainfall event. It can predict the spatial and temporal distribution of soil erosion processes and rate but also the runoff and sediment discharge rates at the outlet catchments. The model uses PCRaster, a GIS software package capable of cartographic and dynamic modeling that allows easy simulation of the hydrologic and sediment transport processes occurring on a three-dimensional landscape. The model incorporates a sediment transport routine described by Rose and Freebairn (1985) which calculates the amount of soil loss (*SL*) from the product of sediment concentration (c, in kg/m^3) and water discharge rate (Q). Sediment concentration is estimated using the simplified equation which is written as:

$$c \;=\; 2{,}700\, \lambda\, S\, (C_r) \qquad (1)$$

Thus, the sediment loss (kg/s) at each cell is calculated from Equation 4:

$$SL = 2{,}700\, \lambda\, S\, (1 - C_o)\, (Q) \qquad (2)$$

where λ is the efficiency of sediment entrainment, S is the sine of slope angle, $(1 - C_o) = C_r$ where C_o is the ratio of the area not exposed to runoff or the contact cover fraction, and Q is the water discharge rate (m^3/s).

In order to run the model, time series rainfall rates (mm/hr) for each rainfall event selected for model validation and calibration were set to a 5s time step.

4 Predicting soil erosion according to global change scenarios

Input values for PCARES have been set for each site based on field investigation. Infiltration capacity which is highly dependent on soil and land-use was estimated in the field using rainfall simulation combined in Laos with TRIMS equipment and double ring infiltrometer. Because, saturated infiltration rate was more dependent on land-use rather than on the soil only data for different land-use are being presented here (Table 2). A Manning's number was set up for each land-use and soil combination on each site by expert judgment. The Manning's number will determine the velocity of overland flow and as a consequence, erosion. The presence of crop cover and mulches increase the value of this constant, hence, is highly affected by the kind of land-use and surface condition of the soil. Finally, we considered the amount of cover that remains on the soil surface (proportion of surface cover).

Table 2 PCARES Input values (soil surface cover, Mannings cofficient, rainfall saturation by water; saturated soil infiltration rate) for encountered land-use at the Lao catchment. Values have been set through model calibration.

Land Use	Surface Cover (%)	Manning's n ($m^{-3} \cdot s^{-1}$)	Infiltration Sat. ($mm \cdot hr^{-1}$)
Fallow and pastures	95	0.12	280
Road	05	0.025	2
Foot path	05	0.03	3
Stream	05	0.05	15
Tributary	10	0.04	15
Riparian Buffer	85	0.1	100
Cultivated (corn, vegetables.)	20	0.06	17
Cultivated (with conservation)	48	0.1	60
Orchards	20	0.1	25
Tree Plantation	85	0.1	100

The model calibration was performed on each site using 2000 data. PCARES was afterwards validated on natural events of 2001 rainy season. The model was validated using rainfall events with a rainfall intensity and rainfall amount close to the first quartile, the median and the third quartile of all 2001 events. In addition, the model was also validated on the stronger storm of the season. Validation results for the greatest storm event in Laos are being presented in Figure 1 and 2. This event with a 3 hours duration had a 90 mm amount and a 90 mm/h intensity (September 3rd 2001). Predicted and observed discharge for water and sediment at the outlet of the catchment are being presented. Predicted flow discharge occurred at the same time as observed one. Despite showing similar values of maximum flow discharge values (close to 400 l/s), predicted values highly increased till flow discharge pick and after that decreased with a higher sloping slope (Fig. 1). Finally, estimations highly underestimated total discharge probably due to the contribution of groundwater that is not taking into account in PCARES. On the same way, predicted and observed erosion (kg/l) occurred simultaneously with maximum values on the same order (close to 15 kg/s, Fig.2). However, estimations underestimated total erosion.

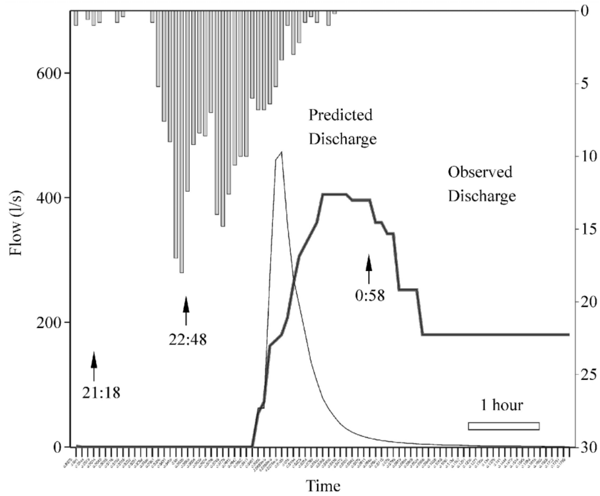

Fig. 1 Validation of PCARES after calibration procedure on a natural rainfall event with a 90 mm amount and a 90 mm/h intensity (September 3rd 2001). Predicted and observed discharge (l/s) at the Lao weir.

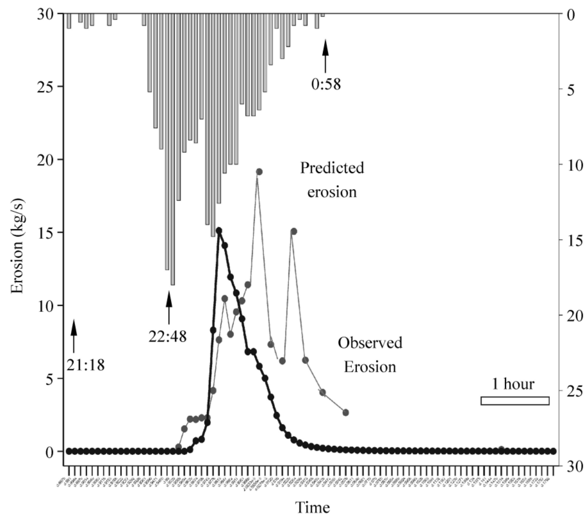

Fig. 2 Validation of PCARES after calibration procedure on a natural rainfall event with a 90 mm amount and a 90 mm/h intensity (September 3rd 2001). Predicted and observed erosion (kg/s) at the Lao weir.

A scenario of annual crop increase till 60% is being presented in Figure 3. This scenario, is compared with the annual crop of 2001, i.e., 9.1%. We present here estimations performed with the same rainfall event of September 3rd 2001, the most erosive of 2001. The main question being: "what would be the erosion response of the Lao catchment to an increase of annual crop proportion?"

Runoff occurred one hour earlier than under the actual land-use and maximum flow discharge increased from 500 l/s to more than 1,000 l/s. Erosion results, not presented here showed similar comportment, total erosion being 4 times higher. Overland flow and erosion dramatically increased with increasing annual crop proportion within the catchment. The Scenario including the generalisation of a bet option of land management on annual crops significantly decreased runoff and soil erosion. Finally, our results confirmed the very high sensibility of soil erosion to land use change as compared to climatic change.

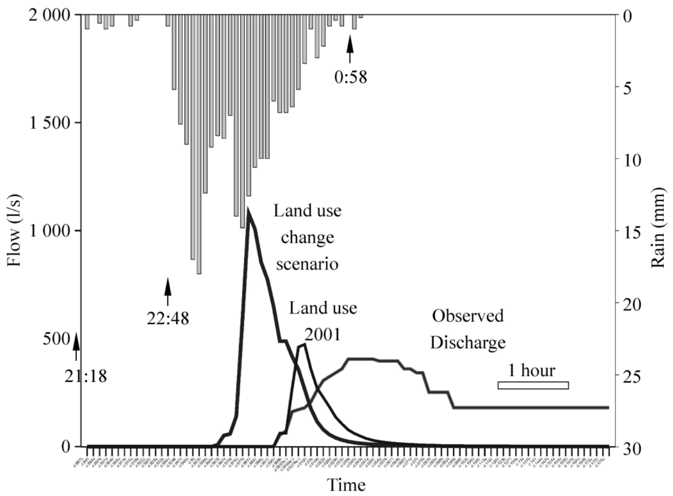

Fig. 3 Predicted flow discharge (l/s) of the Lao catchment according to a scenario of annual cops increase till 60%. Results are compared to the actual annual crop proportion of 9%.

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