Soil & Tillage Research 103 (2009) 119–126

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Assessment of tillage erosion rates on steep slopes in northern Laos

B. Dupin [a,*], A. de Rouw [b], K.B. Phantahvong [c], C. Valentin [b]

[a] Agronomes et Vétérinaires Sans Frontières (VSF), Madagascar
[b] Institut de Recherche pour le Développement (IRD), 93143 Bondy cedex, France[1]
[c] Consultant, Luang Prabang, Lao P.D.R

ARTICLE INFO

Article history:
Received 26 April 2008
Received in revised form 22 September 2008
Accepted 3 October 2008

Keywords:
Tillage erosion
Steep slopes
Shifting cultivation
Upland rice
Job's tears
Weed pressure

ABSTRACT

In the hills of south-east Asia shifting cultivation is developing towards more permanent cropping systems. In association with short fallow periods, fields suffer from weed pressure and this, in turn, leads to more frequent and deeper manual tillage. Due to steep slopes these operations induce tillage erosion. Measurements of such soil losses under on-farm conditions are still scarce. In this study tillage erosion was assessed and a predictive model of tillage erosion was established based on slope angle and contact cover, i.e. basal crop area and weed cover. The experiments were conducted in the Houay Pano, Northern Laos. The farmers cultivate annual crops in rotation with 1–3 year fallow periods without external inputs and using only hand tools. Tillage erosion was assessed using the tracer method across nine slope classes (0.30–1.10 m m^{-1}) for two crops, upland rice and Job's tears (*Coix lacryma-jobi* L.). Soil movement due to land preparation and weeding were assessed separately because different tools are used, a medium size hoe and a small curved hoe. A multivariate regression showed a highly significant relation ($R^2 = 0.83$) between soil losses due to land preparation, slope gradient and contact cover. Predicting models of soil losses due to weeding were also highly significant ($R^2 = 0.79$ for upland rice, $R^2 = 0.88$ for Job's tears), confirming the importance of tillage erosion on steep slopes (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). Tillage erosion has increased exponentially over the last 40 years because of weed invasion associated with short fallow periods; the initially no-till system has changed into a system heavily dependent on tillage to control weeds and this greatly contributes to soil degradation.

1. Introduction

In most tropical areas, the increasing weed pressure resulting from the intensification of upland farming requires farmers to dedicate more labour to weeding (Nye and Greenland, 1960; Roder et al., 1995). In the highlands of Thailand, Laos and Vietnam, shifting cultivation is still a dominant feature of subsistence farming but the system has become increasingly distorted in response to population pressure, inappropriate techniques, but also peculiarly in Laos, to resettlement (Lestrelin et al., 2005). In many areas the fallow period has been shortened locally to 1–3 years whereas ecological sustainability may require a minimum fallow period of at least 8 years to restore soil fertility and control weeds. This has resulted in a drastic decline in land and labour productivity (Fujisaka, 1991; Roder et al., 1995; de Rouw, 2001; Lestrelin and Giordano, 2006; Saito et al., 2006a). Shortening of fallow periods leads to a gradual replacement of a forest-like vegetation by a bush fallow including the dominance of forbs and vines such as *Chromolaena odorata* (L.) R.M. King & H. Rob., *Mimosa diplotricha* C. Wright ex Sauv. var. diplotricha and sometimes coarse grasses such as *Imperata cylindrica* (L.) P. Beauv. var. major (Nees) C.E. Hubb. ex Hubb. & Vaugh. (de Rouw et al., 2005a). In this process, not only the number of weeds in the field increases but the species composition also changes because more aggressive species could adapt to frequent clearing. While shifting cultivation was originally a no-till farming system because weeds were few and could be controlled by hand pulling and cutting with a knife, nowadays tillage is part of the system. In northern Laos, between 40 and 77% of the total labour inputs is lost in weeding (Roder et al., 1997; de Rouw et al., 2002; Saito et al., 2006b) (Table 1).

On steep slopes, tillage operations induce erosion which is the process of downhill soil translocation caused by the force applied by agricultural tools and gravity. This mechanical erosion has been

* Corresponding author at: Projet BV Lac Alaotra, BP 103 Ambatondrazaka 503, Madagascar.
E-mail addresses: b.dupin@avsf.org (B. Dupin), de_rouw@bondy.ird.fr (A. de Rouw).
[1] Seconded to International Water Management Institute (IWMI).

0167-1987/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.still.2008.10.005

Table 1
Labour inputs for slash-and-burn upland rice and Job's tears cultivation, Houay Pano, Laos.

Operation	Month	Upland rice		Job's tears		Tools
		Days ha^{-1}	%	Days ha^{-1}	%	
Slashing fallow vegetation	March	41	15	27	14	Machete
Burning	April	1	0.4	1	0.5	
Land preparation	May	26	9	25	13	Medium size hoe
Hill sowing	June	43	15	8	4	Bamboo stick
1st weeding	June	36	13	53	28	Small curved hoe
2nd weeding	July	38	13	22	11	Small curved hoe
3rd weeding	August	38	13	32	17	Small curved hoe/machete
4th weeding	August	35	12			Machete
Harvest and transport	September–November	25	9	25	13	
Total		283		193		

studied for tractor-plough tillage (Lindstrom et al., 1992; Govers et al., 1996; Lobb et al., 1999; Marques da Silva et al., 2004); yet this process occurs also when farmers use manual tools to prepare and weed their fields (Lewis and Nyamulinda, 1996; Turkelboom et al., 1997, 1999; Thapa et al., 1999a; Nyssen et al., 2000; Zhang et al., 2004; Kimaro et al., 2005; Dercon et al., 2006). Soil clods detached by tillage operations accumulate in the depressions or at the field limit. In the convexities, erosion due to soil tillage is more important because soil losses exceed inputs (Govers et al., 1994). Several authors have reported that tillage erosion from small fields can cause soil losses of the same order of magnitude than those reported for water erosion (Quine et al., 1999; Turkelboom et al., 1999; Van Muysen et al., 1999; Nyssen et al., 2000). In south-east Asia most erosion research has concentrated on water erosion (Hurni, 1982; Hill and Peart, 1998; Chaplot et al., 2003; Valentin et al., 2005). Unlike water erosion, tillage erosion increases with shorter slopes (Turkelboom et al., 1997). Tillage erosion affects the top layer, therefore it has a major effect on soil fertility because typically, nutrients contained in organic matter and ash concentrate in the top centimetres of the soil. The repetition of manual tillage operations induces spatial variability of soil fertility along the slope and possibly soil profile modifications (Thapa et al., 1999b; Kimaro et al., 2005; Dercon et al., 2006). Tillage can also decrease soil resistance to breakdown under splash effects and runoff erosion (Govers et al., 1994).

On the cultivated slopes of south-east Asia only few studies have quantified soil losses due to manual tillage on-farm. Manual tillage, i.e. hoeing on slopes, includes two soil movement processes: one is the translocation of soil by the hoeing action; the other is the "ravel" which is the rolling, bouncing, and sliding of soil clods down slope. One study focussing on deep tillage carried out by farmers in order to free the land from perennial grasses (Turkelboom et al., 1997) quantified chiefly the translocation of the soil since the rough surface in combination with uprooted grasses prevented the ravel. A second study on superficial tillage for weeding purpose (Ziegler et al., 2007) measured mainly the ravel because the surface remains rather smooth. In previous studies, experimental conditions were sometimes unnatural. Fields were near bare because tillage was performed after removing all the weeds from the plots (Turkelboom et al., 1997), or very few weeds were present (Ziegler et al., 2007); the period of experimentation was too early in the season, in December instead of February for land clearing (Turkelboom et al., 1997) and in May for weeding (Ziegler et al., 2007); tillage experiments were space-continuous (Turkelboom et al., 1997; Ziegler et al., 2007), though in those farming systems the aim of tillage is to remove weeds and farmers generally will not till sites without weed cover. Apart from their originality, the merit of these studies lies in the fact that different methods were compared to measure and describe soil losses in the field. In this study the methodology developed by Turkelboom et al. (1999) was adopted: the tracer method for field measurements, and linear functions for different slope gradient classes for predictive models.

The present study investigates manual tillage erosion on steep slopes in situations resembling more closely the typical farm conditions: separate experiments for different types of tillage tools and for different crops, experiments conducted in their proper period according to the cropping calendar, and accounting for the natural weedy vegetation and crop cover in situ, for instance no tillage applied on patches of the field that are weed free. Subsequently, we investigated whether the variables: tool, crop, cover by weed and basal area of crop, could improve the predicting model of tillage erosion used by Turkelboom et al. (1999). Finally, this study aims to assess the historic accumulative tillage erosion of the study site starting in a period in which tillage was not required up to the present where cultivation heavily depends of tillage to control weeds.

2. Materials and methods

2.1. The study area Houay Pano catchment

The catchment, located near the village Lak Sip, in Luang Prabang District, northern Laos covers about 0.60 km^2, and discharges to the Mekong River. UTM 1983 coordinates (zone 48) comprise between 203245.14 to 204679.65 m and 2197318.4 to 2198825.04 m, or 102°10′17″ longitude and 19°51′23″ latitude. The climate is sub-tropical with an annual precipitation over the last 30 years of 1403 mm and a mean annual temperature of 25.3 °C. Almost 90% of the annual precipitation occurs during the monsoon season from April to October. Altitude ranges from 425 to 718 m with a mean slope of 0.56 m m^{-1}. Parent material is composed of schist. From downslope to upslope positions, soils vary from Dystrochrepts, Alfisols to Inceptisols (Soil Survey Staff, 1999). At downslope positions, where slopes range from 0.05 to 0.30 m m^{-1}, deeper soils are formed with rather fertile alluvio-colluvial sediments eroded from the hill slopes. These Dystrochrepts are truncated and show some redoximorphic features (Chaplot et al., 2005). Alfisols cover almost half of the total area and occur on the steeper slopes. They are deep, 2.5–4.5 m, clayey soils, marked by a typical argillic B subsurface horizon with clay films of 1 mm or more. Due to erosion rates, this argillic horizon is frequently exposed at the soil surface (Chaplot et al., 2005). On hill tops and on the steepest slopes, Inceptisols occur. These soils are characterized by a degraded thin soil layer, 0.5–1 m thick. All Dystrochrepts and Alfisols and some Inceptisols are cultivated.

The hill slopes are covered by a mosaic of fallow vegetation and crop land with a predominance of upland rice (*Oryza sativa* L.) and

Job's tears (*Coix lachryma-jobi* L.). In the valley bottom, vegetables and banana are often grown. Only the very steep slopes and the crests are not cultivated, these sites are covered by remnants of dry Dipterocarp forest. The catchment is representative of the no-input rotational shifting cultivation system of south-east Asia, and underwent a reduction of the fallow period from 10 to 15 years about 40 years ago, to 1–3 years currently (de Rouw, 2005; Lestrelin et al., 2005).

2.2. The farming system

The dominant ethnic group of the area are the Khamu. Table 1 shows the cropping calendar, tools and labour inputs for upland rice and Job's tears cultivation. After burning, weeds emerge massively and the farmers clear the land working up the slope. These weeds tend to cover the entire field so the tillage work is space continuous. After sowing farmers start weeding going upslope. Firstly, the larger weeds are eliminated by slashing or hand pulling, and then the small weeds are controlled by tillage. The fields of Job's tears are usually weeded less frequently because this crop is more competitive. In the last weeding round no tillage is used, instead, hand pulling and slashing with a machete allow an easy access to the field for harvesting. The productivity of this farming system is low as farmers obtain a mean yield of 1.2 t ha^{-1} for upland rice and 1.4 t ha^{-1} for Job's tears (de Rouw et al., 2002; Lestrelin and Giordano, 2006).

2.3. Increased use of tillage during the last 40 years

Farmers with fields in the catchment (36 households) were asked to recall how their cropping practices had evolved from a no-till system in which the soil was not otherwise disturbed but by sowing, into a system requiring more and deeper tillage to control weeds. Thus, the farmers identified a first stage in which upland rice was cultivated requiring no land preparation prior to sowing other than burning and no soil disturbance during weeding. The few weeds present were allowed to grow to a certain size they could be hand pulled. A second stage followed comprising no tillage required for land preparation but one weeding round using the small curved hoe for superficial tillage (Fig. 1). Weeds appeared so numerous after sowing that they would cause severe yield reduction if left undisturbed. As these seedlings were too small to be eliminated by hand pulling, they were controlled using superficial tillage. A third stage was identified comprising no tillage required for land preparation but two weeding rounds in the crop using the same small curved hoe. A fourth and last stage was identified as a situation requiring deep tillage with a medium size hoe in order to prepare the land for sowing. Three weeding rounds with tillage using the small curved hoe would follow. From stages 1 to 3, the same group of weed species was encountered in rice fields, only occurring in increasingly greater numbers. Stage 4 is characterized by the invasion of a new group of weeds capable of germinating within 1 or 2 weeks after burning. Their rapid elimination, a necessity for timely sowing, resulted in the adoption of a new tillage tool, the medium size hoe.

Fig. 1. The small curved hand hoe (*oewèk*) used by Khamu farmers for weeding.

This information was checked by direct observations in the field, between 2001 and 2004. In the catchment, fields were in stages 3 and 4, outside the catchment at several hours walking distance from the village; examples of stages 1 and 2 were found. Referring to exceptional events such as 1995, the year of the application of the Land reform, 1973, when the road was built, and events between 1960 and 1975 related to the civil war, we could date approximately these changes in the farming system.

2.4. Experimental set-up

The experiments were conducted during the cropping seasons of 2001 and 2002 in Houay Pano catchment. Additional information on weed control, growth, cover and weed type was gathered in the cropping seasons 2001–2004 by direct observations in the field and interviews with farmers.

Plots were laid out in farmer's fields on linear slopes over 10 m length including the steepest slopes cultivated. Tillage erosion due to land preparation using the medium size hoe was assessed on nine slope classes (0.20–1.10 m m^{-1}) with six replications. Tillage erosion after sowing due to weeding using the small curved hoe, was assessed on seven slope classes: in upland rice (0.20–0.90 m m^{-1}) with four replications and in Job's tears (0.40–1.10% m m^{-1}) with three replications. In total 103 measurements were made, 54 on land preparation, 49 on weeding operations of which 21 were in Job's tears and 28 in upland rice. All tillage work was performed by the farmers with their own tools following local practice.

Initially, small stones were used for tracers, but these were suspected to behave differently from soil clods because of their superior weight and rounded form. After some trials, they were replaced by aggregates collected from the soil surface of the various fields, size 1–2 cm; the latter were oven-dried and painted. For each measurement, 100 such aggregates were used. They were placed along a contour line marked by a string. Slope gradient was measured with a clinometer. Contact cover (%, C_c) was visually assessed in the fields using figure charts (Casenave and Valentin, 1989). This cover represents the percentage of obstacles directly in contact with the ground; it includes the basal area of the crop (%, C_{bac}) and the weed cover (%, C_w). Weed cover included both the cover by green weeds just before their elimination by the tillage operation, and the cover by heaps dead weeds, slashed or pulled out prior to the tillage operation. Rock and gravel that are commonly part of contact cover (e.g. Sidle et al., 2006) were absent in our study. After these measurements, hoeing was then performed by farmers working uphill until the line of tracers was passed. The distance between each displaced aggregate and the benchmark line was measured.

2.5. Calculation of tillage erosion

The soil mass that passes a unit contour length for one tillage pass, or soil flux Q_t (Turkelboom et al., 1999), can be calculated using Eq. (1):

$$Q_t = D_m D_\rho \quad (1)$$

where Q_t is the soil flux caused by tillage (in kg m^{-1} tillage pass^{-1}); D_m is the mean downslope displacement distance of the tracers (m); D is the mean tillage depth; ρ is the bulk density of the soil (t m^{-3}). Bulk density was measured at the onset of every experiment, three replicates, using the cylinder method. Mean soil losses per hectare for one tillage pass can be derived from the soil flux Eq. (1) and from the downslope field length using Eq. (2):

$$TE = \frac{Q_t 10}{L} \quad (2)$$

where TE is the tillage erosion rate (t ha^{-1} tillage pass^{-1}), Q_t is the soil flux caused by tillage (kg m^{-1} tillage pass^{-1}); L is the downslope field length (m). To enable comparisons, a fixed value of L was used (50 m).

Contrary to land preparation, weeding in the crop is not space continuous: only areas covered by weeds are tilled. This manual practice consists of a very shallow scraping of the soil surface with a curved hoe to cut or uproot the weeds. Tillage erosion due to weeding is given by Eq. (3):

$$TE_w = S_w TE \quad (3)$$

where TE_w is the tillage erosion rate (t ha^{-1} tillage pass^{-1}) due to a weeding operation; TE is the tillage erosion rate derived from Eq. (2); S_w is the area effectively tilled during weeding. In practice, we used C_w, the weed cover area, as a surrogate to S_w. C_w was assessed on the plot just before each tillage experiment.

Knowing the number of hoeing operations for land preparation (n_h) and for weeding (n_w), the annual tillage erosion ATE can be calculated using Eq. (4):

$$ATE = n_h TE_h + n_w TE_w \quad (4)$$

where ATE is the annual tillage erosion rate (t ha^{-1} year^{-1}); TE_h and TE_w (t m^{-1} tillage pass^{-1}) are the tillage erosion rate due to land preparation and weeding, respectively; n_h and n_w are the annual number of hoeing operations for land preparation and for weeding with tillage tools, respectively. We used $n_h = 1$ for both crops and $n_w = 2$ for Job's tears and $n_w = 3$ for rice.

2.6. Building a predictive model of tillage erosion

Linear regression analyses were performed with a personal computer version of the SPSS® package using stepwise linear regression. With this procedure independent variables can be added individually to the model at each step of the regression, and therefore changes in the R^2 value can be evaluated. These stepwise regressions were used to identify the best predictors for tillage erosion. In the linear regressions, only parameters statistically significant at the 0.01 level were retained. To enable comparison, field area and slope length has been fixed to 1 ha and 50 m.

The annual soil losses for the different stages of tillage intensity since 1964 could be assessed using Eq. (5):

$$ATE_{(stage\,\alpha)} = n_{h\,(stage\,\alpha)} TE_{h\,(stage\,\alpha)} + n_{w\,(stage\,\alpha)} TE_{w\,(stage\,\alpha)} \quad (5)$$

where $ATE_{(stage\ \alpha)}$ is the annual soil erosion (t ha^{-1} year^{-1}) due to tillage erosion during the stage α; $TE_{h\ (stage\ \alpha)}$ and $TE_{w\ (stage\ \alpha)}$ are the tillage erosion rates due to land preparation and weeding calculated with predictive models built with the results from the field measurements; $n_{h\ (stage\ \alpha)}$ and $n_{w\ (stage\ \alpha)}$ are the annual number of land preparation and weeding operations, respectively.

3. Results

3.1. Soil flux due to land preparation

Seriously infested fields are colonized by weed species whose germination is stimulated by fire such as the vine *Mimosa diplotricha*. After burning, tiny seedlings emerge disseminated all over the field and, if left undisturbed, quickly form a thick, more or less continuous mat. These weeds are controlled by hoeing prior to sowing. Because of the rather uniform distribution of these weeds in the field, the entire surface has to be worked. Hoeing with the medium size hoe remains most often shallow with a mean depth of 2 cm. Consequently, the soil surface stays rather smooth and this enables aggregates to roll and slide down along the slope. However, the cut and uprooted weeds form a mulch together with detached aggregates and this mass prevents aggregates from rolling down. The extent of the mulch-mass varies with the size of the individual plants in the mulch. In cases where *Mimosa* plants were rather big, these seedlings could cover 50% of the field, whereas tiny plants would represent a cover as low as 5%. The effectiveness of this mulch to stop aggregates and prevent soil losses is shown in Fig. 2. A weed cover, also called contact cover, of 50% reduced soil losses by 40% on a 0.60 m m^{-1} slope gradient as compared to cases with a cover of only 5%.

On average, fields of all slope ranges were to a similar degree, about 20%, covered by *Mimosa* at the moment the farmer decided to clear the land using tillage (Table 2). Therefore, tillage erosion due to land clearing largely depended on the slope gradient and to a lesser extent on contact cover. For instance, on a 0.60 m m^{-1} slope gradient, mean aggregates displacement exceeded 1 m leading to soil losses of 3.8 t ha^{-1} (Table 2).

A regression based on the experiments ($R^2 = 0.83$, $n = 54$) was established relating soil losses (TE_h, t ha^{-1} year^{-1}), slope gradient (S, %) and contact cover (C_c, %) using Eq. (6):

$$TE_h = e^{(0.247+0.028.S-0.017\,C_c)} \quad (6)$$

Tillage erosion due to land preparation can thus be estimated.

3.2. Soil flux due to weeding

In contrast to the uniform weed emergence immediately after burning, emergence later in the rainy season is patchier. The subsequent tillage operations are not space-continuous because farmers work the soil where weeds are growing, thus limiting soil

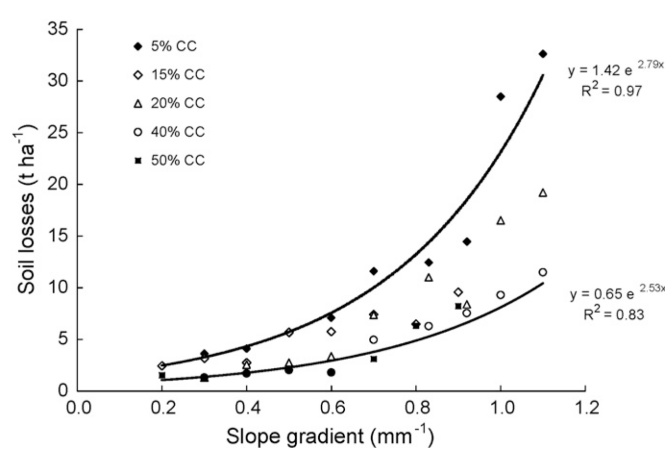

Fig. 2. Tillage erosion during land preparation due to hoeing as influenced by slope gradient and the fraction of the soil surface directly covered by weeds and the basal area of the crop (contact cover).

Table 2
Mean and standard deviation for tillage erosion caused by land preparation using a medium size hoe, tillage depth 2 cm, soil bulk density 0.9 t m^{-3}, $n = 54$, S.D. = standard deviation.

Slope class ($m\ m^{-1}$)	Soil contact cover (%)		Translocation distance (m)		Soil flux (kg $pass^{-1}$)		Soil losses (t ha^{-1})	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
0.2–0.3	22	*21.9*	0.6	*0.30*	11	*5.5*	2.4	*0.82*
0.3–0.4	22	*19.1*	0.7	*0.25*	13	*4.4*	2.2	*1.38*
0.4–0.5	18	*19.1*	1.0	*0.61*	18	*11.0*	2.6	*0.89*
0.5–0.6	18	*14.4*	1.1	*0.52*	19	*9.3*	3.6	*2.20*
0.6–0.7	15	*14.4*	1.8	*0.61*	33	*11.0*	3.8	*1.86*
0.7–0.8	18	*15.4*	2.3	*0.56*	42	*10.2*	6.5	*2.20*
0.8–0.9	22	*15.4*	2.7	*0.69*	49	*12.4*	8.4	*2.68*
0.9–1.0	22	*17.6*	5.0	*2.69*	91	*48.5*	9.8	2.59
1.0–1.1	22	*17.6*	5.9	*2.97*	106	*53.5*	19.6	9.28

The italics values represent standard deviation.

Table 3
Mean and standard deviation for tillage erosion caused by weeding using a small curved hoe, tillage depth 1 cm, soil density rice field 0.95 t m^{-3}, $n = 28$, soil density Job's tears field 0.90 t m^{-3}, $n = 21$.

Slope class ($m\ m^{-1}$)	Weed cover (%)		Crop basal area (%)		Soil contact cover (%)		Translocation distance (m)		Soil flux (kg $pass^{-1}$)		Soil losses (t ha^{-1})		
											($weeding^{-1}$)		($year^{-1}$)
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean
Upland rice													
0.2–0.3	30	*14.1*	23	*6.4*	38	*9.6*	0.4	*0.03*	1.1	*0.43*	0.2	*0.09*	0.6
0.3–0.4	43	*9.6*	26	*8.5*	48	*5.0*	0.4	*0.05*	1.7	*0.53*	0.3	*0.11*	1.0
0.4–0.5	25	*5.8*	35	*10.8*	50	*14.1*	0.7	*0.10*	1.6	*0.34*	0.3	*0.07*	1.0
0.5–0.6	25	*5.8*	19	*2.5*	31	*2.5*	1.0	*0.07*	2.4	*0.66*	0.5	*0.13*	1.4
0.6–0.7	23	*13.9*	22	*5.9*	32	*9.6*	1.3	*0.52*	2.2	*0.42*	0.4	*0.08*	1.3
0.8–0.9	15	*5.8*	23	*6.4*	30	*8.2*	2.5	*0.59*	3.4	*1.08*	0.7	*0.22*	2.0
Job's tears													
0.3–0.4	17	*5.8*	38	*20.2*	47	*23.1*	0.5	*0.22*	0.6	*0.28*	0.1	*0.06*	0.2
0.4–0.5	17	*5.8*	38	*20.2*	47	*23.1*	0.8	*0.59*	1.1	*0.47*	0.2	*0.09*	0.4
0.5–0.6	17	*5.8*	40	*13.2*	43	*15.3*	1.0	*0.64*	1.2	*0.29*	0.2	*0.06*	0.5
0.6–0.7	10	*2.0*	37	*18.9*	42	*18.9*	1.0	*0.38*	0.9	*0.34*	0.2	*0.07*	0.3
0.8–0.9	13	*5.8*	32	*18.9*	38	*20.2*	1.7	*1.42*	1.9	*1.23*	0.4	*0.25*	0.8
0.9–1.0	13	*5.8*	32	*18.9*	38	*20.2*	2.2	*1.16*	2.5	*1.09*	0.5	*0.22*	1.0
1.0–1.1	13	*5.8*	32	*18.9*	38	*20.2*	3.4	*1.60*	3.9	*1.67*	0.8	*0.33*	1.6

The italics values represent standard deviation.

disturbance to about 20–30% of the soil surface in upland rice, and 10–20% in Job's tears (Table 3).

Weeding consisted of a very shallow scraping of the soil surface not exceeding 1 cm of depth with a small curved hoe. In contrast to the land preparation where seedlings are left on the soil surface forming a mulch, farmers during weeding did not leave the uprooted seedlings on the soil surface where there is a risk that they may regrow, but handsfull of weeds were disposed off in places of the ground or outside the field. Thus, because of the rather smooth surface, the dislocated aggregates could roll further down the slope compared to the clearing operation prior to sowing. On the other hand, contact cover of the crop constituted important obstacles for soil displacement. In rice, contact cover was high because farmers planted at high densities, 10–12 hills m^{-2}; but contact cover was also high in Job's tears, not because of dense sowing, limited to 1–2 hills m^{-2}, but because of the stout growth form and strong tillering of the local Job's tears varieties (Table 3). Job's tears being a more robust and more competitive plant compared to upland rice, reduced weed growth. Tillage erosion due to weeding was primarily influenced by slope gradient and this effect was stronger for rice (Fig. 3) than for Job's tears (Fig. 4). The difference between the crops was due to the areas effectively tilled, less so in Job's tears, and to basal area, superior in Job's tears, both impede aggregate displacement. However, the repetitiveness of this operation resulted in soil losses equivalent to 1 t ha^{-1} in both crops.

Stepwise regressions analyses were performed to identify the best predictors for tillage erosion due to weeding operations. Linear regressions selected statistically three characteristics: slope gradient, crop basal area and weed cover, to predict tillage erosion by weeding in Job's tears, Eq. (7):

$$TE_{w\,(Job's\,tear)} = e^{(-3.154+0.025S-0.030\,C_{bac}+0.080\,C_w)}$$
$$\text{with } n = 21 \text{ and } R^2 = 0.91$$

where $TE_{w\ (Job's\ tear)}$ is the tillage erosion rate due to weeding in Job's tears (t ha^{-1} weeding $pass^{-1}$); S is the slope gradient

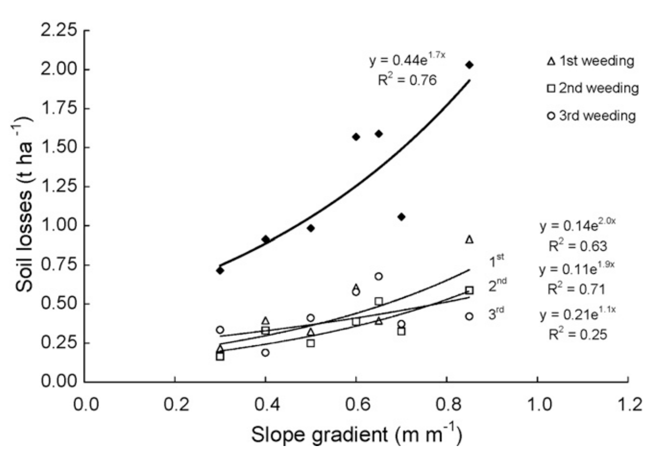

Fig. 3. Tillage erosion due to weeding in upland rice as influenced by slope gradient.

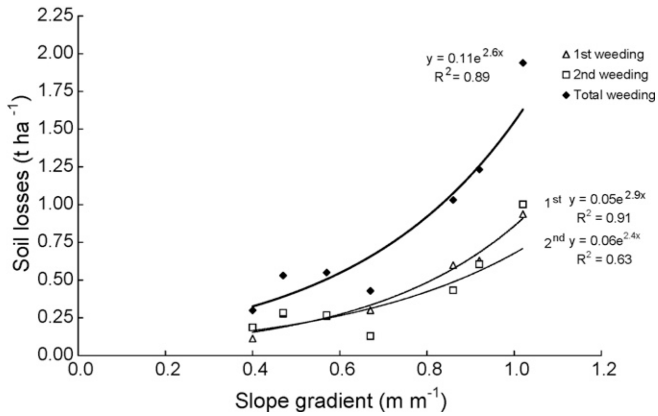

Fig. 4. Tillage erosion due to weeding in Job's tears as influenced by slope gradient.

(%); C_{bac} is the basal area of the crop (%); C_w is the cover of weeds (%).

By contrast, only two characteristics: slope gradient and weed cover were major predicting factors for tillage erosion by weeding in upland rice fields, Eq. (8).

$$TE_{w\,(rice)} = e^{(-3.347+0.029\,S+0.029\,C_w)} \qquad \text{with } n = 28 \text{ and } R^2 = 0.79 \tag{8}$$

where $TE_{w\,(rice)}$ is the tillage erosion rate due to weeding in upland rice (t ha^{-1} weeding $pass^{-1}$); S is the slope gradient (%); C_w is the cover of weeds (%).

Tillage erosion due to weeding operations can therefore be assessed as a function of the slope gradient, the area occupied by weeds and the basal area of the crop.

3.3. Evolution of tillage erosion rates over the last forty years

Fig. 5 shows the level of annual tillage erosion for those fields requiring land preparation prior to sowing. Soil losses are high in both crops. It is slightly higher for the fields cultivated with upland rice than Job's tears due to more weeding passes in the former and less weed infestation in the latter.

The majority of fields in the catchment were in stage 1 up to 1974 (Table 4), in stage 2 up to 1985, in stage 3 up to 2002. Fields in stage 4 started to appear from 1996 onwards and their number increased every year. At the time of the tillage experiments, a quarter of the cultivated fields were in stage 4, the remainder in stage 3.

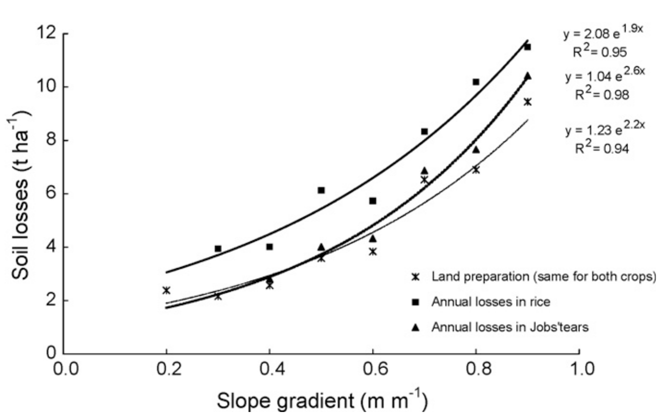

Fig. 5. Annual tillage erosion in upland rice and Job's tears as influenced by slope gradient.

Table 4
Evolution of number and type of tillage operations in shifting cultivation, Houay Pano, Laos.

Period	Fallow duration (year)	Clearing prior to sowing		Weeding in rice	
		Passes	Tool	Passes	Tool
Before 1974	15–25		Not needed	1–2	Hand pulling
1975–1985	8		Not needed	1	Small curved hoe
1986–1995	3–4		Not needed	2	Small curved hoe
1996–2004	1–3	1	Medium size hoe	3	Small curved hoe

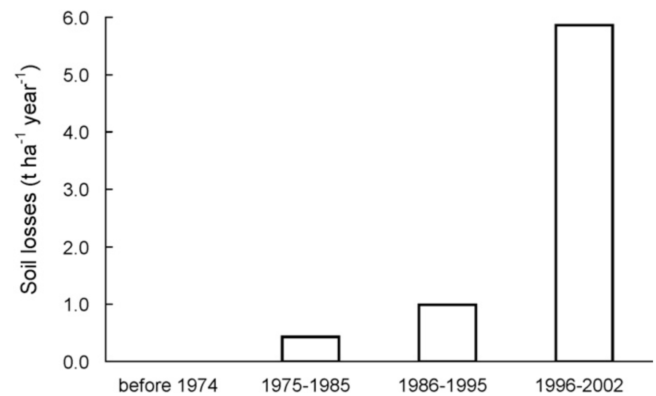

Fig. 6. Evolution of tillage erosion rates during the last forty years on a field with a 60% slope.

In Houay Pano, the intensification of the shifting cultivation system has lead to an exponential increase of tillage erosion (Fig. 6). Shifting cultivation before 1974 did not provoke noticeable tillage erosion rates. After 1974, annual soil losses due to tillage on a 0.60 m m^{-1} slope increased to about 0.4 t ha^{-1}. In 1986, tillage erosion increased to values of 1 t ha^{-1}. After 1996, soil losses increased exponentially to about 6 t ha^{-1} $year^{-1}$ due to the combined action of space continuous tillage and a new tool working the soil at a greater depth.

4. Discussion

Our data confirm the importance of tillage erosion on very steep slopes and the non-linear nature of the relationship between tillage and slope gradient. Manual tillage by farmers working steep slopes in south-east Asia can be remarkably varied; hence it is difficult to compare erosion rates. In the Sichuan study area (Zhang et al., 2004), tillage includes a 20 cm deep digging and local turning of the soil in order to improve its structure rather than control weeds. The operation is space-continuous and produces such a roughness of the soil surface that the ravel of clods is limited. By contrast, the soil is only superficially worked in the shifting cultivation systems of Laos (this study) and in the mountains of north Vietnam (Ziegler et al., 2007), however not with the same type of hand tool. The weeding tool (*ngheo*) of the Vietnamese Tay farmers is in fact a hooked knife hitting the soil surface over a width of 5 cm maximally. It is hard to imagine a space-continuous weeding operation with such a tiny tool. In Laos, the weeding tool (*ouwèk*) is curved sideways, almost like a sickle, the blade making a 90° angle with the handle. The blade makes soil contact over a length of 12–15 cm and this is the maximum width for a tool to move easily in between rice hills that are planted about 20 cm apart. Exactly the same weeding tool is used by the Karen in northern Thailand (Klaus Prinz, pers. comm.). Soil losses due to weeding with an *ngheo* averaged 1.7 t ha^{-1} $pass^{-1}$ (Ziegler et al., 2007), much higher than those observed by weeding with the *ouwèk* (this study), a maximum of 1.0 t ha^{-1} $pass^{-1}$ on the steepest slopes. Part of the difference could be due to the practice of farmers of restricting tillage to areas covered by weeds. Farmers in the study area limit soil disturbance to a minimum not because they consider the negative effect of tillage erosion, and only partly to the work being particularly tedious, but mainly because all soil disturbance triggers additional germination of weeds (de Rouw et al., 2005b). Erosion rates by the *ngheo* are, however, comparable with those measured in Laos under a space continuous tillage on a soil surface with only 5% weed cover and a mean soil depth of 2 cm (land preparation, this study).

The tillage erosion rates in this study, 5.7 t ha^{-1} $year^{-1}$ for 0.60 m m^{-1} slope under upland rice, field of 50 m length, were also lower than in Thailand, 14.8 t ha^{-1} $year^{-1}$ under upland rice, field of 50 m long, for a single tillage pass before sowing with a hoe (Turkelboom et al., 1999). This difference is due to a deeper tillage depth in northern Thailand (10–20 cm) which is performed to control perennial grasses and simultaneously retard the emergence of annual broad-leaved weeds (Van Keer, 2003). In fact, the shifting cultivation system in Thailand underwent similar changes in weed control but it had moved beyond the fourth stage of weed infestation described above. In the Thai study, the bush fallow had been replaced by tall perennial grasses and land clearing prior to sowing required their physical removal, i.e. uprooting of rhizomes of notably *Imperata cylindrica* (Van Keer, 2003). The beginning of a similar invasion was observed in the Lao study (de Rouw et al., 2005a). In that case a continuing agricultural exploitation will only be possible with deeper tillage and larger hoes, as described by Turkelboom et al. (1999) and soil losses due to tillage will probably attain similar, much higher levels. In the case the land remains rather free of perennial grasses, farmers could opt for the cultivation of a wider range of crops, now limited to upland rice and Job's tears. However, the introduction of cash crops, e.g. Maize and cassava into the farming system is significantly associated with higher erosion rates (Valentin et al., 2008) partly due to higher tillage erosion rates (Ziegler et al., 2007).

In this study, soil mean displacement for a 0.50 m m^{-1} slope was 0.99 m which is approximately twice that of 0.53 m recorded by Turkelboom et al. (1999). Compared with other tillage systems, the Lao values are considerable, e.g. a displacement of 0.30 m for ploughing the soil to 8 cm depth by a draught animal (Nyssen et al., 2000) and 0.40 m for manual tillage to 20 cm depth with a hoe (Zhang et al., 2004). Moreover, the function to predict soil translocation from the slope gradient is steeper in our study. All these differences can be explained by the very shallow depth of tillage operation in Laos. Because the soil surface stays smoother, aggregates can roll further down than for a deep tillage, hence the process of ravel is more important. The angle of repose, defined as the slope value under which aggregates start to roll down, should be lower in the Lao system than the values of 0.68–0.78 m m^{-1} reported by (Turkelboom et al., 1999).

Soil losses due to tillage erosion on a 0.60 m m^{-1} slope gradient (5–6 t ha^{-1} $year^{-1}$, this study) are of the same order of magnitude than those due to runoff as measured at the plot scale under similar farmer practices, 5.7 t ha^{-1} $year^{-1}$, mean over 5 years, northern Laos (Phommasack et al., 2000). At the catchment scale, sediments yields, which are primarily due to linear and gully erosion (Valentin et al., 2005) clearly increase with increasing surface cultivated with annual crops (Sengtaheuanghoung et al., 2006). A total linear erosion rate of 9.3 t ha^{-1} $year^{-1}$ was observed at the catchment scale (Chaplot et al., 2005). This last observation could be explained by the practice of tillage erosion in annual crops that increase aggregate detachment rates by the splash effect. The exposed layers resulting from cultivation with annual crops, are more sensitive to crusting, which favour runoff and hence rill and gully erosion downhill (Valentin et al., 2005).

5. Conclusions

Subsistence farming on very steep slopes using hand tools exclusively can cause serious tillage erosion each time farmers cultivate a plot. Though slope gradient has a great influence on soil translocation and the relation is exponential, tillage erosion is not solely a function of slope. Crop choice and local weed pressure, as farmers till only those areas covered by weeds and only in a period when these weeds potentially harm the crop, become important considerations. Soil contact cover is also an important factor as it can trap the rolling and sliding aggregates detached by tillage. Tillage erosion decreases with increasing soil contact cover. Its effect is more important on steeper slopes on which an aggregates potential energy is greater.

Regression models based on current cultivation practices showed that tillage erosion has increased over time. Using the regression models based on current cultivation practices, soil losses have augmented since 1964 following an increase in the number and intensity of tillage operations. The very low labour productivity due to both increasing of weeding operations and soil fertility depletion strongly threatens the farming system. Although the factor slope gradient is paramount in the assessment of soil losses, tillage erosion has increased over time, not so much due to steeper slopes now being cultivated more frequently than they were in the past, but rather, but because the system has changed. On a field level farmers are willing to cultivate very steep slopes if they can avoid the heavy chore of tillage prior to sowing. Minimum tillage on the steepest slopes still results in little erosion as the field area effectively tilled greatly influence soil erosion rates. On the other hand, tillage erosion increases exponentially on any slope once the new practice becomes necessary consisting of a space-continuous tillage prior to sowing. On a catchment scale, tillage erosion is bound to increase in the near future for two reasons. Firstly, a larger part of the catchment will be cultivated each year because the pressure on fallow land increases so land is re-cultivated after an ever shorter period of rest. Secondly, not all fields are yet infested with *Mimosa* or perennial grasses. Due to the on-going progressive invasion of these troublesome weeds, with each rotation, a greater number of steep sloped fields will arrive at a point in which land preparation was imperative. In these cases, the farmers have to change the system: hoeing to a greater depth with a new type of tool in a period of the cropping season that the land used to be weed free.

Acknowledgements

The authors thank the farmers of Ban Lak Sip for their kind cooperation during this study and the National Agricultural Forest Research Institute of Lao P.D.R. (NAFRI) for its useful assistance. The research was part of the Management of Soil Erosion Consortium (MSEC) programme coordinated by the Institut de Recherche pour le Développement (IRD, France) and the International Water Management Institute (Colombo, Sri Lanka).

References

Casenave, A., Valentin, C., 1989. Les états de surface de la zone Sahélienne. Influence sur l'infiltration. Editions Orstom, Coll. Didactiques, Paris.

Chaplot, V., Tessier, J., de Rouw, A., Valentin, C., Khampaseuth, X., 2003. Spatial variability of runoff and interrill erosion under different soils and land uses in a micro-catchment submitted to slash and burn Lao. J. Agric. Forest. 6, 46–55.

Chaplot, V., Coadou le Brozec, E., Silvera, N., Valentin, C., 2005. Spatial and temporal assessment of linear erosion in catchments under sloping lands of Northern Laos. Catena 63, 167–184.

Dercon, G., Deckers, J., Poesen, J., Govers, G., Sánchez, H., Ramírez, M., Vanegas, R., Tacuri, E., Loaiza, G., 2006. Spatial variability in crop response under contour hedgerow systems in the Andes region of Ecuador. Soil Tillage Res. 86, 15–26.

de Rouw, A., 2001. Weed infestation and soil erosion resulting from the breakdown of the slash and burn cultivation system. In: Maglinao, A.R., Leslie, R.N. (Eds.), Soil Erosion Management Research in Asian Catchments: Methodological Approaches and Initial Results, Proceedings of the 5th Management Soil Erosion Consortium (MSEC) Assembly. IWMI Southeast Asia Regional Office, Bangkok, Thailand, pp. 85–93.

de Rouw, A., Baranger, P., Soulileuth, B., 2002. Upland rice and Jobs' tears cultivation in slash and burn systems under very short fallow periods, in Luang Prabang province Lao. J. Agric. Forest. 5, 2–10.

de Rouw, A., 2005. Weed control in shifting cultivation. Improving Livelihoods in the Uplands of the Lao PDR, vol. 1: Initiatives and Approaches, NAFRI, NAFES, NUOL, National Agriculture and Forestry Research Institute, Vientiane, Lao PDR, pp. 78–84.

de Rouw, A., Soulileuth, B., Phanthavong, K., Dupin, B., 2005a. The adaptation of upland rice cropping to ever-shorter fallow periods and its limit. In: Bouahom, B., Glendinning, A., Nilsson, S., Victor, M. (Eds.), Poverty Reduction and Shifting Cultivation Stabilization in the Uplands of Lao PDR. NAFRI, NAFES, NUOL, Vientiane, Lao PDR, pp. 139–148.

de Rouw, A., Phaynaxay, K., Soulileuth, B., Casagrande, M., 2005b. Estimation of weed seeds in cultivated soils, Luang Prabang province, Laos. Lao J. Agric. Forest. 11, 79–94.

Fujisaka, S., 1991. A diagnostic survey of shifting cultivation in northern Laos: targeting research to improve sustainability and productivity. Agroforest. Syst. 13 (2), 95–109.

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.

Govers, G., Quine, T.A., Desmet, P.J.J., Walling, D.E., 1996. The relative contribution of soil tillage and overland flow erosion to soil redistribution on agricultural land. Earth Surf. Process. Land. 21, 929–946.

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. Mount. Res. Dev. 2, 141–156.

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 Tillage Res. 81, 97–108.

Lestrelin, G., Giordano, M., Keohavong, B., 2005. When "Conservation" leads to land degradation. Lessons from Ban Lak Sip, Laos. IWMI Research report 91. IWMI, Colombo.

Lestrelin, G., Giordano, M., 2006. Upland development policy, livelihood change and land degradation: interactions from a Laotian village. Land Degrad. Dev. 18 (1), 55–76.

Lewis, L.A., Nyamulinda, V., 1996. The critical role of human activities in land degradation in Rwanda. Land Degrad. Dev. 7, 47–56.

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

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 Tillage Res. 51, 189–209.

Marques da Silva, J.R., Soares, J.M.C.N., Karlen, D.L., 2004. Implement and soil condition effects on tillage-induced erosion. Soil Tillage Res. 78, 207–216.

Nye, P.H., Greenland, D.J., 1960. The soil under shifting cultivation. Technical communications of the Commonwealth Bureau of Soil Science 51, Harpenden, UK.

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

Phommasack, T., Sengtaheunghung, O., Sipaseuth, N., Phanthaboun, K., 2000. Management of sloping lands for sustainable agriculture in Laos. In: Sajjapongse, A., Leslie, R.N. (Eds.), ASIALAND/Management of Sloping Lands, Report of the eleventh annual review meeting. The International Board for Soil Research and Management (IBSRAM), Bangkok, Thailand, pp. 87–100.

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 countour strips: evidence from caesium-137 measurements. Catena 36, 115–142.

Roder, W., Phouaravanh, B., Phengchanh, S., Keoboulapha, B., 1995. Relationships between soil, fallow period, weeds and rice yield in slash-and-burn systems of Laos. Plant Soil 176, 27–36.

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

Saito, K., Linquist, B., Keobualapha, B., Shiraiwa, T., Horie, T., 2006a. Farmers knowledge of soils in relation to cropping practices: a case study of farmers in upland rice based slash-and-burn systems of northern Laos. Geoderma 136 (1), 64–74.

Saito, K., Linquist, B., Keobualapha, B., Phanthaboon, K., Shiraiwa, T., Horie, T., 2006b. Cropping intensity and rainfall effects on upland rice yields in northern Laos. Plant Soil 284, 175–185.

Sengtaheuanghoung, O., Valentin, C., Ribolzi, O., de Rouw, A., Thiébaux, J.-P., 2006. Enhancing water quality through the better land management of degraded highland regions in Northern Lao PDR. In: Proceedings of the 2nd GWSO-Asia Network Meeting/Workshop. Sun Yat Sen University, Guangzhou, China, pp. 8–11.

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

Soil Survey Staff, 1999. A basic System of Soil Classification for Making and Interpreting Soil Surveys. USDA, Washington, DC.

Thapa, D., Cassel, D., Garrity, D., 1999b. Ridge tillage and contour natural grass barrier strips reduce tillage. Soil Tillage Res. 51, 341–356.

Thapa, D., Cassel, D., Garrity, D., 1999a. Assessment of tillage erosion rates in steepland land Oxisols in the humid tropics using granite rocks. Soil Tillage Res. 51, 233–243.

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 199, 1–16.

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

Valentin, C., Poesen, J., Li, Y., 2005. Gully erosion: impacts, factors and control. Catena 63, 132–153.

Valentin, C., Agus, F., Alamban, R., Boosaner, A., Bricquet, J.P., Chaplot, V., Guzman, T., de Rouw, A., Janeau, J.L., Orange, D., Phachomphonh, K., Phai Do, Podwojewski, P., Ribolzi, O., Silvera, N., Subagyono, K., Thiébaux, J.P., Toan, T.D., Vadari, T., 2008. Runoff and sediment losses from 27 upland catchments in Southeast Asia: impact of rapid land use changes and conservation practices. Agric. Ecosyst. Environ. 128, 225–238.

Van Keer, K., 2003. On-farm agronomic diagnosis of transitional upland rice swidden cropping systems in northern Thailand. Doctorate Thesis. Katholieke Universiteit Leuven, Belgium.

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

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

Ziegler, A.D., Giambelluca, T.W., Sutherland, R.A., Nullet, M.A., Vien, T.D., 2007. Soil translocation by weeding on steep-slope swidden fields in northern Vietnam. Soil Tillage Res. 96, 219–233.