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Soil translocation by weeding on steep-slope swidden fields in northern Vietnam

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Abstract

This study investigated soil translocation associated with weeding on steeply sloped swidden fields attended by ethnic Da Bac Tay farmers in Hoa Binh Province in northern Vietnam. Annual soil loss rates of 4–6 Mg ha^{-1} year^{-1} were found on 20 m plots located on two separate hillslopes. Median soil flux rates were equivalent to 2.6–3.9 kg m^{-1} pass^{-1} for experiments conducted on slopes ranging from 0.54 to 0.84 m m^{-1}. The primary soil translocation process, the mechanical movement of soil via contact with a small hoe (*ngheo*), contributed approximately 60% of the weeding-related soil flux. Ravel, which is the rolling, bouncing, and sliding of soil clods downslope, was a secondary translocation process that accounted for almost 40% of the soil flux. Soil flux was most appropriately described with an exponential function that could predict the occurrence of ravel on steeper slopes. The observed soil fluxes were much smaller than those determined during weeding and hoeing at other tropical and subtropical sites, primarily because the tillage depth was very shallow (<1 cm) and weed density was low at the time of experimentation. The erosion rates associated with weeding were an order of magnitude lower than reported water erosion rates; therefore, the contribution to landscape change was believed to be small. Combined water and tillage erosion estimates indicated a possible unsustainable increase in soil loss on some steep-slope fields within the last few decades that has resulted from shorter fallow periods, longer periods of cultivation before fallowing, and greater weed pressure. Additional work is needed to verify these latter interpretations.

Keywords: Da Bac Tay ethnic group; Composite swidden agriculture; Hoeing; Ravel; SE Asia; Manual tillage erosion

1. Introduction

Population pressure, land scarcity, market development, and government policies have brought about changes to traditional highland agriculture systems in tropical Montane Mainland SE Asia (MMSEA) within the last few decades (e.g., Roder, 1997; Pandey and van Minh, 1998; Rambo, 1996; Sadoulet et al., 2002; Castella et al., 2005; Cramb, 2005; Xu et al., 2005; Weyerhaeuser et al., 2005). Specific examples of the replacement of ‘‘pure’’ forms of swidden agriculture with more permanent cultivation practices have been described for several ethnic groups (e.g., Schmidt-Vogt, 1999; Turkelboom, 1999; Cramb, 2005; Thongmanivong et al., 2005). The long-term sustainability of many of these modified systems is uncertain, particularly with respect to the impact of shorter fallow periods (Pandey and van Minh, 1998; Roder et al., 1997; Mertz, 2002; Vien et al., 2004).

Studies conducted worldwide confirm a relationship between weed infestation and short fallow periods (e.g.,

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Johnson et al., 1991; De Rouw, 1995; Dingkuhn et al., 1999). One ramification of enhanced weed pressure is an increase in tillage erosion on sloping lands (Grandstaff, 1980; Turkelboom et al., 1997; Dupin et al., 2002). Several studies have shown tillage erosion can be of equal or greater importance than water erosion in landscape evolution and soil degradation, particularly on fields with short slope lengths (e.g., Quine et al., 1999; Van Muysen et al., 1999; Turkelboom et al., 1999; Nyssen et al., 2000). Thus, understanding the sustainability of any mountain cultivation system requires estimating erosion associated with manual tillage, in addition to water erosion. The latter process has traditionally been given much more attention in the region (Hurni, 1982; Hill and Peart, 1998; Maglinao et al., 2003; Sidle et al., 2006).

In this work, we investigate soil translocation resulting from weeding practices that are associated with the Da Bac Tay composite swidden agriculture system in Hoa Binh Province, in northern Vietnam. The long-term sustainability of the swidden component of this particular composite agriculture system may now be threatened by contemporary changes in the number of years in succession that crops are cultivated, and to increasingly shorter fallow periods (Lam et al., 2004). In addition to quantifying soil translocation associated with weeding in swidden fields, we estimate the total potential surface lowering since introduction of swiddening on steep hillslopes about 110 years ago; and we explore the connection between such erosion-induced lowering and observed patterns of reduced infiltrability within the soil profile on swidden lands in the area.

2. Study area

2.1. Tan Minh

Tan Minh (20°55′49″N, 105°7′3.6″E) is located WSW of Hanoi, in Da Bac District of Hoa Binh Province in northern Vietnam (Fig. 1). Several hamlets comprise Tan Minh, including Tat, which has been the focus of several recent studies (e.g., Rambo, 1996; Rambo and Vien, 2001; Vien, 1997, 2003; Vien et al., 2004; Lam et al., 2004; Ziegler et al., 2004, 2006). The elevation range is 200–1000 m above sea level. Slopes are steep, typically 0.5–1.7 m m^{-1}, and they remain steep to the valley floor and/or stream channel (Fig. 2). Bedrock is largely sandstone and schist with some mica-bearing granite. Soils are predominantly Ultisols of the udic moisture regime (Ziegler et al., 2004).

The climate is tropical monsoon with approximately 90% of the mean annual rainfall (1800 mm) occurring

Fig. 1. (a) Tan Minh study site in northern Vietnam.

between May and October (Lam et al., 2004). Remnant forest patches exist primarily on steep, inaccessible peaks, runs, and slopes. Mountain slopes are dotted with swidden fields that are farmed by the Da Bac Tay villagers, the primary inhabitants of Tan Minh (Fig. 3e). Juxtaposed with active fields are fallow lands that include various stages of secondary vegetation (e.g., mixtures of small trees, shrubs, bamboo and other grasses). Land-cover distribution is shown in Fig. 2.

2.2. Farming system of the Da Bac Tay

The Da Bac Tay ethnic group – referred to simply as Tay hereafter – is renown for their composite swidden farming system, which combines wet rice cultivation, swiddening (e.g., traditionally upland rice, but now also cassava, maize, canna), home gardens, fish ponds, and the exploitation of fallow and secondary forest lands (Rambo, 1998). The swidden fields are an integral component in this composite system, which has evolved over generations or centuries (Rambo and Vien, 2001). The Tay began farming this region over 100 years ago when the hillslopes were almost entirely forested. Many households now manage as many as 5–8 swiddens, which are often a mosaic of surfaces in various cultivation and fallow stages. Adjoining fields on long hill slopes are now commonly found (Fig. 3a), owing largely to recent intensification of cultivation in the swiddens (Lam et al., 2004).

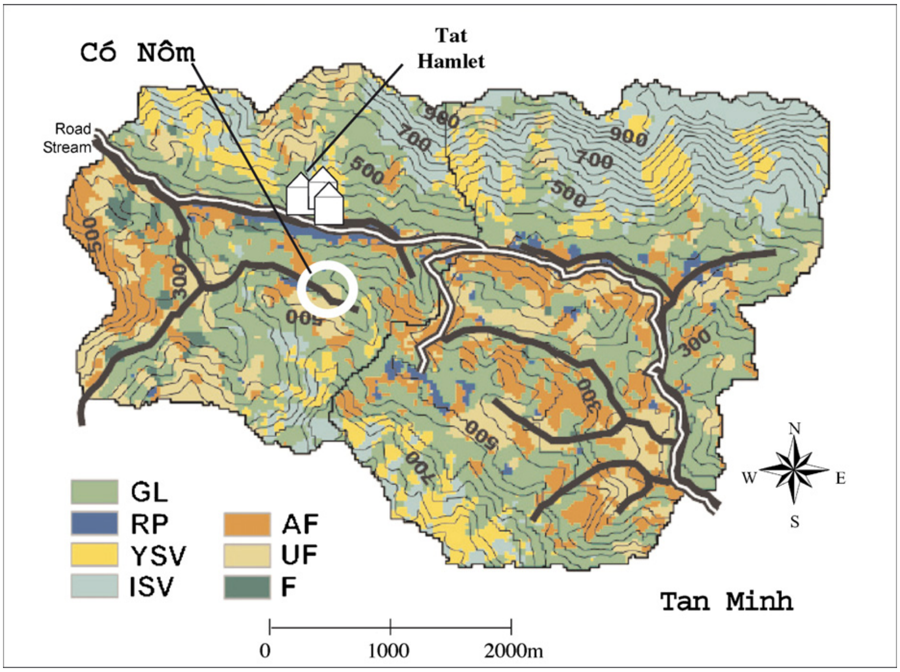

Fig. 2. Location of the Có Nôm study site in Tan Minh. Land covers and percent areas are the following: GL, grassland (38%); RP, rice paddy (3%); YSV, young secondary vegetation (9%); ISV, intermediate secondary vegetation (18%); AF, abandoned field (15%); UF, upland field (15%); and F, forest (1%). Land cover descriptions are presented elsewhere (Ziegler et al., 2004, 2006); a color map is shown elsewhere (Ziegler et al., 2004).

Fig. 3. (a) The general location of fields III and IV on the SW hillslope in Có Nôm; (b) Tay woman weeding a swidden field; (c) Tay man weeding the experimental plot; (d) the 2 cm × 5 cm *ngheo* used by Tay farmers for weeding; (e) Tay child and mother, who is weeding an upland rice field.

Table 1
Description of land-use history and current usage of the plots on the two hillslopes investigated

Hillslope	Field	Plots	Year[a]	Land-use history						
				1991	1992	1993	1994	1995	1996	1997[b]
NE	I	1–3	1	Rice[c]	Cassava	Fallow	Fallow	Fallow	Fallow	Rice
	II	4–6	3	SV	SV	SV	SV	Rice[c]	Rice	Cassava
SW	III	1–3	3	SV	SV	SV	SV	Rice[c]	Cassava	Cassava
	IV	4–6	3	SV	SV	SV	SV	Rice[c]	Cassava	Cassava

[a] The number of years the field has been cultivated within the current cropping cycle (i.e. since the last fallow).
[b] The crop to be planted in the year this study was conducted.
[c] The year this field was cleared. SV (secondary vegetation) includes trees and nua bamboo. Fallow vegetation includes grasses, shrubs, and small trees.

Commencement of swiddening involves clearing of some type of regrowing vegetation, including regenerating trees, bamboo, shrubs, and grasslands. Clearing is done by hand (machete) in late-March for upland rice planting. The ‘‘slash’’ is then allowed to dry throughout April, before burning in May. Planting is performed by hand using dibble sticks to create holes in which to place seeds. Cassava, which was introduced 40–50 years ago, is typically planted earlier in the year. At the time of this study in 1997, farmers were commonly cultivating upland rice for 1–2 years, followed by 1–2 years of cassava. Maize, canna, and ginger were also planted in a large number of swidden fields—often together. The fallow period was only 4–5 years, which is much shorter than the 15–20 years when swidden agriculture was first introduced to the area about 110 years ago.

Following planting and after the commencement of rainfall, fields are weeded meticulously with a small hand-held knife/hoe, called an *ngheo* by the Tay (Fig. 3d). Further weedings are performed (one to two times) before harvesting (Fig. 3b). Rice fields are typically hoed two to three times, cassava one to two times. The farming system of the Da Bac Tay described above is based on the descriptions presented elsewhere (Rambo, 1995, 1996; Rambo and Vien, 2001; Vien, 1997, 2003; Vien et al., 2004; Lam et al., 2004).

3. Methods

3.1. Experiment sites

We conducted 12 tillage erosion experiments on two hillslope complexes, which were situated on opposite sides of the valley in Có Nôm, the swidden area above Tat Hamlet in Tan Minh (Fig. 2). Experiments were conducted on three 20 m plots situated within two separate fields on each of the two hillslopes (a total of 12 plots). The six plots in fields I and II were located on the northeast side of the valley (NE1-6); those in fields III and IV were on the southwest side (SW1-6). The SW hillslope is shown in Fig. 3a. The four fields differed with respect to when cultivation was initiated since the last fallow period (Table 1). Field I was in the first year of rice planting following a 4-year fallow period. The other three fields were in their third year since clearance and cassava was planted. Soils on both hillslopes were Ultisols and the combined depth of A and B soil horizons were greater than 2 m at both sites. The experiments were performed during a relatively dry period in May 1997, which was at the beginning of the annual wet season. Both weed and crop cover where generally low at the time of experimentation.

3.2. Soil property measurements

Within each of the four fields, we collected two 90 cm^3 soil cores (5 cm deep) at 10 m increments on transects beginning at the footslope ($n = 12$ locations). All 24 samples were used to estimate surface bulk density (ρ_b) and soil moisture content in each field. The samples were then split for the determination of organic matter (OM) and available phosphorus (P) content ($n = 12$; methods listed in Table 2). OM was calculated as 1.724 $\times$ the carbon content (via Walkley and Black method) and P was calculated by the Oniani method. Prior to weeding, approximately 500 g of surface soil was collected every 20 m to estimate sand, silt, and clay fractions ($n = 6$; via hydrometer).

3.3. Soil translocation experiments

Experimental plot dimensions were 2 m wide (parallel to the contour) by 20 m long (perpendicular to the contour). Gradients were determined from measurements taken every 1 m with an Abney level ($n = 20$). Within each plot we conducted manual weeding experiments with an *ngheo* using a direct

Table 2
Physicochemical properties for all six fields on each of the two hillslopes investigated

Hillslope	pH[a]	OM[a] (g kg^{-1})	P[a] (mg kg^{-1})	ρ_b (kg m^{-3})	Sand[a] (g kg^{-1})	Silt (g kg^{-1})	Clay[a] (g kg^{-1})
NE	5.8 ± 0.2	63 ± 13	240 ± 100	1035 ± 89	670 ± 50	160 ± 40	160 ± 10
SW	4.3 ± 0.1	42 ± 4	30 ± 10	987 ± 81	520 ± 50	230 ± 40	260 ± 40

Values are medians ± median absolute deviations from the median; OM is the organic matter; P is the available phosphorus; and ρ_b is the bulk density.

[a] Significant difference at $\alpha = 0.10$ (non-parametric Mann–Whitney *U*-test); $n = 12$ for OM and P; $n = 24$ for ρ_b; $n = 6$ for sand, silt, and clay fractions.

collection (backstop) method to capture translocated soil. The dimensions of the *ngheo* were approximately 2 cm × 5 cm (Fig. 3d). Beginning at the base of the plot, a Tay farmer moved upslope, ‘‘tilling’’ the field in sequential 1 m subplots to remove weeds (Fig. 3c). Tillage was unidirectional: although the farmer moved in the upslope direction, the tillage motion and resulting soil translocation direction was predominantly downslope (Fig. 4a). This unidirectional tillage simulated the traditional approach.

At the base of the 20 m plot, we held a plastic tarp to form an L-shaped backstop that captured material transported during weeding (Fig. 4a). The folded tarp both blocked soil clods bounding downslope and provided a flat surface on which material transported by the scraping action of the *ngheo* would settle. We held the tarp flush to the soil surface to prevent translocated soil from passing underneath. The width of the tarp was the same as the width of the plots (2 m); therefore, material bounding wide of the tarp was not measured and represented an underestimation error (see Section 5). For the initial 1 m subplot, the farmer stood on the folded tarp surface to prevent an edge-effect error related to weeding this lower-most subplot differently than those above—an inherent problem with trough-type measurements (Turkelboom et al., 1997, 1999).

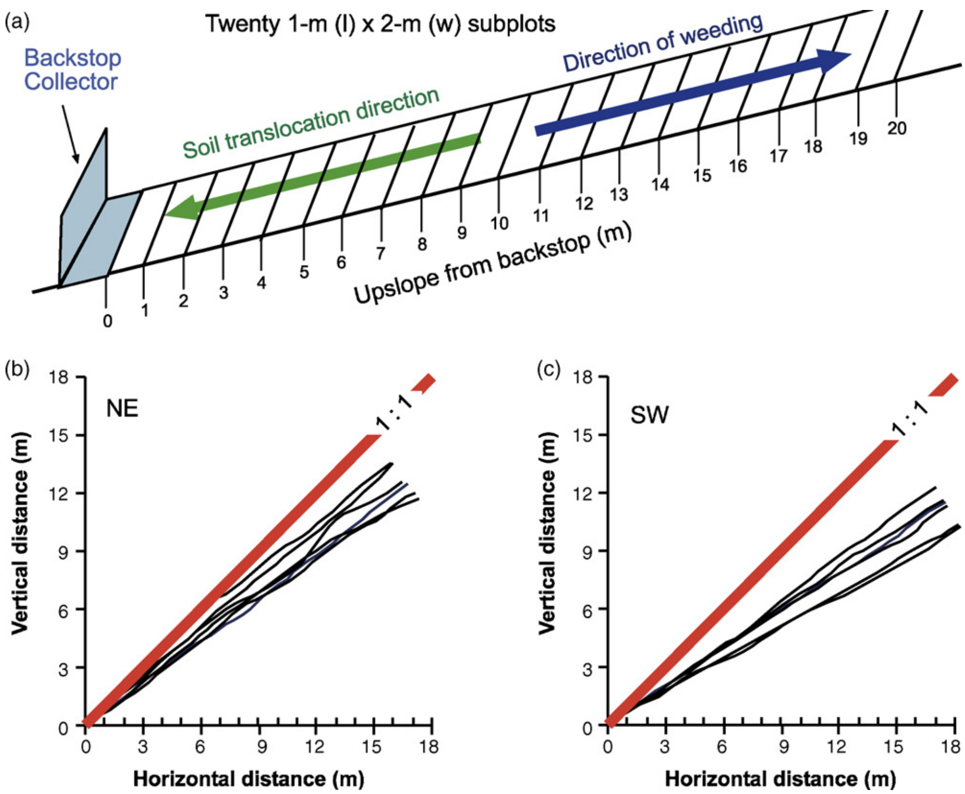

Fig. 4. (a) Schematic of the 20 m (long) × 2 m (wide) experimental plots, which were divided into 1 m × 2 m subplots; (b and c) downslope profiles of the six fields comprising the NE and SW fields; the thick line indicates a slope of 1 m m^{-1}.

3.4. Soil translocation and soil loss calculations

Following weeding each 1 m sub-section, transported material was bagged and subsequently transferred to the laboratory where each was dried at 105 °C for 24 h. Incremental translocation of soil (TS_i, kg m^{-1} tillage pass^{-1}) on each subplot was quantified as

$$TS_i = \frac{MS_i}{w} \quad (1)$$

where MS_i is the mass of translocated soil that originated from subplot i (collected at the base of the entire plot) and w is the plot width (2 m). TS_i represents the soil from each subplot that contributed to the total soil flux from the plot (SF, kg m^{-1} tillage pass^{-1}), which was calculated as the sum of all TS_i values:

$$SF = \sum_{i=1}^{20} TS_i \quad (2)$$

where one tillage pass represents weeding the entire 20 m plot in one direction (moving from the bottom to the top).

Soil loss (SL, Mg ha^{-1}) from the 20 m plots was calculated as

$$SL = \frac{SF}{L} \times 10 \quad (3)$$

where L is the plot length (20 m) and 10 is a unit conversion factor.

The depth-averaged translocation distance (d) was calculated as

$$d = \frac{SF}{DT\,\rho_b} \quad (4)$$

Where ρ_b is the dry bulk density of the tilled layer and DT is the estimated depth of tillage, determined from the bottom-most subplot as

$$DT = \frac{MS_1}{2\rho_b} \quad (5)$$

where MS_1 is the mass of translocated soil from the bottom-most subplot (Eq. (1)) and 2 is the area of the subplot. Here, we assumed that all tilled material was collected from this 1 m subplot.

The upslope distance corresponding to the nth percentile of translocated soil (λ_n) was calculated as (Lobb et al., 2001):

$$\lambda_n = CDF_n(TS_i) \quad (6)$$

where n is either the 50th, 75th, 90th, or 95th percentiles of the cumulative density function (CDF) determined from the soil translocation values (TS_i) of each subplot (from Eq. (1)).

Ravel is the general term used for describing material rolling, sliding, and bouncing downslope (Rice, 1982; Gabet, 2003). In this experiment, soil transported from two or more meters upslope of the lower plot boundary was considered to be ravel. The percent ravel contribution to total soil flux was calculated as follows

$$Ravel = \frac{\sum_{i=3}^{20} TS_i}{SF} \times 100\% \quad (7)$$

where TS_i and SF are as above.

3.5. Flat-slope estimates

Prior to the 12 weeding experiments conducted in swidden fields, we performed three preliminary hoeing experiments on 1 m plots within house gardens (HG) in Tat Hamlet. Although the soil conditions in the gardens were not identical to those in the swidden fields, these demonstration studies allowed us to quantify soil translocation by the *ngheo* on a relatively flat slope (0.03 m m^{-1}). Quantifying a "flat-slope" value was necessary for examining the relationship between soil translocation and slope gradient over a wider range of slopes than those represented by the experimental fields in the swiddens. In these experiments, soil translocation distance was $\leq$1 m; therefore, the resulting soil flux estimates would not have been greater had we conducted these demonstration experiments on 20 m plots.

3.6. Statistical analyses

Statistical significance for all variables was assessed with the nonparametric Mann–Whitney U-test (M–W U-test) at the 0.10 significance level. Model efficiency (ME) between predicted (P_i) and observed (O_i) soil flux values was calculated as follows (Nash and Sutcliffe, 1970):

$$ME = 1 - \left(\frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2} \right) \quad (8)$$

where a value less than zero indicates performance worse than simply taking the mean of observed values ($\bar{O}$) and perfect agreement between observed and predicted values results in an ME value of one.

4. Results

Some physicochemical properties were significantly different for soils on NE versus SW hillslope plots

(Table 2). For example, the NE plots were sandier (i.e., sandy loam texture; USDA classification) than the SW plots (i.e., sandy clay loam texture); and consequently, they had significantly lower clay percentages (Table 2). Organic matter, pH and P were also significantly higher on the NE plots. The depth to the B horizon was slightly shallower on the NE hillslope (ca. 0.15 m versus 0.23 m). Soil color in the subsurface profiles was also distinctly different with the clay-rich Bt soil horizons on the SW slope being substantially more red (7.5R 3/8) than the yellowish Bw subsoil on the NE side (2.5Y–10YR 6/8).

With the exception of one plot on the NE hillslope, all slope profiles were linear (Fig. 4b and c). Slope gradients for the NE plots were significantly greater than for the SW plots (Table 3). The soil moisture content at all sites was similarly low, ranging from 0.05 to 0.15 g g^{-1} (Table 3).

Soil flux from all plots during weeding experiments ranged from 0.4 to 6.4 kg m^{-1} $pass^{-1}$ (Table 3). Median SF values (±one median absolute deviation) for NE and SW plots were 2.6 ± 1.6 and 3.9 ± 2.3 kg m^{-1} $pass^{-1}$, respectively (Table 3). The corresponding median soil loss rates for NE and SW plots were 1.3 ± 0.8 and 2.0 ± 1.1 Mg ha^{-1} $pass^{-1}$, respectively (Table 3). Although soil flux differences between the two hillslopes were not statistically significant, they do tend to group with respect to NE-versus-SW fields (Fig. 5a)—and this appears to be related more to soil conditions than to land-use history (Tables 1 and 2). Unexpectedly, soil flux on the steeper NE plots was about 30% lower than that on the SW plots (Table 3).

When the household garden demonstration plot (HG) and swidden hillslope experiment data are considered together, a non-linear increase in soil flux with slope is apparent, despite substantial scatter in the hillslope plot data (Fig. 5a). Because we investigated soil translocation over a narrow range of slope gradients (0.54–0.84 m m^{-1}), it was not possible to determine unequivocally the best equation to describe the slope–SF relationship. Comparison with other studies in the literature supports that an exponential function is appropriate for this non-linear relationship (e.g., Turkelboom et al., 1997, 1999; Dupin et al., 2002). The following fitted exponential equations, for which S is median plot slope (m m^{-1}), had model efficiency values of about 0.60 (Fig. 5a):

$$\mathrm{SF_{NE}} = 0.01\ \mathrm{e}^{7.03S} \tag{9}$$

$$\mathrm{SF_{SW}} = 0.01\ \mathrm{e}^{8.95S} \tag{10}$$

Approximately 60% of the material collected at the base of the 20 m plots originated from the first two subplots. Fig. 5b shows a negative relationship between

Table 3
Data for tillage experiments on 12 plots on the NE and SW hillslopes and the house garden (HG) demonstration plots

Plot	Slope[a] (m m^{-1})	SM (g g^{-1})	SF (kg m^{-1} $pass^{-1}$)	SL (Mg ha^{-1} $pass^{-1}$)	d (m)	DT (mm)	λ_{50} (m)	Ravel (%)
NE1	0.74	0.09	0.8	0.4	6.9	0.1	3.6	73
NE2	0.70	0.06	1.9	0.9	2.9	0.6	1.7	43
NE3	0.69	0.15	0.4	0.2	1.9	0.2	1.0	30
NE4	0.85	0.08	3.9	1.9	1.7	2.2	0.9	17
NE5	0.77	0.06	4.5	2.2	3.0	1.5	1.5	34
NE6	0.85	0.07	3.3	1.7	2.4	1.4	1.6	43
SW1	0.66	0.11	1.4	0.7	1.5	1.0	0.7	23
SW2	0.57	0.06	3.6	1.8	3.2	1.1	3.7	54
SW3	0.56	0.05	1.6	0.8	2.3	0.7	1.2	20
SW4	0.67	0.15	6.4	3.2	3.2	2.0	1.9	48
SW5	0.73	0.10	6.1	3.1	1.5	4.0	0.8	27
SW6	0.65	0.09	4.2	2.1	2.7	1.6	1.8	46
Summary[b]								
NE	0.76 ± 0.06	0.08 ± 0.01	2.6 ± 1.6	1.3 ± 0.8	2.6 ± 0.6	1.0 ± 0.7	1.6 ± 0.4	39 ± 6
SW	0.66 ± 0.04	0.10 ± 0.03	3.9 ± 2.3	2.0 ± 1.1	2.5 ± 0.7	1.4 ± 0.5	1.5 ± 0.6	36 ± 12
HG	0.03	n.d.	0.13	0.07	<1.0	1.0	<0.5	0.0

SM is the soil moisture (g (H_2O) g $(soil)^{-1}$); SF is the soil flux on the 20 m field (Eq. (2)); SL is the soil loss rate (Eq. (3)); d is the depth-averaged translocation distance (Eq. (4)); DT is the depth of tillage (Eq. (5)); λ_{50} is the distance corresponding with 50% of the translocated soil (Eq. (6)); and Ravel is the percentage of transported material that was ravel (Eq. (7)).

[a] Significant at $\alpha = 0.10$ (non-parametric Mann–Whitney U-test) for NE-versus-SW data only.

[b] Summary data for NE and SW hillslopes are medians ± median absolute deviation about the median. For the demonstration experiments at the household garden (HG), SM was not determined (n.d.).

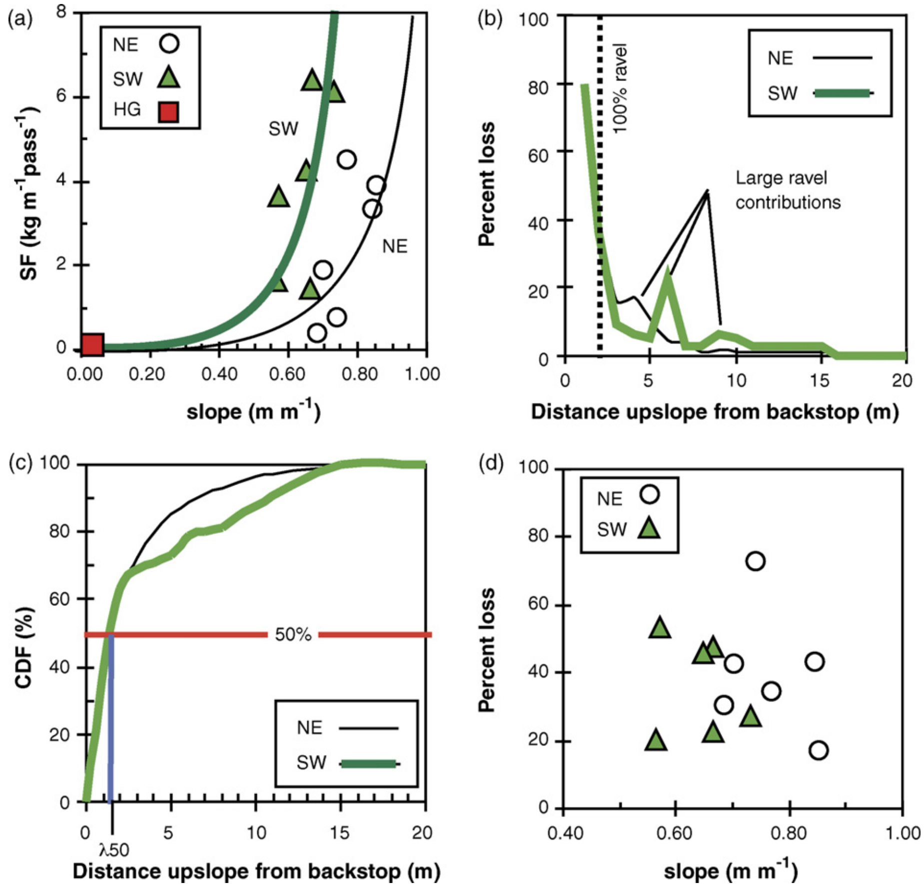

Fig. 5. The following are shown for the six plots on each of the two NE and SW fields (Table 1): (a) Soil Flux (SF) determined on the 20 m plots (the fitted lines, Eqs. (9) and (10), have model efficiency values of about 0.60); (b) median cumulative soil loss for various upslope distances on the 20 m experimental plots (ravel, which is material transported from the upper 18 m comprises nearly 40% of the total); (c) median cumulative density function (CDF) for sediment lost from upslope areas of the plot; λ_{50} is the upslope distance above which 50% of the translocated material originated (horizontal line); and (d) relationship between the proportion of ravel transported on a plot and slope angle. For all medians, $n = 6$.

the percentage of material transported and the distance to the upslope subplot where weeding occurred. The estimated depth-averaged translocation distance (d) was 2.6 ± 0.7 m (medians $\pm$ MAD) for all plots (Table 3). In comparison, Turkelboom et al. (1997) reported a displacement distance of 1.10 ± 0.43 m (mean $\pm$ S.D.) for a 0.82 m m^{-1} slope gradient. Dupin (personal communicaton) noted that mean aggregate tracer displacement was as high as 2.6 m when surface contact cover was low (approximately 5%).

At Tan Minh, the general exponential decay of translocated material from increasingly higher upslope subplots is irregular, owing to the non-uniform translocation of soil clods from individual upslope subplots (Fig. 5b). On 7 of the 12 plots tested, soil clods dislodged from the upper 5 m were transported to the backstop. The 50th percentile distance over which soil was translocated (λ_{50}) was approximately 1.50 m for both hillslopes (Fig. 5c; Table 3). On some plots, λ_{50} was as high as 3.7 m (Table 3). The median λ_{75}, λ_{90}, and λ_{95} distances were, respectively, the following for the two fields: NE (3.3, 6.6, and 9.9 m) and SW (4.0, 11.0, and 13.1 m).

5. Discussion

5.1. Soil flux associated with weeding

Our observed weeding-related soil fluxes were much lower than those associated with hoeing practices in other tropical or sub-tropical locales (Lewis and Nyamulinda, 1996; Rymshaw et al., 1997; Turkelboom et al., 1999; Dupin et al., 2002, 2003; Zhang et al., 2004; Kimaro et al., 2005). If we assume three weedings per year, the median annual soil loss rate for all 20 m plots ranged only from about 4 to 6 Mg ha^{-1} year^{-1} (i.e., estimated as three times the values in Table 3). The observed soil fluxes

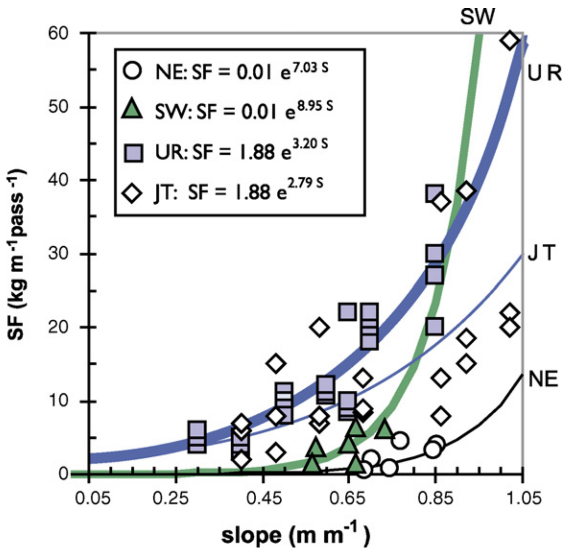

Fig. 6. Comparison of soil fluxes determined for NE and SW plots with those for upland rice (UR) and Job's tear (JT) at a site in Lao PDR (Dupin et al., 2002). Model efficiency values (Eq. (8)) for NE, SW, UR, and JT are 0.56, 0.58, 0.85, 0.43, respectively; S is slope (m m^{-1}).

(0.4–6.4 kg m^{-1} $pass^{-1}$) were much lower than those associated with weeding in fields of upland rice and Job's tear (*Coix lacryma Jobi*) over a common range of slope gradients in Lao PDR (7–22 kg m^{-1} $pass^{-1}$; Fig. 6; Dupin et al., 2002). Our fluxes are, however, comparable with those associated with weeding in upland rice fields in Thailand using small hoes (estimated at 4 kg m^{-1} $pass^{-1}$, Turkelboom et al., 1999).

Estimated ''tillage'' depth in Tan Minh was <1 cm. This shallow depth was indicative of the shallow root depth/density of the weeds at the time of the season when we conducted the study (i.e., before the onset of the truly wet period when weed growth would be highest). The mean tillage depth associated with weeding using a small curved hoe (6 cm × 10 cm) at the Lao PDR site was about 2 cm (Dupin, personal communication). In addition to the greater tillage depth, the higher soil fluxes reported at the Lao PDR site probably reflect a greater intensity of hoeing, which was related to greater weed coverage.

5.2. Ravel transport

Soil translocation associated with tillage has been characterized as a diffusive process that increases linearly with gradient on low-to-moderate slopes (e.g., Lindstrom et al., 1992; Govers et al., 1994; Quine et al., 1999). Important factors influencing soil translocation by tillage include bulk density, tillage related variables (depth, direction, speed, size of tillage implement), and initial soil conditions, such as moisture content and tillage history (Lobb et al., 1995; Van Muysen et al., 1999; Poesen et al., 2000; Lindstrom et al., 2001; Van Oost et al., 2006). Soil movement during tillage occurs primarily through soil impact with the tillage implement. Because this impact is often brief, the average distance that soil is moved is relatively short (e.g., typically less than 1.0 m). Some degree of bouncing and rolling of material also takes place before the translocated soil comes to rest, but this transport process is usually limited when slopes are not great (Lobb et al., 1999). On steep slopes, however, dislodged soil clods can roll long distances downslope (Rymshaw et al., 1997; Turkelboom et al., 1997, 1999). Turkelboom et al. (1999), for example, found substantial clod movement when gradients exceeded 0.7 m m^{-1}; they reported this slope angle was the maximum angle of repose at their Thailand research site.

Torri and Borselli (2002) divided tillage translocation into three motion phases: (1) a drag phase, whereby soil is transported in contact with the implement; (2) a jump phase, during which soil clods are ejected by the tillage tool; and (3) a rolling phase, for which soil clods role/slide under the effects of gravity, resistance, and initial velocity (also see Lobb et al., 1999). In our experiments, we could distinguish two types of motion. The first was the initial displacement of soil caused by the hoeing/weeding action (often airborne and occurred over relatively short distances). The second was the rolling of aggregated material (clods) over comparatively long distances downslope after being displaced by hoeing. The first type encompassed the drag and jump phases of Torri and Borselli (2002), with the jump phase dominating. The second was a more extreme version of the rolling phase whereby displaced clods moved several meters downslope because of the steep-slope angle.

The term ravel is appropriate for describing the second soil translocation process we observed during the experiments in Tan Minh—and probably that described by others working on steep hillslopes (e.g., Rymshaw et al., 1997; Turkelboom et al., 1997, 1999; Dupin, personal communiction). The systematic process we employed to measure soil translocation on consecutive 1 m subplots (i.e., Eq. (1)) allowed us to estimate that ravel comprised more than one-third of the soil translocated on both NE or SW hillslope plots (Table 3). These estimates are lower bounds because some ravel was generated on the two lowest subplots, but we were not able to separate that from the material translocated by the direct action of the hoe. On the six plots where ravel exceeded 40% of the soil translocated, median slope angle was 0.69 m m^{-1}—nearly identical to the 0.70 m m^{-1} angle-of-repose threshold reported by Turkelboom et al. (1999).

Linear-diffusive equations, which are appropriate for predicting soil flux related to mechanized or animal-powered tillage erosion on lesser slopes (e.g., Lindstrom et al., 1992; Govers et al., 1994; Quine et al., 1999) are not appropriate for predicting soil flux related to manual hand hoeing/weeding on very steep slopes where ravel is present. Both Turkelboom et al. (1997) and Dupin et al. (2002) used an exponential model to describe the non-linear increase in soil flux with slope in the prior studies. In a later assessment, Turkelboom et al. (1999) used a complex step equation, in part, to model the non-linear soil flux response as slope approached the maximum angle of repose of soil clods. By including the data from the household garden demonstration plots (HG), the SF–slope relationships on the NE and SW hillslopes are exponential (Fig. 5a). However, a better prediction would have been facilitated by investigating over a larger range of slope gradients, as was done in the Lao PDR study (Fig. 6).

Because we did not anticipate a substantial contribution of ravel to soil flux, the 2 m width of the backstop was not sufficient for capturing all ravel transported downslope. An estimate of the ‘‘missed’’ portion is 10%. Our reported fluxes are, therefore, minimum estimates. A better approach would have been to increase the width of the weeded plot by twice the maximum horizontal displacement distance of clods rolling downslope. For example, we would have needed a 4 m plot width for the case that clods bounded within 1 m either side of our 2 m backstop.

The percentage of ravel transported from any plot was not simply a function of slope gradient (Fig. 5d). Variations in physical conditions among the plots were also important (e.g., weed coverage, which we did not quantify). For example, three plots having substantial ravel transport from the upper 10–20 m subplots were located on the SW hillslope where a hard surface crust had formed. The crust was likely related to the packing of stable microaggregates by raindrop impact when the soil was unprotected following harvesting prior to testing (Janeau et al., 2003; Singer and Shainberg, 2004); we have observed similar crusts on unprotected upland fields in northern Thailand (Ziegler et al., 2000). Higher clay content of the SW soil may also have contributed to greater aggregate stability or soil cohesion of the dislodged clods, compared with sandier NE soils (Levy et al., 1993; Levy and Miller, 1997; Chappell et al., 1999). Thus, the combination of the surface crust and greater stability/cohesion probably facilitated ravel movement on the SW slope because (1) the crust required more force to remove the weeds and breakup the soil, thereby displacing more or larger soil clods (this is analogous to either a greater depth of tillage or greater tillage speed) and (2) the greater stability/cohesion allowed dislodged clods to travel farther downslope before disintegrating.

5.3. Sustainability implications of weeding-induced erosion

Tillage erosion can be equal to or greater than that of water erosion (Van Oost et al., 2006)—particularly on short fields (e.g., slope length <10–15 m; Turkelboom et al., 1997). Estimated soil loss rates caused by water erosion on upland rice, cassava, and fallow plots in Tan Minh are listed in Table 4. These relatively high erosion rates, ranging from 35 to 92 Mg ha^{-1} $year^{-1}$, were determined via erosion pin studies on nearby unbounded, 10 m × 10 m square plots on slopes ranging from 0.8 to 1.2 m m^{-1} (Vien, 1997, 1998). From the originally reported values we have subtracted the tillage erosion rates associated with three and two annual weeding passes for upland rice and cassava, respectively. Although the pin-based erosion rates on the short 10 m plots may be elevated by run-on water from above, they are consistent with substantial rilling we observed at the base of several long (>30 m) cultivated hillslopes in the swiddens at Tan Minh.

Tillage with hand implements can create a tillage step at the upper field boundary, where soil from upslope accumulates, and soil on the downslope field is cut away (Turkelboom et al., 1999; Kimaro et al., 2005). We rarely saw a tillage step on swidden fields in Tan Minh—in part, because the degree of soil translocation associated with weeding was small, but also because

Table 4
Soil loss rates via water erosion for three surfaces associated with the Da Bac Tay upland swidden farming system

Surface	Year	Water erosion (Mg ha^{-1})	Tillage erosion (Mg ha^{-1})
Upland rice	1st	69	6
	2nd	72	6
Cassava	1st	39	4
	2nd	35	4
Fallow	1st	92	0
	2nd	39	0
	3rd–15th	0	0

Water erosion rates are estimated from erosion pin data by Vien (1997, 1998), with the tillage erosion values subtracted out. Tillage erosion estimates are computed as the medians of six plots on the SW slope during this experiment multiplied by the worst-case-scenario number of weedings per year for rice (3) or cassava (2).

upper and lower parts of the swiddens fields were not typically permanently bound by vegetative strips/barriers. Ravel did accumulate at the base of some fields behind grass/shrub thickets and swidden slash piles. It is not clear however, if Tay farmers were intentionally using the slash to trap translocated soil. As frequently as we saw these types of erosion barriers we saw other farmers cultivating very steep slopes immediately above the stream channel, where no buffering could occur. In such instances, soil translocated downslope as ravel represented an absolute loss of soil and associated nutrients, not just a redistribution on the hillslope.

Kimaro et al. (2005) determined that tillage erosion contributed to the formation of truncated soils at their site in Tanzania. To determine the contribution that weeding has potentially contributed to soil profile truncation in Tan Minh, we estimate cumulative lowering since swiddening commenced about 110 years ago. We divide swiddening in Tan Minh into pre-cooperative (1890–1957), cooperative (1958–1988), and post-cooperative (1989–2000) periods. We ‘‘simulate’’ soil lowering on a swidden field that is cultivated in a manner consistent with the timing/management practices that were prevalent during each period (Rambo, 1998; Rambo and Vien, 2001; Vien, 1997, 2003; Vien et al., 2004; Lam et al., 2004). For this calculation, we make several generalizations, particularly for the early pre-cooperative period, including the following:

1. During the pre-cooperative period, a swidden cycle consisted of 2 years of upland rice cultivation, followed by 15 years of fallow.
2. During the cooperative period, 2 years of upland rice was followed by 1 year of cassava cultivation; and the fallow time decreased to 7 years.
3. In the post-cooperative period, a second year of cassava was planted—for a total of 4 years of cultivation; and the length of fallowing decreased to 5 years.
4. For the cooperative and post-cooperative periods, weeding was performed three times for upland rice cultivation and twice for cassava. We assume that weeding was performed only once during pre-cooperative period because the long fallow periods ensured relatively low weed pressure (as it is believed to be the case in other areas of MMSEA, cf. Turkelboom et al., 1997).
5. The water and tillage erosion rates associated with rice, cassava, and fallow for any year during the three periods are those listed in Table 4. Negligible erosion is assumed to be associated with dibbling and harvesting.
6. Surface lowering was determined by converting the rate of soil loss into a depth by dividing by a bulk density value that is consistent with the corresponding depth (D_p, meters) in the soil profile. This relationship (Fig. 7a), which is based on soil profile data collected at Tan Minh (Table 5), is described by the following equation: $\rho_b = 1006 + 490D_p$ (the values are shown in Fig. 6a).

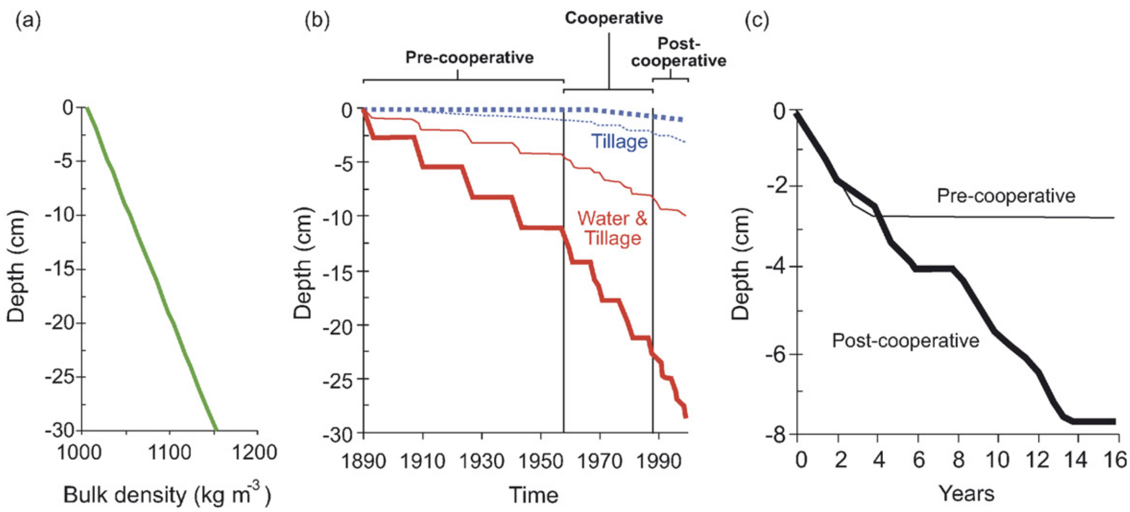

Fig. 7. (a) Relationship between bulk density (ρ_b) and soil profile depth that is used in the calculation of the lowering estimates shown in panel b; (b) estimated soil surface lowering for tillage erosion only and water + tillage erosion since 1890, the time when swidden agriculture was introduced to the study area; (c) comparison of estimated surface lowering by water and tillage erosion for a 15-year period during the pre-cooperative (long fallows) and post-cooperative (short fallows) periods.

Table 5
Median bulk density (ρ_b) and saturated hydraulic conductivity (K_s) at four subsurface depths for disturbed forest and three land covers associated with swidden agriculture

Depth (m)	ρ_b		K_s	
	Forest (kg m^{-3})	Swidden (kg m^{-3})	Forest (mm h^{-1})	Swidden (mm h^{-1})
0.0	970 ± 50	1050 ± 70	63 ± 31	53 ± 36
0.1	1060 ± 130[a]	1200 ± 60	142 ± 26[a]	34 ± 11
0.4	1200 ± 90	1190 ± 40	132 ± 96[a]	38 ± 17
0.7	1230 ± 10	1160 ± 40	83 ± 44	31 ± 20

Values are medians ± one median absolute deviation from the median; $n = 4$ and 12 for forest and swidden categories, respectively.
[a] Statistical difference between the forest and swidden values for this property and at this depth (Mann–Whitney U-test, $\alpha = 0.05$).

During fallow periods when erosion rates were zero, a soil formation rate of 0.2 mm year^{-1} was used (Sparovek and Schnug, 2001; from Skidmore, 1982). The simulated field is one that rests at the crest of a hill, such that deposition of soil originating from upslope fields does not occur.

The estimated soil loss associated with both water and tillage (via weeding) erosion is almost 30 cm for the 110-year period (Fig. 7b). The estimated cumulative soil lowering via weeding alone is less than 2 cm when averaged over the entire length of the simulated field (Fig. 7b). The thin lines in Fig. 7b represent alternative lowering estimates for both tillage and water erosion processes. Here we recognize the following: (1) our weeding methodology may have underestimated tillage erosion rates, because the backstop was too narrow and the weed pressure was low during testing (see Section 5.2); and (2) the water erosion estimates via the pin experiments possibly overestimated water erosion (based on comparison with more recent data collected at another site in Hoa Binh Province; Maglinao et al., 2003). The alternative lowering estimates, which are based on doubling tillage erosion and halving water erosion rates, still indicate dominance of water versus tillage erosion. However, the estimated lowering from both water and tillage erosion is not indicative of major landscape-shaping processes.

More important than the absolute magnitude of the lowering since 1890, however, is the acceleration in soil loss that is estimated to have occurred in recent times (Fig. 7b and c). This acceleration, which results from the combination of shortened fallow periods, greater weed infestation (and therefore increased hoeing), and longer periods of cultivation before fallowing, may represent an unsustainable situation in the sense that the soil ‘‘life time’’ is increasingly becoming shorter. Soil life time represents the amount of time remaining before the soil can no longer guarantee efficient crop production (Stamey and Smith, 1964; Sparovek and Schnug, 2001).

5.4. Potential hydrological consequences

Turkelboom et al. (1999) point out that the tillage steps caused by manual hoeing can create areas of soil loss with reduced permeability. In a prior work in Tan Minh, we found comparatively low values of saturated hydraulic conductivity (K_s) within the soil profile at swidden sites, as compared with a forest site (Ziegler et al., 2004). Median forest K_s values down to 0.7 m were greater than 80 mm h^{-1}; meanwhile, mean K_s at swidden sites was typically <40 mm h^{-1} (Table 5). We initially interpreted these differences as being related to the cumulative effects of water erosion in the swiddens (Ziegler et al., 2004; Vien et al., 2004). In general, lowering on the order of 30 cm could be sufficient to greatly reduce K_s in many tropical soilscapes (Elsenbeer, 2001); the effect of lowering associated with the conservative estimate would be much less important. However, one cannot simply compare near-surface K_s at the swidden sites with that at 10–30 cm depths below the forest to answer this question unequivocally. Nevertheless, the maximum estimated degree of lowering does support the notion that long-term agriculture activity has affected hydrological response on some hillslopes in the swidden areas.

5.5. Final considerations

Given the history of erosion in Tan Minh it is likely that there may have been significant variation in soil physicochemical properties among plots on each hillslope—and perhaps within each plot themselves. Better insight regarding the observed soil translocation differences may have been possible with supplementary in-plot soil data (e.g., bulk density, texture, organic matter). In addition, future studies of this nature could be improved by considering the following points: (1) an extensive weed cover inventory could serve as a general index of the degree of tillage in cases where tillage depth cannot be determined directly; (2) annual soil flux estimates should be based on multiple weeding sessions conducted throughout the course of the year, because soil flux is affected by both changes in weed cover and increases in crop cover; (3) experimental plot lengths should exceed the total downslope distance that dislodged clods typically roll; (4) the range of slopes for experimentation should be wide enough to capture both the critical threshold for severe ravel to occur, and the lower threshold where soil translocation by tillage is negligible; and (5) the influence of crop cover and surface microtopography, including small-scale changes in curvature, should also be investigated, as these variables affect ravel transport.

6. Conclusions

Two distinct processes were associated with soil translocation by weeding on steep-slope fields at the Tan Minh site in northern Vietnam: (1) the mechanical movement of soil material downslope by the small, curved *ngheo* (this is the primary translocation process) and (2) a secondary ravel process, which is characterized by the movement of dislodged soil clods comparatively long distances downslope. Ravel comprised almost 40% of the observed soil flux related to weeding. Both transport processes were controlled initially by the total volume of soil dislodged, which was a function of the depth of tillage and the total area tilled—and both factors were related to weed density. As weed density was low at the time of testing, the maximum observed soil flux for the 20 m plots was 6.4 kg m^{-1} pass^{-1}, which was low compared with fluxes reported for weeding and hoeing activities on steep slopes in other tropical and subtropical locations. Owing in part to the presence of the ravel, soil flux increased exponentially with increasing slope angle; and dislodged clods occasionally traveled the entire 20 m plot length, particularly for slopes greater than about 0.7 m m^{-1}. Because tillage erosion rates were low compared with estimated water erosion rates, the contribution of tillage erosion via weeding to landscape alteration is believed to be small. The combined lowering associated with both water and tillage erosion could however contribute to the observed patterns of reduced saturated hydraulic conductivity on some hillslopes at the site.

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References

Castella, J.-C., Pham, H.M., Suan, P.K., Villano, L., Tronche, N.R., 2005. Analysis of village accessibility and its impact on land use dynamics in a mountainous province of northern Vietnam. Appl. Geogr. 25, 308–326.

Chappell, N.A., Ternan, J.L., Bidin, K., 1999. Correlations of physicochemical properties and sub-erosional landforms with aggregate stability variations in a tropical Ultisol disturbed by forestry operations. Soil Till. Res. 50, 55–71.

Cramb, R.A., 2005. Farmers' strategies for managing acid upland soils in Southeast Asia: an evolutionary perspective. Agric. Ecosyst. Environ. 106, 69–87.

De Rouw, A., 1995. The fallow period as a weed-break in shifting cultivation (tropical wet forests). Agric. Ecosyst. Environ. 54, 31–43.

Dingkuhn, M., Johnson, D.E., Sow, A., Audebert, A.Y., 1999. Relationships between upland rice canopy characteristics and weed competitiveness. Field Crop. Res. 61, 79–95.

Dupin, B., Phantahvong, K.B., Chanthavongsa, A., Valentin, C., 2002. Assessment of tillage erosion rates on steep slopes in the northern Lao PDR. Lao J. Agric. Forest. 4, 52–59.

Dupin, B., Phantahvong, K.B., Chanthavongsa, A., Valentin, C., 2003. Tillage erosion on very steep slopes in northern Laos. In: Maglinao, A.R., Valentin, C., Penning de Vries, F. (Eds.), From soil research to land and water management: Harmonizing people and nature. IWMI, Southeast Asia Regional Office, pp. 105–112.

Elsenbeer, H., 2001. Hydrologic flowpaths in tropical rainforest soilscapes—a review. Hydrol. Process. 15, 1751–1759.

Gabet, E.J., 2003. Sediment transport by ravel. J. Geophys. Res. 108, B1, 2049, doi:10.1029/2001JB001686, 22-1-22-8.

Govers, G., Vandaele, K., Desmet, P.J.J., Poesen, J., Bunte, K., 1994. The role of tillage in soil redistribution on hillslopes. Eur. J. Soil Sci. 45, 469–478.

Grandstaff, T., 1980. Shifting cultivation in northern Thailand—possibilities for development. In: Resource Systems Theory and Methodology Series, No. 3, The United Nations University, Tokyo.

Hill, R.D., Peart, M.R., 1998. Land use, runoff, erosion and their control: a review for southern China. Hydrol. Process. 12, 2029–2042.

Hurni, H., 1982. Soil erosion in Huai Thung Choa—northern Thailand. Concerns and constraints. Mt. Res. Dev. 2, 141–156.

Janeau, J.L., Bricquet, J.P., Planchon, O., Valentin, C., 2003. Soil crusting and infiltration on steep slopes in northern Thailand. Eur. J. Soil Sci. 54 (3), 543–554.

Johnson, D.E., Lee, P.G., Wilman, D., 1991. Experiments with upland rice in southern Belize: fertilizer application, weed control, plant spacing, sowing rate and variety. J. Agric. Sci. 116, 201–215.

Kimaro, D.N., Deckers, J.A., Poesen, J., Kilasara, M., Msanya, B.M., 2005. Short and medium term assessment of tillage erosion in the Uluguru Mountains, Tanzania. Soil Till. Res. 81, 97–108.

Lam, N.T., Patanothai, A., Rambo, A.T., 2004. Recent changes in the composite swidden farming system of a Da Bac Tay ethnic minority community in Vietnam's northern mountain region. Southe. Asian Stud. 42, 273–293.

Levy, G.J., Miller, M.P., 1997. Aggregate stabilities of some southeastern US soils. Soil Sci. Soc. Am. J. 61, 1176–1182.

Levy, G.J., Eisenberg, H., Shainberg, I., 1993. Clay dispersion as related to soil properties and water permeability. Soil Sci. 155, 15–22.

Lewis, L.A., Nyamulinda, V., 1996. The critical role of human activities in land degradation in Rwanda. Land Degrad. Dev. 7, 47–55.

Lindstrom, M.J., Nelson, W.W., Schumacher, T.E., 1992. Quantifying tillage erosion rates due to moldboard plowing. Soil Till. Res. 24, 243–255.

Lindstrom, M.J., Lobb, D.A., Schumacher, T.E., 2001. Tillage erosion: an overview. Ann. Arid Zone 40, 337–349.

Lobb, D.A., Kachanoski, R.G., Miller, M.H., 1995. Tillage translocation and tillage erosion on shoulder slope landscape positions measured using 137-Cs as a tracer. Can. J. Soil Sci. 75, 211–218.

Lobb, D.A., Kachanoski, R.G., Miller, M.H., 1999. Tillage translocation and tillage erosion in the complex upland landscapes of southwestern Ontario. Can. Soil. Till. Res. 51, 189–209.

Lobb, D.A., Quine, T.A., Govers, G., Heckrath, G.J., 2001. Comparison of methods used to calculate tillage translocation using plot-tracers. J. Soil .Water Conserv. 56 (4), 321–328.

Maglinao, A.R., Valentin, C., Penning de Vries, F. (Eds.), 2003. From soil research to land and water management: harmonizing people and nature. IWMI, Southeast Asia Regional Office, p. 270.

Mertz, O., 2002. The relationship between length of fallow and crop yields in shifting cultivation: a rethinking. Agroforest. Syst. 55, 149–159.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models. Part I. A discussion of principles. J. Hydrol. 10, 282–290.

Nyssen, J., Poesen, J., Haile, M., Moeyersons, J., Deckers, J., 2000. Tillage erosion on slopes with soil conservation structures in the Ethiopian highlands. Soil Till. Res. 57, 115–127.

Pandey, S., van Minh, D., 1998. A socio-economic analysis of rice production systems in the uplands of northern Vietnam. Agric. Ecosyst. Environ. 70, 249–258.

Poesen, J., Turkelboom, F., Ohler, I., Ongprasert, A.S., Vlassak, K., 2000. Tillage erosion in northern Thailand: intensities and implications, vol. 46. Mededelingen Koninklijke Academie Voor Overzeese Wetenschappen, pp. 489–512.

Quine, T.A., Walling, D.E., Chakela, Q.K., Mandiringana, O.T., Zhang, X., 1999. Rates and patterns of tillage and water erosion on terraces and contour strips: evidence from caesium-137 measurements. Catena 36, 115–142.

Rambo, A.T., 1995. Defining highland development challenges in Vietnam. In: Rambo, A.T., Reed, R.R., Le Trong Cuc, M.R., DiGregorio, (Eds.), The Challenge of Highland Development in Vietnam.. Program on Environment, East-West Center, Honolulu, HI.

Rambo, A.T., 1996. The composite swiddening agroecosystem of the Tay ethnic minority of the northwestern mountain of Vietnam. In: Rerkasem, B. (Ed.), Montane Mainland Southeast Asia in Transition. Chiang Mai University Consortium, Chiang Mai, Thailand, pp. 69–89.

Rambo, A.T. 1998. The Composite Swiddening Agroecosystem of the Tay Ethnic Minority of the Northwestern Mountains of Vietnam. In: Patanothai. A. (Ed.), Land Degradation and Agricultural Sustainability: Case Studies from Southeast and East Asia. SUAN Regional Secretariat, Khon Kaen, Thailand.

Rambo, A.T., Vien, T.D., 2001. Social organization and the management of natural resources: a case study of Tat Hamlet, a Da Bac Tay ethnic minority settlement in Vietnam's northwestern mountains. Southe. Asian Stud. 39, 299–324.

Rice, R.M., 1982. Sedimentation in the chaparral: how do you handle unusual events? In: Swanson, F.J., Janda, R.J., Dunne, T., S-wanston, D.N. (Eds.), Sediment Budgets and Routing in Forested Drainage Basins, Forest Service. USDA, Washington, DC, pp. 39–49.

Roder, W., 1997. Slash-and-burn rice systems in transition: challenges for agricultural development in the hills of northern Lao. Mt. Res. Dev. 17, 1–10.

Roder, W., Phengchanh, S., Keobulapha, B., 1997. Weeds in slash-and-burn rice fields in northern Laos. Weed Res. 37, 111–119.

Rymshaw, E., Walter, M.F., Van Wambeke, A., 1997. Processes of soil movement on steep cultivated hill slopes in the Venezuelan Andes. Soil Till. Res. 44, 265–272.

Sadoulet, D., Castella, J.-C., Vu, H.N., Dang, D.Q., 2002. A short history of land use change and farming system differentiation in Xuat Hoa Commune, Bac Kan Province, Vietnam. In: Castella, J.C., Dang, K.Q. (Eds.), Doi Moi in the Mountains, Land use Changes and Farmers' Livelihood Strategies in Bac Kan Province, Vietnam. The Agriculture Publishing House, Ha Noi, Vietnam, pp. 21–46.

Schmidt-Vogt, D., 1999. Swidden farming and fallow vegetation in northern Thailand. In: Geoecological Research, vol. 8, Franz Steiner Verlag, Stuttgart, Germany, p. 342.

Sidle, R.S., Ziegler, A.D., Negishi, J.M., Abdul Rahim, N., Siew, R., 2006. Erosion processes in steep terrain – truths, myths, and uncertainties related to forest management in Southeast Asia. Forest Ecol. Manage. 224, 199–225.

Singer, M.J., Shainberg, I., 2004. Mineral soil surface crusts and wind and water erosion. Earth Surf. Process. Landforms 29, 1065–1075.

Skidmore, E.L., 1982. Soil loss tolerance. In: Determinants of Soil Loss Tolerance, ASA Spec. Publ. 45. ASA, Madison, WI, pp. 87–93.

Sparovek, G., Schnug, E., 2001. Temporal erosion-induced soil degradation and yield loss. Soil Sci. Soc. Am. J. 65, 1479–1486.

Stamey, W.L., Smith, R.M., 1964. A conservation definition of erosion tolerance. Soil Sci. 97, 183–186.

Thongmanivong, S., Fujita, Y., Fox, J., 2005. Resource use dynamics and land-cover change in Ang Nhai and Phou Phanang National Forest Reserve, Lao PDR. Environ. Manage. 36, 382–393.

Torri, D., Borselli, L., 2002. Clod movement and tillage tool characteristics for modeling tillage erosion. J. Soil Water Conserv. 57, 24–28.

Turkelboom, F., 1999. On-farm diagnosis of steepland erosion in northern Thailand. Unpublished PhD Thesis. Faculty of Agricultural and Applied Biological Sciences, K.U. Leuven, p. 309.

Turkelboom, F., Poesen, J., Ohler, I., Van Keer, K., Ongprasert, S., Vlassak, K., 1997. Assessment of tillage erosion rates on steep slopes in northern Thailand. Catena 29, 29–44.

Turkelboom, F., Poesen, J., Ohler, I., Ongprasert, S., 1999. Reassessment of tillage erosion rates by manual tillage on steep slope in northern Thailand. Soil Till. Res. 51, 245–259.

Van Muysen, W., Govers, G., Bergkamp, G., Roxo, M., Poesen, J., 1999. Measurement and modeling of the effects of initial soil conditions and slope gradient on soil translocation by tillage. Soil Till. Res. 51, 303–316.

Van Oost, K., Govers, G., de Alba, S., Quine, T.A., 2006. Tillage erosion: a review of controlling factors and implications for soil quality. Prog. Phys. Geogr. 30 (4), 443–466.

Vien, T.D., 1997. Soil erosion and nutrient balance in swidden fields of the Da Bac District, Vietnam. Report No. 10667. Program on Environment, East-West Center, Honolulu, HI.

Vien, T.D., 1998. Soil erosion and nutrient balance in swidden fields of the composite swiddening agroecosystem in the northwestern mountains of Vietnam. In: Paranothai, A. (Ed.), Land Degradation and Agricultural Sustainability: Case Studies from Southeast and East Asia. Regional Secretariat, the Southeast Asian Universities Agroecosystem Network (SUAN). Khan Kaen University, Thailand.

Vien, T.D., 2003. Culture, environment, and farming systems in Vietnam's northern mountain region. Southe. Asian Stud. 41, 180–205.

Vien, T.D., Dung, N.V., Dung, P.T., Lam, N.T., 2004. A nutrient balance analysis of the sustainability of a composite swiddening agroecosystem in Vietnam's northern mountain region. Southe. Asian Stud. 41, 491–502.

Weyerhaeuser, H., Wilkes, A., Kahrl, F., 2005. Local impacts and responses to regional forest conservation and rehabilitation programs in Chinas's northerwestern Yunnan Province. Agric. Syst. 85, 234–253.

Xu, J.C., Fox, J., Vogler, J.B., Peifang, Z., Yongshou, F., Lixin, Y., Jie, Q., Leisz, S., 2005. Land-use and land-cover change and farmer vulnerability in Xishuangbanna Prefecture in southwestern China. Environ. Manage. 36, 404–413.

Zhang, J.H., Lobb, D.A., Li, Y., Liu, G., 2004. Assessment of tillage translocation and tillage erosion by hoeing on the steep land in hilly areas of Sichuan, China. Soil Till. Res. 75, 99–107.

Ziegler, A.D., Sutherland, R.A., Giambelluca, T.W., 2000. Runoff generation and sediment transport on unpaved roads, paths, and agricultural land surfaces in northern Thailand. Earth Surf. Process. Landforms 25, 519–534.

Ziegler, A.D., Giambelluca, T.W., Tran, L.T., Vana, T.T., Nullet, M.A., Fox, J., Vien, T.D., Pinthong, J., Maxwell, J.F., Evett, S., 2004. Hydrological consequences of landscape fragmentation in mountainous Northern Vietnam: evidence of accelerated overland flow generation. J. Hydrol. 287, 124–146.

Ziegler, A.D., Tran, L.T., Sidle, R.C., Giambelluca, T.W., Sutherland, R.A., Vien, T.D., 2006. Effective slope lengths for buffering hillslope surface runoff in fragmented landscapes in northern Vietnam. Forest Ecol. Manage. 224, 104–118.