Lessons from long-term monitoring of soil erosion in three southeast Asian agricultural catchments undergoing rapid land-use changes

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Abstract While soil erosion is reasonably well documented at the plot scale, data remain scarce at the catchment scale and predominantly stem from short-term studies. In this context, the "Management of Soil Erosion Consortium" network, which recently became the Multi-Scale Environmental Changes observatory (MSEC3, http://www.msec3.net/portal/), was established in the late 1990s in three upland catchments of Laos, Thailand and Vietnam. New land management options, introduced in consultation with farmers, were tested in terms of runoff and erosion. These included tree plantations, planted fodder, and no-till cover systems. The MSEC demonstrated that converting land from shifting cultivation systems to short rotations, or permanent cropping of species such as maize, cassava or teak, can result in increased erosion far beyond any tolerable rate of soil loss. Fodder and no-till cover systems are efficient means of controlling soil losses, yet several socio-economical obstacles can limit their adoption.

Key words catchment; runoff; soil erosion; upland rice; maize; cassava; teak; fodder; shifting cultivation; steep slopes

INTRODUCTION

Rapid changes in upland farming systems in southeast Asia fostered by increased population pressure and market drivers have resulted in widespread land degradation (Fox & Vogler, 2005; Lacombe *et al.*, 2010). While soil erosion in southeast Asia has been reasonably well documented at the plot scale (Sidle *et al.*, 2006; Hai An Phan Ha *et al.*, 2012), the links between agricultural activities in the uplands and downstream off-site effects remain largely unknown because of the difficulties in transferring results from plots to a larger scale (Bruijnzeel, 2004). Data remain very scarce at the catchment scale and predominantly stem from short-term studies. Significant progress with analysis, modelling and prediction of the on- and off-site impacts of land use and climate changes on runoff and sediment yields will only be achieved if more long-term catchment studies of hydro-sedimentary processes are available (Tomich *et al.*, 2004; Sidle *et al.*, 2006).

In this context, the "Management of Soil Erosion Consortium" network which recently became the Multi-Scale Environmental Changes observatory (MSEC3, http://www.msec3.net/portal/) was established in the late 1990s and since then benefited from sustained support from Laos, Thailand, Vietnam, and the French Institut de Recherche pour le Développement (IRD). New land management options introduced in consultation with farmers were tested in terms of runoff and erosion. These included tree plantations, planted fodder, and no-till cover systems.

The objective of this paper is to summarize the main results through the consortium over the past 15 years.

THE MSEC (MULTI-SCALE ENVIRONMENTAL CHANGES) OBSERVATORY

Selecting the main catchments involved the participation of the local stakeholders. It was also important to assess how well the catchment represented the overall characteristics of catchments in the region, and its accessibility with respect to monitoring. Table 1 presents the basic biophysical information of these catchments.

Table 1 Main attributes of the selected catchments.

Country	Lao PDR	Thailand	Vietnam
Number of equipped catchments	8	5	5
Catchment size (ha)	0.6–59.3	3.0–93.0	2.6–49.7
Catchment name	Huay Pano	Huai Ma Nai	Dong Cao
Province	Luang Prabang	Phrae	Hoa Binh
Latitude	19°51′10″N	18°13′20″N	20°57′40″N
Longitude	102°10′45″E	100°23′40″E	105°29′10″E
Elevation (m)	400–700	400–480	125–700
Mean slope (%)	18–61	8–15	28–38
Geology	Shale, schist	Siltstone, sandstone	Schist
Annual rainfall (mm)	1305–1738	1028–1493	1048–2506
Number of years	5 (2001–2005)	5 (2001–2005)	5 (2001–2005)
Soils	Alfisol, Ultisol, Entisol	Alfisol, Ultisol	Ultisol
Vegetation and land use	Forest, bush fallow; upland rice, maize, job’s tears, being replaced by teaks	Soybean, mung bean, tamarind, replaced by maize	Cassava, replaced by tree plantations and fodder
Trialled practises	Improved fallows, no till and grass cover crops	None	Fodder, no till and grass cover crops
Hydrology	Permanent flow	Intermittent flow	Permanent flow

MAIN RESULTS

Experimental plots

Several studies conducted under simulated and natural rainfalls on 1-m^2 plots in the MSEC catchments in Thailand (Janeau *et al.*, 2003) and in Laos (Ribolzi *et al.*, 2011) have shown that infiltration increases and soil detachment decreases as slope gradient increases because crusting is less on steep slopes compared to gentle slopes. Infiltration increases with the proportion of mosses on the soil surface (Chaplot *et al.*, 2007). This higher infiltration on steep slopes tends to reduce root exploration of top layers (Pierret *et al.*, 2007). The analysis of data collected from 147 1-m^2 micro-plots in the Laotian catchment confirmed that infiltrability is strongly correlated with the percentage of crust and vegetation cover type. In particular, due to low understorey the mean infiltrability measured under teak plantations (18 mm h^{-1}) and bamboos (14 mm h^{-1}) is of the same order of magnitude as that for bare soils (10 mm h^{-1}) and under upland rice (19 mm h^{-1}). By contrast, fallow (75 mm h^{-1}), paper mulberry (77 mm h^{-1}) and grass (105 mm h^{-1}) limit runoff generation.

In the MSEC catchment in Vietnam the above-ground casting activity of earthworms decreases surface runoff, and soil and nutrient losses (Jouquet *et al.*, 2008, 2012). Conversely the unstable termite sheetings slake down rapidly and generate crusts that promote water runoff and soil detachment (Jouquet *et al.*, 2012). As measured by Podwojewski *et al.* (2008) the cassava cropping system is associated with very high soil detachment rates (700 g m^{-2} $year^{-1}$ in average with a maximum of 1305 g m^{-2} $year^{-1}$, i.e. more than 1 mm $year^{-1}$) due to its low soil cover and repeated weeding operations. Three-year fallow (10 g m^{-2} $year^{-1}$), multilayered tree stands of *Acacia mangium* and *Venicia montana* and the grass fodder *Bracharia ruziziensis* (30 g m^{-2} $year^{-1}$ each) reduce soil detachment. Compared to *Paspalum atratum* and *Stylosanthes guianensis, Panicum maximum* appears to be a more efficient fodder cover favouring infiltration and controlling inter-rill erosion (Hai An Phan Ha *et al.*, 2012).

Hillslope and catchment

In the Laotian MSEC catchment gully erosion is highly correlated with the percentage of annual crops and more sensitive to land-use change than to climate change (Chaplot *et al.*, 2005(b)(c)). Once the gullies develop along the main steep slope, they form new limits between parcels, increasing the parcel length and thus accelerating water erosion rates in a feedback loop (Valentin *et al.*, 2005). Tillage erosion, which shifts soil clods downhill during tillage operations, increases with slope gradient (4, 6 and 11 t ha^{-1} $year^{-1}$ on slopes with gradients of 0.30, 0.60 and 0.90 m m^{-1} respectively). In the Laos MSEC site, tillage erosion has increased exponentially over the last 40 years because of the increasing need to combat weed invasion associated with short fallow periods (Dupin *et al.*, 2009). Among the 57 landslides identified in this region, a large proportion was observed near or within teak plantations that had developed rapidly on steep slopes near roads and waterways (Pierret *et al.*, 2011). In this environment sediments from hill slopes cannot be readily trapped by the riparian vegetation because (i) gullies are connected to the streams, and (ii) bamboos (*Dendrocalamus* sp. and *Cephalostachyum virgatum*), natural grass strips (*Microstegium ciliatum* A. Camus) and bananas have a poor water and sediment trapping efficiencies (Vigiak *et al.*, 2008).

During the rainy season, the runoff flow coefficient assessed at a catchment scale increases with the percentage of the catchments covered by maize and decreases with the percentages of the catchment covered by fallow, tree plantations and planted fodder (Valentin *et al.*, 2008). Sediment yield can be statistically predicted using the surface percentages of maize, Job's tears (*Coix lachryma-jobi* L.), cassava and footpaths. No-till cover crop farming can be very efficient in controlling soil erosion from steep slopes (Valentin *et al.*, 2008) but because this system relies heavily on fertilizers and herbicides its adoption by farmers is questionable (de Rouw *et al.*, 2010).

A detailed study based on the redistribution of ^{137}Cs (Huon *et al.*, 2013) conducted in the MSEC Laotian catchment revealed that using direct comparison of soil erosion between cultivated and forested soils can be misleading, with an overestimation of soil loss due to shifting cultivation because farmers prefer clearing more fertile soils located downhill and leaving forest on poorer soils on the crests. The soil ^{137}Cs activity therefore decreases with topographic position and the number of shifting cultivation cycles. Maximum organic carbon accumulated in a swamp area was found during the period of forest clearing and first cropping (1967–1975). Even though the major part of the soil organic carbon is lost through mineralization, a significant part (10–20%) gets locked up in a very stable form of charcoal ("black carbon") that can be removed by overland flow and transported over long distances (Chaplot *et al.*, 2005a; Rumpel *et al.*, 2006; 2009) but can also be trapped on the flattest parts of the slopes, thus favouring long-term carbon sequestration (Chaplot *et al.*, 2009).

Sediment yield does not respond linearly to rainfall events, as illustrated in the MSEC Thai site where nearly 48% of the total amount of sediments over a 12-year period (1995–2006) was supplied by a single exceptional event (218 mm in 6 h with a maximum intensity of 70 mm h^{-1}).

Environmental policies

In the MSEC Laotian catchment, direct physical evidence as well as indirect indications and farmers' perceptions show that soil erosion has increased the last few decades (Lestrelin *et al.*, 2005, 2012; Huon *et al.*; 2013; Valentin *et al.*, 2008). This tendency is primarily due the shortening of the shifting cultivation cycle down to 3–5 years. While the direct causes of soil erosion therefore appear related to current farming practices, the ultimate causes are primarily related to changes in national settlement and land use policies. Ironically these policies decided by the government and encouraged by international development actors, which aim in part to protect the environment and to conserve land resources, especially forests, have artificially induced land shortage and made shifting cultivation unsustainable (Lestrelin *et al.*, 2005, 2012; Lestrelin & Giordano, 2007). These policies aimed at eradicating shifting cultivation without providing an alternative for food production in uplands. The lack of sustainability of these transitional practices has prompted the need for alternative production systems. These include perennial tree plantations such as teak, which are rapidly expanding in the region with high associated runoff (Patin *et al.*, 2012) and soil erosion rates (Valentin *et al.*, 2008).

Because of declining yields, farmers in the Vietnamese MSEC catchment converted their land from cassava to tree plantations and planted fodder with very positive impacts on soil conservation (Valentin *et al.*, 2008). Substantial reforestation in this area was not a response by farmers to policy incentives but rather to the proximity of a new wood-processing industry and to the short distance to highways (Clément & Amezaga, 2008, 2009; Clément *et al.*, 2009). Besides, farmers in this Vietnamese site are not dependent on the uplands for food as they have paddy fields.

In the Thai and Laotian MSEC catchments, an analysis on the potential and limitations of Payment of Environmental Services (PES) as an incentive for soil conservation (George *et al.* 2009) showed that any PES market is unlikely to emerge without external support. Willingness to pay (WTP) is very low among local stakeholders because environmental service (ES) providers and buyers are generally the same people, or potential ES buyers feel that ES providers are better-off than them.

CONCLUSIONS

– Soil erosion is predominantly influenced by land use and greatly fluctuates according to land use changes.
– Slash-and-burn shifting cultivation with sufficiently long rotations is too often unjustly blamed for soil erosion by policy makers.
– Continuous cropping of maize and cassava promotes high rates of soil erosion at the catchment scale, far beyond any tolerable rate of soil loss.
– Conservative land uses include planted fodder, no-till cover crop farming, and tree plantations, but only if they are associated with an understorey, which is rarely the case of teak plantations.
– While it is crucial to maintain a cover at ground surface to limit soil crusting and runoff generation, it is also important to preserve a mosaic including high infiltration patches to limit runoff velocity and gully erosion.
– Land-use policies, which aimed at forest protection and agriculture intensification, can lead to increased erosion in the uplands.
– Failing to improve land-use management strategies may result in further rapid resource degradation with many negative impacts on downstream communities (sedimentation in watercourses and irrigation canals, reservoir siltation, low surface water quality, and contamination of drinking water.) and a few positive impacts (fertility transfer to the paddy fields).
– Long-term catchment studies are paramount to provide the baseline information essential to design novel management policies.

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