# Environmental Consequences of the Demise in Swidden Cultivation in Montane Mainland Southeast Asia: Hydrology and Geomorphology

Alan D. Ziegler • Thilde B. Bruun • Maite Guardiola-Claramonte • Thomas W. Giambelluca • Deborah Lawrence • Nguyen Thanh Lam

Published online: 30 June 2009 © Springer Science + Business Media, LLC 2009

**Abstract** The hydrological and geomorphological impacts of traditional swidden cultivation in Montane Mainland Southeast Asia are virtually inconsequential, whereas the impacts associated with intensified replacement agricultural systems are often much more substantial. Negative perceptions toward swiddening in general by governments in the region beginning half a decade ago have largely been based on cases of forest conversion and land degradation associ-

A. D. Ziegler (⊠) Department of Geography, National University of Singapore, Singapore, Singapore e-mail: adz@nus.edu.sg

T. B. Bruun Department of Geography and Geology, University of Copenhagen, Copenhagen, Denmark e-mail: tbb@geogr.ku.dk

M. Guardiola-Claramonte Hydrology Department, University of Arizona, Tucson, AZ, USA e-mail: maiteg@email.arizona.edu

T. W. Giambelluca Department of Geography, University of Hawaii, Honolulu, HI, USA e-mail: thomas@hawaii.edu

D. Lawrence Department of Environmental Sciences, University of Virginia, Charlottesville, VA, USA e-mail: Lawrence@virginia.edu

N. Thanh Lam Centre for Agricultural Research & Ecological Studies, Hanoi Agricultural University, Hanoi, Vietnam ated with (a) intensified swidden systems, characterized by shortened fallow and extended cropping periods and/or (b) the widespread cultivation of opium for cash after the Second World War. Neither of these practices should be viewed as traditional, subsistence-based swiddening. Other types of intensive agriculture systems are now replacing swiddening throughout the region, including semi-permanent and permanent cash cropping, monoculture plantations, and greenhouse complexes. The negative impacts associated with these systems include changes in streamflow response, increased surface erosion, a higher probability of landslides, and the declination in stream water quality. Unlike the case for traditional swiddening, these impacts result because of several factors: (1) large portions of upland catchments are cultivated simultaneously; (2) accelerated hydraulic and tillage erosion occurs on plots that are cultivated repetitively with limited or no fallowing to allow recovery of key soil properties, including infiltration; (3) concentrated overland flow and erosion sources are often directly connected with the stream network; (4) root strength is reduced on permanently converted hillslopes; (5) surface and ground water extraction is frequently used for irrigation; and (6) and pesticides and herbicides are used. Furthermore, the commercial success of these systems relies on the existence of dense networks of roads, which are linear landscape features renowned for disrupting hydrological and geomorphological systems. A new conservation focus is needed to reduce the impacts of these intensified upland agricultural practices.

Keywords Slash-and-burn agriculture ·

$$\label{eq:shifting cultivation} \begin{split} & \text{Shifting cultivation} \cdot \text{Opium} \cdot \text{Degradation} \cdot \text{Erosion} \cdot \\ & \text{Landslides} \cdot \text{Streamflow} \cdot \text{Flood} \cdot \text{Drought} \cdot \text{Rainfall} \cdot \text{Roads} \cdot \\ & \text{Pesticides} \cdot \text{Fertilizer} \end{split}$$

# Introduction

The World Bank (2007) estimates that there may still be more than 200 million swiddeners in Montane Mainland Southeast Asia (MMSEA); however, Mertz et al. (2009b), claim the real number is probably much less than 50 million (Mertz et al. 2009b). Other authors have estimated that as many as 400 million swiddeners or forest-dependent people were spread across tropical Asia at one time (Spencer 1966; Ma 1999: Kerkhoff and Sharma 2006). In some areas of Asia swiddening has been practiced for centuries—perhaps since the domestication of rice a few thousands years ago (cf. Hanks 1972). A simplified view of traditional swidden cultivation, which also refers to slash-and-burn and shifting cultivation, involves clearing and burning of forest plots for cultivation of subsistence crops, such as upland rice (Spencer 1966; Schmidt-Vogt 1999; Mertz et al. 2009a, b). The plots are cultivated for one to three seasons before being fallowed for a period typically exceeding six to 15 times the cropping period (Delang 2002; Mertz et al. 2009a). Abandoned fields are replaced with newly cleared land, including areas of regenerated forest on former swidden

Fig. 1 Montane Mainland SE Asia (MMSEA), defined by the green shaded areas, is defined herein as the lands between 300–3,000 m asl. MMSEA includes the upland regions of Cambodia, Laos, Myanmar, Thailand, Vietnam, and China. Courtesy of John Vogler, East–West Center Program on Environment (Honolulu HI) plots. Historically, frequent field relocation, sparse mountain populations, and lengthy fallows limited the extent of active cultivation within swidden landscapes during any given year. Both on-site degradation and off-site environmental impacts were therefore limited in space and time, as was found by Zinke *et al.* (1978) for an intact Lua swidden system in northern Thailand several decades ago.

Over the last several decades the nature of swidden cultivation throughout Southeast Asia has been changing rapidly in response to myriad social, economic, and political factors (Hill 1998; Rasul and Thapa 2003; Padoch *et al.* 2007; Fox *et al.* 2009). Within MMSEA (Fig. 1), initial transformations manifested as shortened fallows and lengthened cropping periods as mountain populations increased and available land diminished (e.g., Turkelboom 1999; Schmidt-Vogt 2001). A shift toward the cultivation of marketable crops followed the evolution of road and irrigation infrastructures, the development of urban market demands for agriculture products, and the initiation of crop substitution programs. Large-scale, permanent cultivation of annual crops, monoculture plantations, and greenhouse agriculture systems are currently becoming the dominant



types of agriculture throughout much of the region (Rerkasem and Rerkasem 1994; Fox and Vogler 2005; Xu *et al.* 2005; Thongmanivong *et al.* 2005; Schmidt-Vogt *et al.* 2009). All of these transformed agriculture systems are generally more intensive than traditional swiddening—both spatially and temporally (Fig. 2). In contrast with traditional swiddening, many negative hydrological and geomorphological impacts result from the conversion to more intensive agricultural systems. This paper summarizes the consequences of the demise in swiddening in MMSEA on streamflow, water quality, surface erosion, and landslide susceptibility. The impacts on biodiversity, soil quality, and carbon storage are addressed elsewhere (Bruun *et al.* 2009; Rerkasem *et al.* 2009).

#### Streamflow

The net impact on the amount and timing of stream discharge of forest conversion for agriculture is determined by the combined effects on evapotranspiration and soil infiltration (Bruijnzeel 2004). The key mechanism of change is a decrease in evapotranspiration on croplands for which rainfall interception is less (van Dijk and Bruijnzeel 2001; Giambelluca *et al.* 1996, 2003). Furthermore, field crops have comparatively shallow rooting depths that limit the amount of water available for evapotranspiration during extended dry periods (Calder 1999). This fundamental difference in evapotranspiration should result in both higher annual and seasonal water



Fig. 2 Examples of changing agrarian practices in MMSEA: a upland rice field that is part of a traditional Lisu swidden landscape in northern Thailand; tree stumps and some mature trees (relict emergents) are left to facilitate forest regeneration; b intensified Khamu swidden system in northern Laos with shortened fallows and whole-sale cultivation of adjacent hillslopes; c former Hmong opium fields converted to

permanent cultivation of vegetables including cabbage and lettuce (northern Thailand); **d** hillslopes in this former Bulan/Hani swidden landscape have been converted to a terraced rubber plantation; paddy rice is still planted in the valley bottom (Xishuangbanna, Yunnan Province China); **e** greenhouse-based flower farm covering an area of nearly 2 km<sup>2</sup> in northern Thailand (Karen workers)

yields, with the bulk of the increase coming during baseflow conditions (Bruijnzeel 1990, 2004) However, this response has typically only been observed in controlled experiments in small catchments where at least one-third of the forest has been converted (Bruijnzeel 2004). A fundamental difference between traditional swiddening and many of the intensified systems replacing it is the total amount of catchment area converted to cropland at any given time. In the case of traditional swiddening, rarely would the total extent of cultivation exceed this one third threshold—except, perhaps, in small sub-catchments.

Water yield changes have not generally been verified in large catchments in MMSEA despite high contemporary forest conversion rates (e.g., Thailand: Dyhr-Nielsen 1986; Alford 1992; Wilk et al. 2001). Nevertheless, a general public perception exists that decreased dry season flows occur commonly in catchments where substantial forest area has been disturbed or converted to agriculture, including swidden cultivation. In theory, significant and wide-spread reductions in the infiltration of rain water could result in increases in wet-season storm flow at the expense of recharging the deep soil or groundwater reserves feeding springs that typically sustain dry-season base flows (cf. Bruijnzeel 2004; Calder 2007). While increases in surface runoff are often reported for several types of land-cover conversion (e.g., mechanized logging, road building), rarely has a reduction in baseflow been shown except through diagnostic or conceptual modeling (cf. Smakhtin 2001; Bruijnzeel 1990, 2004).

In swidden systems, both fire-induced hydrophobicity and raindrop impact on exposed soils before adequate vegetative cover develops may reduce infiltrability, at least temporarily (Turkelboom 1999; Robichaud 2000; Janeau et al. 2003; Podwojewski et al. 2008). For example, the high surface runoff rates observed for initial stages of fallow vegetation in plot studies in northern Thailand probably reflect the presence of seals that formed during the cropping period when soils were exposed to rainfall (Ziegler et al. 2000). However, infiltration rates tend to recover quickly with the regeneration of secondary vegetation in the fallow period (Ziegler et al. 2000, 2004b). Furthermore, the spatial extent of cultivated area in traditional swidden landscapes should be too small for any effect of reduced infiltrability to alter catchment stream flow variables greatly. In addition, the spatial separation between fields sparsely distributed on forested hillslopes in traditional swidden systems facilitates the filtering of surface runoff before it reaches the stream system.

One example where swiddening caused significant increases in stream flow variables was associated with the *Jhum* system in Bangladesh. Clearing and cultivation of a 1-ha sub-catchment resulted in increases in peak discharge by 600% and annual runoff by 16% (Gafur *et al.* 2003). While some change in streamflow in a small sub-catchment are expected following the conversion of such a high percentage of forest (i.e., >33% threshold; see above), the observed changes in Bangladesh may reflect the effects of an intensified swidden system, for which fallow length had been decreased to only 3–5 years. Nevertheless, stream flow variables returned to near normal in the first year of fallow after one year of cultivation, demonstrating the resilience of the swidden landscape against long-lasting hydrological changes. This resilience is facilitated by the rapid regrowth of tropical vegetation, and importantly, the limited decrease in infiltrability, both in degree and in space, caused by swiddening activities.

In contrast, the transition from swiddening to more intensive forms of agriculture creates a situation where substantial reductions in infiltration may produce sufficient surface runoff to increase stormflow peaks and diminish dry season flows. Although this has rarely been confirmed in catchment studies (Valentin et al. 2008), several aspects of agricultural intensification make this scenario plausible: (1) a large percentage of the catchment is converted to cultivated plots that are subject to soil sealing processes (e.g., raindrop impact) for extended periods of time during the year (Janeau et al. 2003; Turkelboom et al. 2008); (2) deep excavation into subsurface soils of low permeability during the creation of planting terraces, such as those used to grow rubber in China (Fig. 2d) and vegetables in the Cameron Highlands of Peninsular Malaysia (Midmore et al. 1996); (3) accelerated tillage erosion that creates lowpermeability tillage steps or results in subsurface soils of naturally lower infiltrability being displaced closer to the surface (Turkelboom 1999; Ziegler et al. 2004b); (4) a fallow period following cultivation that is too short to allow soil porosity and aggregate stability to recover sufficiently to restore infiltrability (cf. Nye and Greenland 1965; Bronick and Lal 2005); (5) creation of extensive compacted path networks that generate overland flow frequently (Fig. 2b; Ziegler et al. 2000, 2001a; Rijsdijk et al. 2007b; Turkelboom et al. 2008); (6) expansion of processing areas, greenhouse complexes, and other types of compacted surfaces of low infiltrability; (7) excessive surface disturbance across the landscape, such as over-grazing and yearly fires (Nikolic et al. 2008); and (8) destruction of natural vegetative buffers capable of infiltrating overland flow (e.g., Rijsdijk et al. 2007a; Ziegler et al. 2007c; Vigiak et al. 2008).

The development of reliable year-round road systems that facilitate commercial agriculture has increased the total area occupied by impermeable surfaces throughout MMSEA (Ziegler and Giambelluca 1997). Roads affect the routing of stormflow to the stream by generating runoff during most rainfall events, intercepting subsurface stormflow at the cutbank, and linking dispersed overland flow sources (Megahan 1972; Wemple *et al.* 2001; Ziegler *et al.* 2001b, 2007b). Whereas the disruption of streamflow peaks related to intensified agriculture may result because a large percentage of the catchment area is "cultivated" simultaneously, the impact of roads may be on the same order of importance despite roads occupying a very small proportion of the catchment area (cf. Bowling *et al.* 2000; Ziegler *et al.* 2004a; Cuo *et al.* 2006, 2008). Collectively, all of the landscape disturbances mentioned above increase the propensity of the generation and concentration of overland flow; increase the connectivity of overland flow moving from the hillslope to the stream system, and, to some extent, reduce the local recharge that sustains higher and prolonged base flows.

Extreme floods in general are often assumed to be caused by forest removal and/or conversion to agriculture, but this notion is unsupported by data (van Dijk et al. 2009). Floods in any basin are caused when more water enters a channel than can be stored or passed downstream (cf. Rodriguez-Iturbe and Rinaold 1997; van Dijk et al. 2009). Large floods in MMSEA frequently occur as the result of intense rainfall from tropical storms (Thi Phuong Quynh Le et al. 2007; Wood and Ziegler 2008). While flooding is largely a function of storm and channel characteristics, landscape changes can increase flood probability. For example, many of the processes related to agriculture intensification described above that reduce infiltrability and concentrate overland could increase the volume and speed surface water enters a stream channel thereby increasing flow peaks (e.g., Gafur et al. 2003; Cuo et al. 2008).

Large-scale forest destruction and conversion to agriculture have been linked to reductions in rainfall (about 25% for a future deforested Amazonia; cf. Nobre *et al.* 1991; Bruijnzeel 2004; van Dijk and Keenan 2007; Malhi *et al.* 2008). Bruijnzeel (2004) estimated the total effect of historical land-cover changes on rainfall in SE Asia would be smaller than 8%. Consistent with this prediction are Kwanyuen's (2000) estimated 2–6 mm year<sup>-1</sup> (~5–15%) reductions in rainfall in three northern Thailand catchments during the period 1951–1997 (however see Wilk *et al.* 2001). Thus, rainfall reductions could contribute to purported reduced dry-season flows in some streams draining headwater catchments. Again, such changes have not been detected at larger scales where river discharges have been monitored routinely for long periods of time.

The most likely cause of dry-season stream desiccation in areas where swiddening has intensified or has evolved into permanent agriculture systems is increased dry-season water use for irrigation (Fig. 2c; Alford 1992; Forsyth and Walker 2008). Unlike seasonal, rain-fed swidden cultivation, year-round planting of commercial crops requires substantial irrigation (Rerkasem 2005). Water diversion from headwater streams is a common irrigation water source throughout the region, northern Thailand in particular (Thanapakpawin *et al.* 2006; Forsyth and Walker 2008). In other areas, such as the Central Highlands of Vietnam, groundwater reserves are used heavily to irrigate commercial crops, including coffee (D'haeze *et al.* 2005). Elsewhere, potentially high dry-season water use by alien species, as suggested for rubber in Yunnan province of China, could potentially contribute to stream desiccation (Fig. 2d; Guardiola-Claramonte *et al.* 2008; Ziegler *et al.* 2009). Another contributing factor to contemporary lowland water shortages in northern Thailand is the difficulty of managing reservoir storage to both maximize water availability for dry-season irrigation of commercial crops and minimize flooding caused by late-season tropical storms (Wood and Ziegler 2008).

#### Water Quality

A fundamental difference between traditional swiddening and the commercial farming of fruit, vegetables, and flowers is the use of pesticides and chemical fertilizers (Midmore et al. 1996; Rerkasem 2005; Sidle et al. 2007). Agrochemicals are increasingly contributing to water quality degradation in upland agriculture areas where swiddening was once prevalent, for example in the Mae Sa catchment in northern Thailand (Ciglasch et al. 2005, 2006; Kahl et al. 2008), Inle lake in Myanmar (Sidle et al. 2007), and potentially, the Cameron Highlands of Malaysia (cf. Ismail et al. 2004; Mazlan and Mumford 2005). In general, excessive doses of chemicals are often used to ensure product marketability or because of insufficient practical experience by farmers (Rerkasem 2005). In large greenhouses and other systems used to cultivate high-value crops, operators often use fertilizers and pesticides. The increasing use of waste water for fertilization in peri-urban systems may also have deleterious environmental consequences when the effluent contains toxic contaminants (Duong et al. 2006; Nguyen et al. 2007).

## **Surface Erosion**

Substantial soil loss has been reported for some swidden crops, including upland rice, for which annual estimates range from 2 to 350 Mg ha<sup>-1</sup> year<sup>-1</sup> (Table 1). This wide variation reflects, in part, differences in farming practices, as well as a host of physical variables related to climate, topography, and soil. The highest rates are typically determined for intensified systems with shortened fallow periods; and most rates only represent soil loss during the cropping phase. If the lower rates associated with lengthy fallow phases are considered, the mean long-term erosion

Location	Crop/Sys <sup>a</sup>	Soil loss rates during phases <sup>b</sup>			Method/note	Crop:Fal <sup>c</sup>
		Crop Mg ha <sup>-1</sup> year <sup>-1</sup>	Fallow Mg ha <sup>-1</sup> year <sup>-1</sup>	YSV Mg ha <sup>-1</sup> year <sup>-1</sup>		
Traditional swidden	ing					
Thailand <sup>d</sup>	UR	Negligible	Negligible	Negligible	Field reconnaissance	1:10
Vietnam <sup>e</sup>	UR, M, JT	6	<1	_	Small catchment studies	1:8 (1980s)
Sarawak <sup>f</sup>	Hill padi	0.16-0.2	0.06-0.46	0.11-0.36	Plot studies	nr
Intensified swidden	ing					
Thailand <sup>g</sup>	UR	90-150	_	_	24-40-m plots; 50-54% slopes	1:5-20
Thailand <sup>g</sup>	OP, M	120-200	_	_		10-20:80+
Thailand <sup>h</sup>	UR	2-350 (60)	Negligible	Negligible	Obs: 10-70 m fields; 31-71% slopes	1-15:1-8
Thailand <sup>h</sup>	М	2-230 (18)	Negligible	Negligible	Obs: 10-70 m fields; 31-71% slopes	1-15:1-8
IBSRAM <sup>i</sup>	UR	5-143	na	na	Variably-sized plots at 7 of 8 sites	na
Vietnam <sup>j</sup>	UR	21-55	0–23	_	22.5-m plots; 22–24° slopes	1:2-5
Bangladesh <sup>k</sup>	Jhum	41	12	-	Monitored 1-ha catchments	1:5-7
Vietnam <sup>1</sup>	UR	13–21	1-11	<1-4	$5 \times 20$ m plots	1-4:2-4
Vietnam <sup>m</sup>	CAS	6–16	1-10	1–2	1 m <sup>2</sup> microplots	na
Vietnam <sup>e</sup>	UR, M, JT	11	<1	_	Small catchment studies	1-2:1-4
Vietnam <sup>m</sup>	CAS	9	_	_	Small catchment study	na
General shifting cul	tivation/slash-and	-burn cultivation				
Thailand <sup>n</sup>	Upland SC	0.1-100	_	_	Regional assessment	nr
Thailand <sup>n</sup>	Steepland SC	>100	_	-	Regional assessment	nr
Tropics <sup>o</sup>	SC	0.4-70 (2.8)	0.05-7.4 (0.2)		Review for SE Asia	nr
Thailand <sup>p</sup>	Yao farmers	28-64	_	-	Cs-137 retrospective study	
Xishuangbanna <sup>q</sup>	SC	49	-	_	Review for China	nr
Bangladesh <sup>r</sup>	SC	42	-	_	Plot studies on 30-46% slopes	
Hainan <sup>q</sup>	SC & S/B	5-32	_	_	Review for China	nr

Table 1 Synthesis of soil loss rates for swidden agriculture in SE Asia

<sup>a</sup> Crops are upland rice (UR), opium poppy (OP), maize (M), Job's tear (JT), cassava (CAS); Systems (Sys) refer to general slash and burn (S/B), shifting cultivation (SC)

<sup>b</sup> YSV is young secondary vegetation; *na* not applicable

<sup>c</sup> Crop:Fal refers to the ratio of years of cropping to fallow; nr not reported; na not applicable

<sup>d</sup> Pa Pae, Chiang Mai province (Zinke et al. 1978; Sabhasri 1978)

<sup>e</sup> Luang Prabong province: crop:fallow for tradition system was typical of the 1980s; 1990s for intensified (Valentin et al. 2008)

<sup>f</sup>East Malaysia: for *padi* (Douglas 1999); also see de Neergaard *et al.* (2008)

<sup>g</sup> Huai Thung Choa, Chiang Mai Province (Hurni 1982, 1983)

<sup>h</sup> Pahka village, Chiang Rai, Thailand: the intensified swidden values are ranges in individual fields; the value in parenthesis is the mean (Turkelboom 1999)

<sup>i</sup>Vlassak et al. (1993) summarizing several experimental sites in Thailand

<sup>j</sup> Rong Can village in Hoa Binh province (Fagerstrom et al. 2002)

<sup>k</sup> Chittagong Hills Tracts for *Jhum*, including cultivation of mixture of upland rice, maize, beans, chilly, turmeric, ginger, cassava, lentils, cucumber, gourd, cotton, jower, water melon, flowers and different vegetables. Fallows reduced from 15–20 to 3–5 years (Gafur *et al.* 2003; Borggaard *et al.* 2003)

<sup>1</sup>Hoa Bihn province (Nguyen *et al.* 2008)

<sup>m</sup> Hoa Bihn province (Podwojewski et al. 2008; Valentin et al. 2008)

<sup>n</sup> Regional assessment for Thailand (Tangtham 1997); also see Henderson and Poonsak (1984)

<sup>o</sup> Bruijnzeel (2004) after Wiersum (1984); median is in parenthesis

<sup>p</sup> Forsyth (1996)

<sup>&</sup>lt;sup>q</sup>China and surrounding region (Hill and Peart 1998)

<sup>&</sup>lt;sup>r</sup> Chittagong Hills Tracts, Bangladesh (Rahman et al. 2001)

rates are greatly reduced, as the soil is only exposed to erosive rainfall for a few weeks during a multi-year cycle (Table 1; cf. de Neergaard et al. 2008). Furthermore, if storage at the base of fields in vegetated hillslope buffers occurs, total export of soil from the hillslope within traditional swidden cultivation may be very low (cf. Zinke et al. 1978; Douglas 1999; Valentin et al. 2008). Many authors acknowledge the generally benign impact of swiddening, in terms of surface erosion (Nye and Greenland 1965: Douglas 1999: Bruijnzeel 2004: Sidle et al. 2006: Forsyth and Walker 2008; Valentin et al. 2008). In some instances, sensitive watershed areas such as ridge tops, hollows, seeps and other riparian areas are purposely avoided by swiddeners (e.g., Sabhasri 1978; Jones 1997; Lim and Douglas 2000). Historically, some swidden farmers may also have intentionally practiced erosion control by preferentially cultivating flatter slopes or deliberately placing charred logs horizontally across the hillslope to form revetments to curb soil loss (cf. Conklin 1957; Sabhasri 1978; Forsyth 1996).

Recent studies in MMSEA suggest that many of the highest reported erosion rates in upland areas are indicative of intensified agriculture systems having some or all of the following characteristics: (1) inadequate erosion-mitigating vegetative cover for several consecutive years or extended periods of time during the rainy season of any one year if more than one crop is planted; (2) the need for repeated weeding; (3) multi-year cropping without a sufficient fallow period during which soil porosity and aggregate stability recover and erodibility decreases; and (4) greater propensity to generate concentrated surface runoff, which contributes to rill erosion and gully formation (e.g., Turkelboom 1999; Ziegler et al. 2004a, b; Chaplot et al. 2005; Sidle et al. 2006; Nguyen et al. 2008; Podwojewski et al. 2008: Turkelboom et al. 2008: Valentin et al. 2008). Reduced-fallow systems in Laos, Thailand, and Vietnam experience substantial soil loss from tillage erosion during plot preparation and weeding (Turkelboom et al. 1997; Ziegler et al. 2007a; Dupin et al. 2009). Throughout SE Asia, high erosion rates are typically reported for various up-and-down-the-slope cultivation practices (Hill and Peart 1998; Sidle et al. 2006). Linear erosion features, including rills and gullies, may also be common in these intensely used landscapes (Fig. 3a; Chaplot et al. 2005; Turkelboom et al. 2008). Downslope furrowing, which is used to promote drainage of surface water from fields, often leads to linear erosion on downslope fields (Fig. 3b; Renard et al. 1998; Ziegler et al. 2001a; Turkelboom et al. 2008). When concentrated flow forms on long hillslopes, no achievable buffer width may be possible to reduce sediment entering the stream (Fig. 3c; Ziegler et al. 2006a, b).

Worldwide, footpaths and terraces are common source areas of erosion within permanent fields constructed on

hillslopes because of the frequent generation of concentrated surface runoff on exposed or compacted surfaces (Collins and Neal 1998; Purwanto and Bruijnzeel 1998; van Dijk and Bruijnzeel 2004; Rijsdijk et al. 2007b). In comparison, many footpaths within traditional swidden landscapes are ephemeral features that affect hydro-geomorphological processes for only a brief period (Ziegler et al. 2001a). Severe surface erosion often results from extensive mechanical disturbance to the soil when creating broad platform terraces, such as those used in the Cameron Highlands of Peninsular Malavsia to grow temperate vegetables for urban markets in the lowlands (Midmore et al. 1996). Similar intensive agriculture areas can also be found in other highland cropping areas of China, Thailand, Vietnam, and the East Malaysian states, but less has been reported about the surface erosion occurring in these areas (Hill 1998; Douglas 2006; Rerkasem 2005). Unless conservation methods are employed, many of these intensified agriculture systems experience substantial soil erosion every year.

Native roads, which are now prevalent in MMSEA, are often the most important contributors to surface erosion on a per unit area basis in remote areas (Sidle et al. 2004, 2006). Because of substantial overland flow generated on and transported by roads, erosion has been shown to be on the same order of importance as that from agriculture lands, despite comprising much smaller areas (Turkelboom 1999, Ziegler et al. 2004a; Rijsdijk et al. 2007a). The growing use of greenhouses creates a degradation situation that is analogous to that of the expansion of settlement areas (Fig. 2e). Although surface erosion on planting beds inside an individual greenhouse is typically reduced, the runoff created on the impervious surfaces within the complex as a whole, including extensive networks of footpaths connecting individual houses, can cause linear erosion if the flow is not managed properly. In general, improper management of the flow of irrigation water across the surface of any hillslope can cause severe linear erosion (Fig. 3e; Midmore et al. 1996; Turkelboom 1999).

## Landslides

The principal effect of forest conversion to permanent agriculture on the initiation of landslides is loss of hillslope root strength (Sidle *et al.* 1985). A converted hillslope typically has the lowest root strength 3–15 years following clearance (Sidle *et al.* 2006). This window of high landslide susceptibility marks the period when a lower triggering threshold (e.g., pore water pressure produced during a rain storm) will induce slope failure. In terms of increased risk of mass failure, both the magnitude of the reduction in root strength below some critical threshold and the period of time root strength remains below the threshold are



Fig. 3 a Rill erosion forming on long (>15 m) bare fields in northern Vietnam (*photo*: P. Schmitter). b Semi-permanent cultivation of cabbage in northern Thailand; down-slope furrows used to drain surface runoff from the fields often contribute to surface erosion when concentrated flow erodes the planting beds; c intensified rice swidden in Xishuangbanna (Yunnan province, China) where fields extend down into the extended stream network; thus limited opportunities

important (Sidle and Ochiai 2006). Thus, critical factors affecting increased risk are the time between forest clearance and initial regrowth and the rate of regrowth.

In the case of traditional swiddening, recovery should begin immediately and take place rapidly (Fig. 4). The traditional practice of leaving living stumps and tall trees (relict emergents) in swiddens foster fast regeneration of deep-root vegetation (Fig. 2a). When forest recovery is delayed, as is the case of lengthened cropping periods, not only is the magnitude of the decrease in root strength greater, but the period of time before hillslope root strength regenerates sufficiently to reduce the risk of failure is longer. Conversion from swidden to permanent agriculture should result in higher probability of slope failure for indefinite periods of time, especially if shallow-rooted crops are grown (Fig. 3d). Furthermore, dense and interconnected networks of roads and paths that are associated with

exist for buffering of surface overland flow. Also seen is erosion (bare soil) associated with walking paths, as well as wash erosion that formed on the upper part of the slope where crop development and surface cover was retarded. **d** Shallow soil slips on young fallow slopes formerly planted with maize; these slopes have subsequently been replaced by rubber; **e** broken irrigation pipes are often the source of linear erosion and, potentially, shallow landslides

agricultural intensification are important contributors to increased probability of landsliding (Turkelboom 1999; Sidle *et al.* 2006; Rijsdijk *et al.* 2007a).

## Discussion

The distinction between traditional and intensified swidden cultivation systems is not clearly made in most assessments of the environmental consequences of swiddening. For many years the popular perception was that swiddening is a destructive system that leads only to forest destruction and land degradation (cf. Fox *et al.* 2000). Extreme examples of exhaustive cultivation on steep slopes by a few groups of swiddeners growing opium poppy in the Golden Triangle undoubtedly helped foster this negative association (Hurni 1982, 1983; Schmidt-Vogt 2001; Delang 2002). Opium



**Fig. 4** Conceptual model of root strength decay following forest clearance and root strength recovery following tree regrowth/replanting. Net root strength is the sum of that associated with decay and regeneration. The period of highest risk is where the net root strength curve falls below some site-specific critical threshold. Also shown are net root strengths for the situation of a delay in replanting/regrowth of 3, 10, and 20 years. For traditional swidden agriculture, recovery would begin immediately if tree stumps are not destroyed and some tall trees (relict emergents) are present (Fig. 1a). Swiddens of shortened fallows and long cropping periods would have increased risk of mass failure. Root strength associated with permanent agriculture would remain low indefinitely (based on Sidle *et al.* 2006)

poppy cultivation exhausted soil fertility and accelerated erosion in cases where individual fields were cultivated 5 to 20 years in succession before abandonment (Hurni 1982). It is incorrect, however, to view this particular practice as traditional swiddening: these systems transformed within the last couple of centuries from subsistence-based practices to systems with a hegemony of opium poppies cultivated for cash-i.e., commercial agriculture (cf. Hill 1998). While there is evidence of commercial opium production in southern China in the late 18th century by ethnic minorities, large-scale production probably started after the Opium Wars (cf. Geddes 1976; Cooper 1984; McCoy 1991; Trocki 1999). The major influx of opium poppy cultivators (e.g., Hmong, Yao, Akha) into the Golden Triangle began about the 1870s (P. Cohen, personal communication). Opium production was not substantial prior to World War II ( $<100 \text{ Mg year}^{-1}$ ); and the boom began in the early 1950s as the western markets opened (McCoy 1991). Production reached 1,000 Mg year<sup>-1</sup> by the 1970s, with a peak of about  $3,000 \text{ Mg year}^{-1}$ occurring in the mid 1990s (McCoy 1991; Cohen, personal communication). During the opium boom-which would have required the transformation of vast landscapes into poppy fields-much of the blame for any type of forest conversion and land degradation was often directed toward ethnic swiddeners, even those who did not cultivate poppies (Poffenberger and McGean 1993; Schmidt-Vogt 2001; Delang 2002; Forsyth and Walker 2008).

Driven by negative views of swiddening, all countries in MMSEA have attempted to control or terminate swiddening at one time or another (Fox and Vogler 2005). Governments in Vietnam and Laos, for example, began implementing programs to end or restrict swidden cultivation in 1968 and 1976, respectively (Fox et al. 2000; Schmidt-Vogt 2001; Thongmanivong et al. 2005; Lestrelin and Giordano 2007; Nikolic et al. 2008). As early as the 1960s, farmers in Yunnan Province China were forced to convert sloped farming land to permanent forest or grassland (Weyeraeuser et al. 2005). Within the last few decades swidden cultivation in Thailand has been controlled through restrictions imposed by conservation measures including the establishment of national parks and wildlife reserves, implementation of a watershed classification system, and delineation of water reserve land (Rarkesem and Rerkasem 1994; Schmidt-Vogt 2001; Delang 2002; Forsyth and Walker 2008).

Because of the emphasis on eliminating swiddening and eradicating opium, the management strategies designed to reduce land degradation in many areas of MMSEA have generally failed to prevent the occurrence of the hydrological and geomorphological impacts that are typical of the intensive agriculture practices found today. Currently, high market demand in urban centers for fruits, vegetables, flowers and other upland products is driving farmers to exert even greater pressure on soil and water resources throughout MMSEA. Reversion to traditional swidden cultivation is not likely feasible at an appreciable scale. Therefore, new conservation policies are needed to reduce the environmental impacts of the practices now being employed. Furthermore, a better understanding of how land-cover/land-use change affects hydrological and geomorphological processes is needed at all levels.

## Conclusion

The long-term environmental impacts associated with traditional swiddening are virtually inconsequential because of the frequent relocation of fields, limited catchment area cultivated at any one time, and rapid regeneration of tropical vegetation following a short cultivation period. Most commonly cited examples of severe land degradation resulting from swiddening are associated with intensified systems, including opium cultivation, having insufficient fallow periods and uncharacteristically long growing periods. Once intensified or converted to more-permanent cash-crop systems, negative impacts become significant because the landscape no longer functions like a forested landscape. Landscapes where traditional swidden cultivation is practiced differ from those where swiddening has been replaced by more intensive agriculture practices because of the following: (1) differences in evapotranspiration between short-rooted cash crops and forests; (2) impairment of rainwater infiltration through repetitive surface disturbance and creation of impermeable surfaces with a high propensity to generate surface runoff; (3) an increase in the total catchment area cultivated at any one time, which increases both the spatial extent and temporal period of exposure to surface erosion processes; (4) creation of a landscape with high connectivity between hillslope overland flow and erosion sources and the stream; (5) surface and groundwater extraction for irrigation; (6) repetitive cultivation and the elimination/reduction of a fallow period, during which soil aggregate stability and porosity would otherwise be restored, some degree of soil formation takes place, and root-strength recovers; and (7) the use of fertilizers and pesticides. These differences lead to the disruption of natural stream flow response at some scales, accelerated surface erosion, elevated stream sediment loads, and greater risk of rainfall-induced landslides. Furthermore, road networks that facilitate highland commercial agriculture are probably responsible for much of the observed turbidity increases and stormflow irregularities in streams draining headwater catchments. Finally, the extent that the environmental consequences of the transition from traditional swiddening to other forms of agriculture will be realized in any one location depends on the interplay between the natural biophysical conditions and the intensity/type of the agriculture practices themselves, which is largely controlled by market demands and land-use policies.

Acknowledgements This work was supported in part by grants from the following agencies: Asia Pacific Network (#ARCP2006-07NMY, ARCP2008-01CMY), SARCS (95/01/CW-005), NASA (IDS/0365-0079), NSF (9614259; DEB-9613613; EAR-0000546), and National University Singapore (FASS: R-109-000-092-133). This paper benefited from input from AIJM van Dijk, JM Fox, P Cohen, JB Vogler, SH Wood, RC Sidle, and RA Sutherland.

## References

- Alford, D. (1992). Streamflow and Sediment Transport from Mountain Watersheds of the Chao Phraya Basin, Northern Thailand: A Reconnaissance Study. Mountain Research and Development 12: 257–268. doi:10.2307/3673669.
- Borggaard, O. K., Gafur, A., and Leif Petersen, L. (2003). Sustainability Appraisal of Shifting Cultivation in the Chittagong Hill Tracts of Bangladesh. AMBIO 32: 118–123.
- Bowling, L. C., Storck, P., and Lettenmeier, D. (2000). Hydrologic Effects of Logging in Western Washington, United States. Water Resources Research 36: 3223–3240. doi:10.1029/2000WR900138.
- Bronick, C. J., and Lal, R. (2005). Soil Structure and Management: A Review. Geoderma 124: 3–22. doi:10.1016/j.geoderma.2004.03.005.

- Bruijnzeel, L. A. (1990). Hydrology of Moist Tropical Forest and Effects of Conversion: A State of Knowledge Review. UNESCO, Paris, and Vrije Universiteit, Amsterdam, The Netherlands.
- Bruijnzeel, L. A. (2004). Hydrological functions of tropical forests: not seeing the soil for the trees. Agriculture, Ecosystems, and Environment 104: 185–228. doi:10.1016/j.agee.2004.01.015.
- Bruun, T. B., de Neergaard, A., Lawrence, D., and Ziegler, A. (2009). Environmental Consequences of the Demise in Swidden Agriculture in Southeast Asia: Carbon Storage and Soil Quality. Human Ecology, this issue.
- Calder, I. (1999). The Blue Revolution, Land Use and Integrated Water Resources Management. Earthscan, London.
- Calder, I. R. (2007). Forests and Water—Ensuring Forest Benefits Outweigh Water Costs. Forest Ecology and Management 251: 110–120. doi:10.1016/j.foreco.2007.06.015.
- Chaplot, V., Coadou le Brozec, E., Silvera, N., and Valentin, C. (2005). Spatial and Temporal Assessment of Linear Erosion in Catchments under Sloping Lands of Northern Laos. Catena 63: 167–184.
- Ciglasch, H., Amelung, W., Totrakool, S., and Kaupenjohann, M. (2005). Water Flow Patterns and Pesticide Fluxes in an Upland Soil in Northern Thailand. European Journal of Soil Science 56: 765–777.
- Ciglasch, H., Busche, J., Amelung, W., Totrakool, S., and Kaupenjohann, M. (2006). Insecticide Dissipation after Repeated Field Application to a Northern Thailand Ultisol. Journal of Agricultural and Food Chemistry 54: 8551–8559. doi:10.1021/jf061521u.
- Collins, R., and Neal, C. (1998). The Hydrochemical Impacts of Terraced Agriculture, Nepal. The Science of the Total Environment 212: 233–243. doi:10.1016/S0048-9697(97)00342-2.
- Conklin, H. (1957). Hanunoo Agriculture: A Report on an Integral System of Shifting Cultivation in the Philippines. Food and Agriculture Organization of the United Nations, Rome.
- Cooper, R. (1984). Resource Scarcity and the Hmong Response. Patterns of Settlement and Economy in Transition. Singapore University Press, Singapore.
- Cuo, L., Giambelluca, T. W., Ziegler, A. D., and Nullet, M. A. (2006). Using Distributed-Hydrology-Soil-Vegetation Model to Study Road Effects on Stream Flow and Soil Moisture. Forest Ecology & Management 224: 81–94. doi:10.1016/j.foreco.2005.12.009.
- Cuo, L., Giambelluca, T. W., Ziegler, A. D., and Nullet, M. A. (2008). The Roles of Roads and Agricultural Land Use in Altering Hydrological Processes in Nam Mae Rim Watershed, Northern Thailand. Hydrological Processes 22: 4339–4354. doi:10.1002/hyp.7039.
- Delang, C. O. (2002). Deforestation in Northern Thailand: The Result of Hmong Farming Practices of Thai Development Strategies. Society and Natural Resources 15: 483–501. doi:10.1080/ 08941920290069137.
- de Neergaard, A., Magid, J., and Mertz, O. (2008). Soil erosion from shifting cultivation and other smallholder land use in Sarawak, Malaysia. Agriculture, Ecosystems and Environment 125: 182–190.
- D'haeze, R. D., Deckers, J., Phong, T. A., and Loi, H. V. (2005). Groundwater Extraction for Irrigation of *Coffea canephora* in Ea Tul Watershed, Vietnam—A Risk Evaluation. Agricultural Water Management 73: 1–19. doi:10.1016/j.agwat.2004.10.003.
- Douglas, I. (1999). Hydrological Investigations of Forest Disturbance and Land Cover Impacts in South-East Asia: A Review. Philosophical Transactions of the Royal Society of London, B 354: 1725–1738. doi:10.1098/rstb.1999.0516.
- Douglas, I. (2006). The Local Drivers of Land Degradation in South-east Asia. Geographical Research 44: 123–134. doi:10.1111/j.1745-5871.2006.00373.x.
- Duong, T. T., Coste, M., Feurtet-Mazel, A., Dang, D. K., Gold, C., Park, Y. S., and Boudou, A. (2006). Impact of Urban Pollution from the Hanoi Area on Benthic Diatom Communities Collected from the Red, Nhue and Tolich rivers (Vietnam). Hydrobiologia 563: 201–216. doi:10.1007/s10750-005-0005-z.

- Dupin, B., de Rouw, A., Phantahvong, K. B., and Valentin, C. (2009). Soil and Tillage Research 103: 119–126. doi:10.1016/j. still.2008.10.005.
- Dyhr-Nielsen, M. (1986). Hydrological Effect of Deforestation in the Chao Phraya Basin in Thailand. Paper presented at the International Symposium on Tropical Forest Hydrology and Application, Chiang Mai, Thailand, 11–14 June 1986, 12 pp.
- Fagerstrom, M. H. H., Nilsson, S. I., van Noordwijk, M., Thai, Phien, Olssen, M., Hansson, A., and Svensson (2002). Does *Tephrosial* candida as Fallow Species, Hedgerow or Mulch Improve Nutrient Cycling and Prevent Nutrient Losses by Erosion on Slopes in Northern Viet Nam. Agriculture Ecosystems and Environment 90: 291–304. doi:10.1016/S0167-8809(01)00208-0.
- Forsyth, T. (1996). Science, Myth, and Knowledge Testing Himalayan Environmental Degradation in Thailand. Geoforum 27: 375–392. doi:10.1016/S0016-7185(96)00020-6.
- Forsyth, T., and Walker, A. (2008). Forest Guardians Forest Destroyers, the Politics of Environmental Knowledge in northern Thailand. University of Washington Press, Seattle.
- Fox, J., and Vogler, J. B. (2005). Land-Use and Land-Cover Change in Montane Mainland Southeast Asia. Environmental Management 36: 394–403. doi:10.1007/s00267-003-0288-7.
- Fox, J., Truong, D. M., Rambo, A. T., Tuyen, N. P., Cuc, L. T., and Leisz, S. (2000). Shifting Cultivation: A New Old Paradigm for Managing Tropical Forests. BioScience 50: 521–528. doi:10.1641/0006-3568(2000)050[0521:SCANOP]2.0.CO;2.
- Fox, J., Fujita, Y., Ngidang, D., Peluso, N., Potter, L., Sakuntaladewi, N., Sturgeon, J., and Thomas, D. (2009). The Political Economy of Swidden in Southeast Asia. Human Ecology, this issue.
- Gafur, A., Jenson, J. R., Borggard, O. K., and Peterson, L. (2003). Runoff and Losses and Nutrients from Small Watersheds under Shifting Cultivation (*Jhum*) in the Chittagong Hill Tracts of Bangladesh. Journal of Hydrology 279: 293–309. doi:10.1016/ S0022-1694(03)00263-4.
- Geddes, W. R. (1976). Migrants of the Mountains—The Cultural Ecology of the Blue Miao (Hmong Njua) of Thailand. Oxford University Press, London.
- Giambelluca, T. W., Tran, L. T., Ziegler, A. D., Menard, T. P., and Nullet, M. A. (1996). Soil–vegetation–atmosphere processes: simulation and field measurement for deforested sites in northern Thailand. Journal of Geophysical Research—Atmospheres 101: D2025867–25885. doi:10.1029/96JD01966.
- Giambelluca, T. W., Ziegler, A. D., Nullet, M. A., Dao, T. M., and Tran, L. T. (2003). Transpiration in a Small Tropical Forest Patch. Agriculture and Forest Meteorology 117: 1–22. doi:10.1016/S0168-1923(03)00041-8.
- Guardiola-Claramonte, M., Troch, P. A., Ziegler, A. D., Giambelluca, T. W., Vogler, J. B., and Nullet, M. A. (2008). Local Hydrologic Effects of Introducing Non-native Vegetation in a Tropical Catchment. Ecohydrology 1: 13–22.
- Hanks, L. M. (1972). Rice and Man, Agricultural Ecology in Southeast Asia. University of Hawaii Press, Honolulu.
- Henderson, G. S., and Poonsak, W. (1984). The Effect of Road Construction on Sedimentation in a Forested Catchment at Rayong, Thailand. Symposium on Effects of Forest Land Use on Erosion and Slope Stability, 7–11 May 1984, EAPI, East– West Center, Honolulu, 247–253.
- Hill, R. D. (1998). Status and Change in Forty Years of Southeast Asian Agriculture. Singapore Journal of Tropical Geography 19: 1–25. doi:10.1111/j.1467-9493.1998.tb00247.x.
- Hill, R. D., and Peart, M. R. (1998). Land Use, Runoff, Erosion and their Control: A Review for Southern China. Hydrological Processes 12: 2029–2042. doi:10.1002/(SICI)1099-1085 (19981030)12:13/14<2029::AID-HYP717>3.0.CO;2-O.
- Hurni, H. (1982). Soil Erosion in Huai Thung Choa—Northern Thailand. Concerns and Constraints. Mountain Research and Development 2: 141–156. doi:10.2307/3672960.

- Hurni, H. (1983). Soil Erosion and Soil Formation in Agricultural Ecosystems, Ethiopia and Northern Thailand. Mountain Research and Development 3: 131–142. doi:10.2307/3672994.
- Ismail, B. S., Ngan, C. K., Cheah, U. B., and Wah Abdullah, W. Y. (2004). Leaching Potential of Pesticides in a Vegetable Farm in the Cameron Highlands. Bulletin of Environmental Contamination and Toxicology 72: 836–843. doi:10.1007/s00128-004-0320-5.
- Janeau, J. L., Bricquet, J. P., Panchon, O., and Valentin, C. (2003). Soil Crusting and Infiltration on Steep Slopes in Northern Thailand. European Journal of Soil Science 54: 543–553. doi:10.1046/j.1365-2389.2003.00494.x.
- Jones, S. (1997). An Actor-Level Analysis of the Constraints on Sustainable Land Management in Northern Thailand: A Study from Chiang Dao District. South East Asia Research 5: 243–267.
- Kahl, G., Ingwersen, J., Nutniyom, P., Totrakool, S., Pansombat, K., Thavornyutikarn, P., and Streck, T. (2008). Loss of Pesticides from a Litchi Orchard to an Adjacent Stream in Northern Thailand. European Journal of Soil Science 59: 71–81.
- Kerkhoff, E., and Sharma, E. (2006). Debating Shifting Cultivation in the Eastern Himalayas. Farmers' Innovations as Lessons for Policy. International Centre for Integrated Mountain Development (ICIMOD), Kathmandu.
- Kwanyuen, B. (2000). Comparative study of rainfall change in the north of Thailand. Proceedings of the international conference: The Chao Phraya Delta: Historical Development, Dynamics and Challenges of Thailand's Rice Bowl, 12–15 December, 2000, Bangkok.
- Lestrelin, G., and Giordano, M. (2007). Upland Development Policy, Livelihood Change and Land Degradation: Interactions from a Laotian Village. Land Degradation and Development 18: 55–76. doi:10.1002/ldr.756.
- Lim, J. N. W., and Douglas, I. (2000). Land Management Policy and Practice in a Steepland Agricultural Area: A Malaysian Example. Land Degradation and Development 11: 51–61. doi:10.1002/(SICI) 1099-145X(200001/02)11:1<51::AID-LDR367>3.0.CO;2-L.
- Ma, Q. (1999). Asia-Pacific Forestry Sector Outlook Study: Volume I— Socio-Economic, Resources and Non-Wood Products Statistics. FAO, Rome.
- Malhi, Y., Roberts, J. T., Betts, R. A., Killeen, T. J., Li, W., and Nobre, C. A. (2008). Climate Change, Deforestation, and the Fate of the Amazon. Science 319: 169–172. doi:10.1126/science.1146961.
- Mazlan, N., and Mumford, J. (2005). Insecticide Use in Cabbage Pest Management in the Cameron Highlands, Malaysia. Crop Protection 24: 31–39. doi:10.1016/j.cropro.2004.06.005.
- McCoy, A. W. (1991). The Politics of Heroin in Southeast Asia. CIA Complicity in the Global Drug Trade. Lawrence Hill, Brooklyn.
- Megahan, W. F. (1972). Subsurface Flow Interception by a Logging Road in Mountains of Central Idaho. In Proceedings, *National Symposium on Watersheds in Transition*. American Water Resources Association: Fort Collins, CO; 350–356.
- Mertz, O., Padoch, C., Fox, J., Cramb, R. A., Leisz, S., Nguyen, T. L., and Tran, T. D. (2009a). Swidden Change in Southeast Asia: Understanding Causes and Consequences. Human Ecology, this issue
- Mertz, O., Leisz, S., Heinimann, A., Rerkasem, K., Thiha, Dressler, W., Cu, P. V., Vu, K. C., Schmidt-Vogt, D., Colfer, C. J. P., Epprecht, M., Padoch, C., and Potter, L. (2009b). Who Counts? The Demography of Swidden Cultivators. Human Ecology, this issue
- Midmore, D. J., Jansen, H. G. P., and Dumsday, R. G. (1996). Soil Erosion and Environmental Impact of Vegetable Production in the Cameron Highlands, Malaysia. Agriculture Ecosystems and Environment 60: 29–46.
- Nguyen, M. K., Pham, Q. H., and Obron, I. (2007). Nutrient Flows in Small-Scale Peri-Urban Vegetable Farming Systems in Southeast Asia—A Case Study in Hanoi. Agriculture Ecosystems and Environment 122: 192–202. doi:10.1016/j.agee.2007.01.003.
- Nguyen, T. L., Vien, T. D., Lam, N. T., Tuong, T. M., and Cadisch, G. (2008). Analysis of the Sustainability with the Composite

Swidden Agroecosystem: 1. Partial Nutrient Balance and Recovery Times of Uplands Swiddens. Agriculture, Ecosystem and Environment 128: 37–51. doi:10.1016/j.agee.2008.05.004.

- Nikolic, N., Schultze-kraft, R., Nicolic, M., Böcker, R., and Holz, I. (2008). Land Degradation on Barren Hills: A Case Study in Northeast Vietnam. Environmental Management 42: 19–36. doi:10.1007/s00267-008-9099-1.
- Nobre, C. A., Sellers, P. J., and Shukla, J. (1991). Amazonian Deforestation and Regional Climate Change. Journal of Climate 4: 957–988. doi:10.1175/1520-0442(1991)004<0957:ADARCC>2.0.CO;2.
- Nye, P. H., and Greenland, D. J. (1965). The Soil Under Shifting Cultivation. Jarrold and Sons, Norwich.
- Padoch, C., Coffey, K., Mertz, O., Leisz, S. J., Fox, J., and Wadley, R. L. (2007). The Demise of Swidden in Southeast Asia? Local Realities and Regional Ambiguities. Geografisk Tidsskrift, Danish Journal of Geography 107: 129–41.
- Poffenberger, M., and McGean, B (eds.) (1993). Community Allies: Forest Co-management in Thailand. Center for Southeast Asia Studies, Berkeley CA.
- Podwojewski, P., Orange, D., Jouquet, P., Valentin, C., Van Thiet, Nguyen, Janeau, J. L., and Duc Toan, Tran (2008). Land-Use Impacts on Surface Runoff and Soil Detachment with Agricultural Sloping Lands in Northern Vietnam. Catena 74: 109–118. doi:10.1016/j.catena.2008.03.013.
- Purwanto, E., and Bruijnzeel, L. A. (1998). Soil Conservation on Rainfed Bench Terraces in Upland West Java, Indonesia: Towards A New Paradigm. Advances in Geoecology 31: 1267–1274.
- Rahman, M. M., Mostafa, G., Razia, S. W., and Shoaib, J. U. (2001). Land degradation in Bangladesh. In Bridges, E. M., Hannam, I. D., Oldeman, L. R., Penning de Vries, F. W. T., Scherr, S. J., and Sombatpanit, S. (eds.), Response to land degradation. Science Publishers, New Hampshire, pp. 117–129, pp 507.
- Rasul, G., and Thapa, G. B. (2003). Shifting Cultivation in the Mountains of South and Southeast Asia: Regional Patterns and Factors Influencing Change. Land Degradation and Development 14: 495–508. doi:10.1002/ldr.570.
- Renard, F., Bechstedt, H.-D., and Nakorn, U. N. (1998). Farming Systems and Soil-Conservation Practices in a Study Area of Northern Thailand. Mountain Research and Development 18: 345–356. doi:10.2307/3674099.
- Rerkasem, B. (2005). Transforming Subsistence Cropping in Asia. Plant Production Science 8: 275–287. doi:10.1626/pps.8.275.
- Rerkasem, K., and Rerkasem, B. (1994). Shifting Cultivation in Thailand: Its Current Situation and Dynamics in the Context of Highland Development. IIED Forestry and Land Use Series No. 4, London.
- Rerkasem, K., Lawrence, D., Padoch, C., Schmidt-Vogt, D., Ziegler, A. D., and Bech-Brun, T. (2009). Consequences of Swidden Transitions for Crop and Fallow Biodiversity. Human Ecology, this issue.
- Rijsdijk, A., Bruijnzeel, L. A., and Sutoto, C. K. (2007a). Runoff and Sediment Yield from Rural Roads, Trails, Settlements in the Upper Konto Catchment, East Java, Indonesia. Geomorphology 87: 28–37. doi:10.1016/j.geomorph.2006.06.040.
- Rijsdijk, A., Bruijnzeel, L. A., and Sutoto, C. K. (2007b). Sediment Yield from Gullies, Riparian Mass Wasting and Bank Erosion in the Upper Konto Catchment, East Java, Indonesia. Geomorphology 87: 38–52. doi:10.1016/j.geomorph.2006.06.041.
- Robichaud, P. R. (2000). Fire Effects on Infiltration Rates after Prescribed Fire in Northern Rocky Mountain forests, USA. Journal of Hydrology 231: 200–229.
- Rodriguez-Iturbe, I., and Rinaold, A. (1997). Fractal River Basins: Chance and Self-organization. Cambridge University Press, Cambridge.
- Sabhasri, S. (1978). Effects of forest fallow cultivation on forest production and soil. Chapter 8, pp. 160–184 in Kunstadter, P., Chapman, E. C. & Sabhasri, S. (Eds.)

- Schmidt-Vogt, D. (1999). Swidden Farming and Fallow Vegetation in Northern Thailand. Geoecological Research Volume 8. Franz Steiner, Stuttgart.
- Schmidt-Vogt, D. (2001). Secondary Forests in Swidden Agriculture in the Highlands of Thailand. Journal of Tropical Forest Science 13: 748–767.

Schmidt-Vogt, D., Leisz, S., Mertz, O., Heinimann, A., Thiha, Messerli, P., Epprecht, M., Cu, P. V., Vu, K. C., Hardiono, M., and Truong, D. M. (2009). An Assessment of Trends in the Extent of Swidden in Southeast Asia. Human Ecology, this issue

- Sidle, R. C., and Ochiai, H. (2006). Landslides: Processes, Prediction, and Land-use. American Geophysical Union, Washington DC.
- Sidle, R. C., Pearce, A. J., and O'Loughlin, C. L. (1985). Hillslope Stability and Land Use, Water Resources Monograph, vol. 11. American Geophysical Union, Washington, DC, p. 140 pp.
- Sidle, R. C., Sasaki, S., Otsuki, M., Noguchi, S., and Abdul Rahim, N. (2004). Sediment Pathways in a Tropical Forest: Effects of Logging Roads and Skid Trails. Hydrological Processes 18: 703– 720. doi:10.1002/hyp.1364.
- Sidle, R. C., Ziegler, A. D., Negishi, J. M., Abdul Rahim, N., and Siew, R. (2006). Erosion Processes in Steep Terrain—Truths, Myths, and Uncertainties Related to Forest Management in Southeast Asia. Forest Ecology and Management 224: 199– 225. doi:10.1016/j.foreco.2005.12.019.
- Sidle, R. C., Ziegler, A. D., and Vogler, J. B. (2007). Contemporary Changes in Surface Area of Inle Lake, Myanmar. Sustainability Science. doi:10.1007/s11625-006-0020-7.
- Smakhtin, V. U. (2001). Low Flow Hydrology: A Review. Journal of Hydrology 240: 147–186. doi:10.1016/S0022-1694(00)00340-1.
- Spencer, J. (1966). Shifting Cultivation in Southeast Asia, University of California Publications in Geography, vol. 19University of California Press, Berkeley.
- Tangtham, N. (1997). Erosion and Sedimentation Studies and Management in Thailand. Paper presented to the International Symposium on Hydrology and Water Resources for Research and Development in Southeast Asia and the Pacific, Nongkhai, Thailand, 16–19 December 1997, organized by UNESCO and National Research Council Thailand. Royal Forest Department, Bangkok.
- Thanapakpawin, P., Richey, J., Thomas, D., Rodda, S., Campbell, B., and Logsdon, M. (2006). Effects of landuse change on the hydrologic regime of the Mae Chaem river basin, NW Thailand. Journal of Hydrology 334: 215–230.
- The World Bank. (2007). www.worldbank.org; accessed October 2008
- Thi Phuong Quynh, Le, Garnier, J., Gilles, B., Sylvain, T., and Chau Van, Minh (2007). The Changing Flow Regime and Sediment Load of the Red River, Viet Nam. Journal of Hydrology 334: 199–214. doi:10.1016/j.jhydrol.2006.10.020.
- Thongmanivong, S., Fujita, Y., and Fox, J. (2005). Resource Use Dynamics and Land-Cover Change in Ang Nhai and Phou Phanang National Forest Reserve, Lao PDR. Environmental Management 36: 382–393. doi:10.1007/s00267-003-0291-z.
- Trocki, C. A. (1999). Opium, Empire and the Global Political Economy: A Study of the Asian Opium Trade 1750–1950. Routledge, New York.
- Turkelboom, F. (1999). On-Farm Diagnosis of Steepland Erosion in Northern Thailand. Ph.D. Thesis, Faculty of Agricultural and Applied Biological Sciences, K.U. Leuven.
- Turkelboom, F., Poesen, J., Ohler, I., Van Keer, K., Ongprasert, S. L., and Vlassak, K. (1997). Assessment of Tillage Erosion Rates on Steep Slopes in Northern Thailand. Catena 29: 29–44.
- Turkelboom, R., Poesen, J., and Trebuil, G. (2008). The Multiple Land Degradation Effects by Land-Use Intensification in Tropical Steeplands: A Catchment Study from Northern Thailand. Catena 75: 102–116. doi:10.1016/j.catena.2008.04.012.

- Valentin, C., Agus, F., Alamban, R., Boosaner, A., Bricquet, J. P., Chaplot, V., de Guzman, T., de Rouw, A., Januea, J. L., Orange, D., Phachomphonh, K., Do Duy, Phai, Podwojewski, P., Ribolzi, O., Silvera, N., Subagyono, K., Thiebaus, J. P., Tran Duc, Toan, and Vadari, T. (2008). Runoff and Sediment Losses from 27 Catchments in Southeast Asia: Impact of Rapid Land Use Changes and Conservation Practices. Agriculture Ecosystems and Environment 128: 225–238. doi:10.1016/j.agee.2008.06.004.
- van Dijk, A. I. J. M., and Bruijnzeel, L. A. (2001). Modelling Rainfall Interception by Vegetation of Variable Density using an Adapted Analytical Model. Part 2. Model Validation for a Tropical Upland Mixed Cropping System. Journal of Hydrology 247: 239–262. doi:10.1016/S0022-1694(01)00393-6.
- van Dijk, A. I. J. M., and Bruijnzeel, L. A. (2004). Runoff and Soil Loss from Bench Terraces. 1. An Event-Based Model of Rainfall Infiltration and Surface Runoff. European Journal of Soil Science 55: 299–316. doi:10.1111/j.1365-2389.2004.00604.x.
- van Dijk, A. I. J. M., and Keenan, R. J. (2007). Planted Forests and Water in Perspective. Forest Ecology and Management 251: 1–9. doi:10.1016/j.foreco.2007.06.010.
- van Dijk, A. I. J. M., van Noordwijk, M., Calder, I. R., Bruijnzeel, L. A., Schellekens, J., and Chappell, N. (2009). Forest–Flood Relation still Tenuous—Comment on "Global Evidence that Deforestation Amplifies Flood Risk and Severity in the Developing World" by C.J.A. Bradshaw, N. S. Sodi, K. S.-H.Peh, and B.W. Brook. Global Change Biology 15: 110–115. doi:10.1111/j.1365-2486.2008.01708.x.
- Vigiak, O., Ribolzi, O., Pierret, A., Sengtaheuanghoung, O., and Valentin, C. (2008). Trapping Efficiencies of Cultivated and Natural Riparian Vegetation in Northern Laos. Journal of Environmental Quality 37: 889–897. doi:10.2134/jeq2007.0251.
- Vlassak, K., Ongprasert, S., Tancho, A., van Look, K., Turkelboom, T., and Ooms, L. (1993). Soil Fertility Conservation Research Report 1989–1992. SFC project, Mae Jo University, Thailand.
- Wemple, B. C., Swanson, F. J., and Jones, J. A. (2001). Forest Roads and Geomorphic Interactions, Cascade Range, Oregon. Earth Surface Processes and Landforms 26: 191–204. doi:10.1002/ 1096-9837(200102)26:2<191::AID-ESP175>3.0.CO;2-U.
- Weyeraeuser, H., Wilkes, A., and Kahrl, F. (2005). Local Impacts and Responses to Regional Forest Conservation and Rehabilitation Programs in China's Northwest Yunnan Province. Agricultural Systems 85: 234–253. doi:10.1016/j.agsy.2005.06.008.
- Wiersum, K. F. (1984). Surface erosion under various tropical agroforestry systems. In O'Loughlin, C. L., and Pearce, A. J. (eds.), Effects of Forest Land Use on Erosion and Slope Stability. IUFRO, Vienna, pp. 231–239.
- Wilk, J., Andersson, L., and Plermkamon, V. (2001). Hydrological Impacts of Forest Conversion to Agriculture in a Large River Basin in Northeast Thailand. Hydrological Processes 15: 2759– 2748. doi:10.1002/hyp.229.
- Wood, S. H., and Ziegler, A. D. (2008). Floodplain Sediment from a 30-Year-Recurrence Flood in 2005 of the Ping River in Northern Thailand. Hydrology and Earth Systems Science 12: 959–973.
- Xu, J. C., Fox, J., Vogler, J. B., Peifang, Z., Yongshou, F., Lixin, Y., Jie, Q., and Leisz, S. (2005). Land-Use and Land-Cover Change and Farmer Vulnerability in Xishuangbanna Prefecture in Southwestern China. Environmental Management 36: 404–413. doi:10.1007/s00267-003-0289-6.
- Ziegler, A. D., and Giambelluca, T. W. (1997). Importance of Rural Roads as Source Areas for Runoff in Mountainous Areas of

Northern Thailand. Journal of Hydrology 196: 204–229. doi:10.1016/S0022-1694(96)03288-X.

- Ziegler, A. D., Sutherland, R. A., and Giambelluca, T. W. (2000). Runoff Generation and Sediment Transport on Unpaved Roads, Paths, and Agricultural Land Surfaces in Northern Thailand. Earth Surface Processes and Landforms 25: 519–534. doi:10.1002/(SICI)1096-9837(200005)25:5<519::AID-ESP80>3.0. CO:2-T.
- Ziegler, A. D., Sutherland, R. A., and Giambelluca, T. W. (2001a). Acceleration of Horton Overland Flow & Erosion by Footpaths in an Agricultural Watershed in Northern Thailand. Geomorphology 41: 249–262. doi:10.1016/S0169-555X(01)00054-X.
- Ziegler, A. D., Giambelluca, T. W., Sutherland, R. A., Vana, T. T., and Nullet, M. A. (2001b). Contribution of Horton Overland Flow Contribution to Runoff on Unpaved Mountain Roads in Northern Thailand. Hydrological Processes 15: 3203–3208. doi:10.1002/hyp.480.
- Ziegler, A. D., Giambelluca, T. W., Sutherland, R. A., Nullet, M. A., Yarnasarn, S., Pinthong, J., Preechapanya, P., and Jaiarree, S. (2004a). Toward Understanding the Cumulative Impacts of Roads in Agricultural Watersheds of Montane Mainland Southeast Asia. Agriculture Ecosystems and Environment 104: 145–158. doi:10.1016/j.agee.2004.01.012.
- Ziegler, A. D., Giambelluca, T. W., Tran, L. T., Vana, T. T., Nullet, M. A., Fox, J. M., Vien, T. D., Pinthong, J., Maxwell, J. F., and Evett, S. (2004b). Hydrological Consequences of Landscape Fragmentation in Mountainous Northern Vietnam: Evidence of Accelerated Overland Flow Generation. Journal of Hydrology 287: 124–146. doi:10.1016/j.jhydrol.2003.09.027.
- Ziegler, A. D., Tran, L. T., Giambelluca, T. W., Sidle, R. C., and Sutherland, R. A. (2006a). Effective Slope Lengths for Buffering Hillslope Surface Runoff in Fragmented Landscapes in Northern Vietnam. Forest Ecology & Management 224: 104–118. doi:10.1016/j.foreco.2005.12.011.
- Ziegler, A. D., Negishi, J. N., Sidle, R. C., Preechapanya, P., Sutherland, R. A., Giambelluca, T. W., and Jaiarree, S. (2006b). Reduction of Stream Suspended Sediment Concentration by a Riparian Buffer: Filtering of Road Runoff. Journal of Environmental Quality 35: 151–162. doi:10.2134/jeq2005.0103.
- Ziegler, A. D., Giambelluca, T. W., Sutherland, R. A., Nullet, M. A., and Tran Duc, Vien (2007a). Soil Translocation by Weeding on Swidden Fields in Northern Vietnam. Soil and Tillage Research 96: 219–233. doi:10.1016/j.still.2007.06.009.
- Ziegler, A. D., Negishi, J. N., Sidle, R. C., Gomi, T., Noguchi, S., and Abdul Rahim, Nik (2007b). Persistence of Road Runoff Generation in a Logged Catchment in Peninsular Malaysia. Earth Surface Processes & Landforms 32: 1947–1970. doi:10.1002/ esp.1508.
- Ziegler, A. D., Giambelluca, T. W., Plondke, D., Leisz, S., Tran, L. T., Fox, J., Nullet, M. A., Vogler, J. B., Dao Minh, Truong, and Tran Duc, Vien (2007c). Hydrological Consequences of Landscape Fragmentation in Mountainous Northern Vietnam: Buffering of Accelerated Overland Flow. Journal of Hydrology 337: 52–67. doi:10.1016/j.jhydrol.2007.01.031.
- Ziegler, A. D., Fox, J. M., and Xu, J. (2009). The rubber juggernaut. Science 324: 1024–1025.
- Zinke, P., Sabhasri, S., and Kunstadter, P. (1978). Soil fertility aspects of the Lua' forest fallow system of shifting cultivation. In Kunstadter, P., Chapman, E. C., and Sabhasri, S. (eds.), Farmers in the Forest. University of Hawaii Press, Honolulu, pp. 134–159.