Modeling Soil Flux by Manual Tillage as a Nonlinear Slope-Dependent Process

Alan D. Ziegler*
Geography Dep.
AS2-04-21
1 Arts Link
Kent Ridge
National Univ. of Singapore
Singapore 117570

Ross A. Sutherland
Dep. of Geography
Univ. of Hawaii at Manoa
445 Saunders Hall
2424 Maile Way
Honolulu, HI 96822

A review of seven studies addressing soil flux related to manual hoeing and weeding in Asia and Africa indicates that tillage erosion from hand-held implements on steep hillslopes can alter topography and influence the distribution of soil and nutrients within fields. Soil flux resulting from manual tillage increases with slope in a near-linear fashion until the slope angle approaches the angle of repose for displaced aggregates. On steeper slope gradients, the increase in soil flux is nonlinear because displaced clods roll, bounce, or slide relatively long distances downslope before coming to rest or breaking down. Because of this ravel-like transport process, soil flux is modeled most appropriately across a wide range of gradients as a nonlinear process. A modified nonlinear ravel model predicted soil fluxes in the reviewed studies better than a linear model, but it was not superior to a general exponential model. Additional field studies are needed to increase the basic understanding and predictability of soil erosion by manual tillage on steep slopes, as this activity is still practiced in many areas of the world.

Tillage translocation is the amount of soil moved per unit width of tillage per unit time relative to the direction of tillage. Soil flux, which is relative to the slope, is the amount of soil moved downslope per unit width of slope per time. Tillage erosion, which is the net redistribution of soil within the landscape as a result of tillage, is one of the most important soil degradation processes on sloping croplands worldwide (Govers et al., 1999; Lindstrom et al., 2001; Van Oost et al., 2006). In many parts of the world, tillage contributes to the denudation of upper portions of hillslopes and causes the accumulation of soil on lower portions of the hillslope (e.g., Lindstrom et al., 1990, 1992; Govers et al., 1994; Lobb et al., 1995; Polyakov et al., 2004). Soil translocation during tillage also influences the distribution of soil and soil properties on hillslopes (Govers et al., 1994, 1996; Quine et al., 1999; Van Oost et al., 2000, 2003, 2006; De Alba et al., 2004; Li et al., 2004). Tillage erosion plays an important role in soil redistribution on the landscape, along with the traditionally recognized processes of wind and water erosion (De Alba et al., 2004; Van Oost et al., 2005). Important in the mitigation of the environmental consequences of tillage erosion is the development of appropriate assessment techniques and simulation models that describe the process accurately (Lobb and Kachanoski, 1999; Torri and Borselli, 2002; Van Oost et al., 2003; Quine and Zhang, 2004b).

Numerous studies addressing soil translocation and soil flux related to mechanized, pull-type implements have been conducted in the last two decades (e.g., Lindstrom et al., 1992; Govers et al., 1994; Lobb et al., 1995, 1999; Montgomery et al., 1999; Van Muysen et al., 2002, 2006; Quine et al., 2003; Quine and Zhang, 2004a,b; De Alba et al., 2006). Within developing areas of the world, a number of studies have investigated this issue with respect to animal-drawn implements (Quine et al., 1999; Thapa et al., 1999; Nyssen et al., 2000; Li et al., 2004). In addition to a recent weeding erosion study conducted in northern Vietnam (Ziegler et al., 2007), only a handful of systematic studies of soil flux related to manual tillage have now been published (Lewis, 1992; Lewis and Nyamulinda, 1996; Rymshaw et al., 1997; Turkelboom et al., 1997, 1999; Dupin et al., 2002, 2003; Zhang et al., 2004; Kimaro et al., 2005). In these studies, several different types of equations were used to describe the relationship between soil flux and slope gradient. Using data reported in some of these studies (Table 1), we evaluate a nonlinear, slope-dependent model against two other equations used commonly for predicting soil flux resulting from manual tillage on steep slopes.

PRIOR MANUAL TILLAGE EROSION STUDIES

The following is a brief review of the manual tillage erosion studies found in the refereed literature. The first two are best classified as demonstration studies; the latter five are systematic investigations of soil flux over a range of slope gradients using various measurement techniques.

Rwanda

Local farmers in Rwanda responded to increased acidity and reduced fertility on terraced Ultisol plots by excavating the upslope berm, thereby bringing more-fertile soil into their plots (Lewis, 1992). This activity, which typically involved excavating a 0.1-m-thick slice of soil from the upslope 0.5-m-high berm, had a soil flux equivalent to about 60 kg m^{-1} pass^{-1}.

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*Corresponding author (adz@nus.e[illegible]g).

677 S. Segoe Rd. Madison WI 53711 USA

Table 1. Five systematic manual tillage erosion studies conducted on steep lands worldwide.

Site	Activity	Condition	Implement	Implement dimensions†	Soil type	Bedrock	Reference
				m			
Thailand	hoeing	Weeds removed	hoe	0.16 by 0.16	Cambisol	phyllite	Turkelboom et al. (1999)
Lao PDR	weeding of upland rice & Job's-tears fields	cropped with weeds	knife	0.06 by 0.10	Alfisol	not specified	Dupin et al. (2002, 2003)
China	hoeing	unspecified	hoe	0.16 by 0.24	Regosols	mudstone and sandstone	Zhang et al. (2004)
Tanzania	hoeing	dry season with standing weeds	hoe	0.165 by 0.185	Cambisols, Regosols, Lixisols, Acrisols	meta-sediments	Kimaro et al. (2005)
Vietnam	weeding of cassava fields	dry season with few weeds	knife	0.025 by 0.05	Ultisols	sandstone, schist, granite	Ziegler et al. (2007)

† Implement dimensions are the width and height, respectively, of the cutting blade.

This small-scale displacement of soil was exacerbated by the undermining of upslope berms until they collapsed. Lewis and Nyamulinda (1996) later described a systematic 4-yr study that monitored dry soil losses related to farming practices including hoeing, sowing, weeding, and harvesting. Daily losses were quantified by collecting soil translocated by farmers onto the apron of a bounded, Wischmeier-type plot (20 m long by 5 m wide, 60% slope). Hoeing of the fields—in a seemingly unusual fashion—from the top of the field to the bottom produced a soil flux of 78 kg m^{-1} yr^{-1}. Fluxes associated with sowing, weeding, and harvesting were 36, 17, and 2 kg m^{-1} yr^{-1}, respectively. Dry erosion (68 kg ha^{-1} yr^{-1}) represented a net loss to the plots, whereas berm erosion represented net accumulation.

Venezuela

Rymshaw et al. (1997) studied various management activities related to subsistence farming in the Venezuelan Andes using 15 sediment traps installed at the outlet of variously sized fields on slopes ranging from 33 to 78%. During a 12- to 14-mo period, the unreplicated traps collected soil translocated by tillage and water erosion processes combined. Soil fluxes ranged from about 2 to 59 kg m^{-1} yr^{-1}. Owing in part to a lack of standardization between plots (i.e., they varied in the number and type of tillage passes, the crops planted, the hillslope shape, and the contributing area), no obvious relationship was found between slope gradient and soil flux. In general, the plots with the highest fluxes were those with the most intense plowing and weeding; the plots with the lowest fluxes were plowed once or never. The volume of material translocated by tillage was often higher than that translocated by water erosion processes, which did not occur on all plots. Roughness caused by standing vegetation reduced soil translocation.

Northern Thailand

Turkelboom et al. (1997, 1999) investigated tillage erosion on steep hillslopes cultivated by Akha villagers in the Chiang Rai Province of northern Thailand (Tables 1 and 2). Traditional shifting agriculture at the site had been replaced by a semipermanent type of cultivation system that was affected adversely by increased weed pressure owing to a decrease in the length of the fallow period. Soil loss by tillage erosion was particularly important on short (<20-m) fields where water erosion was not substantial. Tillage erosion contributed to terrace formation, fertility gradients within fields, and a net soil loss when displaced soil was translocated outside of field boundaries. To quantify soil flux, experiments were conducted using two methods: monitoring stone tracer displacement distance (tracer method) on five slope classes (32–82%), and the direct measurement of the tillage step geometry (trapezoid-step method) on six slope classes (17–71%). Soil movement by manual tillage was measured on weeded plots, for which local farmers tilled the soil with a traditional hoe (0.16 m wide by 0.16 m high), starting at the bottom and moving to the top (soil movement was unidirectional). Soil flux ranged from about 20 to 100 kg m^{-1} $pass^{-1}$ across the range of slopes tested. An exponential function was used initially to describe soil flux for the entire range of tested slopes (Turkelboom et al., 1997). It was later replaced by a compound function to better account

Table 2. Summary of eight experiments from five studies reporting soil flux data used in the model assessment.

Experiment†	Method	Slope range	Slope class	*n*‡	Plot width	Plot length	Tillage depth§	Reference
		%			m			
Thailand	painted stone tracers and trapezoid-step measurement	17–82	11	1	4	4.5–8	0.04–0.13	Turkelboom et al. (1999)
Lao Rice	painted aggregate tracers	30–85	7	4	2	unbounded	0.02	Dupin et al. (2002, 2003)
Lao JT	painted aggregate tracers	40–102	7	3	2	unbounded	0.02	Dupin et al. (2002, 2003)
China	rock fragment tracers	4–43	16	1	1	< 1	0.19–0.24	Zhang et al. (2004)
Tanzania GT	Gerlach troughs	31–67	8	3	1.2	unspecified	0.05–0.06	Kimaro et al. (2005)
Tanzania TRAP	trapezoid-step measurement	31–67	8	3	unspecified	unspecified	0.05–0.06	Kimaro et al. (2005)
Vietnam NE	backstop	69–84¶	5	1	2	20	0.01	Ziegler et al. (2007)
Vietnam SW	backstop	56–73¶	5	1	2	20	0.01	Ziegler et al. (2007)

† Tillage in all studies was unidirectional: plots were worked from the bottom of the plot to the top and displaced soil was drawn downslope. Abbreviations following location name distinguish between two treatments (JT = Job's-tears, NE = northeast hillslope, SW = southwest hillslope) or measurement method (GT = Gerlach trough, TRAP = trapezoid).

‡ Number of times the experiments were replicated at each slope class.

§ Tillage depths are either means or ranges; depths for the China study was specified by the experimenters.

¶ Measurements or estimates were also made at 3% where the effects of slope were negligible.

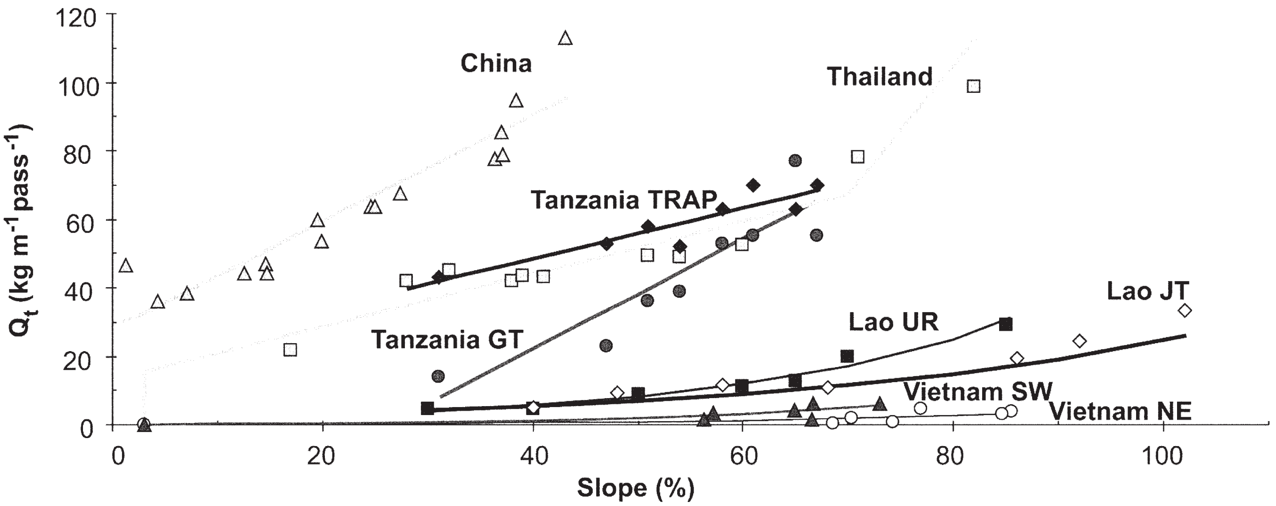

Fig. 1. Soil flux (Q_t) values for various slope gradients determined in five manual tillage erosion studies conducted in China (Zhang et al., 2004), Thailand (Turkelboom et al., 1999), Tanzania (Kimaro et al., 2005), Lao PDR (Dupin et al., 2002), and Vietnam (Ziegler et al., 2007). The fitted curves, which are those used in the respective studies, are of the following form: linear (Tanzania and China, Eq. [1] and [2], respectively), exponential (Lao PDR and Vietnam, Eq. [3]), and a compound function (Thailand, Eq. [4]: slope angle below which sediment flux may be negligible S_0 = 3% and angle of repose S_{AR} = 70%). Abbreviations next to site names refer to the following measurement techniques or hillslope treatments and conditions: GT, Gerlach trough method; JT, Job's-tears field; NE, sandy soil on northeast hillslope; SW, clay-rich soil on southwest hillslope; TRAP, trapezoid-step method; and UR, upland rice field. The Lao PDR data are means of three or four replications.

for the occurrence of rolling clods as slope gradients exceeded the angle of repose (Fig. 1; Turkelboom et al., 1999).

Lao People's Democratic Republic

Tillage erosion in upland rice (*Oryza sativa* L.) and Job's-tears (*Coix lacryma-jobi* L.) fields associated with weeding was monitored by Dupin et al. (2002, 2003) during the cultivation period on three to four replicated plots for seven slope classes: 30 to 85 vs. 40 to 102% (Tables 1 and 2). Soil fluxes were estimated by a tracer method (10–20-mm dried, painted soil aggregates) on 2-m-wide plots. One pass of weeding was performed by shallow scraping (<0.02 m) the soil using a small curved hoe (0.06 m wide by 0.10 m high), which is the local practice. As weeding direction was from the bottom to the top of the hillslopes, soil was always drawn downslope. Soil flux increased exponentially with slope gradient for both upland rice and Job's-tears crop covers (Fig. 1). On the steepest slopes tested, dislodged clods occasionally rolled downslope in excess of 10 m. Soil flux resulting from weeding upland rice was higher than that for Job's-tears because a greater percentage of weed and crop cover on the latter limited the distance soil was translocated. Mean annual soil loss rates from all types of manual tillage combined ranged from about 2 Mg ha^{-1} yr^{-1} on intermediate (30%) slopes to 20 Mg ha^{-1} yr^{-1} on steep (100%) slopes for both upland rice and Job's-tears fields despite differing in tillage and weeding practices (four weedings for upland rice and one hoeing and two weedings for Job's-tears). Annual soil losses due to tillage erosion were on the same order of magnitude as those for water erosion.

China

Zhang et al. (2004) quantified soil translocation in Sichuan Province, China, where tillage erosion had contributed to thin soil layers and exposure of parent material at upper slope positions of farmer's fields (Tables 1 and 2). Estimated tillage erosion rates on 15-m land parcels ranged from about 50 to 150 Mg ha^{-1} yr^{-1}. Using rock fragment tracers (3–4 by 3–4 by 1.5–2 mm), they quantified tillage-induced soil translocation for 16 slope gradients ranging from 4 to 43%. During the experiments, the land was worked using large hoes (0.16 m wide by 0.24 m high) from the bottom of the field to the top—thus, the soil was always drawn downslope. Tillage depths, which were specified by the experimenters, ranged from 0.19 to 0.24 m. Soil flux, which was represented with a slope-dependent linear equation, ranged from 36 to 113 kg m^{-1} pass^{-1} across the range of slope gradients studied (Fig. 1).

Tanzania

Kimaro et al. (2005) studied soil translocation resulting from shallow tillage in the Uluguru Mountains in Tanzania using the trapezoid-step measurement method and 0.6-m-wide Gerlach troughs. For the latter, three replicates on 1.2-m-wide plots on eight slope gradients ranging from 31 to 67% were investigated. Each unweeded plot was tilled in the dry season in the upslope direction; soil was always drawn downslope. Weeding was performed in the dry season before cover clearance with 0.17- by 0.19-m steel-bladed hoes that produced a tillage depth of about 0.05 m. The relationship between soil flux and slope gradient was expressed by a linear equation (Govers et al., 1994). The range of soil fluxes determined by both the trapezoid-step and Gerlach trough methods varied greatly across the range of slopes tested: 43 to 70 vs. 14 to 77 kg m^{-1} pass^{-1}, respectively (Fig. 1). Differences were attributed to the abnormal way that farmers hoed immediately above the Gerlach troughs (i.e., experimental error). Medium-term (~30 yr) soil tillage fluxes (42–148 kg m^{-1} yr^{-1}) were greater than those attributed to water erosion (7–25 kg m^{-1} yr^{-1}). Soil translocation by manual tillage may also have contributed to the development of shallow soils and the accumulation of soil material behind grass barriers along contour bands.

Northern Vietnam

Soil movement caused by weeding by the Da Bac Tay ethnic group was investigated in the Hoa Binh Province of northern Vietnam (Ziegler et al., 2007). Investigations were performed on six unreplicated plots, ranging in slope from 56 to 84%, located on two hillslopes differing in soil condition (Fig. 1, Tables 1 and 2). Experiments involved weeding 2-m-wide plots, from the bottom to the top of the 20-m plots, using a small curved knife (0.03 m wide by 0.05 m high). Tillage was unidirectional; soil translocation was always downslope. Additional measurements were made on a 3% slope to estimate the mass of material translocated solely by the hoe. The primary soil translocation process, movement of soil by the hoe, contributed a little more than 60% of the soil flux. Ravel, which is the rolling, bouncing, and sliding of soil clods downslope, was a secondary translocation process that comprised almost 40% of the total soil flux. Soil flux was 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 at other manually tilled steep sites, primarily because the tillage depth was very shallow (∼0.01 m) and weed density was low at the time of experimentation. Erosion rates associated with weeding were an order of magnitude lower than reported water erosion rates; therefore, the contribution to landscape evolution was believed to be small.

REPRESENTATIONS OF SOIL FLUX

Slope-dependent soil fluxes reported in the latter five reviewed studies and fitted equations describing changes in soil flux with slope gradient are shown in Fig. 1. A total of eight data sets are shown, as three of the studies presented data for two treatments or measurement methods. Four different mathematical representations were used in the reviewed studies to describe slope-dependent soil flux (Q_t) caused by manual tillage (Fig. 1). Kimaro et al. (2005), for example, used a diffusion-type equation (Govers et al., 1994):

$$Q_t = KS \qquad [1]$$

where K (kg m^{-1}) is the tillage transport coefficient that represents erosivity and S is the slope gradient (%). The following linear equation, used initially by Lobb et al. (1999) and Quine et al. (1999) to describe soil flux related to unidirectional tillage, was used in the investigations conducted in China and Tanzania (Zhang et al., 2004; Kimaro et al., 2005):

$$Q_t = \alpha + \beta S \qquad [2]$$

where α is the tillage transport constant and β is the tillage transport coefficient. Simply stated, α is the soil flux caused by the implement alone, without the influence of slope; β represents soil erosivity.

Three studies that found a nonlinear increase in Q_t with slope gradient expressed soil flux with an exponential equation (Turkelboom et al., 1997; Dupin et al., 2002; Ziegler et al., 2007):

$$Q_t = b_0 \exp\left(b_1 S\right) \qquad [3]$$

where b_0 is analogous to the tillage transport constant in Eq. [2] and b_1 controls the nonlinear increase in Q_t with increasing slope gradient. In a later reassessment, Turkelboom et al. (1999) replaced the exponential equation with the following compound function:

$$Q_t = \begin{cases} 0 & S \le S_0 \\ \alpha + \beta S & S_0 < S < S_{AR} \\ lD\rho_b & S \ge S_{AR} \end{cases} \qquad [4]$$

where Q_t was 0 on gentle slopes (S_0) where farmers tilled in opposing directions (omnidirectional rather than unidirectional tillage on steeper slopes). On intermediate slopes, Q_t was estimated with Eq. [2]. For slopes greater than the average angle of repose for soil clods (S_{AR}), Q_t was determined as a function of bulk density (ρ_b), depth of tillage (D), and the downslope distance (l) that had a slope greater than or equal to the angle of repose. Turkelboom et al. (1999) used 3 and 70% for S_0 and S_{AR}, respectively.

CONCEPTUALIZATION OF SOIL FLUX

The physical movement of soil during manual tillage occurs primarily by pulling or pushing by the tillage implement. 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; Torri and Borselli, 2002); however, dislodged soil clods can roll several meters downslope on steep slopes (Rymshaw et al., 1997; Turkelboom et al., 1997, 1999; Ziegler et al., 2007). Ziegler et al. (2007) distinguished two types of translocation related to weeding on steep slopes in Vietnam: (i) the initial displacement of soil caused by the hoeing or weeding action (often airborne and occurring across distances ≤1 m), and (ii) the rolling of large aggregated material (clods) distances exceeding 15 to 20 m downslope after being displaced—i.e., ravel. Ravel is an important sediment transport process in steep, arid and semiarid environments where sparse groundcover provides little resistance to the downslope movement of soil particles or clods (Anderson et al., 1959; Krammes, 1965; Rice, 1982; Gabet, 2003). Ravel may be initiated by numerous processes, including animals burrowing or moving within brush or across steep slopes, fire (e.g., when material is set in motion or obstructing vegetation is burned), small landslides, vibrations (e.g., from aircraft or earthquakes), and material falling from vertical slopes onto the top of ravel piles (Anderson et al., 1959; Krammes, 1965; Kirkby and Statham, 1974; Rice, 1982; Florsheim et al., 1991; Gabet, 2003).

The reviewed studies collectively indicate that the relationship between soil flux and slope is near linear until the gradient approaches a threshold (S_{AR}), which is the angle of repose for displaced clods (cf. Turkelboom et al., 1999). Afterward, the increase is nonlinear, owing to the contribution of ravel (Fig. 2). As slope approaches the maximum farmable gradient (S_{max}), Q_t approaches a maximum flux (Q_{max}), which is equivalent to the removal of all displaced material from the tilled plot—an unachievable limit for any realistic tillage situation. Below a slope gradient of S_0 (e.g., 3%, Turkelboom et al., 1999), soil flux depends on omni- vs. unidirectional tillage.

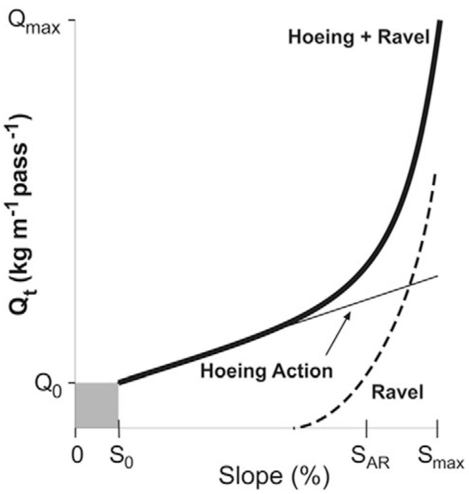

Fig. 2. Conceptualization of nonlinear slope-dependent soil flux (Q_t) related to manual tillage erosion (thick line); S_0 is the slope gradient below which sediment flux may be negligible if farmers till in random directions, S_{AR} is the angle of repose, S_{max} is the slope for which all dislodged soil would be translocated from the plot, which corresponds with the maximum possible flux rate (Q_{max}), and Q_0 is equivalent to the tillage transport constant (i.e., the flux caused by the implement alone without the influence of slope angle). The shading indicates the uncertainty in the relationship between Q_0 and S_0 at low slope gradients. The near-linear response between Q_t and slope gradient is associated primarily with the hoeing action alone (thin line). The nonlinear response as the gradient approaches the S_{AR} is related to the addition of a ravel transport component (dashed line).

When farmers do not have a preferred direction of tillage, soil flux is presumed to be zero (note that tillage patterns may in fact be affected by cultural phenomena such as field shape and the position of the field entrance). For unidirectional tillage, however, Q_0 is equivalent to the soil translocation caused by the hoeing action alone. Several factors influence Q_0, including bulk density, tillage-related variables (depth, direction, speed, and the shape and size of the tillage implement), and the initial soil conditions, such as moisture content and tillage history (Lobb et al., 1995, 1999; Lindstrom et al., 2001). Rarely is Q_0 measured directly in the field (Ziegler et al., 2007). Typically, it is determined as a regression constant (e.g., α in Eq. [2]).

NONLINEAR SOIL FLUX MODEL

Gabet (2003) derived a nonlinear slope-dependent model for the mass flux of dry ravel by first considering the downslope distance (l_d) traveled by a decelerating particle [L]:

$$l_d = \frac{v^2}{2\left(-dv/dt\right)} \qquad [5]$$

where v is the initial velocity [L T^{-1}] in the downslope direction and dv/dt is acceleration [L T^{-2}]. While the initial velocity of ravel can be in any direction, it tends to be downslope for the case of manual hoeing on upland fields. The downslope distance traveled is related to several factors including the slope angle, surface roughness, and the physical properties of the ravel material. Combining Eq. [5] with the following momentum equation:

$$\frac{dv}{dt} = g\sin\theta - \mu g\cos\theta \qquad [6]$$

yields (cf. Kirkby and Statham, 1974)

$$l_d = \frac{v^2}{2g\left(\mu\cos\theta - \sin\theta\right)} \qquad [7]$$

where θ is the slope gradient (°), g is gravitational acceleration [L T^{-2}], and μ is a kinetic friction coefficient that encompasses friction from rolling, bouncing, and particle collisions down a slope. Incorporating l_d from Eq. [7] into the following general mass flux equation [M L^{-1} T^{-1}] for discrete events across a unit slope contour:

$$Q_t = \left(\frac{l_d}{\text{event}}\right)\left(\frac{\text{mass}}{\text{event}}\right)\left(\frac{\text{events}}{\text{area}}\right)\left(\frac{\text{events}}{\text{time}}\right) \qquad [8]$$

yields the following downslope mass flux equation proposed by Gabet (2003):

$$Q_t = \frac{\kappa}{\mu\cos\theta - \sin\theta} \qquad [9]$$

where κ [M L^{-1} T^{-1}] accounts for the distribution of initial velocities, gravitational acceleration, the frequency and spatial density of tillage disturbance, and the average mass of the displaced material; here, Q_t and κ have units of kilograms per meter per pass. Equation [9] is valid for situations where sediment is mobilized in the downslope direction, such is the case for unidirectional manual tillage. The derivation requires the assumption that the last three terms in Eq. [8] and the initial velocity term in Eq. [7] are not slope dependent, which implies that the process initializing the sediment movement acts equally across all slope gradients. This assumption is reasonable, as only moderate correlations have been reported between slope gradient and tillage depth (Turkelboom et al., 1999; Kimaro et al., 2005). Field experiments supporting the derivation of Eq. [9] are presented elsewhere (Gabet, 2003).

MODEL ASSESSMENT

We compared the nonlinear ravel model (Eq. [9]) fit to data collected in some of the prior manual tillage experiments (Table 2) with the fits of the linear (Eq. [2]) and exponential models (Eq. [3]). In all cases, model parameters, such as α and β (Eq. [2]), b_0 and b_1 (Eq. [3]), and μ and κ (Eq. [9]), were determined using a model-fitting optimization procedure that reduced the model efficiency (ME) between predicted (P_i) and observed (O_i) soil flux values. Model efficiency was calculated as (Nash and Sutcliffe, 1970)

$$\text{ME} = 1 - \left(\frac{\sum_{i=1}^{n}\left(O_i - P\right)^2}{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2}\right) \qquad [10]$$

where a value less than zero indicates that the model performs worse than simply taking the mean of the observed values ($\bar{O}$), and perfect agreement between observed and predicted

Table 3. Parameters, model efficiency (ME, Eq. [10]), and RMSE (Eq. [11]) for three models fitting the eight soil flux (Q_t) data sets; slope is expressed as either a percentage (S) or in degrees (θ).

Site†	*n*	Linear (Eq. [2]) $Q_t = \alpha + \beta S$				Exponential (Eq. [3]) $Q_t = b_0\exp(b_1 S)$				Nonlinear (Eq. [9]) $Q_t = \kappa/(\mu\cos\theta - \sin\theta)$			
		α‡	β	ME	RMSE	b_0	b_1	ME	RMSE	κ	μ	ME	RMSE
Thailand	11	5	98	0.86	0.14	19.74	1.91	0.92	0.11	33	1.3	0.94	0.10
Lao Rice	7(4)§	0	25	0.69	0.35	1.35	3.63	0.97	0.10	4	1.0	0.94	0.15
Lao JT	7(3)§	0	21	0.83	0.19	3.49	1.91	0.86	0.17	6	1.3	0.98	0.08
China	16	28	156	0.88	0.12	33.01	2.63	0.93	0.09	26	0.7	0.95	0.07
Tanzania GT	8	0	84	0.63	0.26	4.08	4.22	0.84	0.17	11	0.9	0.78	0.20
Tanzania TRAP	8	19	74	0.83	0.06	28.32	1.33	0.83	0.06	54	1.6	0.83	0.06
Vietnam NE	7	0	3	0.38	0.60	0.02	6.13	0.61	0.48	0.4	1.0	0.57	0.50
Vietnam SW	7	0	6	0.47	0.49	0.12	5.36	0.58	0.43	1	0.9	0.57	0.44

† Abbreviations following location name distinguish between two treatments (JT = Job's-tears, NE = northeast hillslope, SW = southwest hillslope) or measurement method (GT = Gerlach trough, TRAP = trapezoid).

‡ α was restricted to be non-negative.

§ The model was fit through the mean of three or four values.

values results in an ME value of 1. The RMSE index was also used to assess goodness of fit:

$$\mathrm{RMSE}=\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(P_i-O_i\right)^2}\ \frac{100\%}{\bar{O}} \qquad [11]$$

The RMSE has a value of 0 when the predicted and observed values are equal.

Optimized model parameters and associated ME and RMSE values for each fitted data set and model considered are listed in Table 3. Both the ME and RMSE indices for nonlinear and exponential models indicate a better fit than the linear model (Table 3). For example, the mean (± SD) ME for the linear model was 0.70 ± 0.19 vs. 0.82 ± 0.15 and 0.82 ± 0.17 for the exponential and nonlinear models, respectively (Table 3). Mean (± SD) RMSE values for the three models were 0.28 ± 0.19 (linear), 0.20 ± 0.16 (exponential), and 0.20 ± 0.17 (nonlinear). The fit of the nonlinear model is shown in Fig. 3.

Only in the case of the Tanzania trapezoid study, where the steepest gradient tested was only 67%, was the fit of the linear model equivalent to the other two models. The general inadequacy of the linear model reflects observations of soil flux being nonlinear, especially when the slope exceeds ~70% (Turkelboom et al., 1999; Dupin et al., 2002; Ziegler et al., 2007). While Eq. [9] has sufficient complexity to model the nonlinear response across the entire range of slopes considered (S_0–$S_{\max}$ shown in Fig. 2), the fit was not superior to that of the general exponential function. The RMSE values for the nonlinear model were less than those of the exponential model for only three of the eight data sets (Table 3). Furthermore, observed RMSE differences were negligible except for the Lao Job's-tears data, but this could be an artifact of fitting a small data set.

Use of the nonlinear model rather than the general exponential model is justifiable in the sense that parameters μ and κ are controlled by factors affecting the relationship between slope and ravel (see above). Specific values for κ are, however, difficult to estimate directly because the terms in Eq. [8] are described by frequency distributions; using average values for these quantities may not yield the correct average sediment flux (Gabet, 2003). The linear model retains utility for modeling

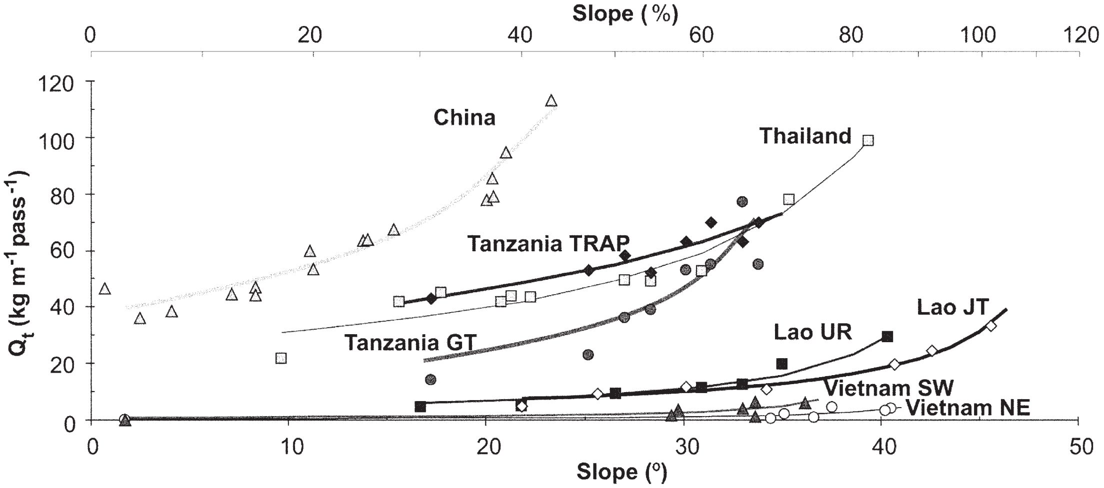

Fig. 3. Predicted (curves via the nonlinear diffusion model, Eq. [9]) vs. measured (symbols) values of soil flux (Q_t) reported in five studies conducted in China (Zhang et al., 2004), Thailand (Turkelboom et al., 1999), Tanzania (Kimaro et al., 2005), Lao PDR (Dupin et al., 2002), and Vietnam (Ziegler et al., 2007). Abbreviations next to site names refer to the following measurement techniques or hillslope treatments and conditions: GT, Gerlach trough method; JT, Job's-tears field; NE, sandy soil on northeast hillslope; SW, clay-rich soil on southwest hillslope; TRAP, trapezoid-step method; and UR, upland rice field.Model efficiency and root mean square error values for the predictions are reported in Table 3.

soil flux realistically on gentle slope gradients where ravel transport is not an important process. Additionally, the tillage transport coefficients (K in Eq. [1], β in Eq. [2]) provide a means of comparing the slope-dependent soil flux relationship related to site conditions, tillage implement, and tillage practice across an intermediate range of slope gradients (e.g., Lindstrom et al., 2001). If only the studies conducted across a wide range of slope are considered (i.e., Thailand, Lao PDR, and Vietnam), the parameter κ is highly correlated (coefficient of determination > 0.98) with the tillage transport coefficient β (Table 3).

FUTURE RESEARCH

Again, two distinct soil transport processes are associated with manual tillage: (i) airborne displacement by the hoeing action (occurring across short distances) and (ii) rolling of material downslope following displacement on steep slope gradients (akin to ravel). The former dominates on lower slope gradients; the latter becomes important as the slope gradient approaches the angle of repose for resting material (Fig. 2). Because of these unique relationships with a specific range of slope gradients, a combination of two mathematical expressions, applied across an appropriate range of slope gradients, may best model soil flux by manual tillage. This is visualized as the addition of the hoeing and ravel subcomponents in Fig. 2.

Both of these soil translocation subprocesses are affected by tillage depth and intensity. For example, fluxes in China associated with plot preparation with large hoes having tillage depths exceeding 0.2 m were the highest; the lowest were determined during weeding experiments with small knives in Lao PDR and Vietnam (Tables 1 and 2). The Vietnam values were lower than those at the Lao PDR site, in part because of lower weed density at the time of the experiment, which resulted in a comparatively shallow plot-average tillage depth. Another important factor affecting ravel transport in particular is the downslope surface roughness. In the case of hoeing in preparation for planting, the downslope surface would have a much greater resistance to rolling material than a planted field during weeding. On the other hand, dense crop cover should reduce ravel transport during weeding. Ravel transport should therefore change during the growing season as crops mature.

In the spirit of facilitating further model development, we recommend that new experiments be conducted across a wide range of slope gradients to allow quantification of the soil flux associated with both the hoeing and ravel translocation components (Fig. 2). On slopes where ravel is present, plot lengths should be greater than the maximum travel distance of large clods displaced during tillage. Attention should also be given to various hillslope microtopographical features that may affect ravel transport. Studies should encompass the entire growing season, in accordance with traditional hoeing and weeding practices, to quantify the effects of changes in crop and weed density and surface conditions. Related to this, special consideration should be given to the degree of downslope roughness created by hoeing and weeding, tillage depth, and the percentage of the surface area affected by tillage (especially for weeding experiments). Two sustainability issues related to tillage erosion and ravel include redistribution of soil and nutrients on hillslopes and the absolute loss of soil and nutrients via clods rolling beyond field boundaries—possibly into the stream system, where they would be transported from the basin.

CONCLUSIONS

A review of seven field studies indicates that manual tillage is an important landscape-shaping process that affects the distribution of soil properties on hillslopes in areas of the world where it is still practiced. Simulation of this process is complicated because the relationship between soil flux and slope gradient is nonlinear, owing to the presence of a ravel-like translocation process on slopes exceeding the angle of repose for soil clods. The modified ravel model investigated here described the nonlinear soil flux response better than a linear model; however, it was not superior to a general exponential model. Soil flux related to manual tillage may ultimately be best described by combining linear and nonlinear models to describe the distinct subprocesses of airborne displacement of material by hoeing action for all slope gradients and the subsequent ravel movement for steep gradients. Such a model was not tested owing to data limitations. Additional testing of the nonlinear model alone, however, is probably unwarranted unless focus is directed toward identifying direct relationships between model parameters (μ and κ) and the specific physical phenomena that affect soil flux by manual tillage. Additional field studies are needed not only for model development but also for facilitating comprehensive agroecological assessments of agricultural practices in upland areas where manual tillage is important.

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