The multiple land degradation effects of land-use intensification in tropical steeplands: A catchment study from northern Thailand[1]

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Abstract

The strongly incised mountain landscape of Northern Thailand has changed dramatically during the last few decades due to increased population pressure, agricultural commercialization, limitation to use old fallows and reforestation of upper catchments. The traditional shifting cultivation with fallow periods of 7 years and longer was gradually replaced by 1 to 4 year fallow periods. As a result, in high population areas the landscape became dominated by rainfed parcels, wetland terraces, secondary fallow vegetation and patches of disturbed forest. This new land-use system triggered severe land degradation.

The objective of this research was to assess the multiple effects of land-use intensification in a tropical steepland environment on land degradation processes. A case study was conducted at Pakha village (located in Thailand's northern most Chiang Rai province), which is dominated by steepland with average slope gradients ranging from 30 to 70%. Soil erosion processes were monitored in a selected catchment for 2 years, and informal interviews were conducted to elucidate farmers' perceptions regarding land degradation processes.

The rapid land-use changes at the Dze Donglo catchment (164 ha) resulted in severe and accelerated land degradation, including tillage erosion (386 ton/year), inter-rill and rill erosion (502 ton/year), gully erosion (423 ton/year), and landslides (7572 ton during 1994). Water erosion is most common in intensively farmed areas. The combination of runoff-generating areas, runoff concentrating features and connectivity led to extensive gully erosion. Landslides were most common in steep fallows and in wetland terraces along incising streams. Many of these steepland degradation processes interacted with each other (i.e. rills with gully erosion, tillage erosion with water erosion, gullies with landslides). The observed land degradation processes matched very well with farmers' perceptions. This study enabled to identify 'potential land degradation hotspots' and indicates the necessity to analyze steepland degradation processes in a holistic way.

Keywords: Land degradation, tillage erosion, rill erosion, gully erosion, landslides, steeplands, land use change, connectivity, northern Thailand.

1. Introduction

Tropical mountainous areas are inhabited by an estimated 500 million people, many of whom practice subsistence agriculture (Jackson and Scherr, 1995). In the mountains of mainland Southeast Asia, a gradual process of agricultural commercialization has taken place over the last

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50 years, resulting in a decline of shifting cultivation and an increase of paddy rice and cash crops (Fox and Vogler, 2005). Over the last three decades, this transition occurred in the hills of Northern Thailand, where it has been driven by population increase, immigration, the protection of the state controlled remaining forest areas, limitation to use old fallows, reforestation of upper catchments, the expansion of rural communication infrastructures, and market integration (Trébuil et al, in press). The traditional shifting cultivation system, characterized by at least 7 year long fallow periods, was gradually replaced by short fallow periods (1 to 4 years) or even permanent agriculture, which currently occupies more than half of the farmed area. As a result, in highly populated areas the hill landscapes became dominated by rainfed fields, wetland terraces, secondary fallow vegetation, and patches of (disturbed) forest.

As headwater streams comprise 60-80% of the cumulative length of river networks (Benda et al, 2005), land-use changes in headwater areas can have important downstream impacts. Areas with hillslopes steeper than 20% are defined as steeplands (Lal, 1990), and when cultivated under tropical conditions, they are prone to land degradation. However, soil erosion processes on these steeplands have been poorly documented so far. In Northern Thailand, soil loss from agricultural land is almost exclusively measured at runoff plots. The reported soil loss rates vary tremendously (between 0.1 and 500 ton/ha/year, summary by Turkelboom, 1999). This large range is caused by differences in topography, soil conditions, rainfall, and land-use systems. These results indicate that soil loss in agricultural land can be considerable and become a threat to long-term agricultural sustainability. On the other hand, these data also indicate that cultivation of steep slopes does not automatically result in high soil loss rates. Therefore, simple standard recommendations for land management are not advisable for these highlands.

Researcher-controlled runoff plots help us to quantify the intensity of soil erosion at plot level and to identify the role of some controlling factors, but one can wonder whether the narrow focus on runoff plots is the best approach to obtain a realistic assessment of soil erosion in steep catchments and to design sustainable catchment approaches.

Many of the measurements from standard runoff plots give a false illusion of accuracy by dissection of the actual farming circumstances into single-variable “slices”, whereas most biophysical systems are dominated by interactions (Stocking, 1996).

Plots introduce artificial boundary conditions. In actual conditions, soil erosion by water is often interconnected along the hillslope. Erosion research at the micro and field level often overlooks other forms of erosion (e.g. gully erosion, tillage erosion, mass movement) or erosion generated by non-agricultural landscape features, such as trails, roads, and settlements.

Land users’ management practices have an important impact on soil erosion. As land-use on tropical hillslopes is usually managed by smallholders, their heterogeneous and variable soil and cropping practices are very difficult to imitate under on-station conditions. As a result, ‘farmer treatments’ are often unrealistic (e.g. continuous upland rice cultivation for 7 years, or weed-free cultivation).

Very often, the focus on on-station runoff plots results in a disconnection between researchers and the actual farming conditions.

As a consequence, the importance to study soil erosion beyond the borders of the classical runoff plot has been recognized over the last decade (Evans, 1993; Poesen et al, 1996a). Van Noordwijk et al (2004) advocate the need for a landscape approach which includes lateral flows, as these form an important part of the causal chain of environmental management issues. Catchment studies were also strongly endorsed by the Technical Advisory Committee of the Consultative Group on International Agricultural Research (TAC, 1996). For these reasons, catchment studies have been gaining popularity in recent years, but what is the best approach to understand and manage catchment dynamics in tropical steeplands?

Erosion models are regularly used as an alternative to overcome the lack of empirical data from steeplands. One group of studies are linking models for inter-rill and rill erosion (e.g. (R)USLE) with GIS-derived terrain mapping data (Funnpheng et al, 1991; Rao et al, 1994; Ravishankar et al, 1994; Vezina et al, 2006). Such a theoretical exercise provides an attractive shortcut. However, by using a model beyond its limits of validity, it is very likely that irrelevant or unrealistic conclusions are produced. There are some catchment-based soil erosion models, such as EGEM (Ephemeral Gully Erosion Model, Merkel et al, 1988), LISEM (Limburg Soil Erosion Model, De Roo et al, 1994), WEPP (Water Erosion Prediction Model; Flanagan and Nearing, 1995), EUROSEM (Morgan et al, 1998) and WATEM-SEDEM (Van Rompaey et al, 2001). These models do not always take into account the range of mechanisms responsible for gully erosion or the presence of site specific features, such as contour trenches, tracks, and roads, that concentrate overland flow (Souchère et al, 2003; Moeyersons, 2003) leading to major errors in the spatial and temporal prediction of linear erosion. They also do not include mass movement processes along gully sides and the extension of gullies by head cutting (Poesen et al, 1998). Finally, all of them have been developed and calibrated for gently undulating landscapes (slopes < 20%). Considering the controversial findings and recommendations of a model-based study in the highlands of Tigray (Northern Ethiopia), Nyssen et al (2006) warns against the transposing of environmental models from one region to another without field checks. Extensive fieldwork remains necessary for site-specific calibration and validation. Neglecting to do so may result in improper understanding of the processes at hand, and consequently in ill-targeted and costly remediation schemes.

Hydrological approaches at the catchment scale are an alternative to study water and sediment movement in steep catchments. In such studies, stream flow and sediment loads of catchments and basins are usually correlated with rainfall, topography or land-use parameters (e.g. Management of Soil Erosion Consortium, MSEC for South-East Asia, Valentin et al, 2006). Such an approach provides insights about what is moving out of a catchment and can identify some possible causing factors. However correlations do not reveal processes and the catchment is usually treated as a 'black box'.

Detailed studies at the catchment level have led to a better measurement and understanding of the effects of roads and paths as runoff and sediment sources (Morgan, 1980; Herweg, 1988; Tapp, 1990; Bruijnzeel, 1990; Harden, 1992, 1996; Grieve et al, 1995; Ziegler and Giambelluca, 1997). Rural settlement areas were also identified as major runoff producing areas (Moeyersons (1989) in Rwanda, Rydgren (1990) in Lesotho, and Purwanto (1999) in Indonesia). However, most of these studies focus on these water erosion processes in isolation.

Based on the above observations, one realizes that tropical steeplands are in dire need of much more empirical and holistic catchment studies. Such type of research should aim at a better identification of steepland erosion processes and their determining factors and interactions. A few integrated catchment studies were conducted in the gentle sloping areas of north-western Europe (e.g. Papy and Souchère, 1993; Vandaele and Poesen, 1995; Davidson and Harison, 1995; Poesen et al, 1996b) and in Mediterranean, sloping olive orchards (Klewinghaus et al, 2006). Besides the usual landscape features, they emphasise the importance of field parcel patterns, roads, and tillage directions for the occurrence of erosion features. Similar catchment studies in tropical steeplands remain very rare (e.g. Rijsdijk and Bruijnzeel (1990) and Purwanto (1999) who studied terrace-dominated valleys in Java). Therefore, the objective of this research in northern Thailand was to assess and better understand the multiple effects of land-use intensification and market integration on land degradation processes in a tropical steepland environment.

2. Study area and methodology

2.1. Study area

The study was conducted at the village of Pakha, located in Mae Chan District of Thailand's northern most Chiang Rai Province (20°8' North and 99°37' East, Fig.1). From the geomorphology point of view, it represents the steeper and wetter highlands of Northern Thailand. Average annual rainfall is about 2,100 mm. From socio-economic point of view, it represents an advanced stage of transition to short-fallow and semi-commercial agriculture. The latter criterion was chosen, as it is expected that this will be the future situation for many of the present subsistence and semi-remote villages in the highlands of south-east Asia.

Pakha village was established in 1977 in an area with secondary forests and fallow land. For about 10 years, Pakha farmers practised shifting cultivation and agriculture was dominated by upland rice, maize and a limited production of beans. Land pressure increased rapidly due to a ten-fold increase in population over 20 years, the enforcement of restrictions regarding the access to fallow land, and reforestation programmes. In 1995, the population density in Pakha was 65 inhabitants per km^2, which is relatively high for a steepland environment. The first change in land-use (1983-1988) was caused by rice shortages, which led to the construction of irrigation channels and paddy fields on gentle sloping areas. The second major change (1990-1993) was caused by the construction of new asphalted roads, which resulted to the adoption of short-duration cash crops (mainly common cabbage).

The Dze Donglo catchment of Pakha village (Fig. 2) was selected for this study because of its diverse and semi-permanent land-use pattern. This is a deeply-dissected catchment of 168 ha, and the elevation ranges between 660 and 1164 m a.m.s.l. There are five permanent springs resulting in two major streams in the catchment, which feeds into the Mae Chan river, that eventually joins the Mekong river. The total (permanent and intermittent) stream length in the catchment is 7.1 km. Water of the highest source drops 420 m in a 2.25 km stretch (equivalent to an average fall of 1 m per 5.6 m). Consequently, the stream floor is mostly very rocky and several small waterfalls can be found. The hydrology of the upper part of the catchment is seriously altered by a number of irrigation channels. The biggest impact on the catchment hydrology comes from a 600 m long channel, which drains two streams and half of the village runoff into an irrigated rice field.

Two major types of parent material are found in the catchment: phyllite and shale in the upper part (59% of the catchment), and granite in the lower part (41%). The dominant soil types are Humic Umbrisol, Haplic Regosol, and Dystric Cambisol. About 80% of the catchment is covered by either forest or secondary fallow vegetation (Fig. 2). According to the Akha tradition, the village compound and the forest are located at the top of the catchment. The large fallow vegetation area is the result of past shifting cultivation practices. In 1995, only 15% of the catchment surface was cultivated (25 ha, Fig. 3). Slopes of the cropped field parcels are very steep: seventy percent of the fields have slope gradients between 40% and 70%. Slope length of the fields varies between 6 and 150 m, but half of them are between 20 and 60 m long. The median field size is 0.3 ha. The cultivated land is used for rainfed agriculture (83%) and terraced wetland (or 'paddies') (17%). As only 27% of the total cultivated area was newly cleared during the 1995 crop year, the land-use can be called semi-permanent.

From the village centre, four wide and gentle-sloping paths lead to different valley slopes. Two paths were widened in 1995 in order to allow pickup trucks in the catchment to collect the cabbage harvest or to transport tree seedlings for reforestation purposes. Secondary paths are branching out from these primary paths to access individual fields. The secondary paths are narrow and usually quite steep (average: 38%, range: 11-84%).

Soil conservation measures are very common: in 73% of the field parcels at least one soil conservation measure is practised (Table 1). Most of them are indigenous soil conservation measures. The most popular ones are: diversion ditches, (cultivated) mulch strips, and terraces. Alley cropping with nitrogen fixing shrubs was introduced by a local NGO since 1987, but was implemented in only four fields.

2.2. Methodology

During the 1994 and 1995 cropping seasons, we assessed tillage erosion, water erosion and landslides by using the below methods.

Tillage erosion

Farmers manually till their land with a hoe (steel blade 16 cm wide and between 10-20 cm long, wooden handle about 80 cm long). Soil movement by manual tillage was measured at different slope gradients (17%, 32%, 41%, 51%, 60% and 82%) in farmers' field plots. Soil translocation was assessed by measuring the movement of tracers and the tillage step dimensions at the top of the plot. Soil flux by tillage erosion was quantified by linear functions for different slope gradient classes. The angle of repose of soil clods (= slope gradient above which clods of the tilled top layer start to slide and roll down the slope, also called 'dry ravel') in field conditions was assessed at 15 sites by measuring the slope gradient of the soil surface where dry ravel occurred as a result of tillage and walking. The equations to calculate soil translocation for the different methods are discussed in more detail by Turkelboom et al. (1997 and 1999).

Rill erosion at the field plot level

Rill erosion in steep field plots was assessed via a semi-quantitative integrated diagnostic erosion survey. The main principle of this approach is that erosion damages are monitored after each intense rainstorm. This method was selected as no artificial boundaries had to be constructed and as farmers' soil and crop management was not disturbed. Several researchers applied a similar approach under European conditions: Evans and Nortcliff (1978), Evans (1980), Colbourne and Staines, 1985, Boardman (1988) and Davidson & Harrison (1995) in the United Kingdom; Auzet et al (1990, 1993), Govers (1991) and Vandaele & Poesen (1995) for the undulating loess plains of North-Western Europe; and Prasuhn (1992) and Bussoni et al (1995) for an Alpine environment. But there are very few examples of such erosion surveys in the tropics so far: Manyatsi and Sishwashwa (1991) in Swaziland, Herweg (1992) in Ethiopia, and Chaplot el al. (2005) in Laos. In the latter study, the authors found that the non-stationarity of linear erosion and landscape relations impeded the construction of a statistical model. Hence, he concluded that other environmental factors are involved, and that thresholds for rill erosion should be investigated.

In Pakha, 51 hydrological-isolated 'monitoring plots' (hence called 'plots') were selected from the available field parcels over 2 rainy seasons (Fig. 4). 'Field parcels' are defined as areas planted with the same crop, and with similar soil and crop management. The plots were 10 m wide and had variable slope lengths (10-50 m) and gradients (31-72%). Before the start of the rainy season, the 'stable' parameters were measured (soil depth, slope gradient, slope length, and soil fertility). During the rainy season, the 'dynamic' parameters of the monitoring plots were measured or assessed (farmer land management practices, erosion symptoms, aggregate stability, and soil cover). All the different components of soil cover were monitored separately during the erosion survey, but they were aggregated into 'total above-ground cover' and 'total contact cover' to facilitate the analysis of the relationship between soil cover and erosion features. Rainfall depth (mm/storm), duration (min/storm), and intensity (mm/h) were measured inside the catchment. Based on these observations, empirical relationships could be assessed between the chronological appearance and development of erosion symptoms on one hand, and rainfall, the effects of cultivation practices and physiographic conditions on the other hand. To gain insight into the complex and diverse data-set generated by this survey, the following analysis approach was used:

Accelerated erosion (AE) for a plot was defined by the appearance or expansion of rill channels. By combining rainfall with AE data, the exact timing of AE could be identified.

Based on the maximum development of erosion features, total soil loss by rill erosion was calculated. The contribution of interrill erosion to the total interrill + rill erosion was estimated to be in the range of 20 to 30%.

The effects of the stable parameters were evaluated by comparing them with the calculated total soil losses. This enabled to identify critical thresholds for steepland erosion.

The effects of the dynamic variables on erosion were evaluated by relating the occurrence of accelerated erosion (AE) to the corresponding value of the dynamic variable.

The combined effects of the stable and dynamic parameters were evaluated by means of an integrated matrix.

The understanding of these relationships led to the identification of the causes and critical thresholds for rill erosion on steepland. The on-farm methodology and data analysis procedures used in this research are fully described in Turkelboom (1999).

Gully erosion at catchment level

Gullies have been defined as recently developed drainage lines of ephemeral streams with steep-sided channel banks, and actively eroding head scarp, caused by erosion due to intermittent flow of water, usually during and immediately after heavy rains (Poesen et al, 2003). These channels are deep enough to interfere with normal tillage operations (Bradford and Priest, 1980; SSSA, 1987). Because 'normal' tillage conditions vary both in space and time, there are no widely agreed dimensions for distinguishing gullies from rills (Poesen et al, 1998). In this study, gullies were defined as concentrated flow channels which are incising through the plough layer and cut into the compacted non-tilled soil. This means that a gully is at least 15 cm deep. The (often reddish) sub-soil is surfacing, and the gully bottom has an irregular shape (caused by migrating knick points). The width/depth (w/d) dimensions were generally close to one. However, when gullies were able to develop over a long distance w/d became « 1, until the gully reached a stony horizon or the bedrock.

The Dze Donglo catchment was surveyed for gullies twice during the 1995 rainy season. The survey concentrated on areas that had no permanent soil cover. The areas under forest and fallow vegetation were not covered by the survey, as preliminary observations indicated that gully erosion did not occur at these land use types. Studies in South-East Asia indicated that forest and fallow vegetation have high saturated hydraulic conductivity rates and negligible runoff and erosion rates (review of Southern China studies by Hill and Peart, 1998; review of studies in South-East Asia by Sidle et al, 2006; Laos study by Valentin et al, 2006). The basic unit for observation was one or more field parcels with a common border (hence called 'fields'). A border is defined as a clear delineation that influences the hydrological flow, such as: ridges, fallow vegetation, border strips consisting of weeds, paths and border ditches. A total of 64 'fields' in Dze Donglo were identified and 59 of them were monitored. For each field, evidence of runoff inflow and runoff outflow was assessed. All gullies were mapped, and for each gully the different causes were identified. A distinction was made between the 'runoff generating factors' and the 'factors causing runoff concentration'. Contour concavity was expressed in degrees (˚); the concavity angle was measured on a topographic sheet by drawing lines perpendicular on the mid-slope contour line. The methodology used for this gully survey is described in Turkelboom (1999).

Survey of mass movement

Mass movement features were surveyed and measured during the 1994 rainy season. Causes of landslides were analysed and their dimensions were measured. The volume of the slides was calculated by using different geometric shapes described by Ohler (1995).

3. Results and analyses

3.1. Tillage erosion by hoe

In tropical wet forests, the long fallow period in traditional shifting cultivation systems acts as an effective weed-break (de Rouw, 1995). Consequently, there was formerly no need for tillage and weeding at Pakha, as the weed pressure in newly cleared field parcels was minimal. The switch from shifting cultivation to semi-permanent cropping systems increased weed infestation, which necessitated the gradual increase of soil tillage intensity. A typical indicator for tillage erosion is a tillage step at the top of a field parcel, characterized by a more compacted soil and a lower soil fertility status. At the time of the survey, farmers at Pakha used for upland rice and cabbage field parcels four land preparation operations before sowing and one soil-moving weeding operation after. For maize and soy bean, there were only two soil-disturbing cultivation practices before crop establishment.

For the slope gradient class between 3% and 70%, soil fluxes range between 16 to 67 kg/m contour/tillage pass. Soil loss rates (ton/ha) resulting from manual tillage can be calculated if the soil flux, the plot length, and tillage and weeding operations are known. For example: erosion rates in an average field parcel (slope gradient 30% - 60%, slope length 30 m - 50 m) range between 7 and 20 t/ha/tillage pass. The on-site effects of tillage erosion will be more pronounced, if the slope length of the field parcel is short, if it is planted to upland rice or cabbage, or when weed infestation is high. On slope gradients steeper than 70%, the soil loss rates are much higher due to dry ravel (Turkelboom et al, 1997 and 1999). Based on the soil flux formula for tillage erosion and description of tillage practices for different cropping systems (see Turkelboom et al, 1999), an accumulated 'soil loss' by tillage erosion of 386 ton/year was calculated for all cultivated fields for the 1995 land use situation at the Dze Donglo catchment (equivalent to an average 15 ton/ha cultivated land /year).

3.2. Rill erosion

The two year erosion survey at field plot level enabled to identify a number of soil erosion thresholds for tropical steeplands under semi-permanent cultivation (Table 2):

Least erosive rainy event: The minimal rain depth, which can potentially generate visually detectable rill erosion channels at Pakha, is 10 mm/day. When daily rain depth exceeds 20 mm, it is almost sure that new rill channels can be observed. The season of erosive rainfall (or critical period) runs from May to September, but the risk is higher during May 1-June 15, and July 20-September 10.

Thresholds for slope gradient and length: Rills could be observed in nearly every plot, even on the lowest slope gradients (31%) and in the plots with the shortest slope lengths. This means that the surveyed slope conditions were above the threshold for rill erosion. Therefore, it was investigated whether a threshold could be found for more severe types of erosion. "Plough layer erosion" (= complete displacement of plough layer by rill erosion and saturated soil flow) was observed in plots with slope gradients steeper than 47% and slope lengths longer than 25 m. A higher frequency was observed when the slope gradient was more than 57%.

The fallow effect: The residual effect of forest clearing on aggregate stability, which keeps erosion at low rates, is well documented (Kellman, 1969; Morgan, 1995; Chappell et al, 1999; Chapelot et al, 2005). During this study, a similar (though less-lasting) effect from degraded fallow clearings (dominated by bamboo, bushes, and grasses) was found: it was observed that rill erosion was much less severe in recently cleared plots compared to plots cleared several years ago. Laboratory and rainfall simulator experiments on meso- and macro-aggregates originated from different land use types showed that differences in aggregate stability can be explained by the high fine root content in the topsoil of recently cleared plots (Turkelboom, 1999). The presence of fine roots increase soil cohesion and the resistance of topsoils to concentrated flow erosion (Gyssels et al, 2005; De Baets et al, 2006). In older field parcels (> 1 year), fallow-originated roots gradually decompose and intrinsic soil properties become more important to explain the soil erodibility. On very steep slopes (70% and more) the angle of repose of soil aggregates is exceeded and consequently the 'fallow effect' is not effective as many of the stable clods roll down the slope.

Thresholds for soil cover: The analysis of the timing of accelerated erosion (AE) showed that rill erosion becomes negligible when 'total above-ground cover' is larger than 50% and 'total contact cover' is more than 30%. The duration of the erosion-prone period for each crop can be calculated by applying the cover thresholds to the cover evolution diagrams. The erosion-prone period for short-duration crops (maize, beans and cabbage) is about 40 days with a variation of ca. 10 days. Upland rice is prone to rill erosion for about 120 days, due to the late sowing, extensive land preparation and weeding, and slow growth of the canopy. Consequently, upland rice plots are relatively unprotected all along the first erosive peak of the rainy season. During the erosion-prone periods, weeds, crop residue, and rock fragments provide the major share of the total above-ground/contact cover, especially in plots planted to maize and beans. This implies that one cannot generalize the erosion risk for certain 'crops', but that rather 'cropping systems with their associated land management practices' have to be considered.

Thresholds for effectiveness of buffer strips: Field evaluation of buffer strips (with mulch and/or nitrogen fixing shrubs) indicated that the percentage of the gaps within the buffer strips determines their effectiveness for controlling rill erosion. When the gaps are more than 20% of the total buffer strip length, their effectiveness declines rapidly.

The integration of the above-mentioned thresholds led to a matrix which indicates the rill erosion risk for different field plot situations (Table 3). For each combination, the rill erosion risk percentage was calculated by dividing the number of field plot visits when accelerated erosion (AE) was observed by the total number of field plot visits made after a rainstorm. For example: if an erosive storm hits an old steep (>57%) plot with a long (>25 m) slope, while soil cover is less than the thresholds, there is a 50% chance that accelerated erosion will occur. Considering the decrease in fallow clearings and the reduced vigour of upland rice growth (due to soil fertility decline and possibly nematodes), it can be reasonably argued that rill erosion at the filed plot level in Pakha has strongly accelerated since the mid 1980's. Based on the observed median soil erosion rates for the different land use types and assuming that all the fields of the Dze Donglo catchment were hydrologically isolated, an accumulated 'soil loss' by interrill and rill erosion of 502 ton/year was calculated for the 1995 land use situation (equivalent to 20 ton/ha cultivated land/year).

3.3. Gully erosion and runoff and sediment connectivity

Gully erosion is quite common at the Dze Donglo catchment: nearly half of the observed fields experienced gully erosion (28 fields out of 59, Fig. 2). For the whole catchment, 2.3 km of gullies were measured, which represents an estimated soil loss of 423 ton/year at the catchment level (assuming an average gully depth of 30 cm, gully width of 50 cm and a bulk density of 1.2. kg/dm^3). Gullies were found at natural drainage lines (valley-bottom gullies) and at hillside slopes (valley-side gullies). Two major scenarios of gully development were identified:

Fields with a large in-situ runoff generation (11 fields): These are large and steep fields that can generate sufficient runoff by themselves to create gullies, regardless of runoff inflow. Their slope length varies between 60 and 148 m, their slope gradient between 43% and 70%, and their size between 0.4 to 1.7 ha. They are mostly planted to maize-based cropping systems (6 fields), while 3 fields were cropped with upland rice. All the fields had between 1 to 4 runoff concentrating features inside their area.

Fields with significant runoff inflow (or 'run-on') (18 fields): The fields of this category are smaller than the first category, but run-on is here the major cause of gully development. Field observations indicated that almost all fields with significant run-on also had gullies (Fig. 6.). In most of these fields, a runoff concentrating feature can also be found, although they are not essential.

'Run-on caused gullies' were more common than the 'in-situ caused gullies'. This is in agreement with the results of other erosion surveys (e.g. Speirs and Frost, 1985; Davidson and Harrison, 1995; Herweg, 1996). This observation raises the issue of runoff and sediment connectivity within the Dze Donglo catchment. To better understand this complex process, it is analysed in 4 interconnected sub-processes:

Upper catchment connectivity: In the upper reaches of the Dze Donglo catchment, footpaths are the most important modifiers of the natural hydrological pathways, because they can easily transfer runoff from one spot to another, and because they can generate runoff by themselves. The infiltration capacity of foot paths is assessed to be less than 10 mm/hour, leading to quick-response Hortonian overland flow. Despite their compacted surface, they still generate significant sediment (Ziegler et al, 2000). In the 1.68 km² study catchment, footpaths had a total length of 9.4 km (or 5.6 km footpath/km² catchment). Field observations made immediately after storms confirmed that runoff from one location can flow several hundreds meters down the slope via wide and gentle sloping footpaths and discharge at topographic low points (or discharge nodes) into lower (unprotected) fields (Fig. 5). Similar runoff pathways were observed in north-western Europe by Evans and Morgan (1974) and Watson and Evans (1991).

Run-on to fields: Due to the patchwork pattern of the fields, about 60% of the fields in the catchment are free from significant run-on (Fig 6). By far the most important landscape feature that provides protection against run-on is fallow vegetation, followed by agricultural infrastructure (such as terraces, diversion ditches, irrigation channels, and paths). As a consequence, little direct runoff flow from one field to another was observed (Fig. 7). For the other 40% of fields of the catchment, the most important sources of run-on are: footpaths, diversion ditches and cabbage furrows (Fig. 7). Foot paths are by far the most important cause of run-on, as they are often located above or in the middle of the fields.

Runoff concentration within fields: Contour concavity is an evident landscape property that leads to runoff concentration. The minimum contour concavity measured to generate a gully was 40°, but an increased risk was observed with increasing contour concavity. However, man-made linear features in the landscape were more important for gully development than contour concavity at the Dze Donglo catchment (Fig. 8). This is a consequence of the relative intense land-use in the steep catchment. The linear features responsible for gully concentration, in declining importance, are: diversion ditches (DD), sloping footpaths, and furrows.

Diversion ditches (Fig. 9) are a popular measure to control runoff discharge on the steep slopes of Pakha (average slope gradient of fields with DD's was 56%, S.D.= 8%). A total of 63 diversion ditches with a total length of 1.4 km were observed in the 25 ha of cultivated land (i.e. 5.6 km DD/km² cultivated land). Most DD's were found to be quite effective in draining excessive runoff out of the fields. Only when the ditch gets clogged by too much sediment (either from eroded soil clods or weeding deposits), runoff can break through the ditch wall and create a new gully at the clogged point. Farmers always try to make the diversion ditches in such a way that they will end in a stream, an existing gully, a forest, or a fallow. If the fallow vegetation is dense enough, runoff can be slowed down and sediment will be trapped. However, when a proper buffer or drain is lacking, a diversion ditch result in a relocation of a gully (or a number of rills) to a location where it cannot, or cause limited, harm to the crop.

Destination of runoff outflow (and its transported sediments): The following 3 scenarios were observed:

From 11% of the fields no significant outflow was observed. This mainly concerned terraced or relatively flat fields.

Outflow from about 57% of the fields in the catchment is retained, at least temporarily, in sediment traps (Fig. 10). This means that a large fraction of the sediment originating from rainfed fields is deposited inside the catchment. It may take years, or even decades before they can reach the hydrological network. The most important sediment traps in the catchment are dense and long fallow land (for 25% of the fields), terraces (19%), and lower fields (13%). Thanks to fallow land, sediment sink areas can be found along the steep valley slopes. This process was confirmed during soil profile descriptions, which showed that colluvial sedimentation took place on slopes up to 60%. This is not exceptional as Moeyersons (1990) described colluviation in grassland on slopes up to 78% in the Rwandan hills.

It was assessed that runoff outflow of about 33% of the fields was able to reach the temporary and/or permanent hydrological network directly. This connectivity is mostly made possible by gullies and diversion ditches crossing a strip of fallow vegetation or through lower fields. The determining factor whether runoff and sediments reach the hydrological network is not so much dependent on the intensity of runoff flow, nor on the elevation of the fields (many of the 'polluting fields', as they are scattered over different elevation zones). What is most critical to identify fields that are potential sediment sources causing downstream sedimentation and pollution, is the vertical distance and the type of vegetation between the bottom of an eroding field and the hydrological network. As many temporary streams are progressively cutting upstream (as a result of accelerated erosion and landsliding in the catchment), many fields higher-up in the catchment are getting connected to the hydrological network.

The runoff of half the settlement area and of all landslide areas is directly drained into streams and irrigation channels.

It can be concluded that gully development is closely related with the spatial design of large and/or compacted runoff-generating areas, runoff-concentrating features, and connective elements within the catchment. Discharge nodes from paths and DD's facilitate the connectivity of water and sediment to headwater streams (Sidle et al, 2006). Paths are relatively more important for upper catchment connectivity, while diversion ditches are more important for lower catchment connectivity. Considering the increased connectivity in the central part of the Dze Donglo catchment, it can be assumed that the number of gullies have significantly increased over the last decades.

3.4. Landslides

Sixteen landslides were recorded in the Dze Donglo catchment during the wet 1994 rainy season (2319 mm/year, return period = 5 years) (Table 4, Fig. 2). For the 168 ha catchment, a total of about 6310 m^3 of soil was removed by landslides. With an assumed soil bulk density is 1.2 g/cm^3, this represents a soil loss rate of 45.1 ton/ha/year at the catchment scale. Most of the landslides occurred in that year, although a few of them might be from the previous year(s). Three rainfall events of 1994 could be pinpointed for causing some of the landslides. They all occurred during the second half of the rainy season (from the end of July to the beginning of

September), when soils became thoroughly saturated by previous storms. The rainstorms preceding the landslides had a depth varying between 54 mm and 94 mm. Two of the three storms were very long (between 16 h to 24 h), while one storm lasted only 3 hours. These storms by themselves were not so exceptional, as their return period was less than 1 year. They were probably effective in generating landslides because they occurred at the end of a heavy rainfall period (i.e. significant rainfall occurred during the preceding 5 days). This is in agreement with a study conducted in Chengdu, Sichuan Province, South-western China showing that precipitations amounting to 50 - 100 mm per day are sufficient to initiate small-scale and shallow landslides, while landslide frequency increases when rainfall between 150 - 200 mm during 2 days is reached (Li, 1990). Other proposed thresholds for landslides are 50 mm/day (FAO, 1979) and 40 mm/event (Moeyersons, 1990).

Two different types of landslides were distinguished: 'translational debris slides' and 'debris flows' (based on the classification according to Selby, 1993, derived from Varnes, 1958):

Translational debris slides are the most common type of landslide occurring in Pakha (12 in total), and world-wide (according to Selby, 1993). As they took place on steep slopes with little soil stratum development (slide plane slope varied between 71% - 120%), the slides were invariably very shallow (< 0.5 m). Due to their shallow nature, the volume of transported soil is modest (50 to 300 m^3 soil/slide, Table 4). The combination of hollows, oversteepened slopes and fallow vegetation seemed to have caused these landslides:

Fallow vegetation has a shallow rooting and hence a limited anchorage capacity to the bedrock, in contrast to a mature forest (Sidle et al, 2006).

The hollows (together with the fallow vegetation which enhances infiltration) led to a convergence of subsurface storm flow, and consequently to a higher, temporary ground water levels compared to surrounding areas. Rainstorms with sufficient intensity or duration are able to raise the water table to near the soil surface. Only when the capacity of the soil to drain is exceeded long enough for pore water pressures to rise substantially, can the soil lose sufficient strength and fail (Selby, 1993).

Removing the toe support in oversteepened slopes by path cut-out or incising streams can weaken the shear resistance.

Most of the sediments from the landslides were removed by the streams or by intermittent water erosion processes.

Debris flows were less common (only 4 cases), but the volume of displaced soil was much higher (Table 4). As they occurred on more gentle colluvial slopes, where soil is deeper (3 - 9 m), larger soil volumes were affected. All of them were a result of human-induced soil saturation, i.e. flooding of paddy wetland or water flow in an old irrigation channel. Wetland terraces at Pakha have a relatively high percolation rate (average 16 mm/day), due to their young age and limited puddling practices (Dessein, 1994). Consequently, the saturation of the soil profile leads to extra loading and the build up of positive pore water pressure (Carson, 1985; Wu and Thornes, 1995). In addition, the affected paddies were bordering V-shaped stream cuts resulting in active seepage. All these factors resulted simultaneously in the reduction of shear strength of the terraces and finally triggered a debris flow. To avoid further collapse, farmers did not use the nearby terraces for paddy cultivation. The majority of the sediment was taken away by seepage and runoff water.

In summary, the major causes of landslides at the Dze Donglo catchment are undercutting of slopes, zero-order hollows with secondary vegetation, and soil saturation by wetland paddies. It is interesting to note that no landslides occurred in rainfed fields. This can partly be explained by the field selection by farmers preferring gently sloping fields, but also by the high runoff coefficient of rainfed fields. High runoff means less infiltration, and thus less chance for pore water pressure to build up and therefore a lower risk for landslides.

The return period for the 1994 landslides is not known. However, considering 1) the low return period of the responsible rainstorms, 2) the concave, irregular shapes at the catchment (which indicates the occurrence of past landslides), 3) the drainage network (which has extended significantly upslope by successive landslips), 4) the large area of fallow land and the gradual decay of roots of cut trees, 5) the re-routing of runoff water by footpaths, DD's and irrigation channels, and 6) the expansion of paddy land, it can be reasonably assumed that landslides are a recurrent and increasing phenomenon in this environment.

4. Discussion: Integrated analysis of land degradation at Dze Donglo catchment

It could be questioned whether the observed erosion and mass movement phenomena are a result of natural denudation processes? In such an erosive and steep environment, natural processes are certainly at work. However, when such areas are faced with active expansion of gullies, frequent occurrence of landslides and regressive channel head development, then these are clear indicators of a changing environment, such as deforestation or land use change (Oostwoud Wijdenes and Bryan, 1991; Selby, 1993). As the above soil erosion processes all occur at the Dze Donglo catchment, it can be reasonably argued that the recent land-use changes at Pakha are the driving force of the on-going land degradation.

In the next sections, land degradation at Dze Donglo catchment will be discussed in an integrated way: quantitative comparison between the different land degradation processes, interactions between land degradation processes, land degradation hotspots in tropical steeplands, and farmers' perceptions about land degradation.

4.1. Quantitative comparison of different land degradation processes

The rates of the different soil erosion processes at Dze Donglo catchment are compared in Table 5. Assuming that the 1994 landslides have a return period of 10 years, the rate of soil losses is very close for the 4 studied soil erosion processes. However, this comparison should be handled with caution for the following reasons:

Variability: There is a huge range of observed erosion rates at the plot level. For example: for inter-rill + rill erosion from 2 to 350 ton/ha/year, and for tillage erosion from 4 to 130 ton/ha/year (and up to 300 ton/ha/year in case of dry ravel), depending on slope gradient, slope length, cropping system and field parcel history.

Spatial scales: Inter-rill, rill, and tillage erosion have clear impacts at the field parcel level, but a large portion of this type of soil erosion is deposited at the bottom of the field parcel or at downslope buffer areas. This is in contrast to soil losses from landslides or from many of the gullies, which generate both a loss at the field level and at the catchment level.

Temporal scales: Where tillage, rill, and gully erosion are seasonally recurring phenomena, the return period of different type of landslides in this steepland environment is not known yet.

Other land degradation processes: For obtaining a complete figure of soil losses in the catchment, other non-measured land degradation processes should be considered as well, such as terrace wall retreating, stream bank and stream bottom erosion.

Nevertheless, the major message from this table is that if one want to understand land degradation at the catchment level, it is essential to look at all the different soil erosion processes at the same time. Looking at only one erosion process in isolation will give a very biased picture.

4.2. Interaction between different land degradation processes

An obvious interaction between soil erosion processes is the contribution from rill erosion to gully erosion. However, there are a few other less obvious interactions.

Tillage erosion and water erosion

Tillage erosion and water erosion are quite different processes: Water erosion removes soil mainly from the lower part of a field parcel, whereas tillage erosion primarily denudes the top and the convex part of a field parcel. In addition, slope length has an opposite impact on both processes: while water erosion is positively correlated with plot length, tillage erosion is negatively correlated with it (Turkelboom et al, 1997). However, tillage and water erosion do not act independently. The impact of tillage on soil erodibility during water erosion is well established

(Govers et al, 1994; Poesen et al, 2003). During fieldwork at Pakha additional interactions were observed.

The tillage step with low soil fertility at the top of a field parcel can become several meters long, especially on steep slopes (Turkelboom et al, 1997). This compacted area can result in a faster generation of Hortonian overland flow (HOF) compared to the rest of the field parcel. Consequently, it was often observed that (pre)-rills were initiated from the tillage step during intensive storms.

Manual tillage results in a distinct discontinuity of cohesion in the topsoil. This differentiation was quantified by means of a torvane device during the erosion survey. Cohesion of a cultivated topsoil fluctuated on average between 25 and 75 kP (at field soil moisture), due to regular disturbances and the impact of rainfall and runoff. The plough border (= limit between the tilled soil layer and the non-tilled sub-soil) has a much higher cohesion (average: 100 kP, range: 40-150 kP, at field soil moisture). This discontinuity in cohesion has an important impact on rill cross-section development and hydrological responses. Consequently, the depth of rills is strongly determined by the tillage depth.

Tillage can result in an accumulation of loose soil at the bottom of the field parcel (i.e. soil banks) which can be an important delivery source of easily erodible sediment, especially when the field parcel is close to the fluvial network (Govers et al, 1994).

Gullies and landslides

The linkage between water erosion and landslides in steeplands is important and indicates a positive feedback mechanism that is working as follows: Rapid runoff response from open, compacted areas and overflowing irrigation facilities result in peak flows in the streams, and consequently in accelerated stream incision in two directions:

Vertical stream incision causes over-steepened slopes along the streams, which can cause translational debris slides in fallow land and debris flow of paddies. A dramatic example of the latter is the massive landslide in paddy fields along the eastern stream (Fig. 3). A slide resulted in the loss of about 1000 m^2 of paddy land and 4800 m^3 of soil (or 65% of the total soil volume displaced by landslides during 1994). About half of the runoff from the 2.4 ha residential area drains into the eastern stream, and is assumed to have caused vertical incision of this stream. The coincidence of steep riverbank slopes with an adjacent large water saturated paddy area made this area a potential hotspot for landsliding.

As a result of increased gullying and sliding, the hydrological network is extending uphill (e.g. 2 landslides close to the most western paddy field of the catchment). The expansion of the drainage network into the upper reaches of the catchment generates steeper slopes along the channel, results in a higher erosion risk, and increases the probability for runoff and sediments to reach the hydrological network.

4.3. Land degradation hotspots at tropical steeplands

Based on the observations made during the tillage study, the plot erosion survey, and the catchment survey, 'potential land degradation hotspots' within the catchment can be identified (Table 6). It is important to make a distinction between two different types of critical areas. The first type refers to the risk of in-situ soil (and hence productivity) loss in cropped fields. This risk is mostly related to the slope characteristics and the location of the field. Intensively used areas are especially at risk. Other risk factors relate to the age of the field and the speed of soil cover development.

The second type of risk is related to sediment delivery to streams. Potential sediment sources are determined by the distance to the hydrological network. Elevation is by no means a good proxy in this respect, as many streams retreat upstream due to accelerated erosion. The only alternative to indicate these 'hot spots' is by a detailed analysis of the temporary and permanent hydrological network and of its surrounding buffer zones.

4.4. Farmer perceptions of land degradation

Some farmers were very knowledgeable about the impacts of soil erosion and the related erosion processes. These farmers considered rainfall combined with frequent tillage to be the main factors causing increased erosion. Other erosion-contributing factors they mentioned were: slope gradient, slope shape (concave versus convex), slope length, soil type, cultivation of higher-up fields, presence of roads and channels, cultivation period and weed infestation. Farmers could also rank crops and vegetation according to their susceptibility to erosion: upland rice is considered the most susceptible followed by maize, beans, fruit orchards, and forest. This ranking coincides well with the research findings at the plot, field and catchment levels (see Table 2, 3 and 6; Fig. 7 and 8). The recurrence of landslides is reflected in the mythological stories told by the local villagers. According to a story told by the elders, slides are caused by a giant, underground snake or pig-like monster (Pjengcha), which creates environmental and political havoc every 13 years. This could indicate a cyclical nature of landslides. However, farmers agree that there are more landslides than in the past because. One farmer said: "The land is becoming like old people, they are not strong enough to hold anything anymore". Such a statement indicates an increased vulnerability to landslides.

5. Conclusions

Land-use intensification at Pakha led to the reduction of fallow land, enlarged area under rainfed agriculture, increased tillage operations, and the expansion of paths and irrigation infrastructure. The earlier natural hydrological equilibrium at the Dze Donglo catchment became severely disturbed during this transition, and led to a lot extra potentially erosive Horton overland flow (HOF), irrigation water, and changes in the subsurface flows. This caused landscape instability and the acceleration of different land degradation processes:

Tillage was a response to increased weed infestation, but led to degradation of soil aggregate stability, soil fertility decline, and tillage erosion. Tillage erosion is dominating in short field parcels (<20 m) and on very steep slopes (> 70%).

In hydrologically isolated field parcels, the risk for rill erosion is determined by soil cover, steepness and length of the field parcel, and the effect of the preceding fallow vegetation on macro-aggregate stability (the 'fallow clearing effect'). Especially, upland rice and cabbage field parcels are prone to rill erosion.

The major sources of HOF are rainfed fields, paths and the settlement area. This excess runoff, produced in localised areas, combined with connective pathways and runoff concentrating factors generates rill and gully erosion on its way to the hydrological network. Gullies can be generated either in-situ in the fields or, more importantly, initiated by run-on. Connectivity in the catchment is strengthened by a network of paths, diversion ditches, adjoining fields, rills and gullies. On the other hand, there are many sediment sinks in the catchment, which inhibits hydrological connectivity.

Changes in sub-surface flow in steep fallow hollows have increased the risk of shallow lateral landslides. Wetland cultivation can function as a protective sink, but can also result in an increased risk for landslides, especially along oversteepened stream cuts.

This research demonstrates that a holistic assessment of land degradation at the catchment level is essential to better understand the various processes at work. At this stage of mountain land-use, the effect of land-use factors (e.g. paths, DD's, terraces, land-use patchiness) on erosion and mass transport overshadows the effects of topography. Similar conclusions were obtained by other studies in tropical areas (Whitlow, 1988; Strömquist, 1992; Valentin et al, 2006). This has important implications for erosion monitoring and modelling at the catchment scale, and for planning soil conservation and catchment management.

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Tables

Table 1. Frequency of soil conservation measures at the Dze Donglo catchment (Pakha, Chiang Rai Province, northern Thailand, 1995).

Soil conservation measure	No. of fields	%
Mulch strips	8	13
Cultivated mulch strips	2	3
Buffer strips with Leucaena (alley cropping)	4	6
Diversion ditches	17	27
Terraces	8	13
Combination of previous measures	8	13
No measures	17	27
Total	64	100

Table 2. Thresholds for rill erosion on steeplands, based on erosion survey at field plot level during 1994 and 1995 (Pakha, Chiang Rai Province, northern Thailand).

Erosion controlling -		**Threshold**	**Detection of**
- factor	**- parameter**		
Rainfall	Period	May 1 - June 15	Increased erosivity risk
		July 21 - Sept. 10	
	Storm depth	> 10 mm	Accelerated erosion (AE)
	Storm duration	≥ 37 min	"
	$I_{30\ max}$	≥ 15 mm/h	"
	EI_{30} erosivity	≥ 53 MJ·mm/ha·h	"
	Peak storms	5 –15 storms/crop cycle	± 80% of the total erosion
Slope	Gradient & length	≥ 47% + ≥ 25 m	Plough layer erosion
Age of field	Years after clearing	> 1 year	Increased rill erosion risk
Cover	Total cover	< 50%	Period prone to rill erosion
	Total contact cover	< 30%	"
Cropping system	Upland rice	121 ± 28 das*	Period prone to rill erosion
	Maize	44 ± 13 das	"
	Beans	38 ± 9 das	"
	Cabbage	38 ± 6 das	"
Buffer strips	Gaps in buffer strip	> 20% gaps/total length	Increased rill erosion risk

* das = days after sowing (or planting in case of cabbage).

Table 3. Soil erosion risk (in %) for different combinations of field plot characteristics (based on erosion survey at plot level at Pakha, 1994 and 1995).

		Slope characteristics			
		< 57%		**≥ 57%**	
Soil cover	**Field plot history**	**< 25 m**	**≥ 25 m**	**< 25 m**	**≥ 25 m**
< critical cover	**New clearing**	12 %	7 %	25 %	50 %
	Cleared more than 1 year ago	29 %	29 %	33 %	51 %

x % For each field plot combination, the erosion risk is calculated as follows:

$$\% = \frac{No.\ of\ \ field\ \ plot\ visits\ \ when\ \ accelerated\ erosion\,(AE)\ \ was\ \ observed}{Total\ No.\ of\ field\ plot\ \ visits\ after\ rainstorm} \times 100$$

x % = High erosion risk

x % = Medium erosion risk

x % = Low erosion risk

Table 4. Overview of landslides measured at the Dze Donglo catchment during 1994 (Pakha, Chiang Rai Province, northern Thailand).

Mass movement typology [1]	Dominant cause(s)	Surrounding vegetation	Parent material	N	Slope slide plane (%)	Depth (m)	Le v
Translational debris slide	River incision	Bamboo & secondary vegetation	Phyllite (7) Granite (3)	10	84-120	0.3-0.4	0.
Translational debris slide	Fallow vegetation Plan concavity Steepness Path	Bamboo & secondary vegetation	Granite	2	71-88	0.5	1.
Debris flow (rotational)	Soil saturation of wetland	Paddy wetland	Phyllite	3	26-44	3.2-8.5	0.
Debris flow	Old irrigation channel	Seasonal fallow	Phyllite	1	10	2.2	
Total				16			

[1] Classification according to Selby (1993, derived from Varnes, 1958).

[2] 6 smaller slides could not be measured due to inaccessibility. Their volume was estimated at 50 m^3 each.

Table 5. Quantitative comparison of land degradation processes at Dze Donglo catchment based on observations during 1994 and 1995 (Pakha village, Chiang Rai Province, northern Thailand).

Land degradation process	Accumulated 'soil loss' for the Dze Donglo catchment (= 168 ha) (ton/year)	Average 'soil loss' rate for the total cultivated land (= 25 ha) (ton/ha/year)	Average 'soil loss' rate for the whole catchment area (= 168 ha) (ton/ha/year)
Tillage erosion	386	15	2.3
Rill erosion	502	20	3.0
Gully erosion	423	17	2.5
Landslides (1994*)	7572	252	45.1
Total	8883	304	52.9

*: Return period for the 1994 landslides is unknown.

Table 6. Overview of high risk areas for different erosion processes at the catchment level (based on field research at Pakha).

Type 1: Sites at risk for in-situ soil loss

By tillage erosion

- Upper part of short fields (slope length < 25 m).
- Very steep (slope gradient > 70%) or convex fields.
- Cropping systems requiring several tillage and weeding operations (e.g. upland rice and cabbage).

By rill erosion

- Very steep and long fields (slope gradient > 57% and slope length > 25 m).
- Fields used for more than 1 year after fallow clearing.
- Fields with crops that have a slow vegetation cover development (especially upland rice).

By gully erosion

- Large, steep fields with a runoff concentration agent (e.g. path, diversion ditch, plan concavity).
- Fields with run-on inflow at the top. This situation is typical of areas with a high land-use intensity.
- Fields under artificial water concentration (e.g. paddy, irrigation channel, ponds).

By landsliding

- Paddy terraces located immediately above incised stream banks or above hollows.

Type 2: Risky sites for sediment delivery to the river network

By gully / stream erosion

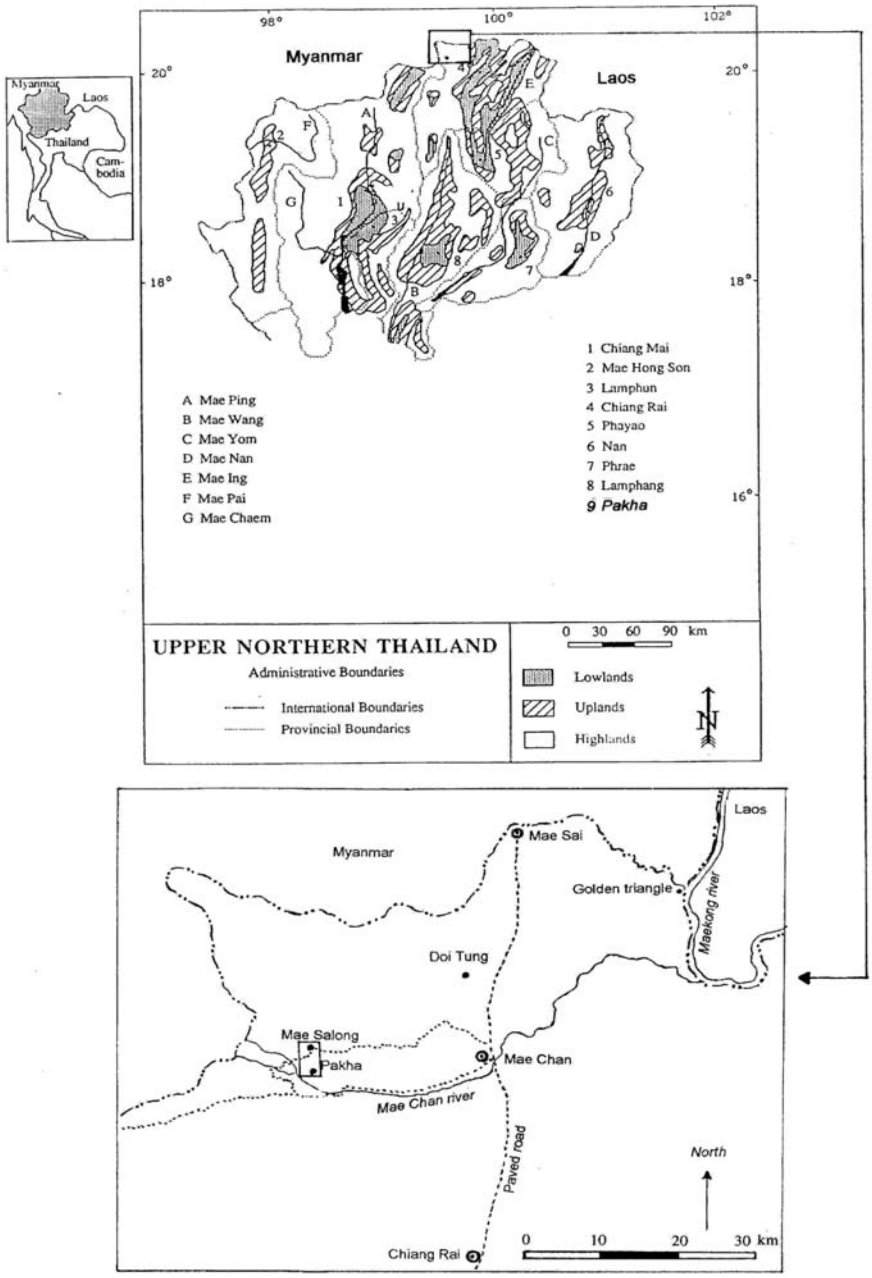
- Fields connected by diversion ditches and gullies to the hydrological network.
- Residential area and footpaths, if they are interconnected to the hydrological network.
- Streambeds which did not yet reach equilibrium (e.g. steep stream banks, absence of stone cover on river bed).

By landsliding

- Paddy terraces located immediately above incised stream banks or above hollows.
- Steep land (>70%) with plan concavity and secondary vegetation (e.g. bamboo).
- Oversteepened slopes along streams.

Figure captions

Figure 1. Map of Northern Thailand indicating the study site.
Figure 2. Topographic map of the 168 ha Dze Donglo catchment during the 1995 rainy season with indication of land-use, gullies and landslides (Pakha village, Chiang Rai Province, northern Thailand).
Figure 3. Land use of Dze Donglo catchment showing the patchwork of field parcels and a large rotational debris flow in the terraced area (Pakha village, Chiang Rai Province, northern Thailand).
Figure 4. Rill erosion at one of the monitoring plots used during the plot level erosion survey (Pakha village, Chiang Rai Province, northern Thailand).
Figure 5. Compacted foot paths resulting in a high response runoff and sediment generation (Pakha village, Chiang Rai Province, northern Thailand).
Figure 6. Relationship between significant runoff inflow (run-on) and gully development at field level in the Dze Donglo catchment during the 1995 rainy season (Pakha village, Chiang Rai Province, northern Thailand).
Figure 7. Impact of land use above agricultural fields on either hydrological isolation or runoff inflow at fields in the Dze Donglo catchment during the 1995 rainy season (Pakha village, Chiang Rai Province, northern Thailand).
Figure 8. Frequency of runoff concentrating features leading to gully development in the Dze Donglo catchment during the 1995 rainy season (Pakha village, Chiang Rai Province, northern Thailand).
Figure 9. Diversion ditches are dug at steep field parcels to protect them from runoff inflow (Pakha village, Chiang Rai Province, northern Thailand).
Figure 10. A sediment trap at the bottom of an upland rice field (Pakha village, Chiang Rai Province, northern Thailand).



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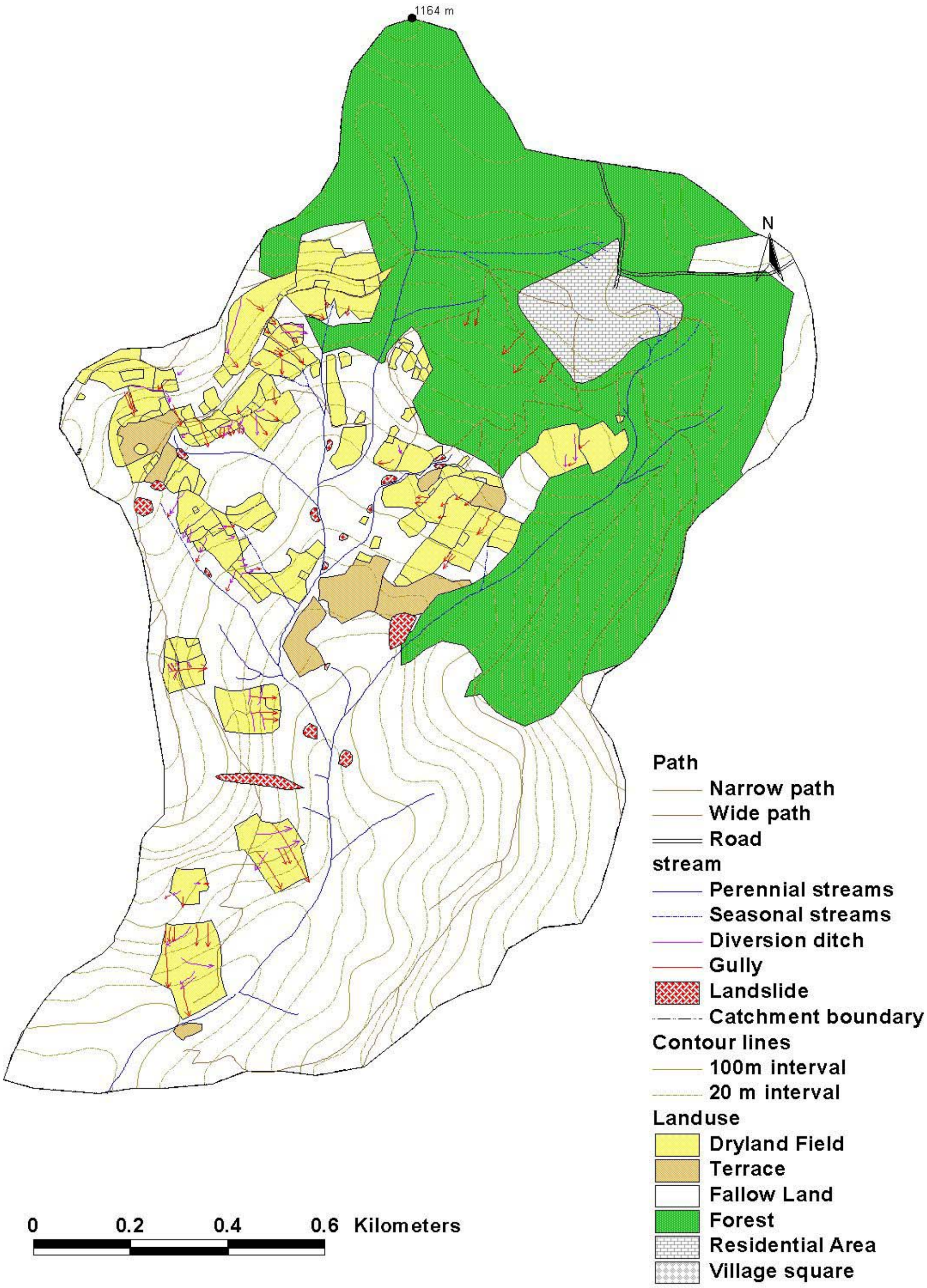

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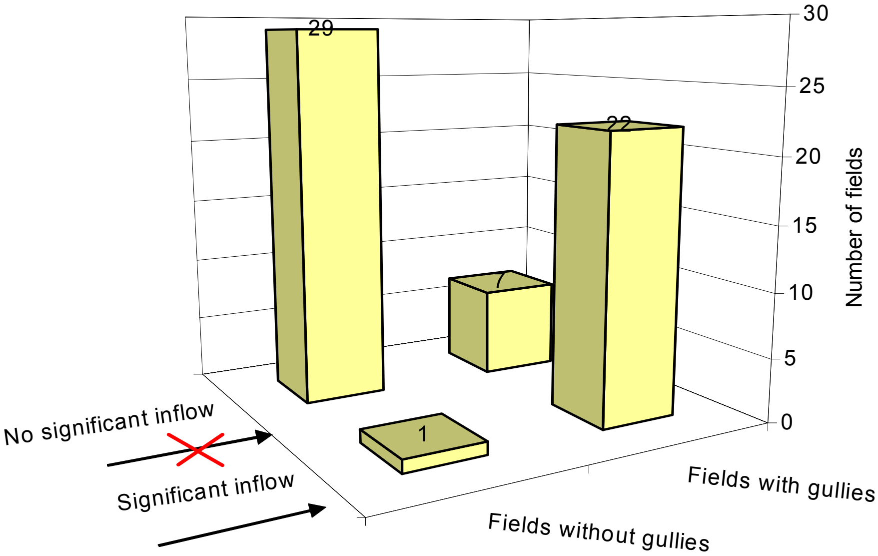

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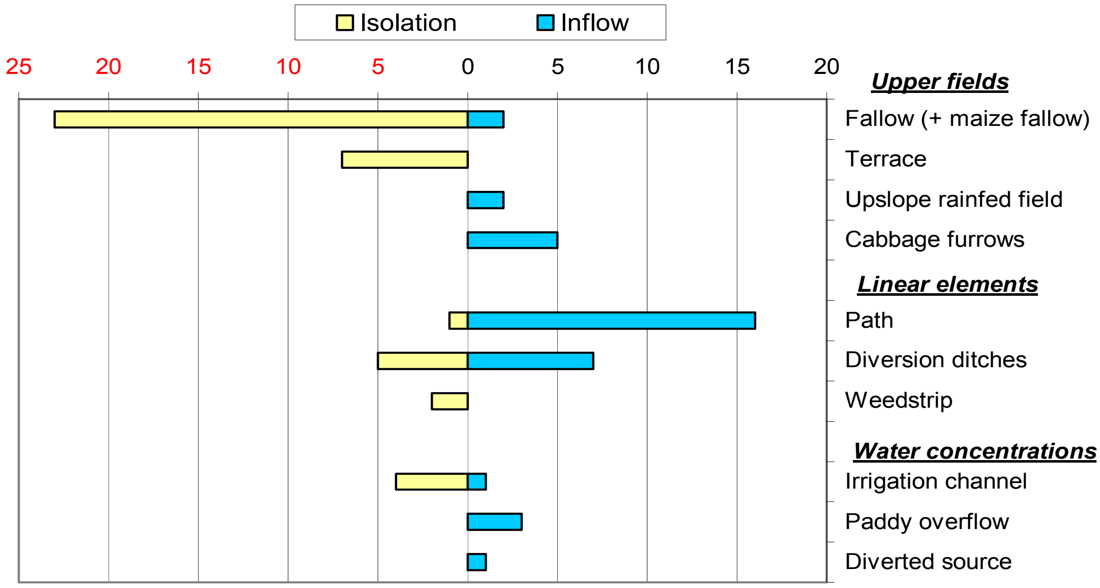
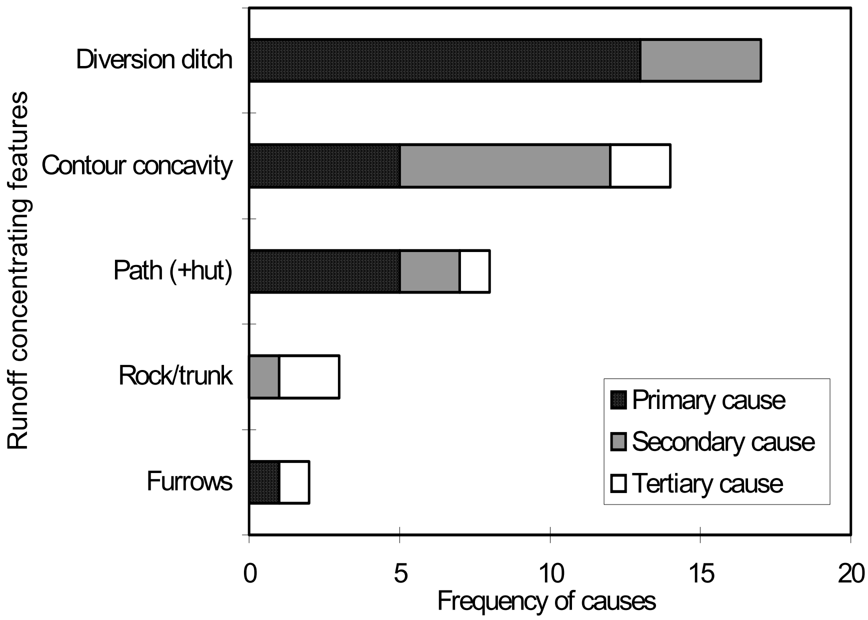


Figure 7. Impact of land use above agricultural fields on either hydrological isolation or runoff inflow at fields in the Dze Donglo catchment during the 1995 rainy season (Pakha village, Chiang Rai Province, northern Thailand).



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