Erosion and Nutrient Loss on Sloping Land under Intense Cultivation in Southern Vietnam

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Abstract
To help improve the well-being of the local people, a joint Vietnamese-UK team set out to establish a way of estimating soil and nutrient losses under different land management scenarios, using field data extrapolated through remote sensing and GIS, to obtain catchment-wide estimates of the impact of land cover change. Immigration from remote provinces to the Dong Phu District of Binh Phuóc Province, about 120 km north of Ho Chi Minh City, has led to disruption of soil surface stability on easily eroded clayey sandstones, creating rapid nutrient depletion that affects crop yields and siltation in the channel of the Rach Rat river downstream. The poor farmers of the areas see crop yields drop dramatically after two or three years of cultivation due to the fertility decline. Soil loss varies dramatically between wet season and dry season and with ground cover. Erosion bridge measurements showed a mean loss of 85.2 t ha^{-1} y^{-1} under cassava saplings with cashew nuts, 43.3 t ha^{-1} y^{-1} on uncultivated land and 41.7 t ha^{-1} y^{-1} under mature cassava. The rates of erosion were higher than those reported in many other parts of Vietnam, reflecting the high erodibility of the friable sandy soils on the steep side-slopes of the Rach Rat catchment. However, although the actual measurements provide better soil loss data than estimates based on the parameters of soil loss equations, a large number of measurement sites is needed to provide adequate coverage of the crop and slope combinations in this dissected terrain for good prediction using GIS and remote sensing.

KEY WORDS *catchment; soil erosion; erosion bridge; GIS; remote sensing; ground cover*

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ACRONYMS

DEM	digital elevation model
DSS	Decision Support Systems
ETM	Enhanced Thematic Mapper
GIS	Geographic Information System
GPS	Global Positioning System
ILWIS	Integrated Land and Water Information System
MUSLE	Modified Universal Soil Loss Equation
MSEC	Management of Soil Erosion Consortium
NDVI	Normalised Difference Vegetation Index
PCARES	Predicting Catchment Runoff and Soil Erosion model
RUSLE	Revised Universal Soil Loss Equation
SLM	sustainable land management
SPOT	Système Pour l'Observation de la Terre
SWAT	Soil and Water Assessment Tool

Introduction

War and changing economic circumstances have produced much internal migration of traditional cultivators within Vietnam. Major changes in land cover and land use occurred in many upland areas after 1975. Much forest that was damaged in the war was further degraded when people had to find food and land for crops in the 1970s and 1980s (Phuong, 2000). Many migrants moving into the uplands had no choice but to settle on land that previous farmers had not used for agriculture because it was of low fertility and was not easy to cultivate. When such land was cleared it often became subject to severe erosion and rapid declines in fertility.

One such area lies approximately 120 km north of Ho Chi Minh City, in the vicinity of the Dông Tãm and Tãm Phuóc settlements in the Dong Phu District of Binh Phuóc Province. Here the surface of a basalt plateau has long supported successful agriculture, but the dissected slopes of the plateau edges, where the easily eroded, clayey sandstones that lie beneath the basalt are exposed, are much less fertile and are readily eroded when their plant cover is removed. People of differing ethnic backgrounds and cultural traditions are using these fragile soils with increasing intensity. A partnership between the Sub-Institute of Geography in Ho Chi Minh City, the Environmental Department of Bien Phuóc Province, the British Council and the University of Manchester developed a low-cost initiative to:

1. estimate soil and nutrient losses under different land management scenarios;
2. produce land cover maps from remotely sensed images, in order to analyse land cover change over time;
3. link the field erosion measurements to the terrain cover maps to produce erosion estimates for the whole catchment;
4. build capacity within the Sub-Institute of Geography by training young Vietnamese scientists in these methods, and
5. apply these methods to manage steep soils, increase agricultural productivity and improve the well-being of the local people.

Erosion estimates in the tropics are becoming increasingly available as more plot and small catchment experiments are carried out (Douglas, 2006), but there are few reliable prediction procedures. Many agencies still rely on using the Revised Universal Soil Loss Equation (RUSLE), which is widely regarded as a standardised soil erosion prediction equation that can be used for many land use situations. However, in many situations, the RUSLE may not deal adequately with the distribution and connectivity of bare soil interspaces and vegetation patches which can be much more important in determining soil loss than the absolute amount of bare soil (Weltz *et al.*, 1998). This is particularly likely to be the case under the high rainfall intensities during many tropical rainstorms.

In this study, the aim was to obtain good measures of erosion under a variety of land uses to understand the impacts of cropping practices and to be able to recommend improvements in sloping land cultivation to the provincial authorities. Organic matter, nitrogen and phosphorous losses were also assessed to examine which crop combinations had the lowest losses, in order to recommend more sustainable agricultural practices. It was also hoped that these erosion measurements could be used as ground truth data in a GIS to

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extrapolate these values, according to land use and slope categories, to the whole catchment. This would ultimately facilitate an erosion risk mapping system which would help the provincial environment department improve its rural land use management.

The study area

The Rach Rat catchment, which drains the study area (Figure 1), is formed by a series of streams that dissect the basaltic plateau in the northern part of the Sai Gon River basin. Locally the terrain consists of short slopes of up to 35° descending from the plateau to the narrow floodplains along 3rd and 4th order streams. Steep, ephemeral, zero-order streams cut back into the convex slopes, often exposing the clayey sandstones and their readily erodible soils.

Four groups of soils occur in the study area:

1. fertile ferralsols, which occur on the basalt plateau;
2. ferralsols over schist on valley side slopes of over 15° slope, which are stony, thin, low in organic matter and have lateritic horizons;
3. localised areas of black andosols, which have developed on tuff and volcanic ash, and
4. fluvisols, which are found on the alluvial floodplains (soil data from authors' field work).

The climate is markedly seasonal, with a wet season dependent on the south-monsoon from April/May to September and then on the occasional passage of typhoons from the South China Sea until December. Mean annual rainfall is 2044 mm but totals vary considerably from year to year. Humidity ranges from around 64% in

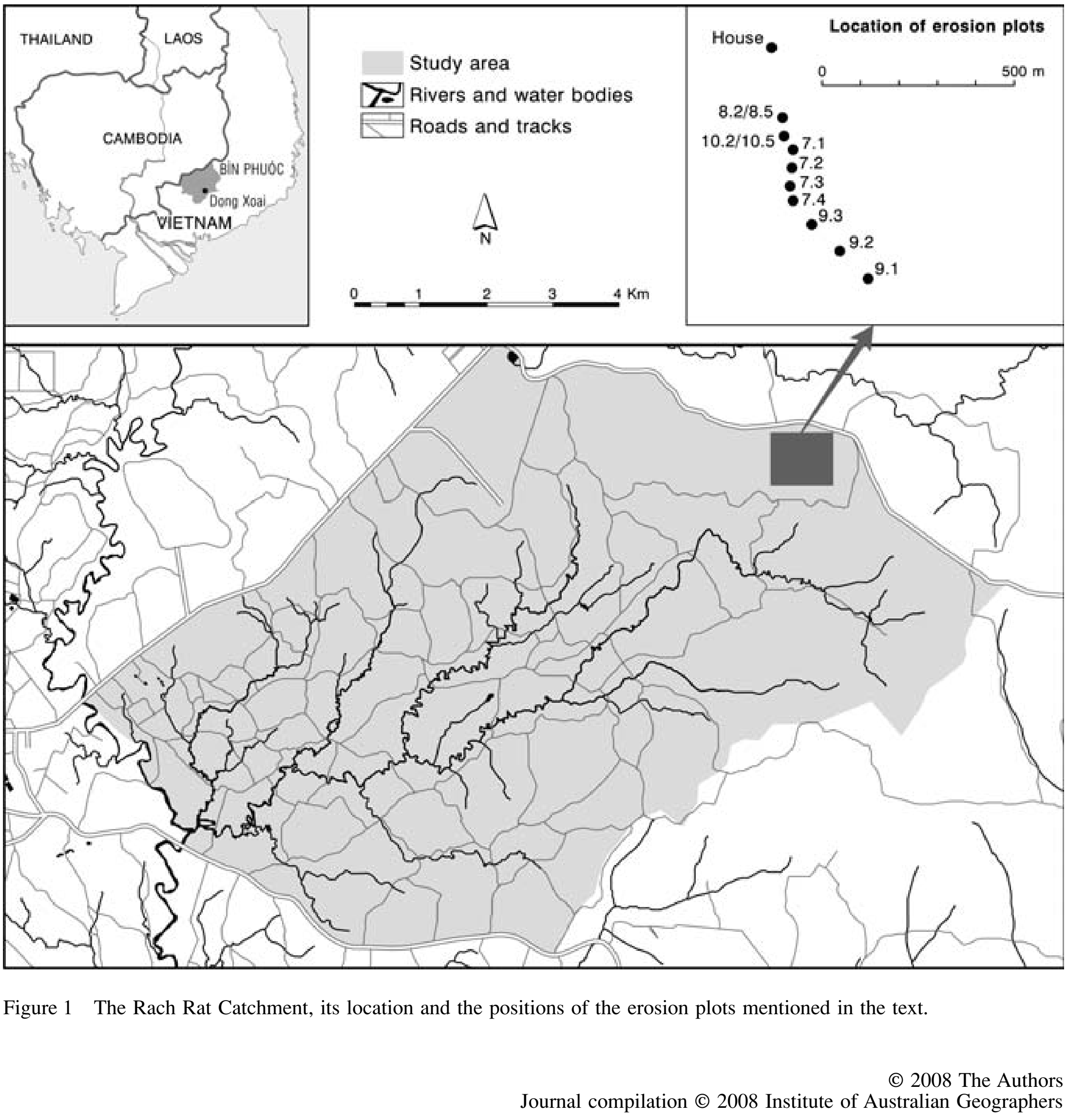

Figure 1 The Rach Rat Catchment, its location and the positions of the erosion plots mentioned in the text.

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the dry months to 80% in the wet season, with mean daily minimum temperatures of 23°C and maximum temperatures of 32°C (data from General Statistics Office of Vietnam: http://www.gso.gov.vn).

Small-scale logging and agriculture depleted the original tropical monsoon forest natural cover, up to 1986. Since then, large-scale clearance for agriculture has marked the start of the transition from a command to a capital economy, known as *Doi moi*, which permitted settlers to claim land by clearing for small-scale agriculture (Hardy, 2000; Kerkvliet, 2006). Burned tree stumps are now all that remain of the original forest, with strips of bamboo forest along steep, uncultivable valley sides.

Perennial tree crops such as cashew, coffee, banana and longan are grown on the plateau in 4–5 ha plots, alongside larger and much longer-established rubber plantations. Annual crops are grown during the wet season, with land left fallow in the dry season. Two crops of maize are sown in May and September and harvested in August and December. Maize is also grown below young cashew trees up to canopy closure at four years old. Cassava is planted at the start of the wet season in May and harvested in December. The whole plant is pulled up to harvest the root, so the soil surface is significantly disturbed and the soil erosion potential increased. Cassava monoculture is favoured by farmers, but cultivating cassava results in much more erosion than most other crops because the plants are widely spaced and grow slowly for the first 3–4 months after planting (Howeler, 2002). On the floodplains, wet paddy rice is planted during the wet season and harvested in the dry season. This seasonality of crop cover affects both soil exposure and the reflectance on satellite images

Previous work on erosion in Vietnam

A wide range of work on erosion has been undertaken in Vietnam, particularly in parts of the highlands affected by timber harvesting, shifting cultivation and forest clearance (for reviews see Douglas, 2006; Sidle *et al.*, 2006; and Vezina *et al.*, 2006). Examining the information on the impacts of crop cultivation in sloping terrain relevant to the current study, the national State of the Environment Report cites characteristic soil loss figures of 0.05 t ha^{-1} y^{-1} for a permanent coffee plantation with ground cover of 90–96% in the wet season, and 2.4 t ha^{-1} y^{-1} for a grass cover of 70–80%. Fallow land with a 10–15% ground cover lost 223 t ha^{-1} y^{-1}. Under a year-old coffee plantation, inter-cropped with shade trees, the soil loss was 44–59 t ha^{-1} y^{-1}, while land with extensive annual crop cultivation has a soil loss as high as 250–300 t ha^{-1} y^{-1} (Environmental Database Division, 2002).

Since 1970, several plot and catchment studies in Vietnam have specifically examined soil loss under the types of crop found in the Rach Rat catchment, particularly cassava, a common crop in areas recently opened up by migrants, and ground nut (Table 1). Such studies may be comparable with the measurements made in this study. Cassava provides only 47% to 56% ground cover at its peak growth, and thus tends to have higher soil losses than tree crops that provide more complete and continuous soil protection. Mixed cropping or intercropping can increase this protection (Toan *et al.*, 2001). Elsewhere, the exposure of soil after harvest emerged as a critical factor affecting soil loss, with the percentage of the total catchment area cultivated with annual crops as the best predictor of sediment yield (Maglinao *et al.*, 2002). Nevertheless, most soil erosion is likely to occur in the wet season when the most erosive rains occur. For example, soil loss from a plot under groundnuts at Pleiku in Tay Nguyen (the Central Highlands) totalled 89.2 t ha^{-1} y^{-1} in 1980, but in June alone the loss rate was 42 t ha^{-1} y^{-1}, with another 36.1 t ha^{-1} y^{-1} being lost in August (Douglas, 1997).

In Binh Phuóc Province, at Dong Tam Village in Dong Xoai District, studies of farmers' preferences showed highest cassava yields under cassava monoculture (30.23 t ha^{-1} y^{-1}), but only slightly less under a peanut intercropping combination (30.22 t ha^{-1} y^{-1}). Nevertheless, although the gross income from the intercropping system was greater (9 889 000 Dong ha^{-1} (A$793.25)) than that under cassava monoculture (8 767 000 Dong ha^{-1} (A$703.25)), 60% of farmers favoured the monoculture because the extra costs involved in the intercropping system reduced the net income to 138 000 Dong ha^{-1} (A$11.05) less than under monoculture (Nguyen Huu Hy *et al.*, 2001).

Previous work on remote sensing and Geographic Information Systems (GIS) for erosion modelling in Vietnam

Digital terrain models and empirical erosion equations to assess erosion risk are widely used techniques (Ziegler *et al.*, 2004). For example, The Soil and Water Assessment Tool (SWAT)

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Table 1 Influences of crop cover on soil loss from plot and catchment studies in Vietnam. *Sources*: A: Maglinao *et al*., 2002; B: Ministry of Planning and Investment, 2001; C: Douglas, 1997; D: Nguyen The Dang and Klinnert, 2001; E: Andersson, 2002; F: Nguyen Huu Hy *et al*., 2001; G: Nguyen Van Dung *et al*., 2004.

Location, Province	Mean annual rainfall (mm)	Soil/parent material	Groundcover	Soil Loss (t ha^{-1} y^{-1})	Source
Ban Don, Tay Nguyen			Bare soil	150–200	C
Pleiku	1650	Basaltic	Untilled, fallow land	21.1	C
Dong Cao, Hoa Binh	1500		Cassava monoculture	4.4	A
Pleiku	1650	Basaltic	Cassava	9.2	C
Tan Minh, Hoa Binh Province	1825	Ferrallic acrisols on ortho-gneiss	Cassava	25.6	G
Dong Tam, Binh Phuóc Province			Cassava monoculture	30.2	F
Bavi region, Hatay province	1750	Acidic, low fertility soil	Cassava monoculture	34	E
		Grey, infertile soil	Cassava monoculture	105.5	D
Dong Tam, Binh Phuóc Province			Cassava intercropped with groundnut	30.2	F
Bavi region, Hatay province	1750	Acidic, low fertility soil	Cassava intercropped with Flemingia	5.4	E
Dong Cao, Hoa Binh	1500		Natural grass/cassava intercropping	1.6	A
		Grey, ferrallic soil	Maize monoculture	68.7	D
Pleiku	1650	Basaltic	Maize with green beans	9.0	C
Pleiku	1650	Basaltic	Groundnuts	54.2	C
Tan Minh, Hoa Binh Province	1825	Ferrallic acrisols on ortho-gneiss	Hill rice (second year after forest clearance)	30.1	G
Pleiku	1650	Basaltic	Hill rice	24.0	C
Pleiku	1650	Basaltic	Sweet potato	2.9	C
Bao Loc, Lam Dong			Mulberry	125	B
Ban Don, Tay Nguyen			Tea: no erosion control	115–200	C
		Grey, ferrallic soil	Tea monoculture	30.2	D
Bao Loc, Lam Dong			Tea	26	B
Ban Don, Tay Nguyen			Tea: erosion control	5–94	C
Bao Loc, Lam Dong			Coffee	50	B
Pleiku	1650	Basaltic	Old coffee	0.1	C
		Grey, ferrallic soil: pure litchi	Lychee monoculture	15.0	D
Pleiku	1650	Basaltic	Pasture	2.4	C
		Grey, ferrallic soil	Plantation forest	11.2	D
		Grey, ferrallic soil	Natural forest	5.2	D
Tan Minh, Hoa Binh Province	1825	Ferrallic acrisols on ortho-gneiss	Secondary forest	2.9	G

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model developed by the United States Department of Agriculture's Agricultural Research Service, which has been used to study erosion in the Mekong Basin (Al-Soufi, 2000), includes GIS interfaces, weather generator and water management options. The SWAT model calculates soil erosion caused by rainfall-runoff process using the Modified Universal Soil Loss Equation (MUSLE).

In South-East Asia, the Management of Soil Erosion Consortium (MSEC) has been using the physical PCARES model (Predicting Catchment Runoff and Soil Erosion for Sustainability: Pannigbatan, 2000) that simulates runoff from and soil erosion of a catchment during each erosive rainfall event. It predicts both the spatial and temporal distributions of soil erosion processes and rates and the runoff and sediment yield at the catchment outlets. The model uses PCRaster, a GIS software package capable of cartographic and dynamic modelling that allows easy simulation of the hydrologic and sediment transport processes occurring on a three-dimensional landscape. The model incorporates a sediment transport routine described by Rose and Freebairn (1985), which calculates the amount of soil loss (*SL*) from the product of sediment concentration (c, in kg m^{-3}) and water discharge rate (Q).

GIS also has been widely used for land inventory and assessing agricultural potential in southern Vietnam (Viet and Phuong, 1993). Nguyen and Tong (2004) used a GIS Database combined with a spatial analysis algorithm, statistical methods and multiple criteria analysis to establish appropriate Decision Support Systems (DSS) and land suitability assessments for zoning and planning the sustainable development of marine aquaculture in Mekong Delta.

The International Board for Soil Research and Management (Thailand), together with Agriculture Canada and partners in Vietnam, Indonesia and Thailand, have developed a DSS to help in the diagnosis of sustainable land management (SLM) problems and in identifying constraints impeding the achievement of sustainability, especially for sloping terrain and uplands in Southeast Asia (Rais *et al.*, 1998). The DSS-SLM is planned for use at the farm level by extension personnel, agribusiness, non-government organisations and others providing advice to producers. These applications indicate the value of GIS under Vietnamese conditions and the potential for improved soil erosion models.

Use of remote sensing to analyse vegetation change and land degradation

Remote sensing of vegetation in southern Vietnam has been carried out successfully by several research teams. For example, Quy *et al.* (2001) derived a Normalised Difference Vegetation Index (NDVI) from Bands 3 and 4 of Landsat Thematic Mapper and Enhanced Thematic Mapper (ETM) images from 1998 to 2001 to monitor vegetation changes and sand accumulation around the Bau Trang Lake area in Binh Thuan Province, about 200 km northeast of Ho Chi Minh City. They also addressed issues of erosion of the shorelines of the lakes, erosion of river banks and sand accumulation in the lakes.

Methods

To understand the diversity of the land cover and terrain characteristics for the whole catchment area we used Landsat 7 Enhanced Thematic Mapper Plus images (for the 13th of February, 2002, in the early dry season and April 2001 in the late dry season), with a resolution of 30 m × 30 m. Ideally, these images would be taken at times to coincide with the times of measurement, but, as elsewhere in the humid tropics, cloud-free images were only available for a few dates. The images were geometrically corrected and co-registered for multi-temporal analysis. Image quality was enhanced by contrast stretching using the linear image 2% method (Mather, 2004). Principal Components Transformation was then undertaken to produce uncorrelated output bands. The NDVI was used to transform multispectral data into a single image band representing vegetation distribution.

During field visits, socio-economic studies and a preliminary soil survey, training and test data were collected to produce a land cover classification from the co-registered wet and dry season images. A Global Positioning System (GPS) was used to locate the sample areas accurately and to collect points to use in geometric correction of the satellite images. Both supervised and unsupervised classifications were undertaken to produce the resulting land cover map with 15 classes.

A digital elevation model (DEM) was constructed from contour data digitised from a 1997–1998 1:25 000 topographic map. All the digitized data were transferred to the Universal Transverse Mercator projection from the Gauss projection of the original map. Two-metre contours were interpolated from the original 10 metre interval contours. The results were checked

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and corrected from field knowledge and geomorphological understanding. Both ILWIS (Integrated Land and Water Information System) and Vertical Mapper surface modelling and display software (Mendonca Santos *et al*., 2000) were used to derive the DEM. Its accuracy was tested against a DEM derived from a SPOT (Système Pour l'Observation de la Terre, the French high resolution remote sensing satellite) stereo pair of panchromatic images. The DEM was used to generate spatial data on terrain properties contributing to soil erosion such as slope and slope length, and to produce a slope map for the catchment.

Using the DEM and field knowledge, the area was divided into slope elements and crop types. On four transects, permanent erosion bridge measuring sites were set up just below the interfluve (slope angle 9°), the convex creep slope (slope angle about 13°) the transportational midslope (slope angle 14–16°) and the colluvial footslope (slope angle about 9°). The 16 sites provided replicates under three cover types: cashew trees with cassava, cassava only and grass. All sites were on the erodible ferrasols over schists on the slopes below the basalt cap rock. The erosion bridge measures changes in ground level to an accuracy of 2 to 5 mm (Douglas *et al*., 1999; Shakesby *et al*., 2002). Great care has to be taken to make all measurements consistently, removing exactly the same type of loose debris each time, in order that measurements are comparable between sites and at a single site through time. Even so, the temptation to assume high levels of accuracy has to be avoided.

Two runoff plots on the same transportational midslopes enabled the effects of experimental manipulations of ground cover and erosion control measures to be monitored. The two runoff plots contained paired land covers, plot 1 having a grass control and a combination of maize and cashew saplings, while plot 2 had a grass control and cassava monoculture. On each sub-plot there were three erosion bridge transects. Four erosion bridge sites were established down a slope, one just below the slope crest, then at one third and two thirds the distance downslope, and just above the footslope, to give measurements of soil loss on different parts of the slope.

Results of erosion measurements

The Rach Rat River valley is incised into a basalt-capped plateau, with relatively cohesive soils of low erodibility on the plateau surface but with friable, more erodible soils derived from weak sandstones and mud rocks on the valley-side slopes. The cultivation of cassava on the slopes probably causes the greatest erosion in the catchment, with maize cultivation being the second most severe. The erosion bridge measurements show that the greatest erosion risk occurs early in the south-west monsoon period, when heavy rains fall on partially-exposed soils as the young cassava and maize plants provide little protection to the soil. Where cassava is grown among cashew trees, erosion rates are much lower. Permanent tree crops provide better soil protection, but the ground cover between the trees is an important factor.

Soil erosion also varies with position on the slope. The four successive erosion bridge sites down the slope show that although erosion takes place in every period in the uppermost site (7.1), there is accumulation of material further down slope (Figure 2). The spatial and temporal variation is readily apparent. During the first period from April to May, just after the cassava is planted (Table 2), eroded material accumulates at site 7.2, but there is net erosion at the site in period two from May to July, when much sediment accumulates at site 7.3. However, some of that sediment is lost in the July–September period, when accumulation occurs at the lowest site, 7.4. Between April and July when the cassava plants are small, more change in the soil surface occurs at sites 7.1, 7.2 and 7.3 than in the July-September period. The accumulation at 7.4 between July and September possibly reflects local movements from site 7.3 beneath the nearly fully grown plants.

At a more detailed scale, there is considerable variation in the spatial pattern of erosion and

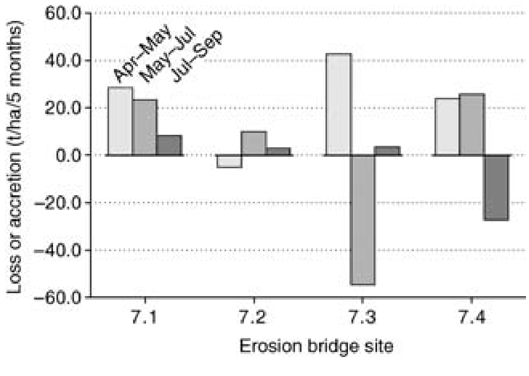

Figure 2 Temporal and spatial variation of soil erosion and accumulation at slope transect 7 in the Rach Rat Catchment.

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Table 2 Summary of Erosion Bridge results for different land use types in the Rach Rat catchment (Soil loss expressed as t ha^{-1} y^{-1} to the nearest tonne, negative values imply that, over the period, soil accumulated at the site). *Source*: Field data collected by the authors.

Erosion Bridge number	Slope angle	Ground cover	Period Apr–May 2002	Period 2 May–Jul 2002	Period 3 Jul–Sep 2002	Period 4 Sep–Oct 2002	Period 5 Oct 2002–Jan 2003
7.1	13.0	Cashew trees and cassava	28	23	8		
7.2	14.3	Cashew trees and cassava	–5	10	3		
7.3	14.3	Cashew trees and cassava	42	–54	3		
7.4	16.5	Cashew trees and cassava	24	25	–27		
8.1–8.3	9.0	Cassava and cashew saplings		52	–8	15	26
8.4–8.6	9.0	Grass fallow		3	–3	10	32
10.2	13.6	Cassava			362	5	36
10.5	13.6	Grass fallow			159	44	–1

accumulation across each erosion bridge site. Comparison of soil surface measurements in April and September 2002 at erosion bridge sites 7.1 to 7.4 shows that every transect has some sectors where net erosion occurred and some where net accretion developed (Figure 3).

The temporal variations in erosion clearly indicate that seasonal changes in crop cover are highly significant. Ploughing, planting or weeding activities will have impacts on the soil surface at the erosion bridge measurement scale. The contrasts between sites and crops and

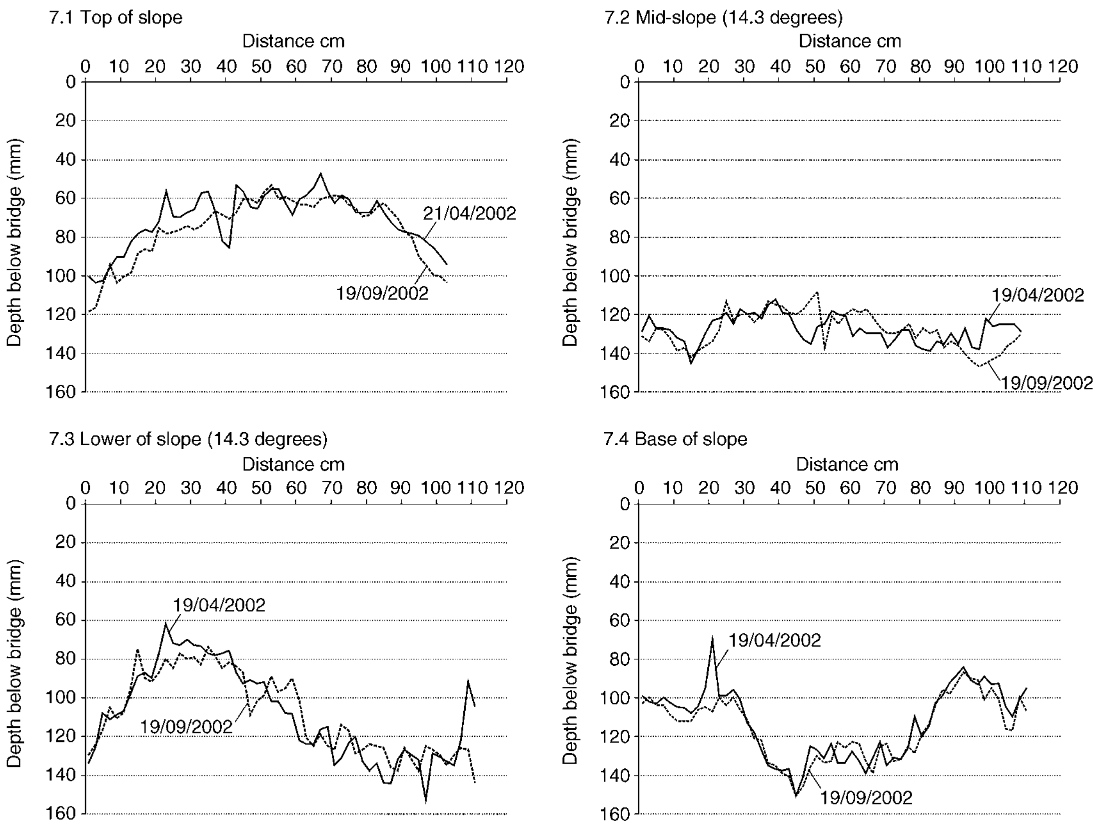

Figure 3 Erosion bridge measurements in April and September 2002 at site 7 in the Rach Rat catchment showing the variation in soil accumulation and erosion over a distance of 1.2 metres under cassava and cashew trees.

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observation periods (Table 2) show rates of erosion varying by an order of magnitude between periods. This is understandable in view of the likely occurrence of erosive rains early in the wet season when many crops have little ground cover. Any attempt to classify erosion rates on the basis of land use types must recognise this diversity. A simplified classification must indicate the wide range of rates that can occur (Table 3).

Under permanent tree or shrub cover, erosion rates are lower than under annual crops. Soil loss is lower where crops grow close to the ground, as with sweet potato and groundnut, than under tall, long stemmed crops such as cassava and maize. Walking in the fields, abundant evidence of splash erosion is visible between the stems of maize plants. The effects of erosion in areas of maize and cassava may be reduced by hedgerows or by intercropping with rows of plants that provide better ground cover. However, the adoption of such measures depends on the awareness and perceptions of the farmers concerned. Farmers generally prefer to grow cassava as a monoculture as the extra work and costs involved in intercropping are not rewarded by sufficient extra income.

The eroded soil carries considerable quantities of nutrients and organic matter (Table 4), which reflect the space and time differentials in the amount of eroded matter. Lower soil protection when the cassava is young in the May–July period (Plot 8.1) means much higher soil and nutrient losses from that plot than from the grass fallow plot (Plot 8.4). However, the differences are much less in the July–September period when the cassava has matured and the plants trap eroded soil. In the fallow period of the dry season when the grass dies back (October–February), more soil and nutrients are lost from the control (grass fallow) plot.

The land cover: development of the land use map from Landsat 7 ETMs

To detect land use changes, the 30 m resolution Landsat 7 ETMs from 2001 and 2002 were used. The images were interpreted using the ENVI (Environment for Visualizing Images from Research Systems Inc.) software package (Varshney and Arora, 2004). The pre-processed

Table 3 Summary of Erosion Bridge results for different land use types in the Rach Rat catchment. *Source*: Compiled from field data by the authors.

Rank (Highest rate first)	Simplified land use class	Range of erosion rates likely in the Rach Rat catchment, depending on slope and soil (t ha^{-1} y^{-1})
8	Bare soil	50–500
7	Cassava and maize	30–300
6	Groundnut, peanut	15–150
5	Hill rice and sweet potato	10–100
4	Inter cropping systems: trees and annual crop	10–75
3	Mulberry and banana trees	7–50
2	Tea and coffee	6–60
1	Forest, Plantation, fallow (but vegetated)	5–100

Table 4 Soil and nutrient losses from the paired erosion plots. *Source*: Field data collected by the authors.

Loss	May–July 2002	July–Sep 2002	Sep–Oct 2002	Oct 02–Feb 03	Total
Plot 8.4	Grass Fallow	Grass Fallow	Grass Fallow	Grass Fallow	
Soil (t ha^{-1} y^{-1})	3.29	−3.67	10.05	31.91	41.58
N (kg ha^{-1} y^{-1})	6.91	−7.70	21.10	67.01	87.32
P_2O_5 (kg ha^{-1} y^{-1})	1.74	−1.94	5.33	16.91	22.04
Organic Matter (kg ha^{-1} y^{-1})	129.28	−144.07	394.93	1254.05	1634.20
Plot 8.1	Young cassava	Maturing cassava	Harvested Crop	Fallow/Bare	
Soil (t ha^{-1} y^{-1})	52.49	−7.63	14.67	25.71	85.24
N (kg ha^{-1} y^{-1})	110.23	−16.03	30.80	53.99	178.99
P_2O_5 (kg ha^{-1} y^{-1})	27.82	−4.05	7.77	13.63	45.17
Organic Matter (kg ha^{-1} y^{-1})	2062.85	−299.99	576.46	1010.43	3349.76

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images were geometrically corrected by the image-to-map procedure. This procedure involves selecting the area of interest from the entire spatial database, examining the extracted area on screen by superimposing different spatial database layers on the selected image, deciding on the final map components, annotating the map and creating a plot-file to obtain the hard copy map (Figure 4).

To facilitate the interpretation of the computer analysis the satellite images were first interpreted visually. Much more exposed soil (blues tones) is seen in the late dry-season April image where the wet season annual crops of maize, cassava and rice have been harvested and are about to be replanted. The perennial tree crops, cashew, coffee, banana, rubber, teak and fruit trees, such as longan, appear as red in both images. Slight changes in reflectance due to seasonal changes in leaf pigments help to discriminate between them. For example, the oldest rubber leaves are yellow in March and fall in April, but the tree is not completely deciduous with leaves of different ages growing together.

The images were analysed with the NDVI and Principal Component Analysis. An unsupervised classification was obtained with the isodata method (Tou and Gonzalez, 1974). Training and test data were collected by GPS to produce a land cover classification through the maximum likelihood method (Richards, 1994). The accuracy of the land use classification was assessed by using the Kappa coefficient method, a statistical measure of the agreement, beyond chance, between two maps (the output map of classification and the ground-truthed map) (Stehman, 1966).

Development of a pilot soil erosion assessment methodology

A GIS-based soil erosion assessment model for the catchment (Figure 5) was developed to estimate soil erosion rates across the catchment, based on derived relationships between independent variables (slope, soil type and NDVI characteristics extracted from map layers) and the dependent variable (erosion rates measured at each of the monitoring sites).

Unfortunately, the results of the regression analysis were not sufficiently robust to generate a final model. This was partially due to the spatial resolution of the input datasets (which was limited to the cell resolution of the imagery used) and partly because the carefully selected erosion measurement sites were too closely clustered. When the image interpretation was completed, the different vegetation combinations found on the erosion bridge transects could

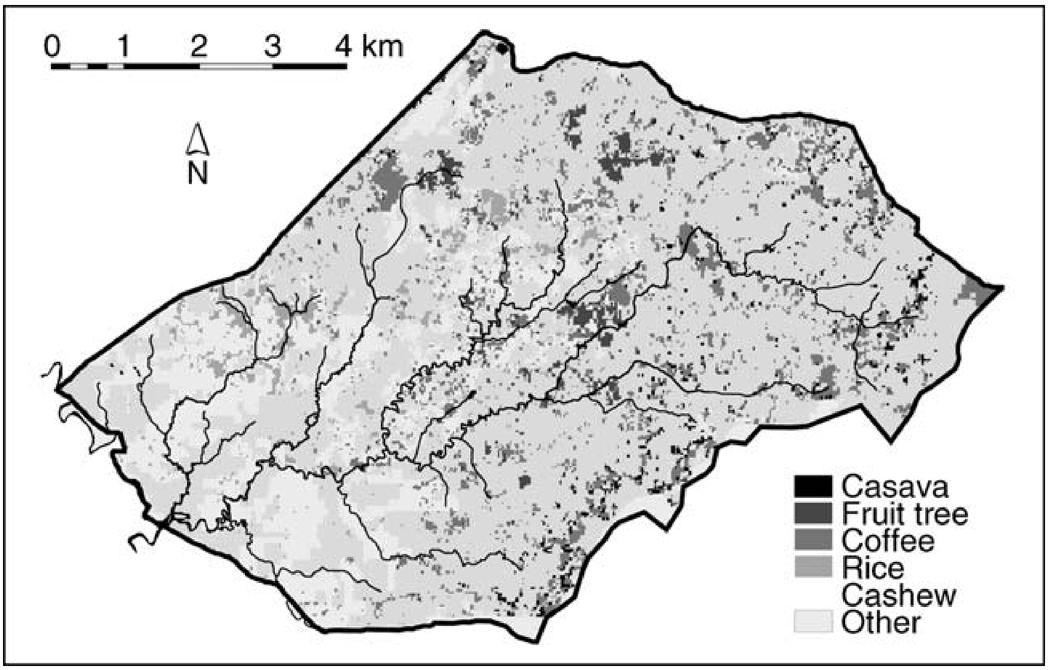

Figure 4 Land use map for dry season cover in April 2002, based on Landsat 7 ETM. Because the individual patches of each crop are small, the land cover has been simplified to a small number of categories, with the smallest patches removed.

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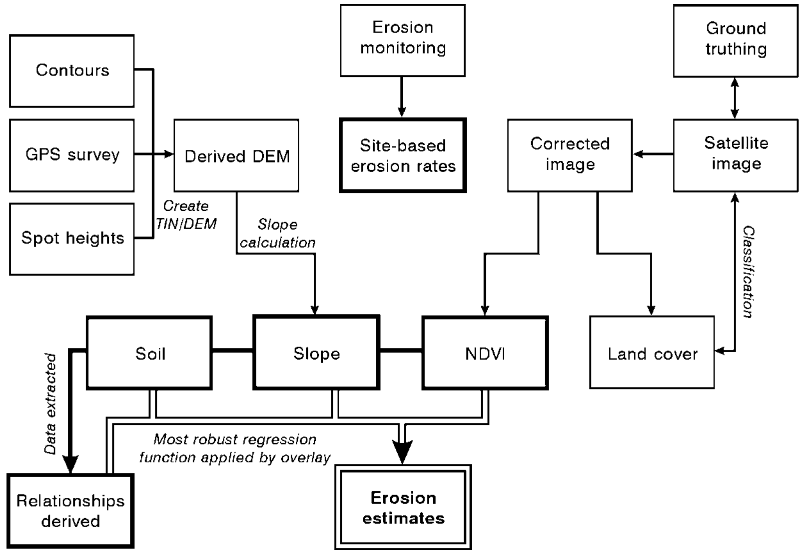

Figure 5 Summary of pilot GIS erosion assessment methodology.

not be distinguished from one another at the scale of image resolution and analysis. The individual patches of cassava, cashew trees and cassava, and grass, were too small to be detected, yet this was the detailed pattern of smallholder cultivation that gave rise to the severe soil losses. This scale problem, associated with the small size of the vegetation patches for which erosion-bridge data were collected and the resolution of the available cloud-free imagery, showed some of the problems of working to find practical solutions in tropical regions. The study area was selected because of the problems of soil erosion, not because it was ideal for research. Funding limitations restricted data acquisition, both in the field and in terms of the imagery that could be obtained. Future work will have to expand the number and spatial coverage of monitoring sites to improve the reliability of regression relationships and expand the number of datasets to use as the basis of dependent variables. This would involve higher costs and would not be replicable of large areas.

One alternative would be to attempt to make a qualitative assessment of relative erosion patterns. The map layers and categories in Table 5 could be used as the basis for an erosion potential matrix which could then provide the basis for mapping areas as high, medium and low erosion potential (using overlay analysis). However, further field work and ground truthing would be necessary to be sure that the full range of slope and crop combinations was included.

Conclusions

The erosion results clearly indicate the value of ground cover at all seasons. The losses from bare soil and between young row crops are high, but of the order of magnitude indicated by previous work (for example, Nguyen The Dang and Klinnert, 2001 in Table 1) and by the Vietnam State of the Environment Report (Environmental Database Division, 2002). The particularly friable, highly erodible nature of the soils on the side slopes of the Rach Rat Catchment contributes to the high rate of erosion of poorly protected soils in the study area. The immediate application of this finding is to try to reduce soil loss by changing farming practices, but this requires extra labour and financial inputs by poor migrant farmers who are unfamiliar with the soils of the area. Contour planting and conservation hedgerows were proposed by the research team, but few farmers were able to adopt them.

Total nitrogen losses from the cassava plot at 179 kg ha^{-1} y^{-1} are high compared with losses from hill country cassava cultivation reported in northern Vietnam of 33 to 88 kg ha^{-1} y^{-1} (Tran *et al.*, 2004). Phosphorous losses are also higher than at the northern Vietnam site. In four experiments conducted in Thailand and Colombia, annual losses of total N and available P ranged from 3.5 to 37 kg ha^{-1} y^{-1} and 0.02 to 2.2 kg ha^{-1} y^{-1}, respectively (Howeler, 2001). For Vietnam, studies of cassava cultivation have suggested losses of N in eroded soil ranging from 43.4 kg ha^{-1} y^{-1} in the central highlands of southern Vietnam to

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Table 5 Possible map layers to be used in a qualitative analysis of erosion. *Source*: The Authors.

Map Layer	Erosion potential → Categories	High	Med	Low
Slope	Steep	*		
	Medium		*	
	Low			*
Landform types (see map overpage)	Plateau surface			
	U-shaped river valley			
	V-shaped river valley			
	Steep valley side			
	Floodplain			
NDVI (or land cover types)	High			
	Medium			
	Low			
Additional layers can be added as data become available				

65 kg ha^{-1} y^{-1} in the north central coastal region of the country. Equivalent P losses range from 4.8 to 10 kg ha^{-1} y^{-1} (Howeler. 2001). Thus the nutrient losses from the Rach Rat catchment appear high, reflecting the severity of the soil loss under the prevailing agricultural practices. Possibly the levels of fertiliser applications differ between the Rach Rat catchment and the other areas studies, but the need for reduction of soil erosion is readily apparent.

While the team failed to find a rapid, relatively inexpensive method of predicting erosion in an area where the arrival of migrant farmers was creating a major soil degradation problem, it did find new evidence of the severity of soil and nutrient losses on the highly erodible soils of the slopes of the Rach Rat catchment, and developed a good land cover map from remote sensing. It persuaded one farmer to change his way of cultivation as a demonstration project, and took the first steps in meeting the needs of the local people and of the provincial officials responsible for the environment. The remaining issue is to overcome the scale problem, to be able to use the potential of remote sensing and GIS effectively, and to upscale from the erosion bridge and erosion plot scale to the catchment and the district scale.

To do this will require more careful research design, access to higher resolution imagery, field measurements over a wide range of crop and terrain conditions, and closer examination of farmers' attitudes and practices, including the cost and benefits of introducing more intercropping, hedgerows and agriforestry techniques. Taking science to the community and putting it into practice is likely to be more difficult then merely carrying out scientific studies. If we fail to bridge that science information gap, the problems of poverty and land degradation are likely to remain with us for much longer.

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