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Changes in the relationship between soil erosion and N loss pathways after establishing soil conservation systems in uplands of Northeast Thailand

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ABSTRACT

Slow establishment of green barriers together with competition for nutrients and water between crops and contour hedges hamper their acceptance by rural communities in tropical mountainous regions. Alternatively, a combination of hedges/barriers and minimum tillage may shift the pathway of N losses from water erosion towards leaching. In Northeast Thailand, run-off, soil loss, N leaching (by resin cores) and crop response were monitored in grass barriers (*Vetiveria zizanioides*, *Brachiaria ruziziensis*) and hedgerow (*Leucaena leucocephala*) based soil conservation systems in fertilized/unfertilized treatments from their establishment in 2003 to 2005. In all treatments, maize was grown on a moderate slope gradient (21–28%) under minimum tillage conditions and relay cropped with a legume cover crop (*Canavalia ensiformis*). After 3 years, maize grain yields increased from 1.5 and 3.2 to 3.8 and 5.5 Mg ha^{-1} in the unfertilized and fertilized control plots. Over the same period, yield increases were lower for soil conservation treatments reaching yields of 2.0–2.7 Mg ha^{-1} without fertilizer and 3.9–4.2 Mg ha^{-1} with fertilizer. After 3 years, runoff (190–264 m^3 ha^{-1}) and soil loss (0.2–1 Mg ha^{-1}) in fertilized plots with barriers showed an average decrease of 72% and 98%, respectively, compared to 2003, the reduction being lower in unfertilized plots. The control had a much higher soil loss in the first year (24.5 Mg ha^{-1}), but also showed much reduced erosion (1.6–2.5 Mg ha^{-1}) in the third year, partly due to reduced rainfall but also due to the combined effects of minimum tillage and surface mulch. Runoff, however, did not decrease on the control plots over the years in the same way as it did under soil conservation (runoff only after >12 mm day^{-1}). Average cumulative N losses by runoff, soil loss and leaching were reduced from 55 kg N ha^{-1} in the control to 37–40 kg N ha^{-1} in the barrier treatments. The dominant N loss pathway shifted from above ground N losses to leaching with the establishment of barriers and hedges. Due to the positive maize yield development and partial control of soil loss, minimum tillage combined with legume relay cropping under the trial conditions indicates a potential alternative to contour barrier/hedgerow systems for soil conservation on moderate slopes in tropical mountainous regions.

1. Introduction

Currently, soil degradation by erosion affects 1966 million hectares worldwide (Lal, 2007). Lal (1998) estimated average soil erosion in tropical countries at 200–1000 Mg km^{-2} year^{-1} depending on slope gradient and rainfall characteristics. This degradation process does not only lead to loss of soil particles, but additionally plant nutrients and water storage capability are reduced, resulting in severe decline of crop yields and environmental quality. In northern Vietnam, Fagerström et al. (2002) measured erosion induced N losses up to 150 kg ha^{-1} for upland rice over 2 years, on an average slope of 20–28%, while Dung et al. (2008) observed erosion and leaching losses of 126 kg N ha^{-1} over two unfertilized rice crops in a similar setting.

Among attempts to reduce erosion and related nutrient losses, contour hedgerow systems are one of various soil conservation measures recommended for tropical mountainous regions. They are based on the concept of inter planting leguminous trees or fodder grasses with annual food crops. Hedgerow systems effectively reduce soil loss, runoff and associated nutrient losses on sloping terrain (Baudry et al., 2000; Morgan, 2005). In Thailand, Kongkaew (2000) showed that soil loss could be reduced to less than 2 Mg ha^{-1} per year after establishing *Leucaena leucocephala* hedges or ruzi grass (*Brachiaria ruziziensis* Germain et Evrard)

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barriers in maize (*Zea mays* L.) based cropping systems. Similar results were observed in China and Spain where as much as 30–80% of runoff water was reduced by introducing hedgerows to the system owing to a prolonged infiltration time due to the hedgerows, and improved soil infiltration rates (Huang et al., 2006; Raya et al., 2006). Additionally, hedgerow systems also have an important role in reducing nitrogen losses from water erosion. In Kenya, Owino et al. (2006) proved the effectiveness of narrow grass barriers in controlling nutrient loss by erosion, i.e. Napier grass (*Pennisetum purpureum* Schumach.) reduced NO_3^--N and NH_4^+-N losses up to 45–50%.

To date, however, hedgerow systems have not been widely adopted by farmers because of technical problems and lack of fit with farmers' needs (Knowler and Bradshaw, 2007). Reduction of 15–25% of the cropping area due to additional hedgerow planting and competition between hedgerows and crops, as well as high labour requirements are concerns of farmers when applying hedgerow systems. Many studies demonstrated that yield in rows adjacent to hedgerows declined due to competition for light, water and nutrients (Dercon et al., 2006; Kinama et al., 2007; Pansak et al., 2007). In addition, the reduction of runoff by soil conservation measures, such as contour hedgerow systems, might affect downstream production systems such as paddy fields in Southeast Asia, as these fields often depend on runoff for water supply during shortages of rainfall (Sthiannopkao et al., 2007).

Finally, economic factors play a role in determining whether farmers will adopt or not such technology. Contour hedgerow systems have the disadvantage of providing only limited early returns on investment (Bayard et al., 2007). Farmers repeatedly complain about the fact that improved yield response only comes several years after hedgerow establishment (Kiepe, 1996). In addition, the process of natural terrace forming by contour strip planting may lead to exposure of infertile subsoil with negative effects on crop yields (Dercon et al., 2003; Dercon et al., 2007; Morgan, 2005). Therefore, alternatives, which reduce soil degradation and at the same time better meet farmer interests, are required.

Recent studies indicate that minimum tillage combined with cover crops has potential to offer both soil conservation in cropping systems of tropical mountainous regions as well as stable or even improved yields in the course of time without the major disadvantages of contour hedgerow systems (Hobbs, 2007; Shafi et al., 2007). Introduction of conservation measures and reduced tillage is also likely to affect the pathways of N losses to the ecosystem. However, most research to date has focused on aboveground N losses by runoff and erosion neglecting N losses by leaching, although increased drainage and higher N dynamics in leguminous hedges have been observed (Rowe et al., 2005). Research on the performance of conservation agriculture on steep slopes, however, is scarce and, thus, assessing the potential of these technologies in mountainous regions to improve local cropping systems is of high priority to better understand its opportunities and economic and environmental tradeoffs.

The objective of this research was to assess the short to medium term changes in soil erosion, runoff, N losses and crop response in a comparative study as affected by contour barrier/hedgerow and conservation agriculture systems under minimum tillage. Particular emphasis was given to the changes in pathways of N losses, e.g. above (soil loss, runoff) *versus* belowground (leaching) losses.

2. Materials and methods

2.1. Site description

The study was conducted over a period of three consecutive years (2003–2005) at Ban Bo Muang Noi village in Loei province of Thailand (17°33′N and 101°1′E, 572 m a.s.l.). In the lowlands of Loei province, paddy fields are predominant whereas maize, upland rice (*Oryza sativa* L.) and macadamia (*Macadamia* sp.) trees are commonly grown in the uplands.

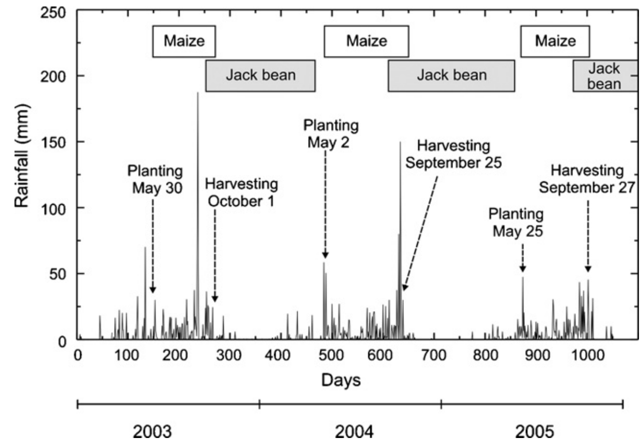

Fig. 1. Daily rainfall distributions for the monitored period of 3 years (2003–2005) at the experimental site in Ban Bo Muang Noi, Loei province, Northeast Thailand. Arrows indicate planting and fertilizer application dates.

The study area has a tropical savannah climate. Annual temperatures range from a high of 44 °C to a low of 11 °C, with a mean temperature of 26 °C in the cropping season. The rainy season lasts from May to September followed by a cool and dry season from October to February/March and a hot dry period in April. The amount of rainfall was recorded by a self-registering rain gauge. The total annual rainfall at the experimental site amounted to 1352, 1288 and 1051 mm in 2003, 2004 and 2005, respectively (Fig. 1). Daily rainfall events with 10–50 mm of rain per day were recorded on 36, 34 and 31 days in 2003, 2004 and 2005, respectively.

The field experiment was established on a Humic Lixisol (Deckers et al., 2002) covered by a 2 years old grassland with a moderate slope gradient ranging from 21% to 28%. The topsoil (0–25 cm) had a silty clay loam texture of 13% sand, 48% silt and 39% clay, a pH (H_2O) of 6, an organic matter content of 3.5%, a total N content of 0.14%, an available P (Bray II) content of 14 mg kg^{-1} and an exchangeable K content of 200 mg kg^{-1} at the start of the experiment.

2.2. Experimental design

Land preparation was done by slash and burn before starting the experimental study. The experiment was established in April 2003 and laid out as a split-plot design with fertilizer application as main factor, soil conservation as subfactor, and two replicates. In total, 16 erosion plots were established. Plot size was 4 by 18 m (72 m^2) with a collection device for runoff water and eroded soil installed at the lower end of each plot (Fig. 2). In all treatments maize (*Zea mays* L.), cv. Suwan 1, was planted (May 30th, 2nd and 25th in 2003, 2004 and 2005, respectively) along the contours by using a planting stick at a spacing of 25 cm along the row and 75 cm between rows.

The two main factor treatments were (i) no fertilizer application and (ii) 60 kg N ha^{-1} plus 14 kg P ha^{-1} via split application. Half of the fertilizer was applied 2 weeks after crop emergence, the second half was given 1 month later. Subfactor treatments were: (i) vetiver grass (*Vetiveria zizanioides* (L.) Nash) barriers (VG), (ii) ruzi grass (*Brachiaria ruziziensis* Germain et Evrard) barriers (RG), (iii) leucaena (*Leucaena leucocephala* (Lam) de Wit) hedges (LH), and (iv) a control without hedgerow (CON).

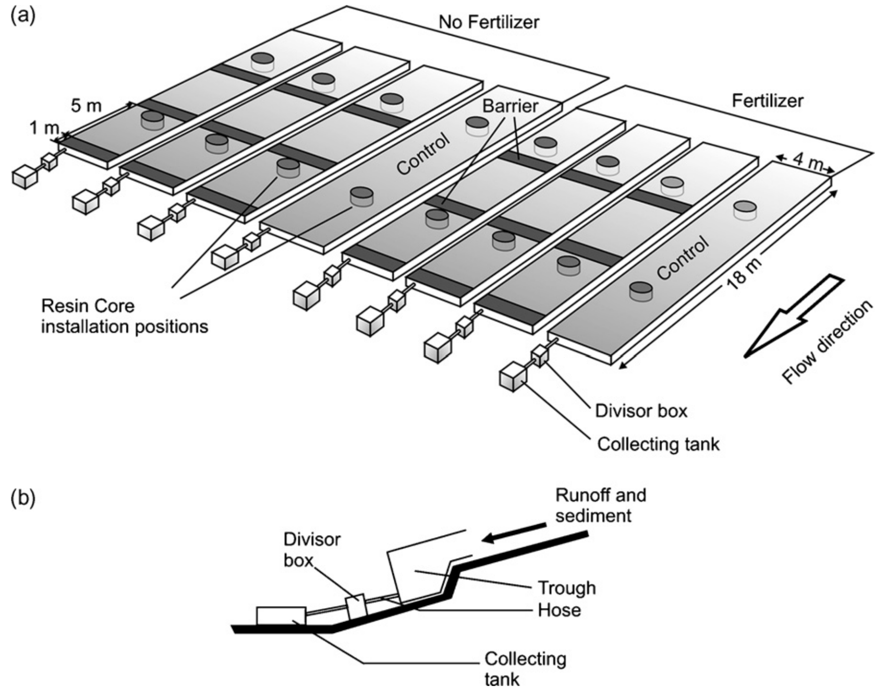

Fig. 2. (a) Experimental layout of erosion plots at Ban Bo Muang Noi, Loei province, Northeast Thailand. (b) Schematic of erosion measurement used for collecting runoff and soil loss.

Leucaena, ruzi grass or vetiver grass were planted in three 1 m wide barriers at intervals of 6 m on 29 April 2003, occupying about 17% of the total plot area (Fig. 2) according to recommendations of the Land Development Department, Thailand and IBSRAM. Six rows of maize were planted between each hedgerow or grass strip. Apart from the initial slash and burn activities followed by hand hoeing to 10 cm depth for land clearing, no further soil preparation was carried out apart from hand weeding. Maize was relay cropped with Jack bean (*Canavalia ensiformis* (L.) DC), planted 1 month before maize harvest, starting in September 2003. After maize or Jack bean harvest (0.3–0.5 Mg ha^{-1} $year^{-1}$), maize stover and all Jack bean material were left on the plots as mulch to protect soil from erosion and suppressing weeds in the following growing season. Plots with hedgerows or grass barriers were pruned 3–6 times per year, and prunings spread evenly over the alley. Thus, over the 3 years a total of 10, 19, 21 and 20 Mg ha^{-1} plant residues were applied as mulch in the control, leucaena, vetiver grass and ruzi grass treatments without fertilizer application, respectively, and 18, 32, 39 and 48 Mg ha^{-1} in the corresponding fertilized treatments. In all treatments, weeding was done by hand when necessary. Therefore, the trial setup was considered as a minimum tillage system (Bergsma, 1996).

2.3. Runoff and soil loss measurement

Soil loss and runoff were collected after every rainfall event by using collecting tanks with a volume of 150 L, starting 1 month after erosion plots and contour hedgerows were established (Fig. 2). These tanks were connected indirectly to the erosion plots via one of 16 outlets of a divisor box placed between erosion plot and tank. The amount of runoff water was measured by introducing a tape measure into the tanks and calculating volume and multiplication by number of outlets. The amount of soil loss was calculated based on the heavier sediment and the suspended sediment fractions. The heavier sediment fraction was collected from collecting channels at the lower end of each plot and weighed.

Subsamples were taken and dried to calculate dry weight of this fraction. Suspended sediment fractions were collected together with the runoff water from the tanks. Runoff samples of approximately 1 L were taken from the tanks after stirring and filtered through Whatman No. 1 filters. After filtration, particles collected on the filter were oven-dried at 105 °C for 24 h to determine amount of sediments in water suspension. For nutrient analyses, runoff samples collected after every rainfall event were preserved with one or two drops of 4 M H_2SO_4 and frozen. The samples were cumulatively kept until laboratory analyses, which were done twice a month. NH_4^+-N and NO_3^--N in runoff water was determined by using the steam distillation method (Mulvaney, 2001). Total N of the heavier sediment and suspended sediment fractions were separately analysed twice a month by the micro-Kjeldahl method (Bremner, 2001).

2.4. Nitrogen leaching

Nitrogen leaching was assessed by the resin core method (Kongkaew, 2000; Lehmann et al., 2001). PVC plastic tubes with a diameter of 20 cm and a length of 12 cm were used. At the lower 2 cm of the tube, a slice was cut and a 1.4 mm mesh polythene net was introduced between the lower (2 cm) and upper (10 cm) PVC rings. The upper part of the PVC tube was filled with a 1:4 (v/v) mixture of resin (cation and anion exchange resin, Amberlite 20) and sand and covered by a thin sand-layer. The cores were installed at 0.9 m below the soil surface in upper and lower slope plot positions (Fig. 2), by opening a small trench to 1 m depth and inserting the resin cores 0.5 m laterally into a tightly fitting hole. The remaining space was filled with soil and the trench closed. At the end of each cropping season, resin cores were cautiously excavated. Thereafter new resin cores were inserted at the same positions and soil was carefully refilled based on its origin. For analyses, each core was cut into three layers, 0–3, 3–6 and 6–9 cm. The total fresh mass was determined and an aliquot (15–25 g) of the resin–sand mixture was extracted with 1 M KCl-solution. The first two resin layers (0–3 and 3–6 cm) were used to determine the NO_3^- and NH_4^+ concentration by steam distillation (Mulvaney, 2001). The last layer of the resin–sand mixture was not considered to avoid interference by capillary rise of water (Lehmann et al., 2001).

2.5. Maize grain and stover yields

Maize was harvested on October 1st, September 25th and 27th in 2003, 2004 and 2005, respectively. After harvest maize grains and stover were oven dried at 70 °C until constant weight was reached. In 2003 and 2004, maize grain and stover yields were determined by harvesting three 3.75 m^2 areas per plot containing a total of 48 plants. In 2005 maize was harvested row wise to assess the impact of soil conservation on the spatial variability of crop performance as reported in Pansak et al. (2007). In all cases maize yields were presented on the basis of the total plot area including barrier area.

2.6. Statistical analysis

Total runoff, soil loss, yield, N losses by soil loss, runoff and leaching were analysed by a partial analysis of variance (ANOVA) to test the effects of fertilizer levels, soil conservation measures, year and their interaction. When significant differences were detected among means, the minimum significant differences were calculated using Tukey's test ($p < 0.05$). Linear and non-linear (were adequate) relationships were fitted for runoff, total soil loss and daily rainfall.

3. Results

3.1. Yield response of maize to soil conservation measures and fertilizer application

Soil conservation measures and fertilizer application significantly ($p \leq 0.01$) affected maize grain and stover yield (Table 1). However, the effect of both changed over time having a significant ($p < 0.05$) interaction. The highest maize grain (5.5 Mg ha^{-1}) and stover yields were reported 3 years after establishment for the control plot without hedgerows and with fertilizer applied. In the same year, the lowest maize grain (2.0 Mg ha^{-1}) and stover yields were obtained on the plots with ruzi grass barriers without fertilizer application. The use of contour hedgerows ($p \leq 0.01$) reduced maize grain and stover yield up to 39% in the second year and up to 47% in the third year as compared to the control without hedges. This decline in maize grain and stover yield was much higher than the reduction of almost 17% in the cropping area as compared to the control plot without hedgerows. The control plots, regardless of fertilizer application, showed a strong yield increase from the first to the second year, but the increase was lower in the third year when fertilizer was applied. The cumulative grain yield over 3 years amounted to 10.7 Mg ha^{-1} in the control without hedgerows/barriers (average fertilizer treatments), 1.3 times higher than in soil conservation treatments (Table 3).

3.2. Runoff and soil loss as affected by soil conservation, fertilizer application and time

Runoff and soil loss were significantly reduced by soil conservation, fertilizer application and year (Table 2). Plots with hedgerow systems showed progressive reduction in runoff and soil loss over time, while the control without hedgerow was characterized by a lower decrease in runoff and soil loss from the first to the second year. However, total soil loss (1.6–2.5 Mg ha^{-1}) from the control plots without hedgerows was also strongly reduced in the third year, confirmed by the significant interaction between soil conservation measures and year. In the third year, the lowest runoff was observed in the fertilized leucaena hedge treatment, while treatments with ruzi grass barriers had the lowest soil loss. Fertilizer application also significantly reduced runoff and soil loss in most treatments in the third year. Nevertheless, after 3 years, runoff from the fertilized control plot was still significantly ($p \leq 0.05$) higher as compared to the hedgerow treatments. With regards to soil loss, a similar observation could be made for the control plot without fertilizer, but not when fertilizer was applied. Cumulative runoff and soil loss

Table 1
Grain and stover yield during 2003–2005 at Ban Bo Muang Noi, Loei province in NE Thailand as affected by fertilizer application and soil conservation measures

	Control without hedgerow			Vetiver grass strip			Ruzi grass barrier			Leucaena hedge		
	2003	2004	2005	2003	2004	2005	2003	2004	2005	2003	2004	2005
Maize grain yield (Mg ha^{-1})												
−F	1.5 ± 0.1	2.6 ± 0.4	3.8 ± 0.0	1.2 ± 0.1	2.1 ± 0.2	2.4 ± 0.1	1.4 ± 0.0	1.6 ± 0.2	2.0 ± 0.1	1.5 ± 0.2	2.1 ± 0.3	2.7 ± 0.2
+F	3.2 ± 0.0	4.8 ± 0.3	5.5 ± 0.0	2.9 ± 0.3	3.9 ± 0.0	3.9 ± 0.3	2.7 ± 0.1	4.1 ± 0.1	4.1 ± 0.1	2.3 ± 0.3	3.9 ± 0.2	4.2 ± 0.6
F-test												
Soil conservation (SC)					<0.001							
Year					<0.001							
Fertilizer application (F)					<0.001							
Interaction												
SC × year					<0.001							
SC × F					0.030							
F × year					0.004							
Maize stover (Mg ha^{-1})												
−F	1.8 ± 0.1	3.1 ± 0.1	3.7 ± 0.0	1.5 ± 0.0	2.5 ± 0.4	2.6 ± 0.2	1.6 ± 0.0	1.9 ± 0.7	2.0 ± 0.1	1.8 ± 0.0	2.5 ± 0.4	2.9 ± 0.0
+F	3.9 ± 0.0	6.3 ± 0.1	6.5 ± 0.2	3.5 ± 0.0	4.6 ± 0.4	4.3 ± 0.2	3.3 ± 0.0	4.9 ± 0.3	4.6 ± 0.1	2.7 ± 0.0	4.7 ± 0.2	4.6 ± 0.7
F-test												
Soil conservation (SC)					<0.001							
Year					<0.001							
Fertilizer application (F)					<0.001							
Interaction												
SC × year					0.030							
SC × F					0.030							
F × year					0.009							

Treatment means and ±standard errors are reported.
−F: no fertilizer application and +F: 60 kg N ha^{-1} and 14 kg P ha^{-1}.

Table 2
Runoff and soil loss during 2003–2005 at Ban Bo Muang Noi, Loei province in NE Thailand as affected by fertilizer application and soil conservation measures

	Control without hedgerow			Vetiver grass strip			Ruzi grass barrier			Leucaena hedge		
	2003	2004	2005	2003	2004	2005	2003	2004	2005	2003	2004	2005
Runoff ($m^3\ ha^{-1}$)												
−F	866 ± 7	739 ± 14	642 ± 66	730 ± 15	705 ± 10	264 ± 20	774 ± 13	546 ± 15	228 ± 152	755 ± 47	712 ± 38	225 ± 35
+F	802 ± 22	648 ± 38	427 ± 55	661 ± 29	339 ± 8	190 ± 10	717 ± 5	527 ± 15	224 ± 26	699 ± 17	398 ± 60	187 ± 74
F-test												
Soil conservation (SC)					<0.001							
Year					<0.001							
Fertilizer application (F)					<0.001							
Interaction												
SC × year					0.030							
SC × F					0.070NS							
F × year					0.010							
Soil loss ($Mg\ ha^{-1}$)												
−F	24.5 ± 0.5	17.8 ± 0.1	2.5 ± 0.2	10.5 ± 0.5	10.4 ± 0.7	0.5 ± 0.2	8.1 ± 1.0	4.0 ± 1.0	0.2 ± 0.0	12.1 ± 0.1	7.5 ± 1.5	1.0 ± 0.1
+F	19.5 ± 0.5	19.5 ± 0.5	1.6 ± 0.1	12.5 ± 0.5	4.7 ± 0.4	0.4 ± 0.1	11.0 ± 1.0	4.0 ± 1.0	0.2 ± 0.1	11.5 ± 1.5	4.4 ± 2.1	0.7 ± 0.2
F-test												
Soil conservation (SC)					<0.001							
Year					<0.001							
Fertilizer application (F)					0.021							
Interaction												
SC × year					<0.001							
SC × F					0.037							
F × year					0.055NS							

Treatment means and ±standard errors are reported.
−F: no fertilizer application and +F: 60 kg N ha^{-1} and 14 kg P ha^{-1}.

over three cropping seasons, from April 2003 to October 2005, amounted up to 2061 $m^3\ ha^{-1}$ runoff and 43 Mg ha^{-1} soil loss in the control without hedgerow, being up to 1.4 and 3 times higher, respectively, than in the hedgerow treatments (Figs. 3 and 4, Table 3). Peaks of runoff and soil loss mainly coincided with strong rainfall events. However, the pattern of runoff and erosion response, in function of time, differed over consecutive years. In 2003, at the beginning of the trial, all treatments followed a similar trend of cumulative runoff. However, in August 2003, 3 months after planting, an extremely high rainfall event occurred, causing high runoff on all plots, but the impact was lower on plots with contour hedgerows. Additionally, fertilizer application strongly reduced soil erosion in the fertilized control plots during this storm event. In 2004, with rains starting earlier in May, the different patterns of runoff and soil loss became very early distinguishable between control and conservation treatments, although there was a poor performance of the unfertilized vetiver strip. After the maize harvest, a last strong rainfall event accentuated the differences but eliminated the earlier observed positive fertilizer effect in the control. Finally, in 2005, runoff produced by the control plots was from the start higher than by the plots with contour hedgerows. In addition, the lack of fertilizer application increased runoff from the beginning of the cropping season. However, with regards to soil loss the response in time was small and similar for all treatments.

3.3. Evaluation of N losses by runoff, soil loss and leaching over time

Hedgerows were significantly ($p \leq 0.01$) more effective at reducing annual N losses by runoff compared to the control without hedgerows (Fig. 5a). Over the three monitored years, the control plot without hedgerows, lost 12–15 kg N ha^{-1} mineral N through runoff, being three to five times higher than the losses from plots with hedgerows (Fig. 5a). Average mineral N losses by runoff significantly ($p \leq 0.01$) decreased by 59% from 2003 to 2005. Total N losses by soil loss were significantly higher in the control compared to the plots with hedges (Fig. 5b). Total N losses by soil loss showed also a significant ($p \leq 0.01$) decline with fertilizer application and with time. Among the different contour hedgerow systems, the treatment with ruzi grass barriers, without and with fertilizer, had the lowest total N losses by soil loss over the three consecutive years.

N losses by leaching were larger in comparison with N losses by runoff or soil loss (Fig. 5c). On an average for the 3-year period, measured annual mineral N losses by leaching were about 9.5 kg ha^{-1} $year^{-1}$. Only in the last year, N leaching losses showed a significant ($p \leq 0.01$) decline. However, soil conservation and fertilizer application did not significantly ($p \geq 0.05$) affect N losses by leaching. Cumulative total N losses over the 3 years of monitoring amounted to 55 kg ha^{-1} in control treatment without hedgerows (average fertilizer treatments), which was about 1.5 times higher than that in the treatments with hedgerows/barriers (Table 3). Additionally, the ratio between N losses by leaching and runoff/erosion decreased from 1.08 in the control to 0.29–0.37 in the conservation treatments.

3.4. Relationships between rainfall and both runoff and soil loss changes through time

Rainfall events of greater than 50 mm per day were only observed in 2003 and 2004, whereas events of 20–25 mm and 25–50 mm were more frequent in 2005 (Fig. 1). In 2003 and 2004, events of more than 100 mm day^{-1} were recorded at 1 day only.

Runoff and soil loss showed significant and strong correlation with rainfall for all treatments both without and with fertilizer and for all years (Figs. 6 and 7). Runoff was more strongly and linearly related to rainfall (R^2 ranging from 0.74 to 1, $p \leq 0.01$) than soil loss. Soil loss was also linearly related to rainfall up to events of about 80 mm day^{-1}, thereafter the relationship tended to become non-linear owing to a proportionally less strong increase in amounts of eroded material. In the final third year of the trial, intercepts of all fitted equations for runoff were negative and clearly reduced. Therefore, the minimum rainfall amount required to initiate runoff was higher for the third year compared to the first year. At the end of the third year, slopes of the fitted linear

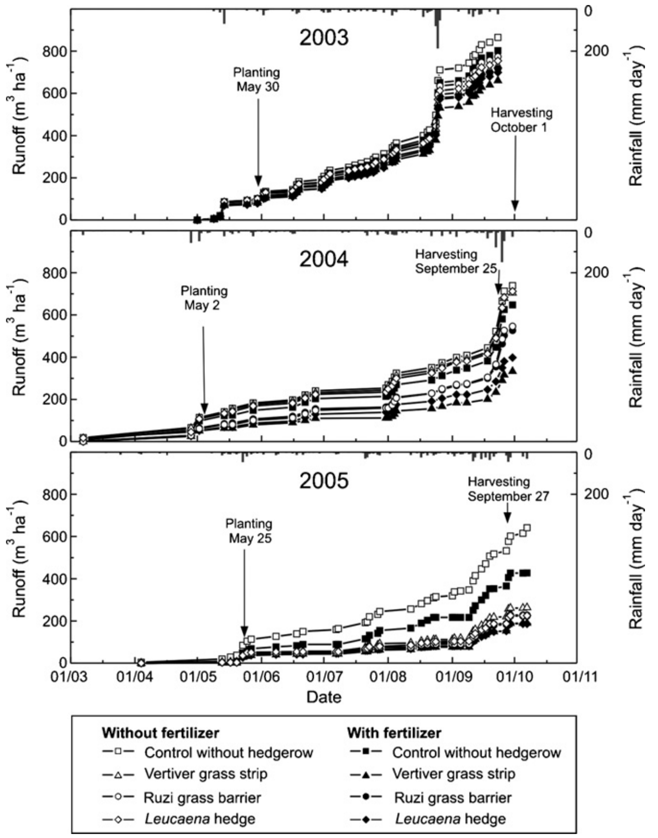

Fig. 3. Comparison of cumulative runoff as affected by soil conservation measure and fertilizer application in a time sequence for the monitored period of 3 years (2003–2005).

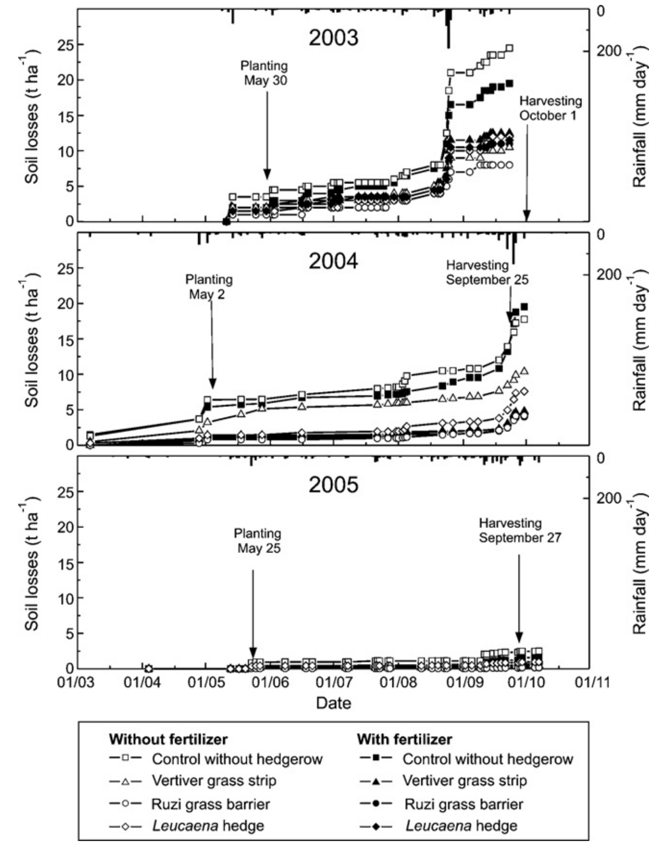

Fig. 4. The comparison of cumulative soil loss as affected by soil conservation measure and fertilizer application in a time sequence for the monitored period of 3 years (2003–2005).

equations were significantly ($p \leq 0.01$) less steep for both runoff and soil loss in the treatments with hedgerows than the slopes obtained from the control without hedgerow. In addition, linear slopes between rainfall and soil loss for all treatments in 2005 were lower than the linear slopes calculated for the data sets from 2003.

3.5. Assessment of soil conservation measures for tropical mountainous regions

The relationships of rainfall *versus* runoff and soil loss for the three consecutive monitored years allowed assessing the effect of minimum tillage, mulching and contour hedgerow systems on runoff and soil loss (Fig. 8). Shortly after establishment of soil conservation measures (line A), rainfall continued to induce high amounts of runoff, even at low rainfall intensities. Implementing only minimum tillage conditions and applying mulch, line B indicates that runoff was not greatly reduced compared to the moment of establishment, while soil loss was effectively halved (i.e. when comparing the slopes). However, the effect of minimum tillage plus mulching delayed the effects of rainfall on inducing runoff, indicated by a continuous decrease of slope and shift of the intercept towards higher rainfall events (threshold for runoff: in 2003 >0.3 mm day^{-1}; 2005: >5 mm day^{-1}). The presence of contour hedgerow systems (line C) induced the largest reduction of runoff by increasing the rainfall threshold initiating runoff (>12 mm day^{-1}) and decreasing the slope by about 26% compared to B, due to increased infiltration, surface cover and probably plant water uptake. Furthermore, the contour hedgerow systems were effective in controlling soil loss by 2/3 compared to B but less than the introduction of minimum tillage. The combined implementation of minimum tillage and mulching, and contour hedgerow systems brought soil loss below 1 Mg ha^{-1} at the end of the monitoring.

Table 3
Cumulative maize yield, runoff, soil loss, mineral N losses and ratio between mineral N losses by erosion and leaching from 2003 to 2005 at Ban Bo Muang Noi, Loei province in NE Thailand

	Cumulative 2003–2005[a]				
	Maize yield (Mg ha^{-1})	Runoff (m^3 ha^{-1})	Soil loss (Mg ha^{-1})	Mineral N losses total[b] (kg ha^{-1})	N losses surface/leaching ratio[c]
Control without hedgerow	10.7	2061	43	54.8	1.08
Vetiver grass strip	8.2	1444	22	37.1	0.37
Ruzi grass barrier	8.0	1510	14	40.3	0.29
Leucaena hedge	8.4	1491	19	39.8	0.34

[a] Data are averages of fertilizer treatments.
[b] Runoff + soil loss + leaching.
[c] Calculation: Σ mineral N losses by runoff + soil loss/mineral N losses by leaching.

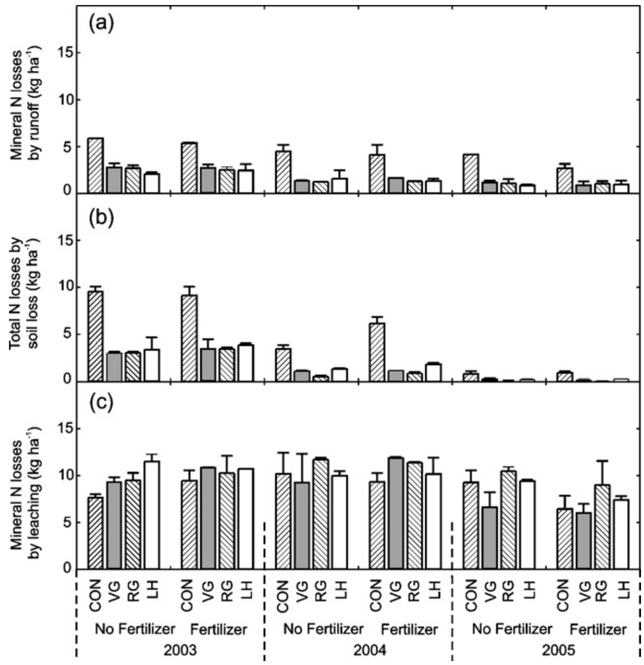

Fig. 5. Annual total nitrogen losses by (a) runoff, (b) soil loss and (c) leaching as affected by control (CON), soil conservation measures (VG = vetiver barriers, RG = ruzi grass barriers, LH = leucaena hedge) and fertilizer application during the study period (2003–2005). Error bars denote standard errors.

4. Discussions

4.1. Impact of fertilizer application on soil conservation measure performance over time

The low crop yields in the contour hedgerow systems were caused by competition between hedgerows and crop grown in alleys. Pansak et al. (2007) showed for the same experimental site (2005 dataset) that competition was mainly due to nitrogen and less due to water and could be reduced by fertilizing the crop in the alleys. Fertilizer leads to lower competition between hedges and crops, and by improving crop development, it reduces as well runoff and soil loss. As at crop establishment, or after maturing of maize, soil was more exposed to the impact of heavy rainfall events, a fast crop development during juvenile growth as well as a good soil cover during ripening is crucial for reducing runoff and soil loss. In 2005, an assessment of maize leaf area index (LAI) indicated that when soil cover was >60% soil erosion was negligible; this threshold was achieved after about 50 days after planting until 15 days before harvesting (unpublished results). The control of runoff and soil loss was not thus only affected by the presence of hedges but also by an improved crop performance. Therefore, fertilizer application also played a major role in reducing runoff and soil loss in time by improving crop establishment and providing more mulch to protect the soil from rainfall splash and erosion. These results point to the importance of fertilizer application to support the performance of soil conservation measures. On the other hand, fertilizer, well timed and in adequate quantity, did not induce increases in N losses by runoff, soil loss and leaching. Thus, well-managed fertilizer applications

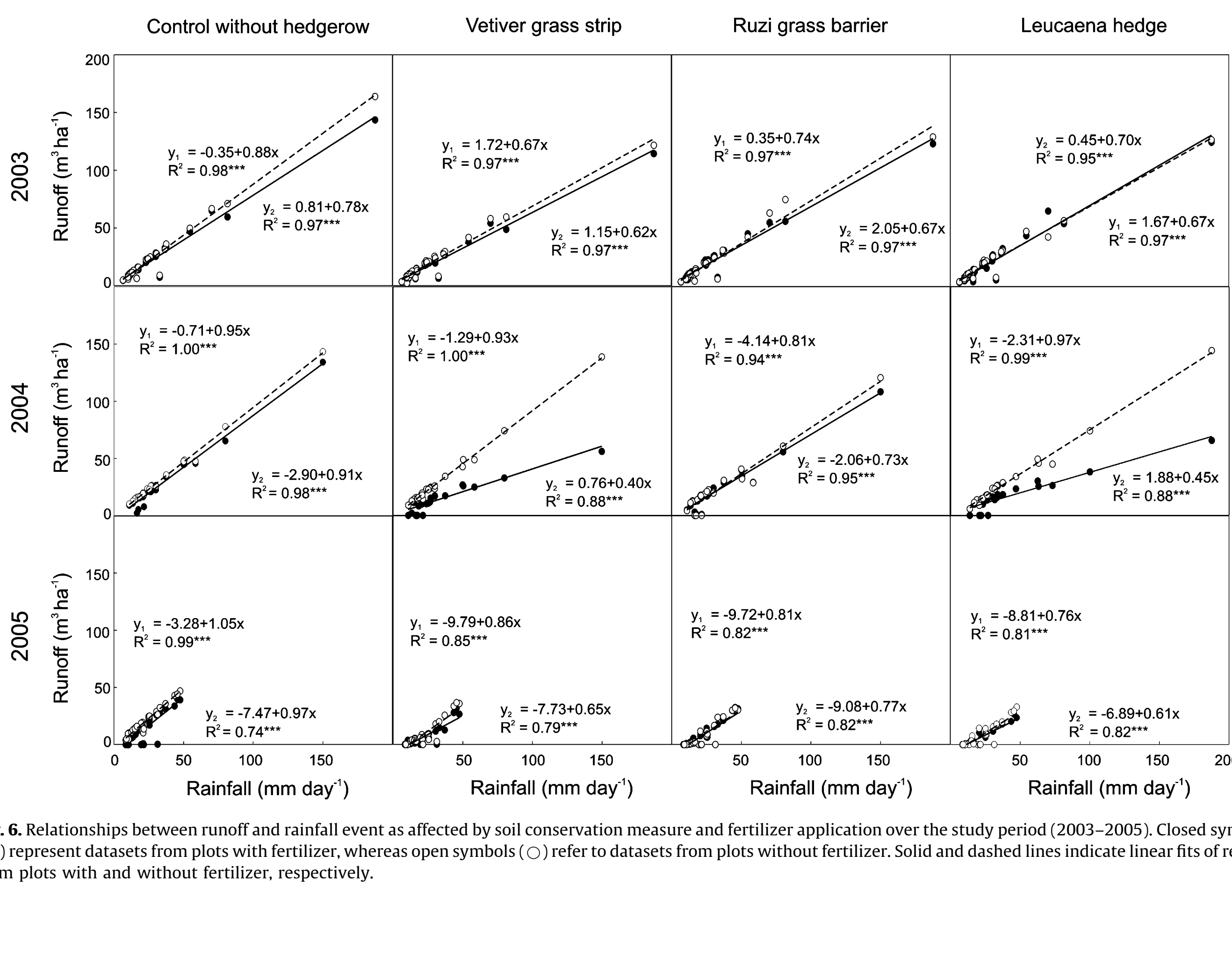

Fig. 6. Relationships between runoff and rainfall event as affected by soil conservation measure and fertilizer application over the study period (2003–2005). Closed symbols (●) represent datasets from plots with fertilizer, whereas open symbols (○) refer to datasets from plots without fertilizer. Solid and dashed lines indicate linear fits of results from plots with and without fertilizer, respectively.

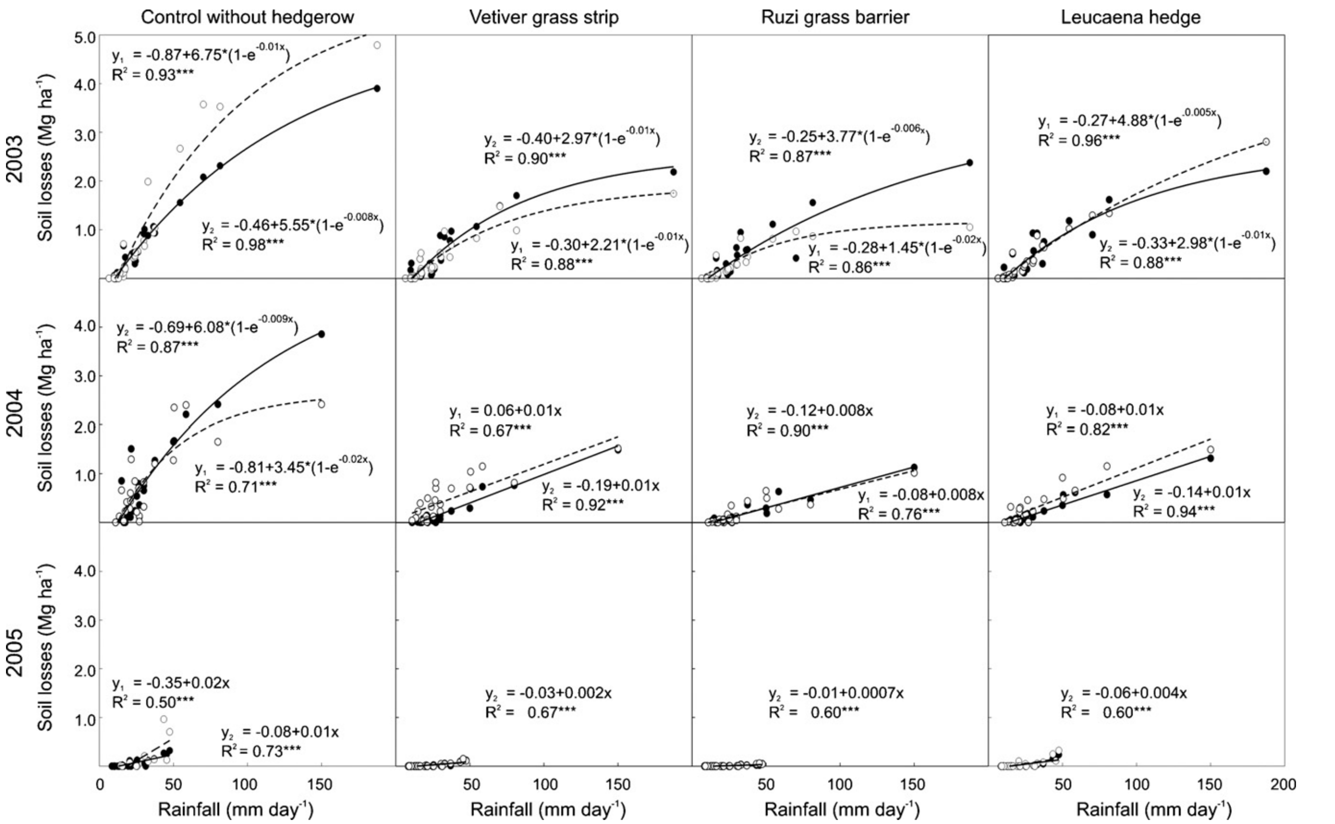

Fig. 7. Relationships between soil loss and rainfall event as affected by soil conservation measure and fertilizer application over the study period (2003–2005). Closed symbols (●) represent datasets from soil conservation measure with fertilizer, whereas open symbols (○) refer to datasets from soil conservation measure without fertilizer. Solid and dashed lines indicate linear fits of results from plots with and without fertilizer, respectively.

foster crop growth and support soil conservation measures without necessarily increasing environmental pollution.

The strong increase in crop yield in the unfertilized control plots without hedgerows suggests that the main reason for this enhanced crop response was an increase in organic matter due to minimum tillage associated with organic inputs to the soil from harvest residues and relay cropping of N_2 fixing Jack beans (Thomas et al., 2007). The positive effects on crop yield by minimum tillage, practiced in combination with mulching and growing a relay cover crop (legumes) have been documented in several studies (Sogbedji et al., 2006; Shafi et al., 2007). These effects are also strongly supported in our study by an observed increase of soil organic matter over 3 years of cropping in all treatments (e.g. 3.5% *vs.* 4.1% in the control). In addition, despite N losses, total N content in the top soil of all treatments showed an increase during the observation period, e.g. on average from 0.14% to 0.15% in plots without fertilizer application and to 0.19% in fertilized plots (unpublished results).

4.2. Temporal dynamics of runoff and soil loss after establishment of soil conservation measures

Over the three consecutive monitored years, the establishment of hedgerows significantly reduced runoff. This can be explained partly by the effect of hedgerow roots increasing the presence of macropores (Rowe et al., 2005), which enhance infiltration. However, mulching has been an additional factor in reducing runoff. This was suggested by the decreasing runoff response to rainfall over the 3 years of monitoring, for all treatments including the control plots without hedgerows. Similar results were observed in Kenya where as much as 80% of runoff was reduced by introducing hedgerows and mulching practice (Kinama et al., 2007). However, the absence of hedgerows did not reduce runoff in control plots to the same extent as in plots with hedges. Nevertheless, despite higher runoff, soil loss from the control plot with fertilization was only 1.6 Mg ha^{-1} in the last year of observation which was linked to the steady increase of the mulch layer from the relay cropped Jack beans and maize stover and reduced rainfall. Annual surface application of stover mulch of about 4–7 Mg ha^{-1} is considered sufficient to considerably dissipate raindrops (Lal, 1998), increase hydraulic roughness, and reduce flow velocity, and thereby decrease soil detachment (Kiepe, 1996). In the study presented here, about 6–16 Mg ha^{-1} of plant residues were recycled in fertilized treatments, easily exceeding the above proposed levels, whereas in treatments without fertilization about 3–7 Mg ha^{-1} of mulch was applied. The greater effectiveness of hedgerow systems in controlling soil loss as compared to runoff has also been observed in other erosion control studies with hedgerow systems (Nyakatawa et al., 2006; Raya et al., 2006). However, the first year dataset on cumulative soil loss showed that soil loss from the control without hedgerows was drastically higher than those with hedgerows. This underlines the important role of hedges in reducing soil loss at establishment of soil conservation measures. In the last monitored year minimum tillage in combination with mulching clearly assisted in reducing soil loss to less than 3 Mg ha^{-1}, while the presence of hedgerow systems became less important in controlling soil loss. While hedgerow systems did not control very well runoff in the first year, in the second year, the observed increased difference between treatments with hedgerows and control without hedgerows implies that hedges/barriers started to play a major role in reducing runoff only after 1 year due to the cumulative effect of

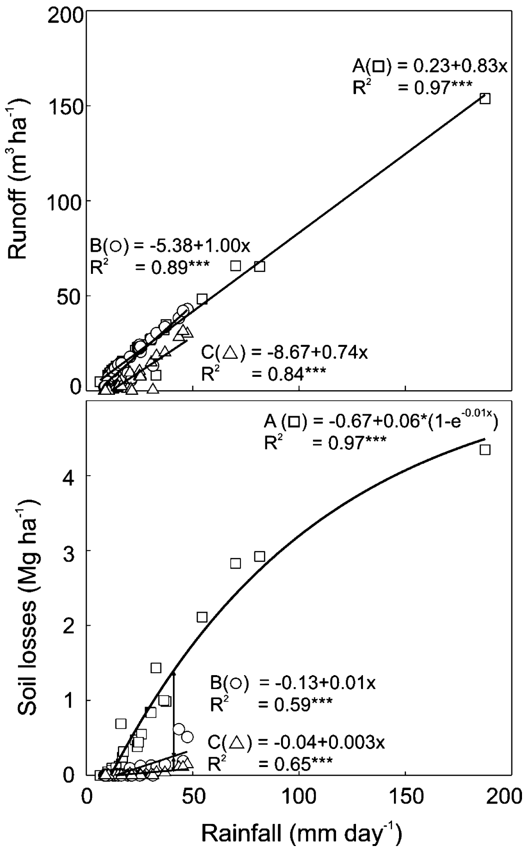

Fig. 8. Schematic representations of relationships between runoff and rainfall and between soil loss and rainfall. Lines indicate the situation at establishment of soil conservation measures (A; data from control treatment 2003), the effects of minimum tillage and mulching (B; data from control 2005) and the additional impact of contour hedgerow system (C; average data from hedgerow/barrier treatments 2005).

terracing, and increasing root (macropores) and biomass (mulch) production with time. The assessment (Fig. 8) showed that hedgerow systems perform well in controlling runoff and soil loss. Although minimum tillage in combination with relay cropping of Jack bean did not reduce strongly runoff as compared to the beginning of plot establishment, it reduced soil loss by a factor of 2 during the establishment phase. In tropical mountainous regions, where water availability is not the limiting factor in the cropping season, a high runoff does not cause restrictions for crop growth in the upland. The observed impact on runoff and soil loss patterns is similar to results from Klik (2000). He reported that conventional tillage, conservation tillage (with cover crop) and no-tillage (with cover crop) at three locations in Austria did not cause any significantly different amounts of runoff, but the lowest annual soil loss was observed in the no-tillage treatment. This agrees with our detailed assessment (Fig. 8) which indicates that minimum tillage and mulching together with relay cropping might be a potential alternative for contour hedgerow systems in tropical mountainous regions providing sufficient control of soil loss without inducing competition and associated negative effects on crop growth. The relay cropped Jack bean even will provide additional N input from biological N_2 fixation.

4.3. N balance and pathways of N losses

The temporal dynamics of N losses caused by runoff and soil loss showed similar behaviour as that of runoff and soil loss. Higher reduction of N losses by runoff and soil loss was found in hedgerows treatments as compared to the control plots without hedgerow over 3 years of monitoring. Therefore, N losses in runoff and soil loss were controlled by volume of runoff and total amount of soil loss. Similar results have been reported by Zöbisch et al. (1995), who found that total loss of nutrients was also dependent on total amount of runoff and soil loss. Mineral N losses through erosion showed a similar trend when compared with other studies (Kongkaew, 2000; Fagerström et al., 2002; Owino et al., 2006). However, treatments, regardless of fertilization, showed no significant difference in N losses as also observed by Uhlen et al. (1996). The lack of difference of N losses between fertilizer treatments can be explained by the improved N uptake by maize and hedgerows. This argument was supported by the better growth of hedgerows in the treatment with fertilizer. Mineral N losses in all treatments were slightly lower in 2005, particularly in the treatments with fertilizer application, as compared to 2003 and 2004. The lower precipitation in the third year of observation is probably the major reason. Additionally, the better development of the vetiver grass and ruzi grass barriers and leucaena hedges with time suggests a higher uptake of mineral N further reducing losses by leaching, and finally the Jack bean relay crop probably also reduced N leaching (Aronsson, 2000).

Our study showed that the hedgerow treatments shifted the main pathway of N losses towards leaching losses of mineral N. This implies that a hedgerow system effectively reduced mineral N losses by surface pathways whereas mineral N losses by leaching increased in some cases due to increased drainage (Rowe et al., 2005) or remained similar to the control due to the competition for mineral N by the tree or grass. Similar results were reported from trials with soil conservation in northern parts of Thailand (Kongkaew, 2000). Nevertheless, the average mineral N losses by leaching of 10 kg N $year^{-1}$ at 90 cm depth were lower than those of sandy loamy soils as found in Northern Vietnam, where the loss was about 40 kg N ha^{-1} $year^{-1}$ for upland rice fields (Trinh, 2007); but were confirmed by modelling the system (unpublished data).

5. Conclusions

Fertilizer application enhances the efficiency of soil conservation measures in improving crop and hedgerow performance and thereby reducing runoff and soil loss. Moreover, it does not have to result in higher N losses by runoff, soil loss and leaching, when fertilizer is properly managed, e.g. by using split applications. Therefore, well-managed fertilizer application does not per se cause an increase in environmental N pollution.

Contour hedgerows were shown to be important in reducing runoff and soil loss, in particular at the beginning of field establishment. When contour hedgerows are combined with the use of additional soil conservation measures, such as minimum tillage and mulching, hedgerows have a less important role to play in the reduction of soil loss in the later phase of establishment. Therefore, temporal barriers, for example a natural vegetation strip, together with minimum tillage and relay cropping (legume) is one alternative option for using contour hedgerows during the initial phase of establishment of a cropping system. It can be easily removed when the system is well established, and it will avoid competition between barriers hedges and crops. Using conservation agriculture (without hedgerows) runoff still exists but is cleaner (at least during small to moderate rainfall events), i.e. much less loaded with sediments, and this is desired for supplying downstream paddy fields with water. Thus, where reducing a systems runoff is not the major goal, a combination of minimum tillage and mulching together with relay cropping with Jack bean, could provide a sustainable agricultural practice on moderate slopes. However this study was carried out on a relatively fertile soil with good water holding capacity, providing good conditions for plant growth and thereby supporting a fast build up of a protective mulch layer. Therefore, this approach would need to be tested on poorer soils and steeper slopes, where the necessary protecting mulch might be washed away to lower deposition areas by heavy rainfall events (Lal, 1989).

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