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Soil Conservation, Erosion and Nitrogen Dynamics in Hillside Maize Cropping in Northeast Thailand

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CHAPTER 1

General introduction

1. General introduction

Soil is under increasing threat from a wide range of human activities that are undermining its long-term availability and viability. One third of the world's agricultural soil or almost 2 billion hectares of land is affected by soil degradation (Ritsema et al. 2007). Within this area, about 1966 million hectares are affected by erosion (Lal 2007). Soil erosion is a global issue because of its severe adverse economic and environmental impacts. The major on-site impact of erosion is the loss of crop productivity and this is mirrored in reductions of crop yield and water and nutrient use efficiency. In regions of the world with variable rainfall distribution the loss of topsoil increases the vulnerability of human food supplies. Off-site impacts of erosion relate to the economic and ecological costs of sediment, nutrients, or agricultural chemicals being deposited in streams, rivers, and lakes. Adoption of soil management practices to reduce erosion may have profound effects on future world food supplies.

1.1 Erosion effects on soil nutrients and crop productivity

Presently, soil erosion affects more than 300,000 km^2 or 65% of the cultivated land area of Thailand (Kunaporn 1999). Almost 17% of agricultural land in Northeastern Thailand is classified as vulnerable area for soil erosion (Land Development Department 1998). In Northeast Thailand, degradation of agricultural land by water induced erosion causes nutrient depletion, low soil productivity, and an ever lower productivity of important food crops. The eroded areas, however, are still used year by year for subsistence agriculture whereas the matrix lands are intensively utilized for income generation by cash crop production. In addition, shortening of fallow periods caused by a steadily growing population contributes to the low and even decreasing crop production.

Soils differ in their susceptibility to loss of productivity as soon as the topsoil is eroded. The differences are related to the depth of the topsoil and the amount of nutrient fertility or presence of unfavourable conditions in the subsoil. Rose and Dalal (1988) summarized the results of a series of experiments conducted on wheat in semiarid regions of Australia. They observed that wheat yield declined linearly with increasing loss of topsoil plotted on a logarithmic scale. For a soil loss of about 10 Mg ha^{-1} (about 1 mm depth of soil), yield reduction was about 20% for sites with a shallow topsoil. The yield reduction was about 50% corresponding with 100 Mg ha^{-1}, 90% for 1000 Mg ha^{-1}, and total loss for 2000 Mg ha^{-1} of soil loss. The rate of decline was more moderate for soils with medium to deep profiles than for the shallower soils with a texture contrast profile or a saline subsoil. For soils with medium to deep profiles, yield reduction was about 5% for 10 Mg ha^{-1} of soil loss, 15% for 100 Mg ha^{-1}, 20% for 1000 Mg ha^{-1}, and 25% for 2000 Mg ha^{-1}.

Loss of fertility is also a major impact of soil erosion, especially in old and highly weathered soils in which soil organic carbon and plant nutrients are concentrated in the upper few centimeters of the soil profile. Loss of soil fertility is the principal cause of yield decrement on eroded soils (Peterson 1964). Nutrient losses are much severer on arable lands, where supplemental fertilizer application may have a masking effect on crop yields (Cleveland, 1995). Kongkaew (2000) reported that in Northern Thailand, N losses by erosion amounted to 30 kg ha^{-1} per year under farmer practice. However, N losses by erosion were only 20% of the total losses, whereas leaching produced 50-80% of the total N losses. Moreover, Sajjapongse (1995) presented that on slopes of 5-7% at the Bavi site in Vietnam, high losses of plant nutrients were observed on bare soil (26 kg N, 13 kg P, and 38 kg K) and farmer's practice (15 kg N, 10 kg P, and 30 kg P) over two years. In contrast, Fagerström et al. (2002) found in Northern Vietnam erosion induced N losses of up to 150 kg ha^{-1} for upland rice, grown over a period of two years on fields with an average slope of 20-28%. Furthermore, experiments conducted at the International Institute of Tropical Agriculture (IITA) in Nigeria showed that the total nutrient loss (PO_4-P, NO_3-N, Ca, Mg and K) in plow-till treatment was 26.8 kg ha^{-1} for the first season, 2.0 kg ha^{-1} for the second season, and 28.8 kg ha^{-1} for both seasons. In contrast, the annual total nutrient loss for both seasons was 3.7 kg ha^{-1} for no-tillage, 14.9 kg ha^{-1} and 7.7 kg ha^{-1} for Leucaena at hedgerow distances of 4 m and 2 m, and 8.6 kg ha^{-1} and 9.5 kg ha^{-1} for gliricidia at hedgerow distances of 4 m and 2 m, respectively (Lal 1976). Lal (1996) also reported that nutrient losses in runoff were higher from watersheds sown to leguminous cover (*Mucuna utilis*) or grazed pastures than from watersheds cropped to corn-cowpea rotations with no-till system. The maximum annual loss of nutrients in runoff ranged from 13.8 kg ha^{-1} for mucuna fallow on degraded soils, 13.5 kg ha^{-1} for grazed pastures on degraded soils, 8.9 kg ha^{-1} for mucuna fallow on less degraded soils, 4.4 kg ha^{-1} for grazed pastures on less-degraded soils to 3.7 kg ha^{-1} in alley cropping systems. Leucaena hedgerows established on contour lines at 4-m intervals were effective in decreasing runoff, soil erosion, and nutrient loss.

1.2 The role of soil conservation measures in erosion control

Soil conservation measures play an important role in reducing soil erosion on sloping farmlands in hilly areas. Monsalud et al. (1995) reported that the erosion of steep sloped maize and groundnut fields was effectively controlled by introducing hedgerow of gliricidia with napier grass at the Tanay site, Philippines. The annual erosion of hedgerow plots was only 3 t ha^{-1} $year^{-1}$. Moreover, Paningbatan et al. (1995) found that leguminous shrub hedgerows reduced the annual erosion of maize and mung bean fields from 100 to 200 t ha^{-1} $year^{-1}$ to amounts of less than 5 t ha^{-1} $year^{-1}$. Similar results were observed in China and Spain where as much as 30 to 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 had an important role in reducing N losses from aqueous erosion. In Kenya, Owino et al. (2006) proved the effectiveness of narrow grass strips in controlling nutrient loss. Napier grass (*Pennisetum purpureum*) reduced NO^{-}_{3}-N and NH^{+}_{4}-N losses by 45-50%.

In Thailand, suitable soil conservation systems for minimising soil erosion have been proposed by several development agencies for more than twenty years. Among them were planting of Vetiver grass strips and perennial fruit trees on bench terraces, maintaining soil cover by leguminous species, and inter-cropping of perennial trees with annual food crops. Each of these conservation systems was promising but in different areas and ways. The success of soil conservation measures often depended on the physical and socio-economic-limiting factors which are involved in a particular area. Locally well adaptated and promising options were integrating perennial crops such as mango, banana, papaya, pineapple, and fodder grass into cropping of important annual food crops such as maize, upland rice, peanut, and cassava. These options were the most interesting ones in terms of financial returns, land efficiency, effectiveness in soil and water conservation, and crop yields as compared to other soil conservation practices (Anecksamphant 1994; Turkelboom et al. 1996). The safety-net role of perennial plants in cropping systems has been widely discussed since the nineties. Schroth (1995) emphasised the 'safety net' function of tree root systems which according to Van Noordwijk et al. (1991) and Rowe et al. (1999) may prevent nutrient losses and improve nutrient cycling. According to nutrients in soils the magnitude of losses was probably minimized by a higher uptake of deeper rooting perennial plants, fertilizer application synchronised with crop demand, and planting of cover crop. Cover crops also play an important role in erosion control and improving soil fertility. Annual cover crops such as local black bean (*Vigna unguiculata*) and lablab bean (*Lablab purpureus*) are able to suppress weeds well (Pintarak et al. 1993). Tillage has to be frequently conducted when there is weed infestation. Then tillage system always resulted in higher soil erosion on hillsides as the bare tilled soil is susceptible to erosive rainfalls. Thus, soil cover provided by cover crops may be a reasonable practice for reducing soil erosion and suppressing weeds because the tillage is minimised. This had been verified by IBSLRAM experiments in Thailand where soil loss was reduced to less than 10 Mg ha^{-1} yr^{-1} by a soil cover of lablab straw (Kongkaew 2000). In terms of yield improvement, planting cover crops improved grain yield of rice by 50 to 70% (Turkelboom and Van Keer 1996).

1.3 The disadvantage of soil conservation measures

To date, however, integrating annual food crops into cropping systems with edible tree species or hedgerow systems have not been widely adopted by farmers because of technical problems and lack of fit with farmers' needs (Bewket 2007; Knowler and Bradshaw 2007). The limiting factors in adoption of contour hedgerow systems consist of: i) fragmented land ownership makes it difficult for farmers to invest optimally in soil and water management systems. ii) extra labour is required for pruning and hedgerow maintenance. iii) many farmers lack in the skills to design and build conservation structures. Substandard and poorly constructed structures are often being the result. iv) land-tenure systems determine the ownership of the structures and influence farmers' interest in conservation and in maintaining the structures. v) irregular rainfall period, event, and intensity reduces the effectiveness of vegetative erosion-control practices (Garrity, 1999). Reduction by 15-25% of cropping area due to additional hedgerow planting and competition between hedgerows and crops is among main farmers' concerns when applying hedgerow systems. Many studies showed that yield in rows adjacent to hedgerows declined due to competition for light, water, and nutrients (Agus et al. 1999; Friday and Fownes 2002; De Costa and Surenthran 2005; Dercon et al. 2006a; Kinama et al. 2007; Pansak et al. 2007). Finally, economic factors play a key role in determining whether farmers will adopt such technology or not. 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). Due to limitations mentioned above, farmers are unlikely to adopt contour hedgerow system. Therefore, alternatives, which reduce soil degradation and at the same time meet farmer interests, are required.

On steep slopes, the impact of contour hedgerow systems on soil properties and crop response has been studied in detail over the past decade (Agus et al. 1997; Turkelboom et al. 1997; Dercon et al. 2003). However, although there are enough indications that spatial variability in soil properties and crop response and consequently the effectiveness of contour hedgerow systems are related to soil translocation by tillage and competition between annual crops and hedgerows, research is scanty in separating the impact of both processes, i.e. soil translocation and competition. In order to get better insight in the processes driving competition between crop and hedgerow, carbon isotope composition of the crops grown in the alleys can offer a possible outcome. Dercon et al. (2006b) highlighted the potential use of ^{13}C isotope discrimination in maize to signal water stress at low to high nitrogen availability. This study showed that changes in $\delta^{13}C$ values in maize could be related to soil moisture status and nitrogen supply. However, even changes in ^{13}C isotopic discrimination due to nitrogen availability could be indirectly linked to water stress. The relationship between ^{13}C isotopic discrimination and water stress is well documented for C_4 plants. Therefore, the use of ^{13}C isotopic discrimination is a good diagnostic tool useable under field conditions to identify causes of competition between crop and hedges which are imperative to better understand competition leading to a decline in crop response closed to the hedges.

1.4 Erosion modelling

Soil conservation systems are still required to be developed and studied from time to time for meeting farmer needs, but experimental testing for their potential application domain or design is costly and time consuming. In addition to the study at the experimental sites, investigation of field properties by modelling can also play an important role in both meeting practical needs of soil conservation goals and advancing the scientific understanding of soil erosion processes. Since modeling can be done in relatively short developing time compared with the establishment of the field experiment, it could be more suitable for predicting long term effects of soil conservation. Development of improved soil erosion prediction technology is required to provide conservationists, farmers and other land users with the tools they need to examine the impact of various management strategies on soil loss and sediment yield and plan for the optimal use of the land. Many erosion models were developed during the last four decades to predict the impacts of soil loss on agricultural productivity. An important line of currently used models started with the Universal Soil Loss Equation (USLE) (Wischmeier & Smith 1965, 1978) and branched into other empirical models such as Revised Universal Soil Loss Equation (RUSLE) and Modified Universal Soil Loss Equation (MUSLE). These empirical models have, until now, been applied to examine the experimental works in plot sites around the world because of their relative simplicity and small number of input parameters compared to other more complex erosion models. USLE, RUSLE and MUSLE models can predict soil erosion by water at plot scale (a standard plot was defined by Wischmeier & Smith (1978) as a land with 22.1 m long, 1.8 m wide size, and 9% of slope). Because of the empirical character of these models, there are some inconveniences to use them. One of them is the need to measure, for each specific situation, a single summary crop or soil parameter, which has other implicit parameters inside. It means that one cannot isolate the effect of each parameter. In addition, the processes that modify the intensity of erosion under various soil and crop conditions cannot be properly explained. Some process models (or physical models) were developed in comparison with USLE-related models. Examples of these models are Rose equation (Rose et al. 1988), Chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS) (Knisel 1980), Griffith University Erosion System Template (GUEST) (Misra and Rose 1990, 1996), and the Water Erosion Prediction Project (WEPP) model (Flanagan and Nearing 1995). The distinct advantage of the physically based models is that they can predict off-site impacts of erosion such as sediment yield, runoff, sediment enrichment rate, and nutrient loss.

1.5 WaNuLCAS modelling

The Water, Nutrient and Light Capture in Agroforestry Systems (WaNuLCAS) model is a process-based model of water, nutrient and light capture in agroforestry systems at plot scale. WaNuLCAS was developed to represent tree-soil-crop interactions in a wide range of agroforestry systems where trees and crops overlap in space and/or time (simultaneous and sequential agroforestry) (Van Noordwijk et al. 1998). The model is based on soil science, tree and crop physiology and integrates above and below ground architecture of crops and trees in a spatial and temporal way. WaNuLCAS is developed under the Stella® modeling environment (STELLA 1994) and linked to Microsoft Excel spreadsheets for input data. The Stella shell allows the users to modify parameters and also add additional model structure. Simulations require a defined soil profile (physical and chemical properties per layer), degree of slope and climate conditions. Values can be set for a large range of input parameters considering, for example, soil management, nutrients and profitability. The field plot is visualized as four horizontal zones with four vertical layers of soil (van Noordwijk and Lusiana 2000). The model has an option to predict water induced erosion. Thus, it can be used to explore positive and negative effects of various combinations of trees and crops, its management, soil, and weather on runoff and soil loss which the output parameters give information on a daily time step. Soil erosion submudule in WaNuLCAS uses Rose equation for calculating event soil loss. This equation is based on the concept of simultaneous erosion and deposition (Rose 1985; Rose and Freebairn 1985; Rose 1998). In this approach, three continuous processes-rainfall detachment, flow detachment, and sediment deposition - are considered simultaneously.

Currently, WaNuLCAS is the most flexible model available for the evaluation of management options in agroforestry systems, crop rotations and hedgerow intercropping systems at different hedgerow spacing and pruning regimes, crop-fallow mosaics and parkland systems with a circular geometry based on site-specific information and farmer management objectives. Simulation results that can be generated by the model include nutrient dynamics, water balances, light use, crop and tree biomass, and crop yield.

1.6 Objectives

The goal of this study was to describe the dynamics of runoff, soil loss and nitrogen losses by erosion and leaching risk under various soil conservation systems and two N-fertilizer application regimes. It also aimed at understanding the interactions between a crop and hedgerow/grass barrier species with regard to crop yield performance.

More specific objectives of this study are:

- 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.
- To assess the use of ^{13}C isotopic discrimination, in combination with standard methods in determining N availability and uptake, in order to better understand (i) competition for water and N between crops and barrier species, (ii) water and N uptake by crops under contour hedgerow systems and (iii) to derive a conceptual framework to assess relationships between crop response, N and water availability and $\delta^{13}C$.
- Using field experimental data to calibrate and validate the erosion submodule of the WaNuLCAS model

- To better understand the role of various soil conservation measures on controlling erosion by using the WaNuLCAS model
- To use the model to assess the magnitude and dynamics of key processes influencing the efficiency of soil conservation measures.

1.7 Outline of the study

This thesis is mainly compiled from two published and one submitted papers. The research topic is dynamics of nitrogen losses of hillside cropping systems with soil conservation measures in Northeast Thailand. The field experiment was established at Ban Bo Muang Noi village in Loei province of Thailand (17°33' N and 101°1' E, 572 m a.s.l.) on a moderate slope gradient ranging from 21-28%. Crop performance, runoff, soil loss and N losses by erosion and leaching were collected from erosion plot after every rainfall event under different soil conservation measures as related to different N-fertilizer application over a period of three consecutive years (2003-2005). In this thesis book Chapter 2 presents the results of a study of changes in the relationship between soil erosion and N loss pathways after establishing soil conservation systems in uplands of Northeast Thailand. Chapter 3 describes ^{13}C isotopic discrimination: a starting point for new insights in competition for nitrogen and water under contour hedgerow systems in tropical mountainous regions. In Chapter 4 a study on assessing alternative conservation strategies on a hillside cropping system of Northeast Thailand by using WaNuLCAS is presented. This work is completed by general discussion and summary.

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CHAPTER 2

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

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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.

Keywords: Runoff; Leaching; Minimum-tillage; Relay cropping; Conservation agriculture; Contour hedgerows; Grass barriers

2.1 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) 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 above-ground 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.

2.2 Materials and methods

2.2.1 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 (17º33'N and 101º1'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. The study area has a tropical savannah climate. Annual temperatures range from a high of 44 ºC to a low of 11 ºC, with a mean temperature of 26 ºC 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.

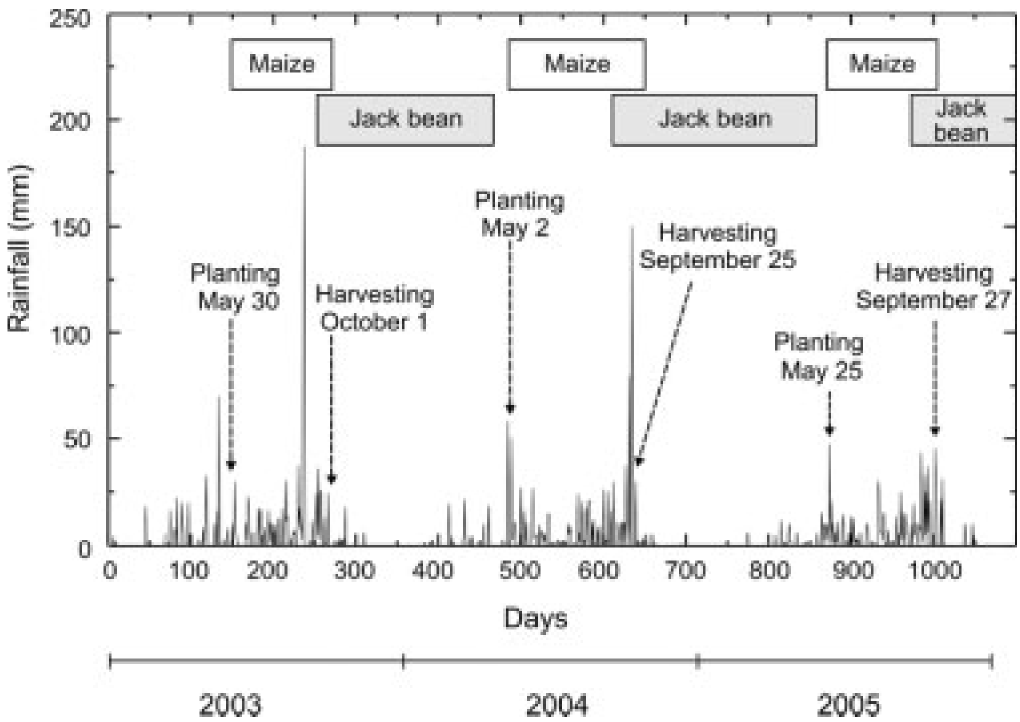

Fig. 1 Daily rainfall distributions for the monitored period of 3 years (2003–2005) at the experimental site in Ban Bo Muang Noi, Loei province, Northeast Thailand. Arrows indicate planting and harvesting dates.

2.2.2 Experimental design

Land preparation was done by slash and burn before starting the experimental study. The experiment was established in April 2003and 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).

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 September2003. 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).

2.2.3 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 ºC 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).

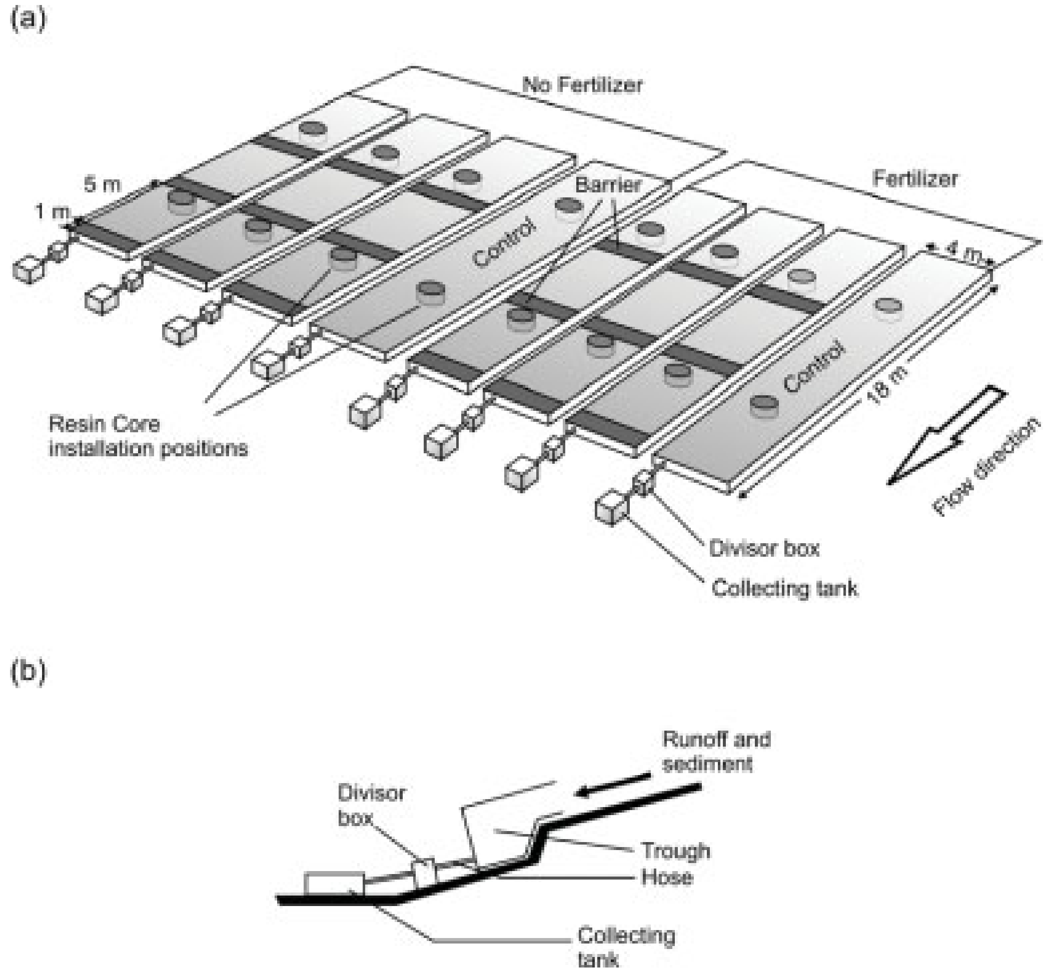

Fig. 2 (a) Experimental layout of erosion plots at Ban Bo Muang Noi, Loei province, Northeast Thailand. (b) Schematic of erosion measurement used for collecting runoff and soil loss.

2.2.4 Nitrogen leaching

Nitrogen leaching was assessed by the resin core method (Kongkaew 2000 and 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).

2.2.5 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.

2.2.6 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.

2.3 Results

2.3.1 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).

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 x Year			< 0.001							
		SC x F			0.030							
		F x 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 x Year			0.030							
		SC x F			0.030							
		F x 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 to 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 x Year		0.030								
		SC x F		0.070NS								
		F x 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 x Year		< 0.001								
		SC x F		0.037								
		F x 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}

2.3.2 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 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 (Fig. 3 and Fig. 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.

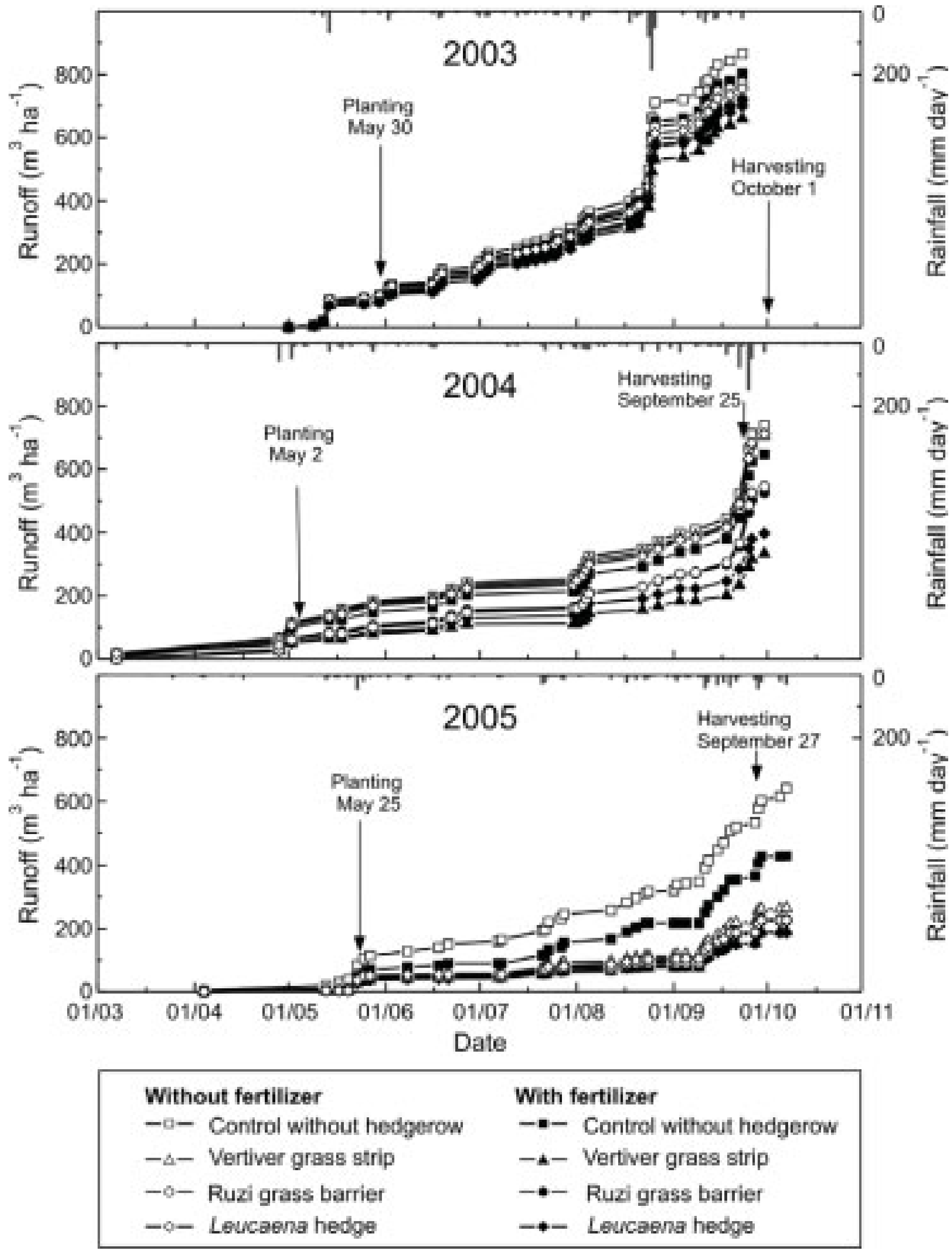

Fig. 3 Comparison of cumulative runoff as affected by soil conservation measure and fertilizer application in a time sequence for the monitored period of 3 years (2003-2005).

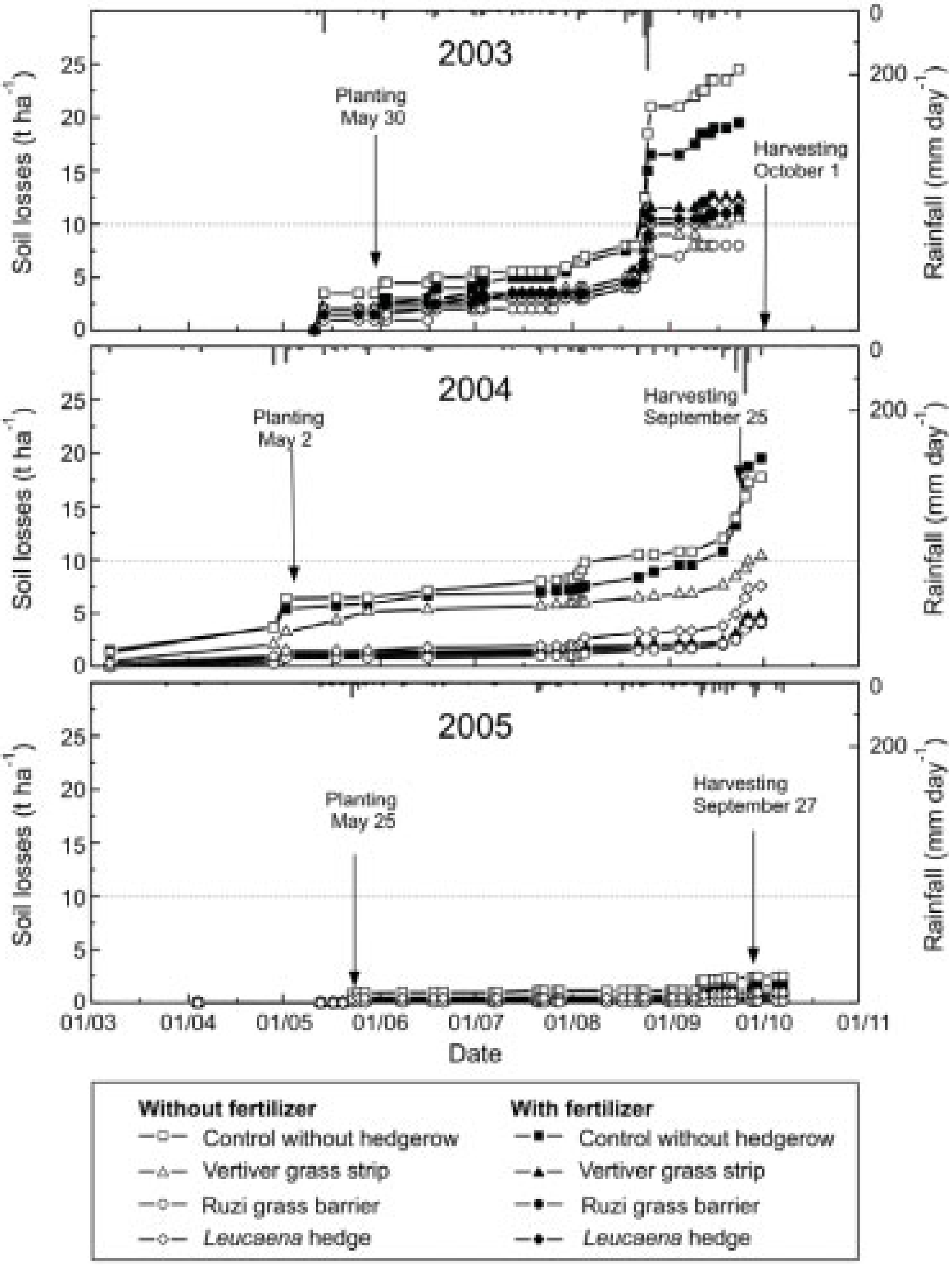

Fig. 4 The comparison of cumulative soil loss as affected by soil conservation measure and fertilizer application in a time sequence for the monitored period of 3 years (2003–2005).

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

	Cumulative 2003-2005[1)]				
	Maize yield	Runoff	Soil loss	Mineral N losses total[2)]	N losses surface/leaching ratio [3)]
	Mg ha^{-1}	m^3 ha^{-1}	Mg ha^{-1}	kg ha^{-1}	
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

[1)] Data are averages of fertilizer treatments

[2)] Runoff + soil loss + leaching

[3)] Calculation: ∑ mineral N losses by runoff + soil loss/ mineral N losses by leaching

2.3.3 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.

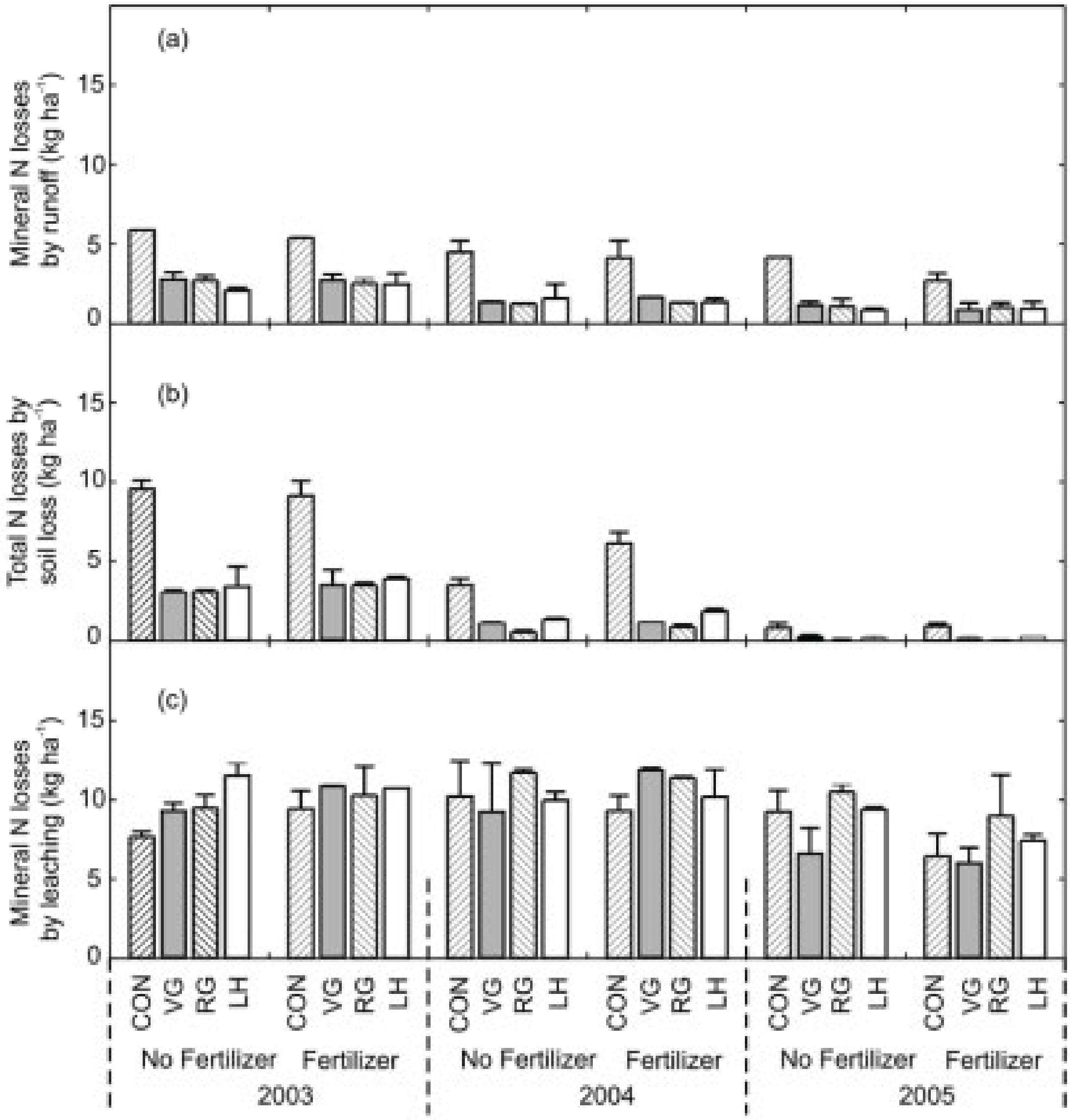

Fig. 5 Annual total nitrogen losses by (a) runoff, (b) soil loss and (c) leaching as affected by control (CON), soil conservation measures (VG = vetiver barriers, RG = ruzi grass barriers, LH = leucaena hedge) and fertilizer application during the study period (2003–2005). Error bars denote standard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

2.3.4 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 (Fig. 6 and Fig. 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 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.

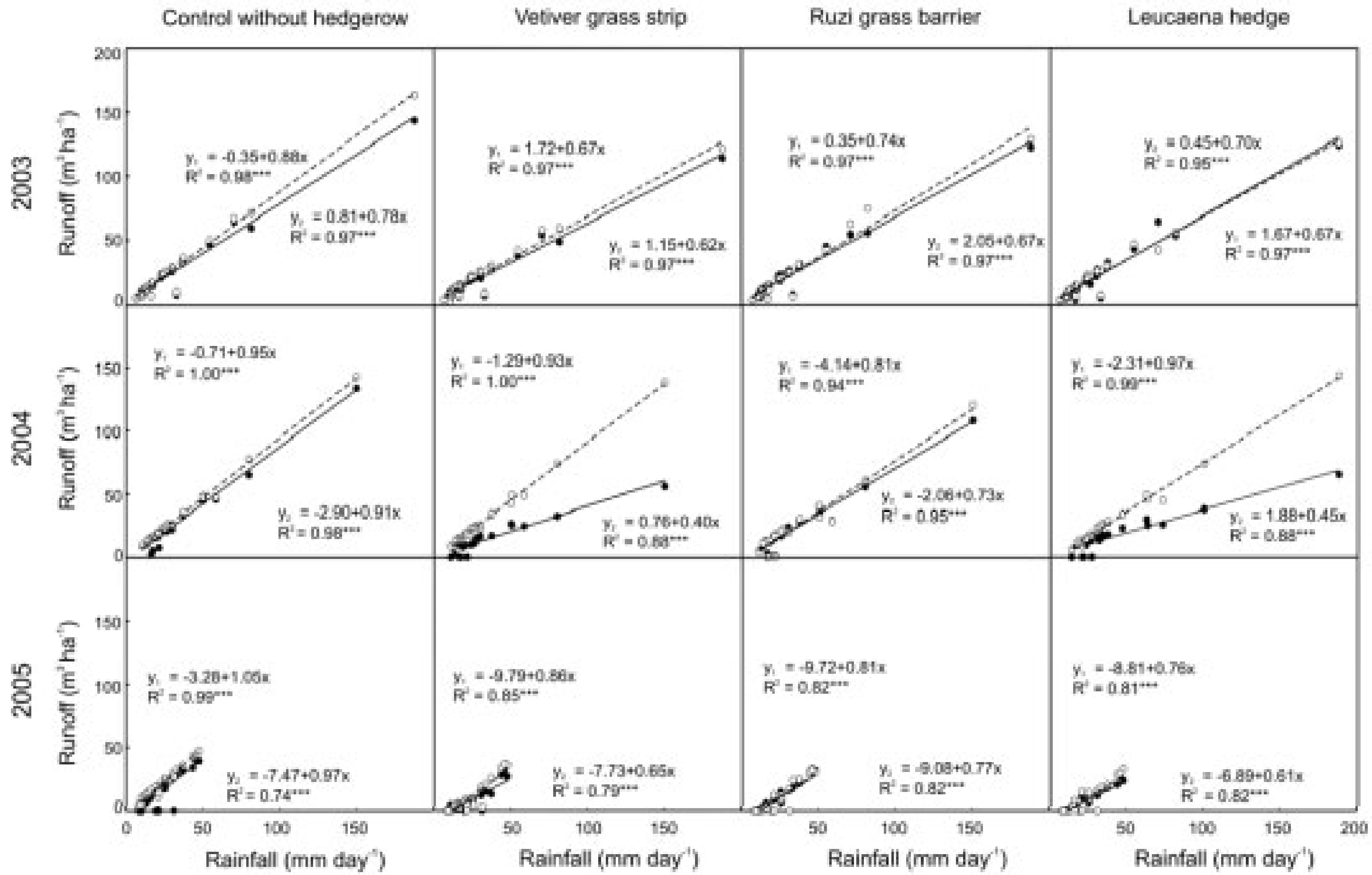

Fig. 6 Relationships between runoff and rainfall event as affected by soil conservation measure and fertilizer application over the study period (2003–2005). Closed symbols (●) represent datasets from plots with fertilizer, whereas open symbols (○) refer to datasets from plots without fertilizer. Solid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

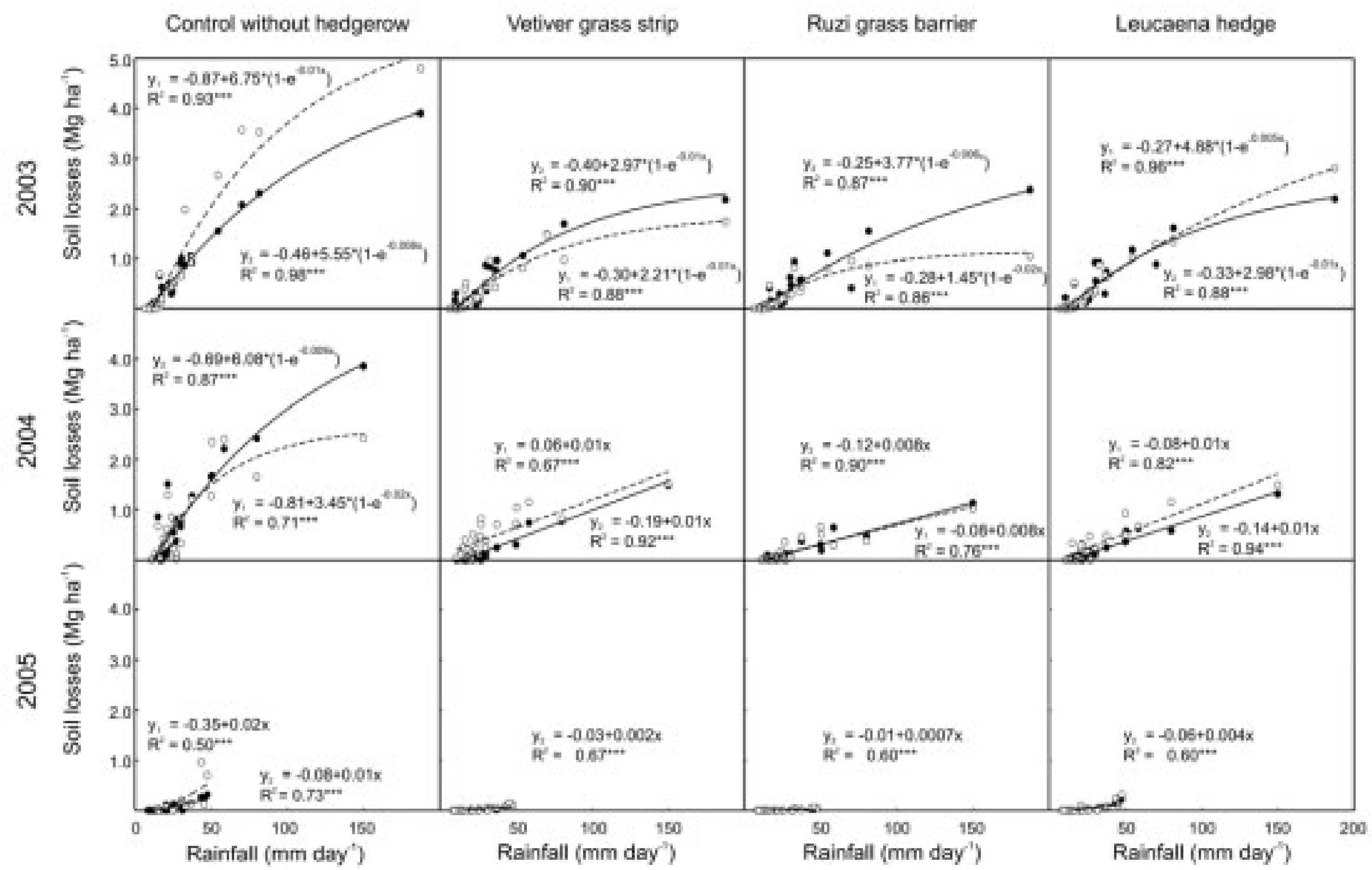

Fig. 7 Relationships between soil loss and rainfall event as affected by soil conservation measure and fertilizer application over the study period (2003–2005). Closed symbols (●) represent datasets from soil conservation measure with fertilizer, whereas open symbols (○) refer to datasets from soil conservation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

2.3.5 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.

2.4 Discussions

2.4.1 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 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 and 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).

2.4.2 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 and 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 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.

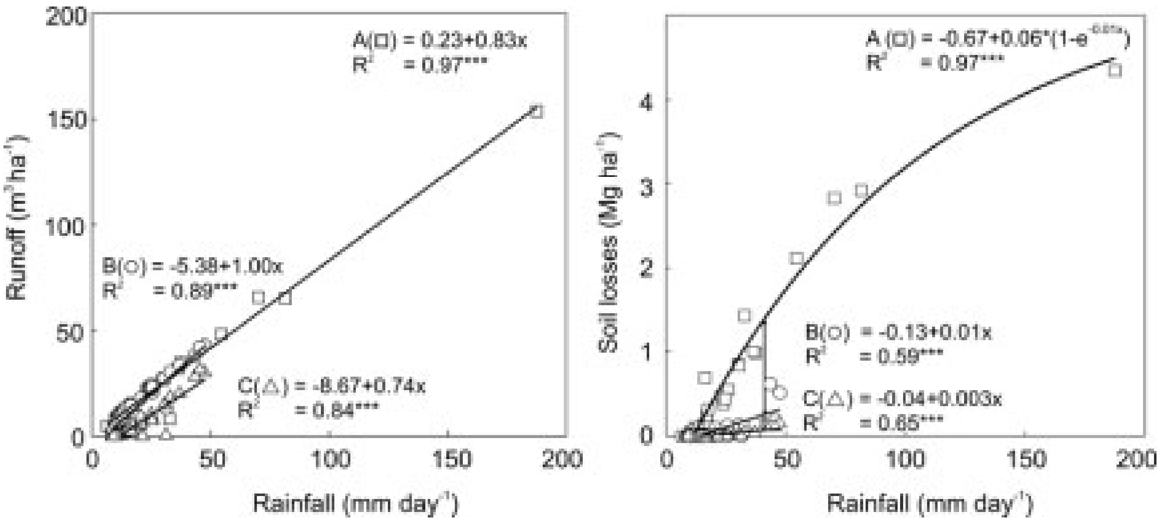

Fig. 8 Schematic representations of relationships between runoff and rainfall and between soil loss and rainfall. Lines indicate the situation at establishment of soil conservation measures (A; data from control treatment 2003), the effects of minimum tillage and mulching (B; data from control 2005)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

2.4.3 N balance and pathways of N losses

The temporal dynamics of N losses caused by runoff and soil loss showed similar behavior 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 and 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).

2.5 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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CHAPTER 3

^{13}C isotopic discrimination: a starting point for new insights in competition for nitrogen and water under contour hedgerow systems in tropical mountainous regions*

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Abstract

Competition for nutrients and water between crops and associated hedgerows reduces overall performance of contour hedgerow systems and hampers its acceptance by rural communities in tropical mountainous regions. Therefore, it is imperative to better understand competition leading to a decline in crop response close to hedges. In the highlands of North East Thailand spatial variability in grain yield of maize (*Zea mays* L., cv. Suwan 1) was assessed for two contour hedgerow systems based on *Brachiaria ruziziensis* Germain et Evrard (Ruzi grass) barriers or *Leucaena leucocephala* (Lam) de Wit hedges without or with fertilizer (60 kg N ha^{-1} and 14 kg P ha^{-1}). Available NO_3^--N was analyzed across the slope. In addition, shoot N concentration and $\delta^{13}C$ values in leaves were measured for maize plants in the center of the alley and in the row next to and at the upper side of barriers or hedges. Despite variable field conditions, $\delta^{13}C$ values were significantly ($p < 0.05$) less depleted close to the barriers or hedges, except for 2 out of 16 plots, suggesting that water deficiency was not the main driver for spatial variability along the alleys. The negative correlation between ^{13}C isotopic

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discrimination and available NO_3^--N in the soil, with R^2 ranging from 0.5 ($p < 0.10$) to 0.9 ($p < 0.01$), assigned a major role to N availability in the reduced crop response towards the barriers. The proposed framework of ^{13}C isotopic discrimination, together with plant and soil N data, is a new approach and was shown to be suitable to determine N and water competition between hedgerows and crops grown in alleys under field conditions.

Keywords: Maize; Nitrogen deficiency; Spatial variability; Stable carbon isotope ratio; Thailand; Water stress

3.1 Introduction

In tropical mountainous regions, soil conservation measures based on contour hedgerows are extremely effective in reducing runoff and controlling erosion on steep slopes (Lal 1989; Craswell et al. 1998; Morgan 2005; Pansak et al. 2006). Through time, this technique gradually develops natural terraces, which further minimize soil erosion and surface run-off (Sims 1997; Van Noordwijk and Verbist 2000; Dercon et al. 2007). However, several studies have indicated that the presence of hedges or grass barriers, and the resulting terrace formation can also have a negative impact on crop response in the alley (Agus et al. 1997; Turkelboom et al. 1997; Dercon et al. 2003, 2006b). The effectiveness of soil conservation measures can be reduced due to (1) competition for nutrients, light and water between crops in the alley and species forming the hedges and (2) exposure of infertile subsoil near the upper part of the alley during terrace formation, in particular on steep land when soils are shallow (Dercon et al. 2006b). Nevertheless, identification of the magnitude of each of these processes at field level is not straightforward; in particular when these elements interact with each other, as in the case of N and water, which are main drivers of competition between crops and hedges under contour hedgerow systems (Livesley et al. 2004; Dercon et al. 2006b). Clay et al. (2005) indicated the challenging nature of quantifying mechanisms responsible for competition-induced yield loss using traditional experimental techniques. In order to obtain a better insight in processes driving competition between crops and hedgerows, stable carbon isotope ratios (δ^{13}C) of crops can offer a solution to quantify crop–hedgerow competition. Dercon et al. (2006a) highlighted the potential use of ^{13}C isotopic discrimination in maize to signal water stress at low to high N availability. Their study showed that changes in δ^{13}C values in maize could be related to soil moisture and N availability. Furthermore, changes in ^{13}C isotopic discrimination due to N availability could also be indirectly linked to water stress. Higher N supply leads to higher ^{13}C isotopic discrimination, because the CO_2 diffusion from the air across the leaf membrane was not sufficiently fast to keep up with CO_2 demand needed to maintain plant productivity (Dercon et al. 2006a). When N supply is high, and not in equilibrium with soil water availability, ^{13}C isotopic discrimination will increase even more (Dercon et al. 2006a). The relationship between ^{13}C isotopic discrimination and water stress is well documented for C_4 plants. Farquhar (1983) and Henderson et al. (1992) described the photosynthesis-induced ^{13}C discrimination by the equation:

$$\Delta_{C4} = a + \left[b_4 + \phi(b_3 - s) - a\right]\frac{p_i}{p_a} \quad (1)$$

where a is the ^{13}C discrimination due to CO_2 diffusion in air (4.4‰), b_4 is the fractionation due to dissolution of CO_2 to HCO_3^- and fixation by Phosphoenolpyruvate or PEP (-5.7‰ at 30°C), b_3 is the ^{13}C discrimination due to RuBisCo (30‰), ϕ (leakiness) is the fraction of CO_2, fixed by PEP carboxylase, which is transported to the bundle sheath and subsequently leaks out, s is the fractionation during this process, and p_i/p_a, the ratio of intercellular to ambient partial pressure of CO_2.

Equation (1) shows that for C_4 plants, such as maize, the variation in ^{13}C isotopic discrimination results from changes in p_i/p_a ratio, but also from variation in leakiness (ϕ) of the bundle sheath. Bundle sheath leakiness (ϕ) depends, like p_i/p_a, on several factors, such as genetic variation, light intensity, water and nutrient stress (Bowman et al., 1989; Ranajith et al., 1995; Buchman et al., 1996, Meinzer and Zhu, 1998). Leakiness can increase with reduced N supply (Ranajit et al., 1995; Meinzer and Zhu, 1998), and would lead to depleted $\delta^{13}C$ values. Depending on the value of ϕ, the factor $[b_4+\phi(b_3-s)-a]$ in Eq. 1 is positive, zero or negative. Therefore, the dependence of Δ on p_i/p_a can also be positive, zero or negative. Despite the fact that the relationship between ^{13}C isotopic discrimination and water stress is well understood, the applications in the field to assess water stress are hampered by complex interaction patterns with other common stress factors, such as light intensity and nutrient deficiencies (Schmidt et al., 1993; Shangguan et al., 2000; Clay et al., 2001a).

The purpose of this study was to assess the use of ^{13}C isotopic discrimination, in combination with standard methods determining N availability and uptake, in order to better understand (1) competition for water and N between crops and barrier species, (2) water and N uptake by crops under contour hedgerow systems and (3) to derive a conceptual framework to assess relationships between crop response, N and water availability and $\delta^{13}C$. In case crops and barriers or hedges compete for N, improving N fertilization may reduce yield loss. However, if water is the main driver, improved barrier or hedge management, or different species to form the barriers or hedges, is needed. Improved management solutions should lead to a better performance of contour hedgerow systems and a higher acceptance by farmers in tropical mountainous regions.

3.2 Materials and methods

3.2.1 Study site

The study was carried out in Ban Bo Muang Noi, a village in Northeast Thailand, located at 570 m a. s. l. (17°33′N and 101°1′E). Average annual precipitation is about 1,300 mm and is characterized by a monomodal pattern, with rains predominantly from May until September. The mean annual temperature is 26°C. The soil at the study site can be classified as Humic Lixisol (Deckers et al. 2002). In the area, subsistence farmers often practice a form of minimum-tillage on the steeper slopes by carrying out maize planting with a wooden stick after burning the field.

3.2.2 Experimental design

The experiment was established in 2003, having 12 plots, each 4 m wide by 18 m long and with slope gradients ranging from 21 to 28%. In all plots maize (*Zea mays* L., cv. Suwan 1) was planted following contours. The experiment was arranged in a split-plot design with two replicates. The main plot was subdivided by fertilizer application rate, i.e. (1) no fertilizer or (2) 60 kg N ha^{-1} plus 14 kg P ha^{-1} via a split application (Figs. 1 and 2). The treatments in the subplots consisted of two types of regionally commonly used contour hedgerow systems with (1) *Brachiaria ruziziensis* Germain et Evrard (Ruzi grass) barriers or (2) *Leucaena leucocephala* (Lam) de Wit hedges, compared to a control without any hedgerows (Fig. 2a). Figure 2b shows the detailed design of the subplots having a green barrier. Where contour hedgerows were installed, in total three alleys were established in each plot. The *L. leucocephala* hedges and *B. ruziziensis* barriers were pruned to 30 cm height five times a year, in order to avoid shading of the maize crop. The prunings were spread across the cropped alley, acting as mulch. Jack beans (*Canavalia ensiformis* DC) were planted as relay crop in all treatments between maize rows 1 month before maize harvest. Both maize and Jack bean stover were applied as mulch in the corresponding plots. Seeding the maize crop using a stick and hand-weeding were the only field preparations performed in all plots. The results reported in this study are from the 2005 cropping season, 3 years after establishing the experiment. Over the 2005 growing season (May to October), total rainfall and potential evapotranspiration were 920 and 520 mm, respectively (Fig. 1).

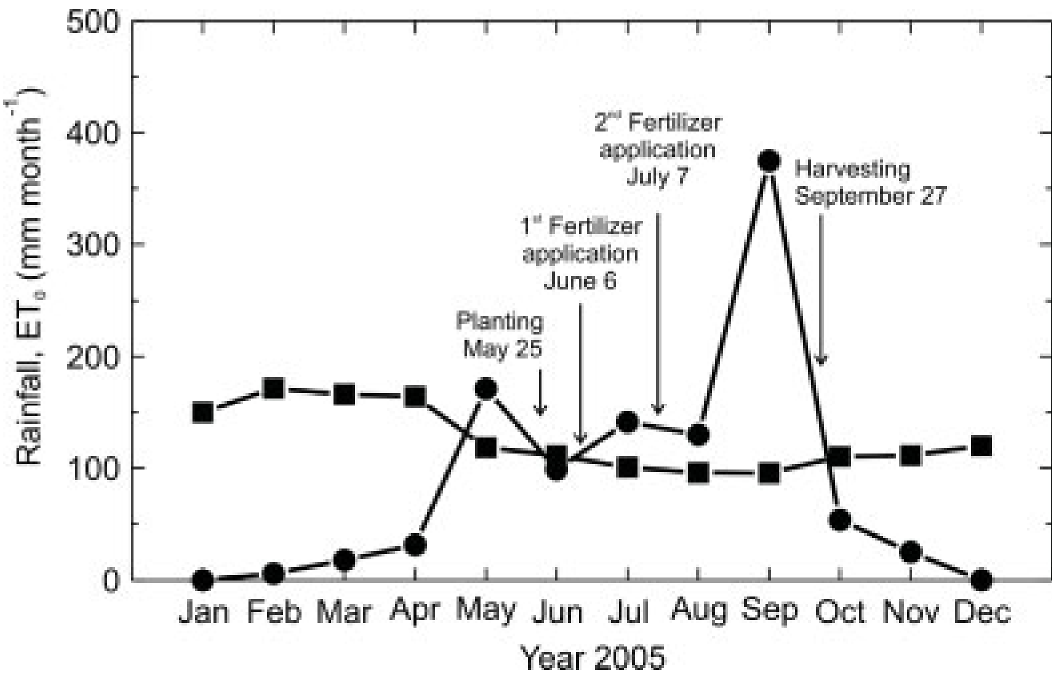

Fig. 1 Monthly rainfall (filled circles) and potential evapotranspiration (filled squares) for year 2005 at the experimental site in Bang Bo Muang Noi, Northeast Thailand. Arrows indicate planting, fertilizer application and harvesting dates.

3.2.3 Spatial variability of crop response

In this study, data from the upper slope alley, or the upper part of the control plot (with an extension of one alley) were omitted to avoid border effects (Fig. 2). Maize grain yield data were collected row wise. In addition, N content in maize grain and stover samples were determined by the Kjeldahl method (Bremner 2001).

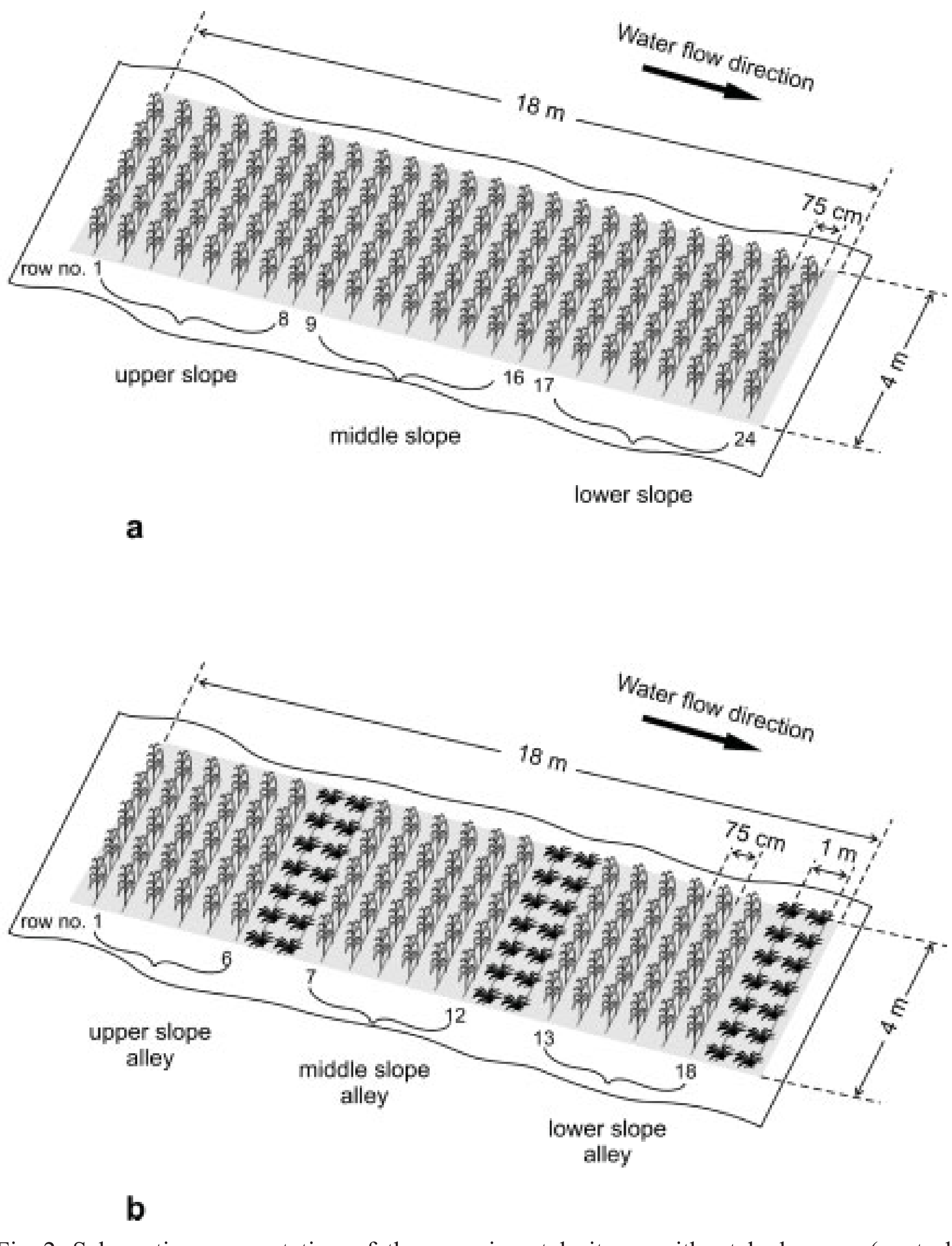

Fig. 2 Schematic representation of the experimental site, a without hedgerows (control plot) and b with *B. ruziziensis* barriers or *L. leucocephala hedges*

3.2.4 Carbon isotope discrimination in maize

In order to determine carbon isotope ratios in maize, the third youngest and fully developed leaf, counted from the top of the plant, was collected at 100 days after planting.

Maize leaf samples were taken from the central row and row next to the downslope barrier, for both middle and lower alleys. In addition, in the control plots leaf samples were taken from plant rows at a similar slope position to the hedgerow treatments. Leaf samples were dried at 70°C for 48 h and finely ground with a ball mill. The $^{13}C/^{12}C$ ratio of maize leaves was determined on four replicates for each sample with a Euro Elemental Analyzer coupled to a Finigan Delta IRMS. The $\delta^{13}C$ was calculated by comparing the ^{13}C to ^{12}C ration of a sample (R_{sample}) relative to the composition of the Pee Dee Belemnite (PDB) standard (R_{PDB}), i.e.,

$$\delta^{13}C_{sample}\ (‰) = [(R_{sample}/R_{PDB})-1]\times 10^3 \quad (2)$$

The $\delta^{13}C$ of maize leaves can be related to carbon-isotope discrimination (Δ), as described by the following equation:

$$\Delta = \frac{(\delta^{13}C_{air} - \delta^{13}C_{plant})}{(1 + \frac{\delta^{13}C_{plant}}{1000})} \quad (3)$$

where $\delta^{13}C_{air}$, $\delta^{13}C_{sample}$ are the stable carbon isotope ratio of air and plant material, respectively, assuming a value of -8‰ for $\delta^{13}C_{air}$.

Dercon et al. (2006a) showed that $\delta^{13}C$ values measured in different plant parts can be used as a historical account of variation in water availability during the entire cropping cycle. As in present study only one maize leaf per plant was sampled at 100 days after planting, measured $\delta^{13}C$ values represent growth conditions for just a part of the cycle towards the end of vegetative growth. Thus extending ^{13}C analysis to other plant parts might reveal further insights into temporal dynamics of competition. However, in this study limited further information on water competition would have been obtained due to the positive water balance over the entire cropping cycle (Fig. 1).

3.2.5 Effect of available Nitrate-N on crop response

Soil (0-15 cm) was sampled (six sub-samples) from each maize row of the plot 120 days after planting. Samples were stored at 4°C and subsequently nitrate-N (NO_3^--N) extracted by shaking 10 g soil in 2 M KCl for 1 hour before filtering the extract. NO_3^--N was determined by the steam distillation method (Mulvaney 2001).

3.2.6 Assessment of conservation measures through the use of crop response index

Under contour hedgerow systems, cultivated area is reduced by establishing barriers. In this study, a slightly changed crop response index (CRI), based on the one proposed by Dercon et al. (2006b), was used to compare current crop response within the alley of the contour hedgerow system with the crop response without the presence of barriers, expressed by:

$$\mathrm{CRI}\,(\%) = \left[\frac{\mathrm{CR_C} - \mathrm{CR_{CWH}}}{\mathrm{CR_{CWH}}}\right] \times 100 \qquad (4)$$

where CR_C is the current crop response (dry weight of grains in kg m^{-2}) in the cultivatable area of one alley of the plot with contour hedgerows, and CR_{CWH} is the crop response in the control plot without hedgerows (dry weight of grains in kg m^{-2}). The mean CRI was calculated for the lower and middle alleys of each plot. According to its definition, a positive CRI indicates a better crop response and a higher effectiveness of the system, while negative values point to poor system performance.

3.2.7 Statistical analysis

A split-plot model was used to test for effects of fertilizer application and use of contour hedgerows. Grain yield and available NO_3^--N in the soil showed a parabolic pattern along the different alleys; hence second-order polynomial equations were used to describe spatial variability in crop response and available NO_3^--N in each alley. In addition, linear relationships of $\delta^{13}C$ values versus available NO_3^--N in the soil and N concentration in the shoot, and of grain yield versus N concentration in the shoot were fitted for every treatment.

3.3 Results

3.3.1 Exploratory analysis of crop response

Maize harvest index, stover and grain yield increased significantly ($p < 0.001$) with fertilizer application (Table 1). In contrast, in the case of *B. ruziziensis* as a barrier without fertilizer the use of contour hedgerows significantly ($p < 0.001$) reduced maize stover and grain yield up to 44 and 49% respectively. This decline in yield was much higher than the reduction of 17% in cultivatable area as compared with the control plot without hedgerows.

A significant interaction ($p < 0.05$) between soil conservation measures and fertilizer application, for both maize stover and grain yield, suggested that the negative impact of hedgerow systems on crop response was less pronounced when fertilizer was applied. Plots with unfertilized *B. ruziziensis* barriers showed the lowest maize grain yield (1,961±65 kg ha^{-1}), while plots with the same type of barriers, but where fertilizer was applied, were characterized by a significantly ($p < 0.001$) higher grain yield (4,261±168 kg ha^{-1}).

3.3.2 Spatial variability in maize grain yield

Based on Fig. 3, showing spatial variability in grain yield across the slope of experimental plots, a clear distinction can be made between control plots and plots with contour hedgerows. Control plots without hedgerows produced rather constant or slightly increasing maize yields along the slope. Average yields of rows from the control plot without fertilizer were 290 g m^{-1}, and, significantly higher ($p < 0.01$), i.e. 430 g m^{-1}, when fertilizer was applied. These values were approximately equal to the maize grain yield obtained from central rows of each studied alley from both contour hedgerow systems (Fig. 3b and c). The contour hedgerow systems formed by *B. ruziziensis* barriers or *L. leucocephala* hedges showed similar spatial patterns in maize yields. They had, in most cases, higher yields in the central rows of the alley and tending to have reduced yields towards barriers or hedges, demonstrated by a parabolic relationship of grain yield versus location within the alley, with R^2 values ranging from 0.60 to 0.90.

Table 1 Mean maize grain yield, stover and harvest index as affected by soil conservation measure and fertilizer application at Ban Bo Muang Noi, Loei province in NE Thailand, 2005

		Control without hedgerow	*B. ruziziensis* barrier	*L. leucocephala* hedge
Maize grain yield (kg ha^{-1})				
No fertilizer		3847 ± 170	1961 ± 65	2760 ± 168
60 kg N ha^{-1} and 14 kg P ha^{-1}		5738 ± 164	4261 ± 168	3968 ± 354
F test	Fertilizer application	< 0.001		
	Soil conservation measure	< 0.001		
	Interaction	0.030		
Maize stover (kg ha^{-1})				
No fertilizer		5121 ± 22	2864 ± 140	3848 ± 182
60 kg N ha^{-1} and 14 kg P ha^{-1}		6876 ± 223	5228 ± 101	4832 ± 367
F test	Fertilizer application	< 0.001		
	Soil conservation measure	< 0.001		
	Interaction	0.020		
Harvest index				
No fertilizer		0.43 ± 0.04	0.40 ± 0.01	0.41 ± 0.01
60 kg N ha^{-1} and 14 kg P ha^{-1}		0.46 ± 0.00	0.45 ± 0.01	0.45 ± 0.01
F test	Fertilizer application	0.001		
	Soil conservation measure	0.200 NS		
	Interaction	0.350 NS		

Standard errors are reported.

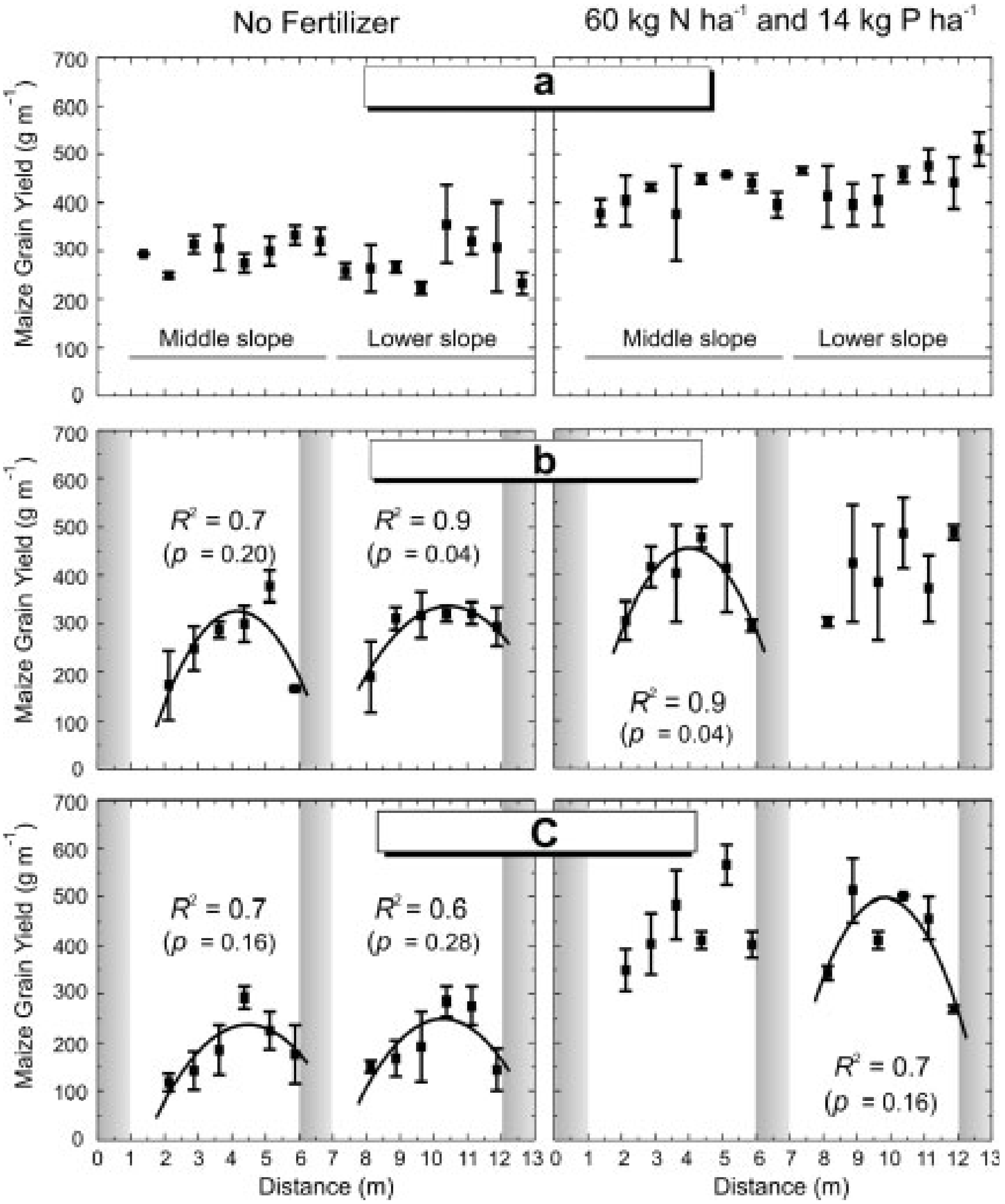

Fig. 3 Maize grain yield as affected by contour hedgerows and fertilizer application for **a** control plot without hedgerows and plots with **b** *L. leucocephala* hedges or **c** *B. ruziziensis barriers.* Error bars denote standard errors. Only those fits having a R^2 higher than 0.50 are shown. Shadings in charts **b** and **c** correspond to hedgerow positions in the plot.

3.3.3 The influence of contour hedgerows on $\delta^{13}C$ values and N concentration in maize

Figure 4 shows $\delta^{13}C$ values of the third youngest leaf at 100 days after planting for two positions in the alley, (1) in the lower part next to the barrier or hedge and (2) in the centre of the alley, as well as for the plants in the control plots (without contour hedgerows) at the same slope positions. The $\delta^{13}C$ values for sampled maize leaves in the unfertilized and fertilized control plots varied from −10.72‰ (±0.05) to −10.88‰ (±0.08), respectively. Maize leaves in plots with *L. leucocephala* hedges (with and without fertilizer) had $\delta^{13}C$ values ranging from −11.38 to −10.54‰ (−10.84‰±0.05), while those in plots with *B. ruziziensis*, ranged from −11.06 to −10.65‰ (−10.79‰±0.05). Statistical analysis could not detect any significant ($p > 0.05$) effect of fertilizer application or hedgerows on $\delta^{13}C$ values. However, a significant ($p < 0.05$) effect of position was detected, in particular within the plots with *L. leucocephala*. Pairwise comparison of $\delta^{13}C$ values of maize leaves in the same alley detected consistently and significantly ($p < 0.03$) higher $\delta^{13}C$ values in the rows close to the *L. leucocephala* hedge, as compared to maize plants located in the central row of the alley. For *B. ruziziensis*, this trend was less clear, but still significant ($p < 0.01$) in plots with fertilizer application. However, this trend was not present in two out of four alleys of the Ruzi grass plots, where no fertilizer was applied. Significantly ($p < 0.001$) higher N concentrations in shoots of maize, for the same two plant row positions in the alleys, were observed in the treatments with fertilizer application. In control plots without hedgerows, average N concentration was around 0.56% (±0.03) and 0.96% (±0.02) for treatments without and with fertilizer application, respectively. In case of plots with contour hedgerows, a clear effect of hedgerow type ($p < 0.001$) was reported. For systems composed of *L. leucocephala* hedges, average N concentrations were 0.79% (±0.02) and 1.04% (±0.03) for treatments without and with fertilizer, respectively. The lowest average N concentration (0.57%±0.03) in shoots of maize was found in unfertilized plots with *B. ruziziensis* barriers, while that in fertilized plots with *B. ruziziensis* barriers was 0.79% (±0.01), similar to unfertilized *L. leucocephala* plots. Finally, N concentration in shoots of maize was systematically and significantly ($p < 0.001$) lower (0.07%±0.02) for plants close to the barriers.

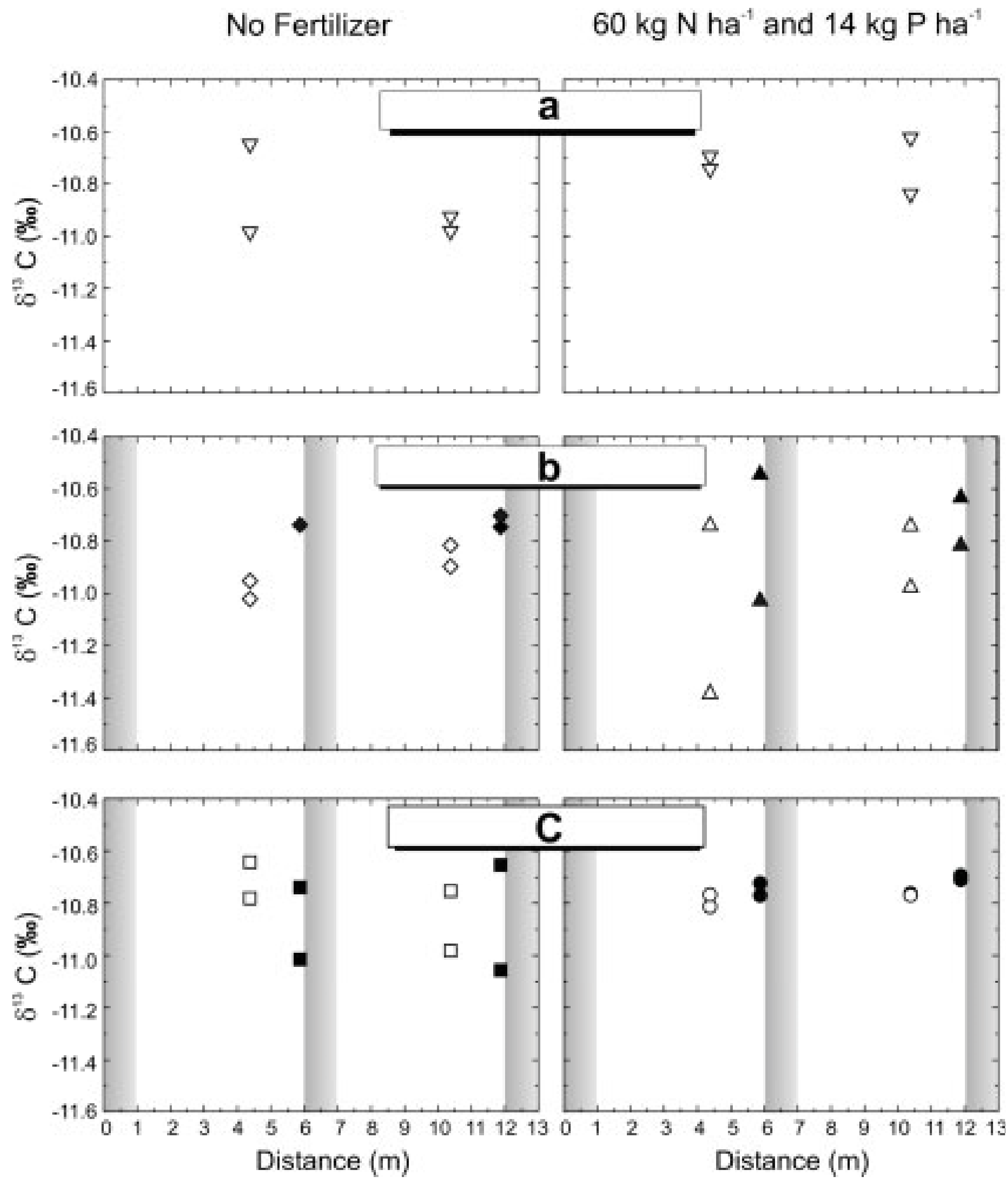

Fig. 4 Influence of contour hedgerows and fertilizer application on δ^{13}C values of the third youngest leaf at 100 days after planting of plants for **a** control plot without hedgerows, and plants at the central row and the row next to the barrier for plots with **b** *L. leucocephala* hedges or **c** *B. ruziziensis* barriers. Shadings in charts **b** and **c** correspond to hedgerow positions in the plot. Closed symbols refer to datasets next to the barrier and open symbols are datasets from the central row in the alley.

3.3.4 Spatial distribution of available NO_3^--N in the soil

In control plots without hedgerows and fertilizer application, average available NO_3^--N in the soil fluctuated around 45 mg kg^{-1} (±1.8), whereas the one that received fertilizer, was significantly ($p < 0.001$) higher, i.e. about 60 mg kg^{-1} (±1.6; Fig. 5). For three out of four plots with *B. ruziziensis* barriers, available NO_3^--N in the alleys (Fig. 5b and c) showed a strong parabolic pattern with a decline towards the barriers, with a R^2 ranging from 0.70 to 0.90. However, this parabolic prediction function was not able to fit successfully the available NO_3^--N of plots with *L. leucocephala* hedges.

3.3.5 Implications of spatial variability for the effectiveness of contour hedgerow systems

The results, shown in Table 2, indicate that both hedgerow systems, using *L. leucocephala* and *B. ruziziensis* as hedge or barrier, were characterized by a negative Crop Response Index (*CRI*). However, fertilization strongly improved *CRI*. The *CRI* for hedgerow systems with fertilizer application (−8 to −1%) was significantly ($p < 0.01$) higher than the *CRI* for those without fertilizer (−32 to −4%). With regard to the soil conservation measures, the system using *B. ruziziensis* barriers had the lowest *CRI*, in particular when no fertilizer was applied (−32% ± 3), indicating its poor effectiveness in crop response. However, the *CRI* was significantly ($p < 0.01$) improved after applying fertilizer, and became similar to the *CRI* of the system using *L. leucocephala* hedges. Despite the improvement, the *CRI* for neither *L. leucocephala* nor *B. ruziziensis* based soil conservation measures became positive, even after fertilizer was applied.

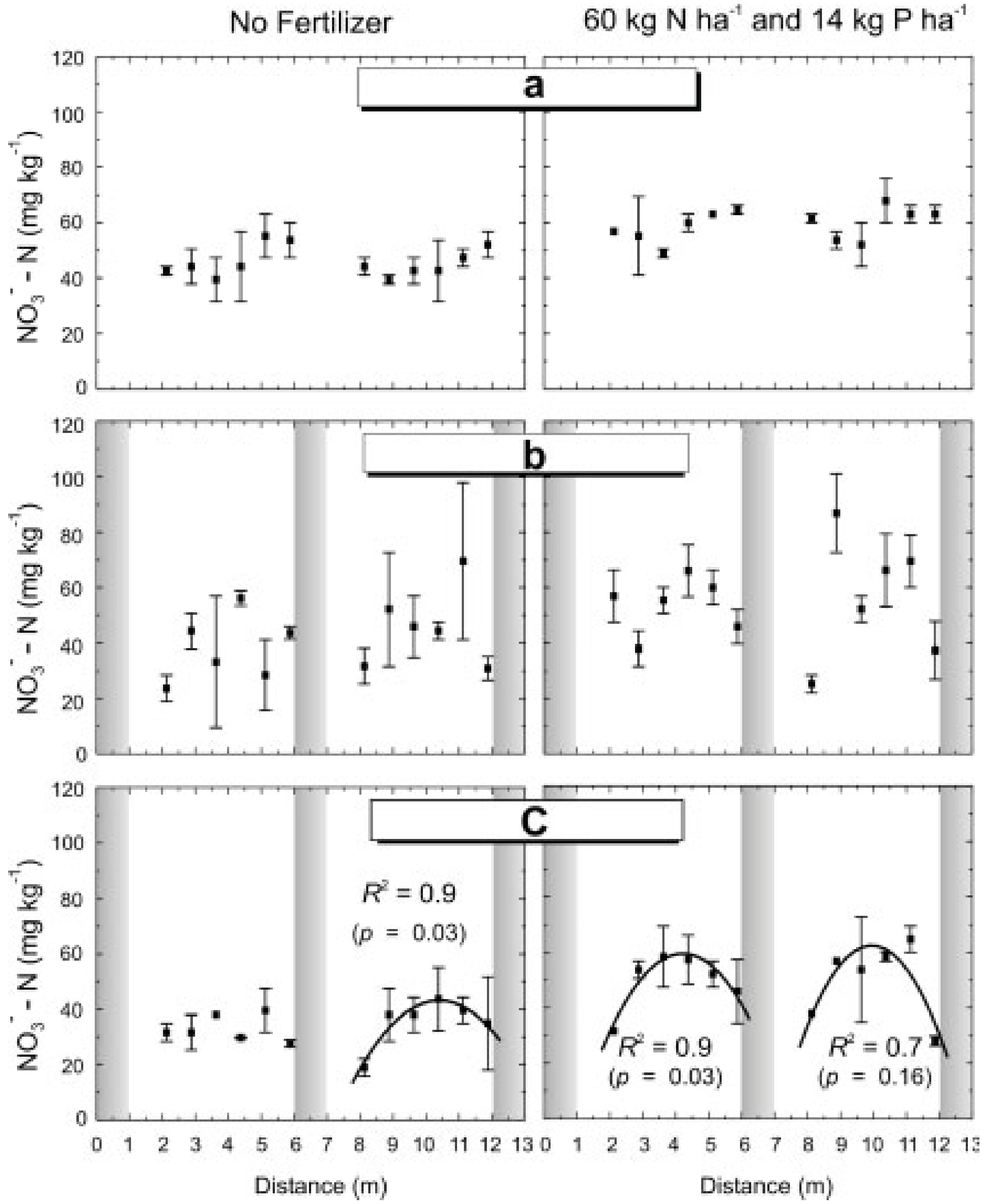

Fig. 5 Available NO_3^--N in soil (0–15 cm) at 120 days after planting as affected by contour hedgerows and fertilizer application for **a** control plot without hedgerows and plots with **b** *L. leucocephala* hedges or **c** *B. ruziziensis* barriers. Error bars denote standard errors. Only those fits having a R^2 higher than 0.50 are shown. Shadings in charts **b** and **c** correspond to hedgerow positions in the plot.

Table 2 The crop response index as affected by soil conservation measure and fertilizer application at Ban Bo Muang Noi, Loei province in NE Thailand, 2005

		Control without hedgerow	*B. ruziziensis* barrier	*L. leucocephala* hedge
CRI				
No fertilizer		0 ± 4	-32 ± 3	-4 ± 7
60 kg N ha^{-1} and 14 kg P ha^{-1}		0 ± 2	-1 ± 3	-8 ± 8
F test	Fertilizer application	0.010		
	Soil conservation measure	0.040		
	Interaction	0.005		

Treatment means and standard errors are reported.

3.3.6 Correlation between $\delta^{13}C$ values and plant and soil parameters

The upper right quadrant of Fig. 6 shows the relationship between $\delta^{13}C$ values of the third youngest leaf at 100 days and available NO_3^--N in the soil at 120 days after planting, for two positions in the alley, (1) in the lower part next to the barrier or hedge and (2) in the centre of the alley. The results showed that $\delta^{13}C$ signatures became depleted with increasing available NO_3^--N, resulting in moderate to strong and significant negative correlations, with R^2 ranging from 0.50 ($p < 0.1$) to 0.90 ($p < 0.01$), in all plots with and without hedgerows or with and without fertilizer. In addition, the predicted linear relationship was constant with similar intercepts, ranging from −10.0 to −10.6‰, and slopes, from −0.007 to −0.015, except for plots with *B. ruziziensis* barriers with fertilizer, which were characterized by a very small but significant slope of −0.002 ($p < 0.001$). Fertilized *L. leucocephala* hedges exhibited the largest variation in $\delta^{13}C$ values of maize leaves, ranging from −10.54 to −11.38‰. Two clusters can be distinguished in most plots with hedgerows. A first group consists of maize plants close to the barrier (closed symbols) having low available NO_3^--N and enriched $\delta^{13}C$ signatures, and the second is composed by plants from the central row of the alley (open symbols), characterized by high available NO_3^--N and depleted $\delta^{13}C$ signatures. Figure 6 also indicates, in the upper left quadrant, $\delta^{13}C$ values as a function of N concentration in the shoot. Similar to the relationship between $\delta^{13}C$ values and available NO_3^--N in the soil, measured $\delta^{13}C$ signatures were negatively and significantly correlated with N concentration in the shoot of maize, for the fertilized plots with *B. ruziziensis* barriers (R^2=0.55, $p < 0.05$) and the unfertilized plots with *L. leucocephala* hedges (R^2=0.79, $p < 0.01$). Maize plants close to the barrier (closed symbols) were mostly characterized by lower N concentrations in the shoot and less depleted $\delta^{13}C$ values. Finally, the lower quadrant of Fig. 6 presents the relationship between N concentration in the shoot and maize grain yield, which is characterized for all plots by positive, moderate to strong, and significant ($p < 0.05$) correlations, with a R^2 ranging from 0.52 to 0.91.

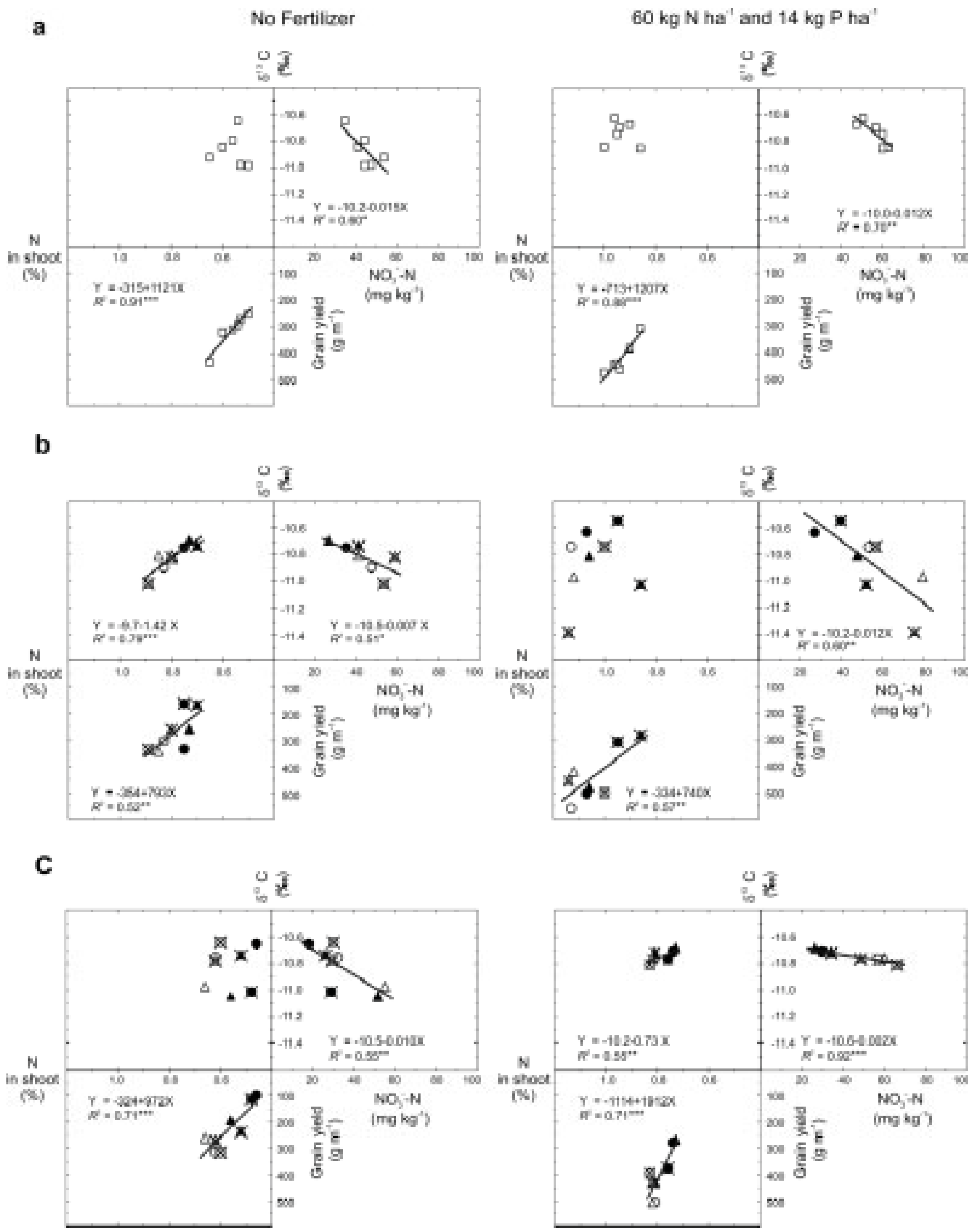

Fig. 6 Relationship between δ^{13}C values of the third youngest leaf at 100 days after planting, available NO_3^--N in soil at 120 days after planting, N concentration in the shoot and grain yield for **a** control plots without soil conservation measures, plots with **b** *L. leucocephala* hedges or **c** *B. ruziziensis* barriers, without and with fertilizer. Square symbols represent control plots without hedgerows. Closed symbols refer to datasets next to the barrier and open symbols to the datasets from the central row in the alley. Crossed symbols represent the alleys at the middle slope and those symbols without cross alleys at the lower slope. Triple asterisks, double asterisks and single asterisks indicate significance at $p \leq 0.01$, 0.05 and 0.1 levels.

3.3.7 Framework for ^{13}C analysis in contour hedgerow systems

The relationships between available NO_3^--N in the soil and ^{13}C isotopic discrimination in the maize plants, led to a proposed framework, presented in Fig. 7. This framework allowed, in combination with shoot N uptake, identifying, in most cases, the cause of observed decline in crop response towards barrier or hedge. As starting point of this framework, the relationship between ^{13}C isotopic discrimination and water availability was deducted from the observed negative correlation between available NO_3^--N in the soil and ^{13}C isotopic discrimination. This negative correlation suggests that the $[b_4+\phi(b_3\text{-}s)\text{-}a]$ term in Eq. 1 is negative for the examined maize variety (*Zea mays* L, cv. Suwan 1), under the current experimental conditions. As water and N stress affect ^{13}C isotopic discrimination oppositely to each other in C_4 plants (Clay et al. 2001b, Yu et al. 2004; Dercon et al. 2006a), and leakiness *(ϕ)* did not play a major role in the measured variation in $\delta^{13}C$ values, similar to the study of Dercon et al. (2006a), the observed negative correlation between available NO_3^--N and ^{13}C isotopic discrimination led to the conclusion that $\delta^{13}C$ values in maize become depleted with decreasing water availability. After identification of the relationship between ^{13}C isotopic discrimination and water and N availability, the developed conceptual framework could group the most commonly observed relationships between NO_3^--N availability and $\delta^{13}C$ values in Fig. 6. Line A refers to observed patterns under a contour hedgerow system, such as the one composed of *B. ruziziensis* receiving fertilizer, with good water availability (enriched $\delta^{13}C$ values) throughout the alley and low to moderate N availability near the barrier and in the center of the alley, respectively. Line B represents both unfertilized contour hedgerow systems, characterized by optimal water and low N availability near barrier or hedge, and limited water and moderate N availability in the central position of the alley. A final identified group is represented by line C showing the observed pattern of fertilized plots with *L. leucocephala* hedges. These plots had the highest N availability in the central rows, but showed as well largest variation in water availability, with lowest availability in the centre of the alley.

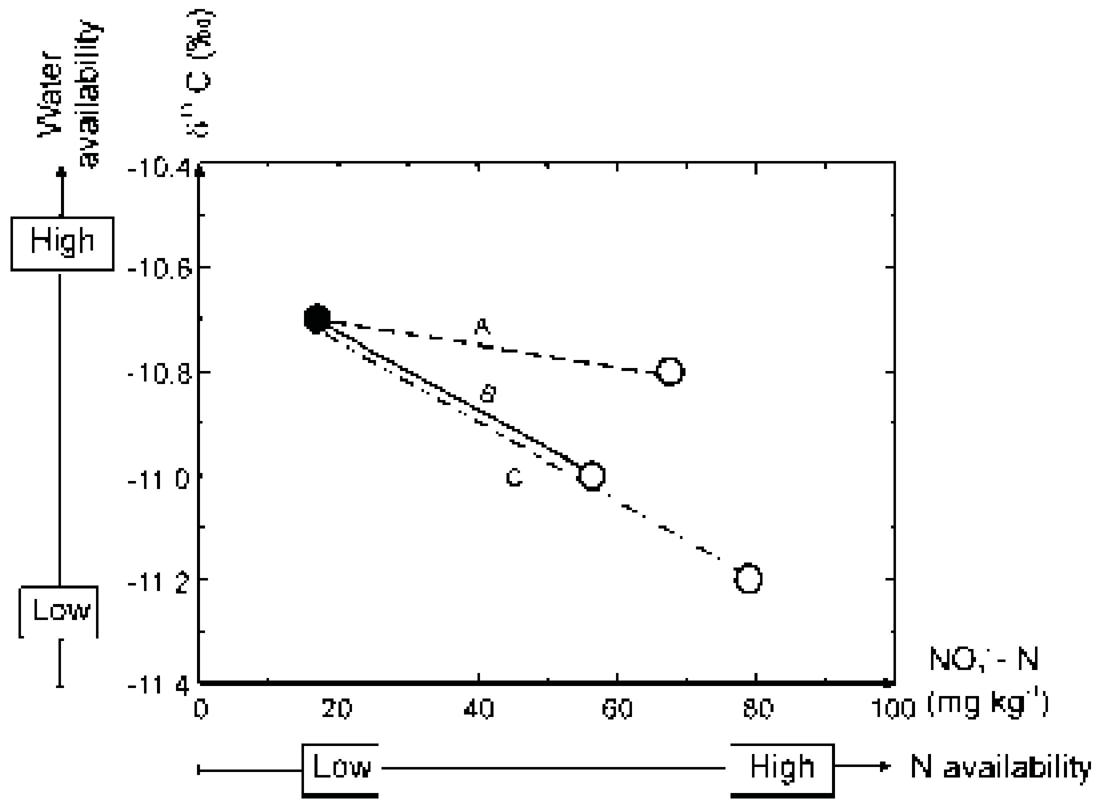

Fig. 7 Schematic representations of observed and theoretical relationships between $\delta^{13}C$ values in maize and available NO_3^--N in the soil at 120 days after planting. Lines indicate *B. ruziziensis* barriers with fertilizer (A), *B. ruziziensis* and *L. leucocephala* without fertilizer application (B) and *L. leucocephala* hedges with fertilizer (C). Closed symbols (●) refer to datasets next to the barrier and open symbols (○) are datasets from the central row in the alley.

3.4 Discussion

In the current study, maize growth showed in most cases limitations towards the hedgerows. The use of minimum tillage and mulching limited the potential of water erosion. Thus, exposure of infertile subsoil near the upper part, due to soil translocation within the alleys, could be eliminated as driving factor for variability in maize growth. Light was also not a driver for competition, as hedgerows and barriers were frequently pruned. However, even after fertilizer application, crop response still showed a decline towards the hedgerows. Finally, as rainfall exceeded potential evapotranspiration during the cropping season, the resulting positive water balance suggested that water was probably not the decisive stress factor for plant growth. Therefore, questions arise about the nature of the competition between crop and hedgerow. Jonsson et al. (1988) suggested that *L. leucocephala* is likely to compete with maize for nutrients and water due to a similar rooting pattern. However, Akinnifesi et al. (1996) reported for *L. leucocephala* hedgerows and maize in an alley cropping system that there was no significant below-ground N competition between hedgerows and maize.

3.4.1 Nitrogen stress along the alleys of the contour hedgerow systems

Detailed analysis of the proposed framework, in combination with additional information on N concentration in the shoot and the grain yield of maize, showed that N deficiency was identified in most cases as the major cause for the observed spatial variability in the lower part, towards the hedges or barriers, of the different alleys. For the unfertilized and fertilized *L. leucocephala* plots, represented by lines B and C in the proposed framework (Fig. 7), enriched $\delta^{13}C$ values in maize close to the barriers, as compared with maize in the central rows, eliminated under the current experimental and climate conditions, water deficiency as the main reason for the observed decline in crop response towards the hedges. In addition, the relationship and slope between available NO_3^--N and $\delta^{13}C$ values suggests that differences in ^{13}C isotopic discrimination were more related to availability of N than to difference in water availability. More N leads to higher ^{13}C isotopic discrimination, resulting in a depletion of ^{13}C. Dercon et al. (2006a) showed that higher N supply favoured ^{13}C isotopic discrimination because the CO_2 diffusion from the air outside to the air inside the leaf is not sufficiently fast to keep up with the CO_2 demand generated by the increased N availability. These results are in line with studies from the humid highlands in Western Kenya, where Immo and Timmer (2000) revealed competition for N in maize – *L. leucocephala* alleys of 8 m. However, they also demonstrated that with reduced spacing of 2 m between alleys moisture and/or light became the limiting factor. On the fertilized plots with *B. ruziziensis* barriers, represented by line A in the framework (Fig. 7), the pattern of $\delta^{13}C$ signatures and their relationship with available nitrate lead to similar conclusions, that nitrogen deficiency and not water stress was determining yield decline towards the barriers. The spatial variability in available NO_3^--N in the fertilized alleys followed a spatial pattern along the alley, similar to that of grain yield, confirming the role of N in the observed reduction in grain yield, even after having received fertilizer. On the unfertilized plots with *B. ruziziensis* barriers, the data points could be well represented by the same line B of the proposed framework (Fig. 7), as used for the unfertilized *L. leucocephala* plots. However, the more variable pattern of $\delta^{13}C$ signatures, on an alley basis, did not allow a uniform diagnosis of the main driving factor of yield decline towards the barriers. The question remains about the nature of nitrogen stress towards hedgerows and barriers. Despite controversial reports in literature about competition between *L. leucocephala* and maize (Akinnifesi et al. 1996; Immo and Timmer 2000), the most obvious reason is large N uptake by *L. leucocephala* hedges and *B. ruziziensis* barriers. The large root network of *B. ruziziensis* in the present experiment (data not shown) favours severe below-ground competition.

3.4.2 Improved water uptake after fertilization

The $\delta^{13}C$ signature pattern in combination with data on available NO_3^--N concentration in the shoot and grain yield pinpointed N deficiency as major reason for yield decline towards the barrier. However, the lower slope of the relationship between $\delta^{13}C$ ratios and available NO_3^--N, and enriched $\delta^{13}C$ signatures in the fertilized plots with *B. ruziziensis* barriers, indicated that some additional factors were involved. The current results suggest an improved water uptake along the alley when fertilized with N. If water availability would not have been improved, lower and not higher $\delta^{13}C$ values, as compared to the unfertilized plots with *B. ruziziensis* as barrier, would have been expected, due to the higher N availability. This conclusion was supported by the data from the fertilized control plots, where maize, despite higher N availability and N uptake, had similar $\delta^{13}C$ signatures, as compared to maize in unfertilized control plots. It is well known that fertilizer application improves rooting density and depth in poor soils (Oikeh et al. 1999). Thus, fertilized maize plants may have had improved access to water and hence water uptake improved in comparison with maize in unfertilized *B. ruziziensis* plots. Water availability thus did not form a major limitation for crop response in fertilized *B. ruziziensis* plots. Pansak et al. (2006) reported that for the same experimental control plots without hedgerow systems, runoff significantly decreased when fertilizer was applied. This further indicated that maize plants on the fertilized control plots had a better water availability and hence improved water uptake. However, fertilization of plots with *L. leucocephala* hedges did not have the same impact on $\delta^{13}C$ signatures. The higher available NO_3^- in the soil, due to the application of hedgerow prunings, made that water availability started to be a limiting factor for crop response. The lower δ13C values, in combination with the steeper slope of the linear regression between available NO_3^--N and $\delta^{13}C$ values, confirmed the increasing importance of water availability in the *L. leucocephala* plots. The lack of this data pattern on the fertilized plots with *B. ruziziensis* barriers showed that there the limiting factor for crop response was N availability, and not water availability. However, further improved N supply in plots with *B. ruziziensis* barriers would probably lead to an increased importance of water availability, and would change the current relationship between $\delta^{13}C$ values and NO_3^--N availability into the relationship of the fertilized *L. leucocephala* plots.

3.5 Conclusion

The proposed ^{13}C isotopic discrimination framework in combination with data on N availability and uptake in the shoot allowed identifying N deficiency as a major driver for the yield decline towards barriers or hedges. The competition for N between hedgerows and maize could be reduced by fertilizing the alleys. Although fertilizer application increased performance of the contour hedgerow system, the *CRI* was still slightly negative for both systems studied. In many plots spatial variability persisted even after fertilizer was applied. The presence of a decline in crop response towards the barriers, even after fertilizer was applied, clearly indicates that there is scope to further improve crop performance. As suggested by Dercon et al. (2003, 2006b) site-specific fertilizer application, such as increased levels close to the barriers, together with a better control of barriers or hedges can be a possible strategy to follow. These improvements can lead to a better overall performance of contour hedgerow systems and a higher acceptance by farmers in tropical mountainous regions. The proposed analytical ^{13}C framework proved to provide further insights into water and N competition in hedgerow systems. The approach pinpointed to the impact of fertilizer application on crop water uptake and indicated the dynamics between driving factors of crop response, such as water and N availability. The use of ^{13}C isotopic discrimination was shown to be a promising tool for the assessment of causes for competition between hedgerows and crops grown in the alleys, under field conditions. Nevertheless, the use of a well structured and documented experimental frame is needed. It is suggested to extend and intensify plant sampling to further evaluate temporal and spatial variations in $\delta^{13}C$ in crop samples and related dynamics in competition for water and N.

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CHAPTER 4

Assessing soil conservation strategies for upland cropping in Northeast Thailand with the Water Nutrient Light Capture in Agroforestry System model*

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Abstract

Soil conservation approaches and agroforestry systems can play an important role in controlling erosion from tropical hillside cropping systems. Experimental testing of their potential application domain and design, however, is costly and time consuming. We therefore tested the ability of the Water, Nutrient and Light Capture in Agroforestry Systems (WaNuLCAS) model version 3.2 to predict runoff and soil loss under various management options. The specific objectives of the study were (i) to calibrate and validate the erosion submodule, (ii) to use the model for a better understanding of various soil conservation measures in controlling erosion and iii) to assess the magnitude and dynamics of key processes influencing the efficiency of soil conservation measures. A 3-year-data set (2003-2005) from a field experiment from the Loei province in Northeast Thailand on the impact of soil conservation (Leucaena hedgerow, Jack bean relay cropping) under minimum tillage measures on runoff and soil loss was used for model calibration and validation. Results indicated that WaNuLCAS was able to predict soil loss and runoff well at the test site; i.e. R2 0.80 and 0.82, respectively. Simulations demonstrated that key parameters for effective soil erosion control were i) adequate representation of soil cover development by the model and an adjusted relationship (soil sediment concentration ratio)

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improved erosion model efficiency from 0.29 to 0.49, and ii) introduction of a dynamic soil structure module (driven by residue inputs) which further enhanced runoff model efficiency from 0.36 to 0.73. Agroforestry scenario simulations clearly showed that soil conservation measures such as Leucaena hedges are effective techniques to control runoff and soil loss. Implementing the dynamic soil structure module in combination with minimum tillage reduced runoff and soil loss via increased macropores and hence drainage over time. Relay cropping with Jack bean played an import role in the control treatment in reducing soil loss during the third year. Hence, WaNuLCAS model is a valuable tool to study, understand (processes) and explore management options for improving tropical hillside cropping threatened by soil degradation.

Keywords: Zea mays L.*;* runoff; soil loss; relay cropping; minimum tillage; hedgerows; modelling

4.1 Introduction

By 2100, the world population may raise to 10 or 12 billion people causing large scale conversion of natural ecosystems to agricultural lands to meet people's demand for food and other goods based on natural resources (Lal 2007). Unsuitable land use and intensive cultivation, however, will lead to soil degradation. One third of the world's agricultural soils or approximately two billion hectares of land are already affected by soil degradation (Ritsema et al. 2005). On these degraded areas water induced erosion is estimated at 1100 million hectares (Lal 2001). Accelerated water erosion has both on-site and off-site effects. The main on-site impact is the decrease in soil quantity and quality, whereas the major off-site effect is the transfer of sediment from upland fields and their deposition downslope. In the course of time these sediments may end up in water bodies where they reduce storage capacity by silting-up of reservoir required for irrigation and decreasing water quality of fish ponds (Van Rompaey et al. 2002). In some cases, increased downstream flooding may also occur due to the reduced capacity of eroded soil to absorb water (Hatfield 2006). Therefore, appropriate soil and water conservation, combating the effects of soil erosion, play an important role to develop more sustainable agricultural production systems.

In Thailand, approximately 34% of the existing cultivation area is affected by top soil erosion due to the clearing of forests for generating new farmland. Another 17% of agricultural lands in the Northeastern region of Thailand are classified as vulnerable area for soil erosion (Land Development Department, 1998). Several soil conservation measures such as grass strips, planting of fruit trees on bench terraces, maintaining soil cover by crops and inter-cropping of trees with annual food crops were proposed for Thailand by the Land Development Department (LDD) and the International Board for Soil Research and Management (IBSRAM) and promoted to farmers managing steep slopes. Many studies reported that soil conservation measures based on contour grass strips or hedgerows are extremely effective in reducing water runoff and controlling erosion on steep slopes (Durán Zuazo et al. 2006; Kongkaew 2000; Melville and Morgan 2001; Pansak et al. 2008). Field testing of their potential, application domain and limitations, however, is expensive, long-standing and laborious. Therefore, using crop and/or soil erosion models (Matthews et al. 2001) can help investigating these systems relatively fast and at relatively low cost as well as to improve our understanding of the driving forces behind their impact and constraints. Toy et al. (2002) provide an overview of soil erosion prediction models playing a role in both meeting practical needs of soil conservation goals and advancing the scientific understanding of soil erosion processes. The efforts of soil erosion assessment tools have resulted in empirical and process based models. An important line of currently used models started with the development of the *Universal Soil Loss Equation* (USLE) (Wischmeier and Smith 1958), which was later revised into the *Revised Universal Soil Loss Equation* (RUSLE) (Renard et al. 1991). One disadvantage of USLE and RUSLE based models is that they are not able to represent deposition processes or sediment pathways, which are important issues for pollution source identification. This led to the development of process based or physical models. Examples are the *Griffith University Erosion System Template* (GUEST) (Misra and Rose 1996) and *Water Erosion Prediction Project* (WEPP) models (Flanagan and Laflen 1997). The Rose equation used in the GUEST model, for example, is suited for erosion and deposition modelling as it addresses the involved processes directly (Rose 1985; Rose and Freebairn 1985; Rose 1998). In this approach, three continuous processes - rainfall induced soil detachment, flow detachment and sediment deposition - are considered simultaneously. This approach allows investigating single erosions events and thus provides an improved link to plant processes.

The way how soils are managed and to which extent they are covered by vegetation plays an important role in minimizing erosion. Trees support soil conservation structures through a stabilizing effect of the tree root system, increased soil cover and maintenance of organic matter (Joshi et al. 2004b; Schroth 1995). The effectiveness of the soil conservation measures can be reduced due to competition for nutrients, light and water between crops in the alley and species forming the hedges. Many studies demonstrated that yields 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). Minimum tillage, relay cropping with a legume cover crop, hedgerow and grass barrier systems or a combination of them can also minimize soil erosion, restore soil fertility and improve crop productivity (Pansak et al., 2008). Because of the close relation between plant development and erosion processes plant-soil models which represent both processes and a spatial representation of impacts by the management system are desirable.

The **W**ater, **N**utrient and **L**ight **C**apture in **A**groforestry **S**ystems (WaNuLCAS) model was developed to represent tree-soil-crop interactions in a wide range of agroforestry systems where trees and crops overlap in space and/or time (Van Noordwijk and Lusiana 1998; Van Noordwijk et al. 2004). It can be used to evaluate various management options in agroforestry systems based on site-specific information and farmer's management objectives. Moreover, the model has an option to predict water induced erosion and can thus be used to explore positive and negative effects of various combinations of trees and crops, their management, soil, and weather on runoff and soil loss.

WaNuLCAS has been used to predict mineral nitrogen leaching, the effect of nutrient limitation on tree and crop production and carbon sequestration under fallow systems in tropical ecosystems (Radersma et al. 2005; Suprayogo et al. 2002; Van Noordwijk and Cadisch 2002; Walker et al. 2007; Walker et al. 2008). To date, WaNuLCAS has not been widely used to predict erosion under various soil conservation measures. The soil erosion submodule of WaNuLCAS is based on the Rose equation (as described above) and as an innovative feature includes a dynamic soil structure submodule that allows to take into account the impact of management induced increased plant residue recycling on biological (faunal) activity and hence macropore formation altering water infiltration and dynamics.

The objectives of this paper were (i) to calibrate and validate the erosion submodule of the WaNuLCAS model, (ii) to determine its performance and efficiency for predicting runoff and soil loss under various management options, (iii) to better understand the role of various soil conservation measures on controlling erosion by using the WaNuLCAS model and iv) to use the model to assess the magnitude and dynamics of key processes influencing the efficiency of soil conservation measures.

4.2 Materials and methods

4.2.1 Model description

WaNuLCAS was developed to simulate interactions between trees, soil and crops at plot level (Van Noordwijk et al. 2004). These interactions can be simulated across four zones and four soil layers on a daily base. This structure allows monitoring below and aboveground competition for growth factors such as water, nutrients (N and P) and light between trees and crops over a wide range of production systems. The four zones allow to represent various production system such as mono cropping, shifting cultivation, fallow systems and alley cropping. Trees can be grown in one of the outer zones (zone 1 or 4). Thus it is possible to have different levels of competition in the other zones and to represent different designs of soil conservation measures. In addition, separating the soil into four layers allows looking at belowground effects of competition between zones at various soil depths. Zone width and layer depth can be adapted to the experimental set up. WaNuLCAS is created in the Stella® modelling environment (STELLA 1994) and linked to Excel spreadsheets for input and output data (Van Noordwijk and Lusiana, 2004). The

Stella shell allows users to modify parameters and also add model structure. Basic principles and processes are reflected in this model via separate modules e.g. climate, soil erosion and sedimentation, water balance, nutrient balance, soil organic matter turnover, tree and crop growth, root growth, nutrient uptake, competition for water and nutrients, and light capture. This study focused on the runoff and soil erosion modules. All simulations were performed by using WaNuLCAS version 3.2 (Van Noordwijk et al., 2004) and Stella® version 8 to explore changes of surface runoff and soil loss as a result of soil cover and structure changes in response to land use systems. The soil erosion and sedimentation modules in WaNuLCAS include several factors that control runoff and soil loss (Fig. 1).

The amount of runoff is primarily affected by the infiltration rate. Soil physical properties such as clay, silt, median particle size of sand, soil organic matter and bulk density are used in pedotransfer functions (Wösten et al. 1998) to predict a value of saturated hydraulic conductivity for water (K_sat). The K_sat value greatly influences the amount of lateral flow and vertical transport of water in the soil, thus affecting soil infiltration.

One innovative option available in WaNuLCAS 3.2 that relates to soil physical properties is the possibility to simulate the temporal dynamics of soil structure. In WaNuLCAS, soil structure is represented by BD/BD_{ref}, where BD/BD_{ref} is defined as soil bulk density relative to a reference bulk density derived from agricultural soils of the same texture and soil organic matter content (Eq. 1, Hairiah et al. 2006).

$$BD/BD_{ref} = [-0.69 + \mathrm{SQRT}(0.692 + 2.08 * (1.21 - (\log(S\_RelSurfInfiltrInit))))]/1.04 \quad (1)$$

where *S_RelSurfInfiltrInit* is initial relative surface infiltration defined as $Ksat/Ksat_{ref}$. Soil structure undergoes continuous changes through the effect of its decay/compaction rate (*S_BDBDRefDecay*) and improvements through faunal activities ("worm activity", creating macropores) on soil hydraulic conductivity (*Ksat*) (Eq. 2) and infiltration rates (Eq. 3).

$$BD\_ModifyerKsatV = -((S\_WormAct + S\_TC\_OldRC) * S\_BDBDRef) + S\_BDBDrefDecay * (\max(0, 1 - S\_BDBDRef)^{S\_BDEqPower}) \quad (2)$$

where *BD_ModifyerKSatV* reflects the impact of earthworm activity on Ksat. Without earthworm activity, only decay/natural compaction rate (*S_BDBDrefDecay*) will affect *Ksat*. How strong the decay rate influences *Ksat* is governed by parameter *S_BDEqPower*.

S_TC_OldRC is a parameter indicating existence of old root channels (based on volume of roots).

$$BD\_ModifyerInfil = -(S\_WormActSurf * S\_BDBD\mathrm{Re}\,f) + S\_BDBDrefDecay * (\max(0,1 - S\_BDBD\mathrm{Re}\,f)^{S\_BDEqPower}) \quad (3)$$

BD_ModifyerInfil is the impact of earthworm activity on surface infiltration. Only earthworm activities on the top soil surface (*S_WormActSurf*) influence surface infiltration. Worm activity itself is the result of inputs of plant material such as leaf litter, pruning, decaying roots and their decay rates (Eq. 4).

$$S\_WormAct = S\_LFoodForWorms * S\_\mathrm{Re}\,lWormLit + S\_SOMFoodWorms * Mn2\_RelImpLayer \quad (4)$$

where *S_WormAct* is earthworm activity, *S_LFoodForWorms* and *S_SOMFoodForWorms* are available food for worm in litter and soil layer, respectively, and *S_RelWormLit* and *Mn2_RelImpLayer* are qualitative parameters indicating impact of worm in litter and soil layer, respectively.

In the WaNuLCAS spreadsheet, the user can define an initial saturated hydraulic conductivity value that differs (exceeds or is lower then) from the default value predicted by the pedotransfer value. The pedotransfer value reflects a surface infiltration rate in absence of major soil biological activities. During the simulation the value will tend to return to this default value, at a rate determined by the *S_BDBDRefDecay* and *S_BDEqPower* parameters (Eq. 2) unless actively maintained or improved by new inputs over time. Depending on the amounts of "food for worms" provided by the structural (*Struct*) and metabolic (*Metab*) organic inputs (litter = *Lit*; soil organic matter = *SOM, Mn2*) (with conversions set by the preference parameters *S_WormsLikeLitStruct*, *S_WormsLikeSOMStruc*, *S_WormsLikeLitMetab* and *S_WormsLikeSOMMetab*, respectively), and the relative impact of the worms on the given location (the *S_RelWormLit* and *Mn2_RelImpLayer* parameters determine the impact for each soil layer and *S_RelWormSurf* the impact on surface infiltration).

Time for infiltration depends on: (i) time interval between rainfall events, (ii) rate of soil water depletion between rainfall events creating soil storage space, (iii) potential rate of infiltration into the soil in relation to the intensity of rainfall and (slope-dependent) opportunities for temporary water storage at the soil surface (ponding), and (iv) the difference between field capacity (soil water content 24 hours after a heavy rainfall event, when the rate of water seepage to deeper layers tends to reach a small value) and "saturated" soil water content, when all soil pores are water-filled. The resulting amount of runoff plays a major role in the transportation step of soil erosion. The calculation of daily soil loss in the WaNuLCAS model is adopted from the Rose equation (Rose 1998; Rose and Freebairn 1985), represented
by Eq. 5:

$$E\_ErosRose\ (Zone)\ [kg\ m^{-2}] = (Q(Zone) * E(Zone))/10 \quad (5)$$

where *E_ErosRose* is daily event soil loss (kg m^{-2}) in each zone. *Q* (*Zone*) is the daily runoff amount (L m^{-2}) in each zone and *E (Zone)* is the sediment concentration in runoff (Mg ha^{-1}) in each zone as calculated in Eq. 6.

$$\begin{aligned} E\ (Zone) = {} & 2700 * SIN(\arctan(AF\_SlopeCurr(Zone)/100)) * (1.0 - (E\_CoverFac(Zone))) \\ & * \lambda * (EXP(-15 * \text{E\_CoverFac}(Zone)))/100 \end{aligned} \quad (6)$$

where *E (Zone)* is sediment concentration in runoff (Mg ha^{-1}) in each zone, *AF_SlopeCurr (Zone)* the current slope of land (sine of inclination angle) in each zone, λ an entrainment coefficient for sediment movement in the absence of soil cover by vegetation (kg soil mm^{-1} rain m^{-2}), and *E_CoverFac (Zone)* is the fractional surface cover (0-1) in each zone. The *E_CoverFac* (Eq. 7) term in the sediment concentration in runoff equation (Eq. 6) is calculated from the cumulative total cover (*E_CoverSum* (*Zone*)).

$$E\_CoverFac\ (Zone) = \min(1, E\_CoverSum) \quad (7)$$

Derived from:

$$E\_CoverSum\ (Zone) = Cq\ \_CovEffCurr\ (Zone) * C\_LAI\ (Zone) + E\_CovEffT(Sp_i) * T\_LAIFff(Zone,\ Sp_i) + E\_CovEffLitter * Mc\_Struc\ (Zone) \quad (8)$$

In Eq. 8, the total cover (*E_CoverSum (Zone)*) provides a variable "soil surface cover", which is the combined crop cover efficiency factor (*Cq_CovEffCurr (Zone)*) in each zone, tree cover efficiency factor (*E_CovEffT* (Sp_i)) of each species, modified by crop leaf area index (*C_LAI(Zone)*), tree leaf area index efficiency factor (*T_LAIEff* $(Zone,Sp_i)$) in each zone and each species, and carbon in litter layer (*Mc_Struc (Zone)*), due to crop residue and tree litter on the soil surface.

The output parameters observed in the modelling work in this study were *BW_Runoff*, daily amount of surface runoff water (L m^{-2}), and *E_ErosRose (zone 1)*, daily amount of soil loss (kg m^{-2}) from zone 1. The Runoff in the upper zones 2, 3, and 4 and the input rainfall parameter accumulatively influence the calculated *E_ErosRose*(*zone 1*), which represents the measured runoff in the field experiment.

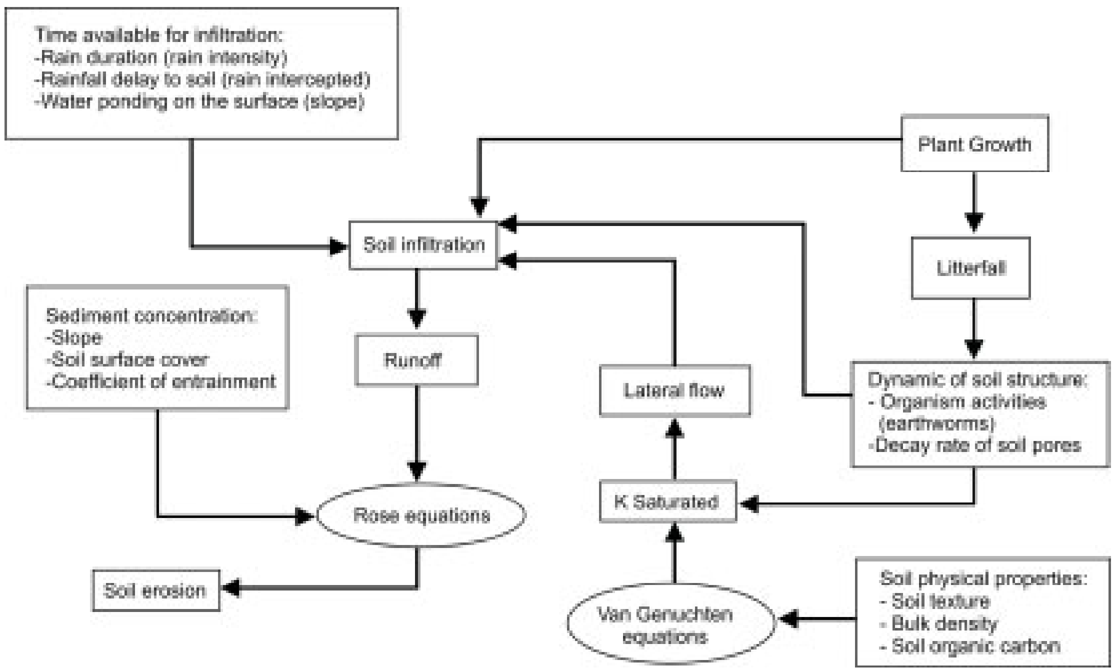


Fig.1 Structure of the WaNuLCAS erosion module and flowchart of involved parameters.

4.2.2 Field data used for simulation

Site specific data for model simulation were taken from a field experiment conducted during 2003 to 2005 at Ban Bo Muang Noi village in the Loei province of Thailand (17°33' N and 101°1' E, 572 m a.s.l.). The trial was established on a moderate slope ranging from 21-28% and is described in detail by Pansak et al. (2008). The soil at the experimental site was classified as a Humic Lixisol with 13% sand, 48% silt, 39% clay in the topsoil (0-25 cm) and a bulk density of 1.33 g cm^{-3}. The top soil had a pH (H_2O) of 6, an organic matter content of 3.5%, an available P (Bray II) content of 14 mg kg^{-1}, an exchangeable K content of 200 mg kg^{-1}, an exchangeable Ca content of 1413 mg kg^{-1} and an exchangeable Mg content of 703 mg kg^{-1}. The experimental site has a tropical savannah climate. Most of the rainfall events were between mid of May and mid of October. Maize is usually grown from May until September. During the observation period the total annual rainfall amounted to 1352, 1288 and 1051 mm in 2003, 2004 and 2005, respectively. Mean annual maximum and minimum temperatures were 44ºC and 11ºC (Fig. 2).

Land preparation was done by slash and burn before planting. The erosion plots were established in April 2003 and laid out as a split-plot design with fertilizer application as main factor, soil conservation as subfactor, and two replications. The main factor treatments were (i) no fertilizer application and (ii) 60 kg N ha^{-1} plus 14 kg P ha^{-1}. Subfactor treatments were four soil conservation measures: (i) a control without hedgerow (CON), (ii) Vetiver grass (*Vetiveria zizanioides* (L.) Nash) strips (VG), (iii) Ruzi grass (*Brachiaria ruziziensis* Germain et Evrard) barriers (RG) and (iv) Leucaena (*Leucaena leucocephala* (Lam) de Wit) hedges (LH). This study focused on a comparison between Leucaena hedges and a control without hedgerow (maize monocropping) under both fertilizer regimes. Further information on trial set up is found in Pansak et al. (2007 and 2008). Each of the erosion plots had a width of 4 and length of 18 m (area = 72 m²) with a collection trough for runoff water and eroded soil installed at the lower end of each plot. In all treatments maize (*Zea mays* L.) cv. Suwan 1 was planted along the contours by using a planting stick at a spacing of 25 cm along the row and 75 cm between rows. After the initial slash and burn activities and hand hoeing to a soil depth of 10 cm for land clearing no soil preparation was carried out in the consecutive year apart from hand weeding. One month before maize harvest, in all treatments Jack bean (*Canavalia ensiformis* (L.) DC) was planted between maize rows. Hedgerows of Leucaena were planted in April 2003, spaced 5 m apart. Leucaena was pruned 3-6 times per year and cut at a height of 80 cm above the ground. In all treatments, maize stalks were cut at harvest and left on the plots as mulch. Jack beans dried up at the end of the dry season and their residues were additionally left on the plots as mulch. In Leucaena hedgerow treatments prunings were chopped with a machete and left as mulch in the respective plots. Over the observation period, 10 and 19 Mg ha^{-1} of plant residues were applied as mulch in the control without hedgerow and the Leucaena treatment when no fertilizer was applied, whereas 18 and 32 Mg ha^{-1} were applied in the corresponding fertilized treatments. Therefore, all treatments were considered as minimum tillage systems.

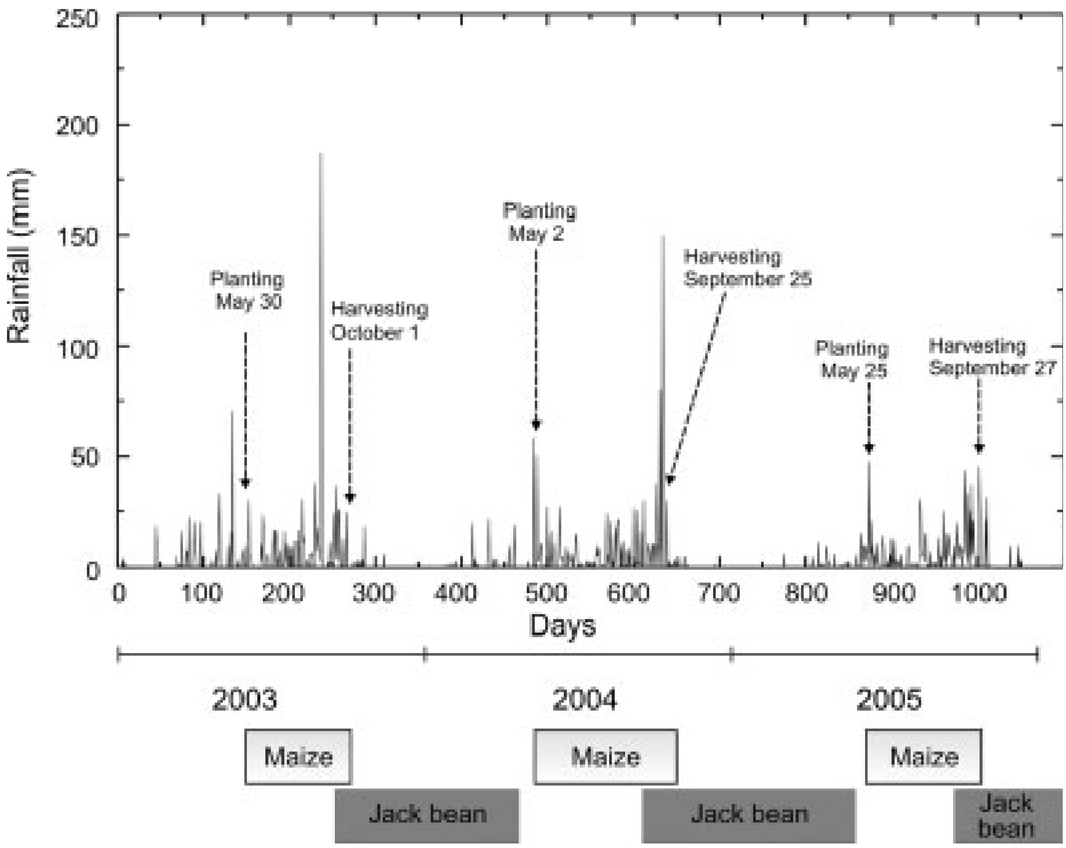


Fig. 2 Daily rainfall distribution and cropping pattern for the three years monitoring period (2003-2005) at the experimental site in Ban Bo Muang Noi, Leoi province, Northeast Thailand. Arrows indicate planting and harvesting dates.

4.2.3 Model calibration and validation

In all simulation runs the total length of the four zones was set to 6 m, representing one third of the total plot length of 18 m in the field experiment (Fig. 3). The width in zone no. 1 was set to 1 m (equal to the strip within the soil conservation treatments) and in zones no. 2 to 4 it was set to 1.67 m. In simulation runs with hedgerows, trees were planted in zone 1 where they served as a buffer strip to control soil loss and runoff. The four soil layers were defined to 0.25 m each, representing the soil profile.

WaNulCAS was calibrated to model the dynamics of runoff and soil loss in the control without hedgerow treatment based on the environmental conditions of Ban Bo Muang Noi, Northeast Thailand. In this treatment maize was planted in all four zones. The initial size of the soil organic matter pools, which were adopted from the CENTURY model (Parton et al. 1987), were based on %N contents and the bulk density of soil layer no. 1. For calculating water movement in the soil, a pedotransfer function in the WaNuLCAS Microsoft EXCEL sheet was used (Wösten et al. 1998). Soil physical properties e.g. sand, clay, median particle size of sand, bulk density and soil organic matter content were required to estimate the parameters for the pedotransfer function based on the Van Genuchten equation (van Genuchten 1980) and to tabulate the relations between soil water content, hydraulic conductivity and pressure head. Simulations were done with minimum tillage condition, nutrient (N, P) and water limitations. The slope gradient was adjusted to 28%. Maize development was calibrated in the crop library of WaNuLCAS adjusting values for the length of vegetative and generative periods for each growth cycle.

For the step of calibration, observed daily runoff and soil loss data from the experimentation period 2003 to 2005 were used and compared to simulated values based on daily rainfall data from the same period. During the first calibration process the WaNuLCAS parameters (site calibration) presented in Table 1 were iteratively modified and applied. Next, the dynamic soil structure submodule (represented by the switch *S_SoilStrucDyn*?) was activated, which means that the soil structure was open for changes through 'earthworm' activities during the simulation time. The third step used a sensitivity analysis to obtain an improved coefficient value from fitting the curve for the relationship between the ratio of normalized sediment concentration and the surface contact cover fraction. Cover in close contact with the soil surface is called "surface contact cover". For the last step of WaNuLCAS calibration, some of the default values of crop specific parameters for maize and Jack bean (relative light use efficiency (RelLUE), harvest allocation (Harvest) and specific leaf area (SLA)) were modified, to better represent crop growth and in view of the model overestimation of runoff and soil loss during the end of the rainy season and of soil loss at the beginning of maize planting.

In order to verify the predictive capability of the model, a validation with an independent dataset was performed after the model calibration described above. Model validation was performed by comparing observed and simulated annual runoff and soil loss of the control without hedgerow and the Leucaena hedgerow treatments, both with and without fertilizer application. The field trial set up on crop and tree management including maize planting and harvesting, timing and amount of fertilizer application, pruning dates, planting, harvesting of Jack beans and mulch provided by Jack beans was entered into the management options spreadsheet of the WaNuLCAS EXCEL file.

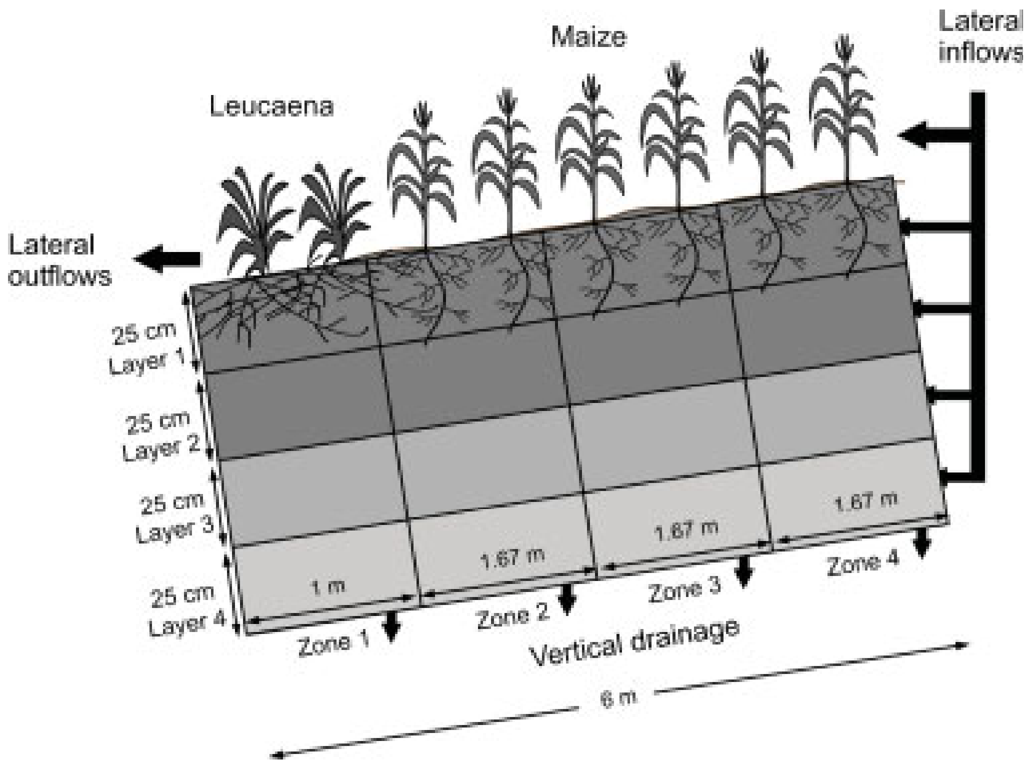


Fig. 3 Model set up based on the field experiment in Ban Bo Muang Noi, Leoi province, Northeast Thailand. In the control without hedgerows Zone 1 was also planted to maize.

Table 1 Description of WaNuLCAS parameters, default and modified values used for model calibration

Parameter name in WaNuLCAS	Default value	Modified value	Description
E_EntrailmentCoeffBarePlot	0.002	0.01	Entrailment coefficient for sediment movement (Rose equation) in the absence of vegetative soil cover
Rain_IntensCoefVar	0.3	1e-008	Variance coefficient of rain intensity
Rain_IntensMean	50	23.8	Average rain intensity per day
Rain_IntercDripRt	10	9	Water dripping from interception surfaces
Rain_IntMult	3	2	Maximum temporary storage of water on interception surfaces
Rain_MaxIntDripDur	0.5	0.5	Maximum water interception delay before dripping
Rain_PondFlwRt	10	9	Rate of ponding surface water flowing to neighboring zone/plot
Rain_PondStoreCp	5	6	Storage capacity of water ponding on surface
S_KsatVDeepSub	20	100	K sat below layer 4
S_BDBDRefDecay	0.001	1e-008	Relative rate of decay of the bulk density, returning the surface infiltration rate toward
S_RelWormSurf	1	0.03	Relative impact of “worms”(soil fauna) increase of infiltration rate of the surface
S_RelSurfInfiltrInit(Zone)	4	20	Surface infiltration rate at the start of the simulation relative to its default value
S_SurfInfiltrPerKsatDef(Zone)	0.0825	0.087	Ratio of surface infiltration and Ksat for the first soil layer in the default condition of the soil as define by pedotransfer function
S_WormLikeLitMetab	1e-005	0.0002	Activity of soil fauna per unit organic input in the litter metabolic pool
S_WormLikeLitSOMMetab	1e-006	0.001	Activity of soil fauna per unit organic input in SOM metabolic pool
S_TRtStrucFormFrac	0.3	2.3	Fraction of contribution of tree root decay on root channels
S_CRtStrucFormFrac	0.1	2.1	Fraction of contribution of crop root decay on root channels
E_TillZone	1	0	On/off switch for tilling activity in each zone (0 = no tillage, 1 = with tillage)
S_KSatHperV$_i$(Zone)	1	2	Ratio of saturated hydraulic conductivity in horizontal and vertical direction for layer *i*

4.2.4 Assessing the role of various soil conservation measures on controlling erosion by using WaNuLCAS

After validation of WaNuLCAS, the model was used to run several scenarios. To confirm the observed positive effect of minimum tillage and relay cropping with Jack bean on controlling erosion (Pansak et al. 2008), the rainfall pattern of the third year of observation was changed to that of 2004 as the rainfall pattern of 2005 did not show the extreme rainfall events as found in 2003 and 2004. In this case rainfall followed the pattern of 2003 and 2004 while 2005 was substituted by 2004 rainfall values (Fig. 2). Thus, the effect of different rainfall patterns could be tested. In the next scenario, the role of various soil conservation measures in controlling erosion was assessed via the effect of the dynamic soil structure module, surface litterfall and surface covered by crop or tree. To test the effect of soil dynamic structure on soil erosion, we set the soil dynamic structure function represented by the variable *S_SoilStrucDyn* in WaNuLCAS-Stella to "zero" instead of "one". Thereafter we eliminated Jack beans to test the effect of surface cover.

4.2.5 Model performance

Model performance was assessed by comparing predicted values against observed data of daily runoff and soil loss. The R^2 was used as a measure of how close to a linear 1:1 relationship observed to predicted results were. In addition, several specific statistical equations (Loague and Green 1991; Walker et al. 2007) were applied in order to improve the analysis of model performance (model goodness of fit), i.e.:

Modeling efficiency (EF);

$$\text{EF} = \left(\sum_{i=1}^{n} (O_i - \overline{O})^2 - \sum_{i=1}^{n} (P_i - O_i) \right)^2 \Big/ \sum_{i=1}^{n} (O_i - \overline{O})^2$$

Coefficient of determination (CD);

$$\text{CD} = \sum_{i=1}^{n} (O_i - \overline{O})^2 \Big/ \sum_{i=1}^{n} (P_i - \overline{O}_i)^2$$

Root mean square error (RMSE);

$$\text{RMSE} = \left[\sum_{i=1}^{n} (P_i - \overline{O}_i)^2 \Big/ n \right]^{0.5} . \frac{100}{\overline{O}}$$

Where P_i are the predicted values; O_i are the observed values; n is the number of samples; and $\bar{O}$ is the mean of the observed data.

By estimating modeling efficiency (EF), it is possible to know how good the model prediction is. A value of one means a perfect one-to-one correspondence between the predicted and observed values. The CD is a measure of the proportion of the total variance of observed data explained by the predicted data; one indicates a perfect prediction fit. The RMSE is expressed in percentage and designates the average error of predicted outcomes. If RMSE is zero, it underlines the goodness of the agreement between measured and predicted data.

4.3 Results

4.3.1 WaNuLCAS model calibration and validation

As a first step of WaNuLCAS calibration, daily runoff and soil loss were simulated based on site specific data without including the soil structural dynamic function. The result was rather poor as indicated by the goodness of fit (GOF) statistics for daily runoff (e.g. EF=0.37) and soil loss (e.g. EF= 0.31) (Table 2). Including the soil structural dynamic function in the simulation run considerably improved the GOF statistics for predicting daily runoff (EF=0.73, R^2=0.72, CD=0.88 and RMSE=0.60), whereas results for soil loss prediction remained poor.

In view of these results, the coefficient of the exponential relationship in the equation of sediment concentration in runoff (Eq. 1) in WaNuLCAS model was investigated. This coefficient value is derived from curve fitting of the relationship between the normalized sediment concentration to that from a bare field (C/C_b) and the surface contact cover fraction (C_f). A coefficient value of 15 in the Rose equation (Rose et al. 1985) and used as a default value in WaNuLCAS 3.2 indicated a rapid exponential decline of the normalized sediment concentration as contact cover fraction increases. At C_f of approximately 0.2 or greater, normalized sediment concentration becomes negligible, apparently indicating that already 20% contact cover showed a very large reduction of soil loss (Fig. 4). Therefore, we reassessed the coefficient value of the exponential relationship based on LAI/soil cover data collected within this study. The modified coefficient value of 5 was obtained from fitting the curve for the relationship between the ratio of normalized sediment concentration and the surface contact cover fraction of the unfertilized control without hedgerow treatment (Fig. 4). The coefficient value of 5 is within the range (5-15) proposed by Rose et al. (1985). This modification improved the accuracy of the predicted value for daily soil loss as indicated by a comparison of GOF values of steps 2 and 3 in Table 2. On the other hand, the GOF test statistics (EF, R^2 and CD) for predicted daily runoff were not affected by this modification; however the RMSE slightly increased (0.60 *vs.* 0.66).

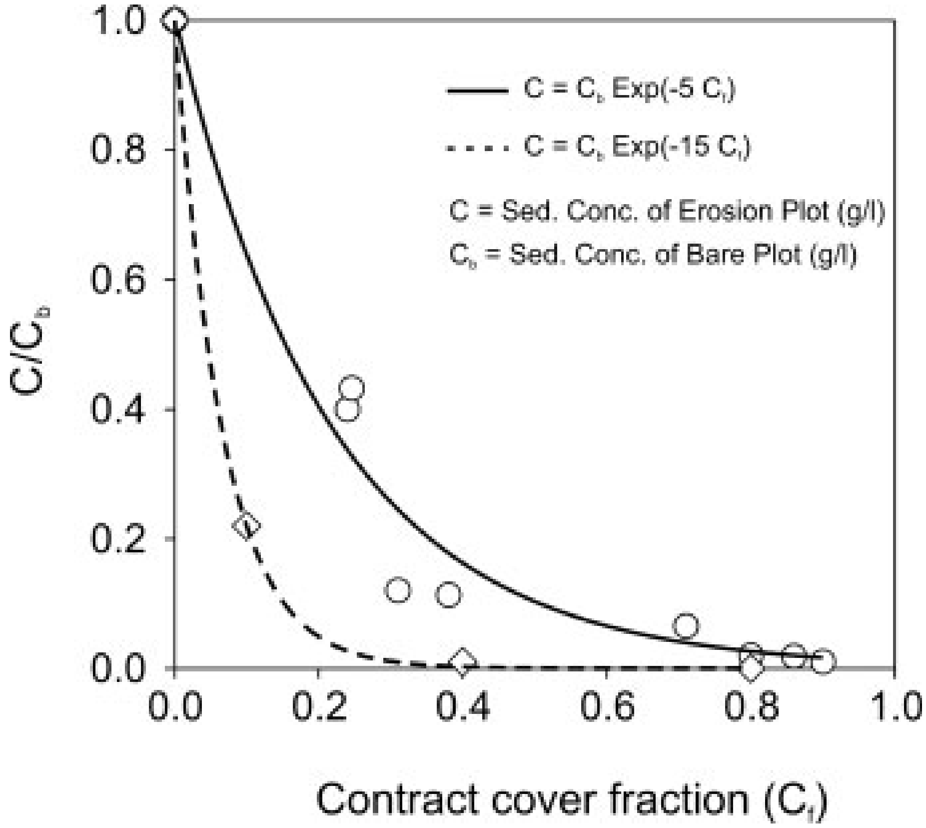


Fig. 4 The dashed curve describes the default relationship between the ratios of soil concentration in runoff (*C*) to that from bare soil field (*Cb*) and the surface contact cover fraction (*Cf*) given in WaNuLCAS Rose erosion equation. The solid curve is the exponential relationship depicted from LAI measurements at Ban Bo Muang Noi, Thailand with a coefficient equal to 5.

The final step of WaNuLCAS calibration improved crop development as described in the Materials and Methods section to better reflect site specific growth conditions. The resulting GOF values showed a further small improvement between observed and predicted values for daily runoff (R^2=0.89) and soil loss (R^2=0.75). This was further supported by other GOF values (Fig. 5 and Table 2).

The model validation was done by using annual runoff and soil loss of the control without hedgerow and the Leucaena hedgerow treatments, both with and without fertilizer application. A comparison between predicted runoff and soil loss versus observed values for three years of scenario simulation showed a reasonable model performance (Fig. 6). The validation showed better fit for annual runoff than for annual soil loss. For runoff the correlation coefficient was 0.82 and the slope of the best fit line was 0.93 (Fig. 6a), whereas annual soil loss was slightly less accurately predicted with a correlation coefficient equal to 0.80 and a slope of the best fit line of 0.88 (Fig. 6b). Trends of the fitting lines, however, showed that both cumulative runoff and soil loss predicted by WaNuLCAS model underestimated the observed values at large events.

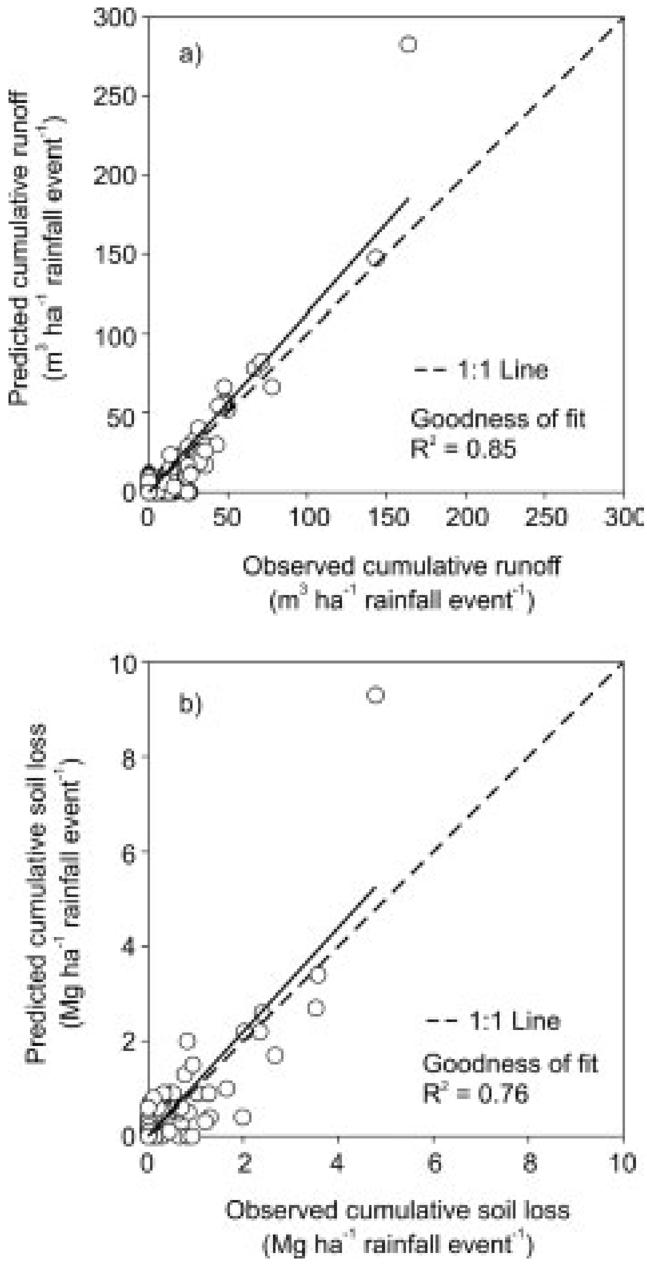
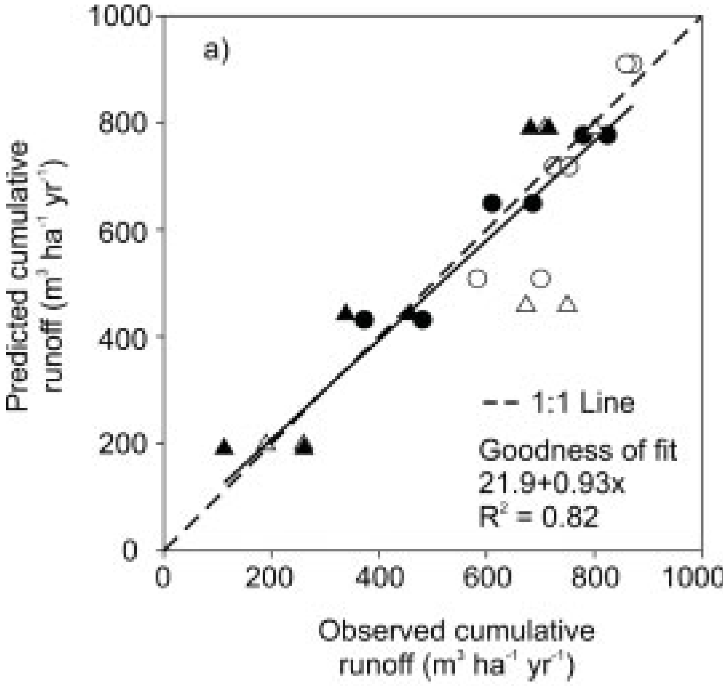


Fig. 5 Relationship between predicted and observed (a) runoff events and (b) soil loss events in the unfertilized control without hedgerows used for model calibration. The solid line represents the regression curve and the dashed line is the one-to-one line.



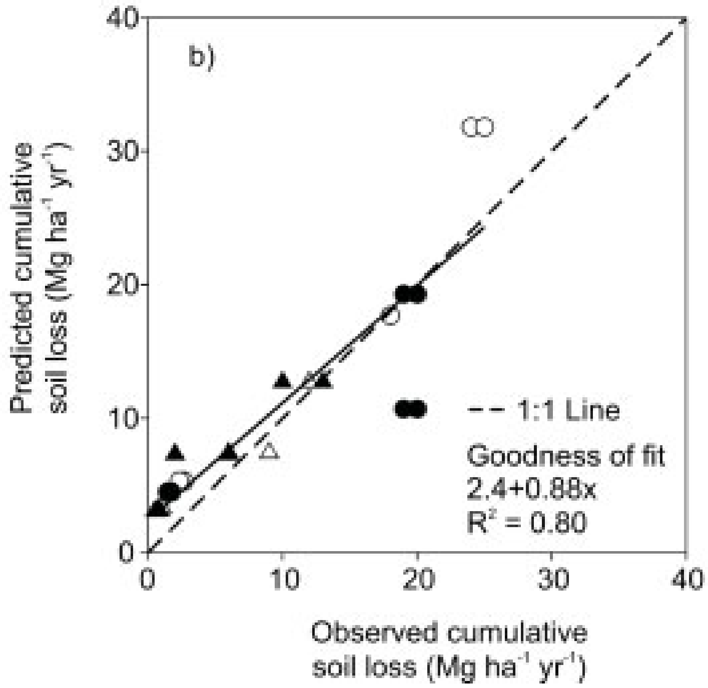


Fig. 6 Relationship between predicted and observed (a) annual runoff and (b) annual soil loss in the unfertilized control without hedgerows used for model validation. Open (○) and closed (●) circles refer to datasets of the unfertilized and fertilized control without hedgerows, and the open (△) and closed (▲) triangles refer to datasets of the unfertilized and fertilized Leucaena hedgerow treatment. The solid line represents the regression curve and the dashed line is the one-to-one line.

Table 2 Effect of calibration steps on model performance statistics for event based runoff and soil loss over a 3-year-period

	Step		EF 1*	R^2 1	CD 1	RMSE 0(%)
Runoff	1	Site calibration without simulating changes in soil structure dynamic	0.37	0.71	0.50	0.90
	2	Site calibration with simulating changes in soil structure dynamic	0.73	0.77	0.88	0.60
	3	The coefficient of crop cover from Rose equation calibration	0.73	0.77	0.88	0.66
	4	Crop development improvement	0.75	0.89	0.66	0.57
Soil loss	1	Site calibration without simulating changes in soil structure dynamic	0.31	0.32	3.92	0.03
	2	Site calibration with simulating changes in soil structure dynamic	0.29	0.30	3.93	0.03
	3	The coefficient of crop cover from Rose equation calibration	0.46	0.47	2.34	0.03
	4	Crop development improvement	0.60	0.75	0.63	0.02

* Best possible result indicating the value for a perfect fit between observed and predicted runoff and soil loss.

4.3.2 The effect of changing rainfall distribution on runoff and soil loss under soil conservation measures

Recently published results from a study at the same site on changes in the relationship between soil erosion and N loss pathways after establishing soil conservation systems showed that minimum tillage and relay cropping with a legume cover crop was similarly effective in erosion control as Leucaena hedgerow and grass strip based soil conservation systems three years after establishment (Pansak et al. 2008). Soil loss decreased from 24.5 Mg ha^{-1} in the first year to 1.6-2.5 Mg ha^{-1} in the third year. This may have been dictated by the reduced rainfall amount in the third year but also due to the combined effects of minimum tillage and surface cover by mulch. Therefore, WaNuLCAS was used to test whether the reduced erosion observed in 2005 was an effect of lower rainfall in that year or the long-term effect of minimum tillage and relay crop with Jack beans. In this scenario the simulated cumulative runoff and soil loss for three years based on rainfall patterns at the experimental site during 2003 and 2005 (original data) were compared to those based on a modified rainfall distribution by substituting the 2005 rainfall pattern (total 1051 mm) with that of 2004 (total 1288 mm) (Fig. 7). This modification increased total rainfall for three years from 3691 mm to 3927 mm. In consequence runoff during the third year increased from 508 to 699 m^3 ha^{-1} in the control and from 198 to 344 m^3 ha^{-1} in the Leucaena hedgerow system when no fertilizer was applied. With fertilizer application, runoff raised from 431 to 688 m^3 ha^{-1} in the control without hedgerows and from 189 to 305 m^3 ha^{-1} in the Leucaena hedgerow treatment. Despite the simulated increase in rainfall the simulation proved that the cumulative runoff under hedgerow systems was still significantly lower than the control without hedgerow after three years of simulation. Moreover, the simulation runs based on a modified rainfall distribution confirmed the results of the field experiment and showed that soil loss of all treatments strongly decreased in the third year. In the third year, however, the cumulative soil loss of the control showed a small increase under the altered rainfall distribution whereas the Leucaena hedgerow showed a small decrease under the modified rainfall distribution.

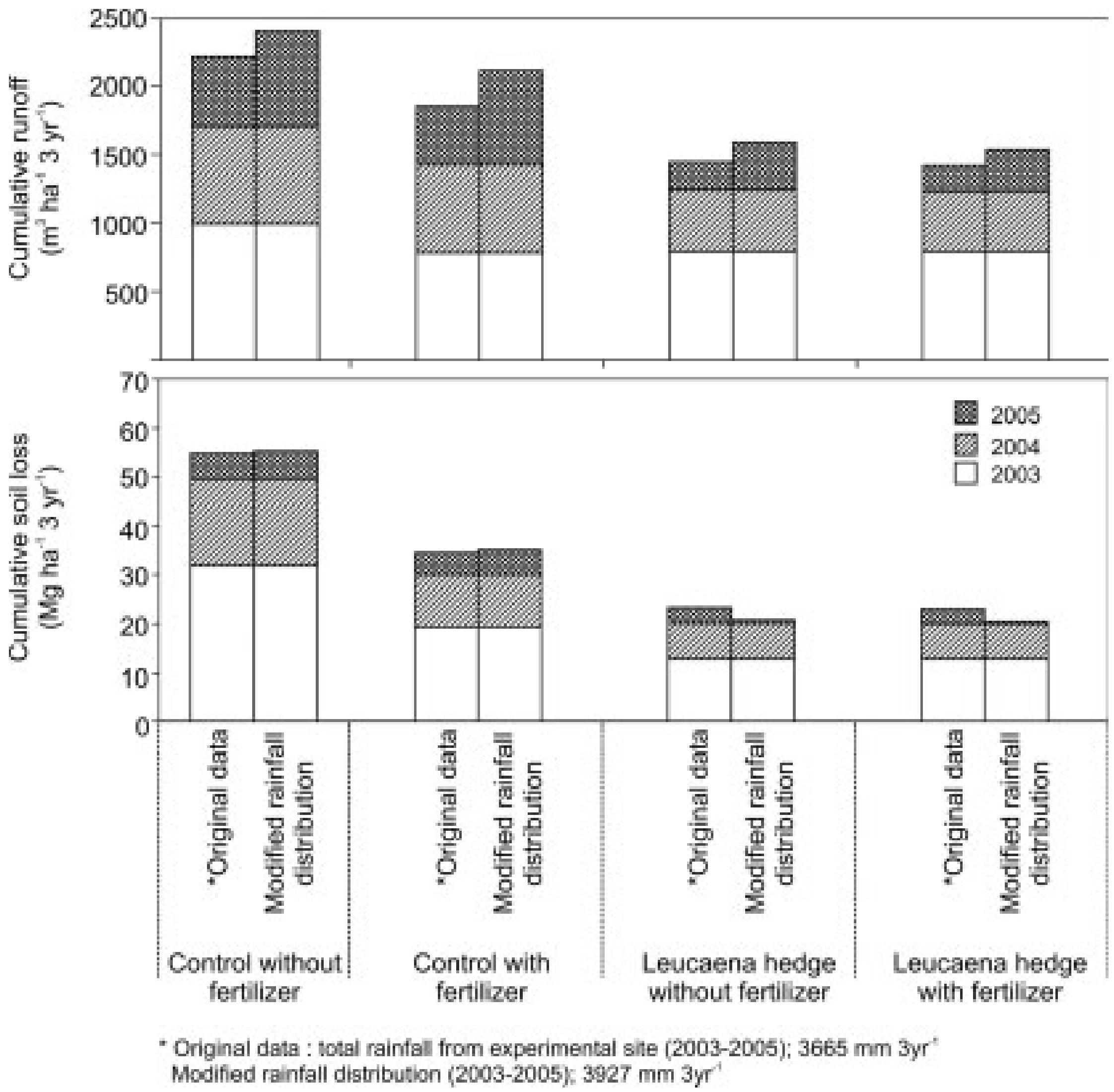


Fig. 7 Comparison between simulated cumulative runoff and cumulative soil loss results based on the original rainfall pattern of 2003-2005 at the experimental site (Original data) and based on a modified rainfall distribution for 2005 by using the rainfall pattern of 2004 (Modified rainfall distribution).

4.3.3 The influence of soil structure dynamic on runoff and soil loss

Simulated runoff under a no-tillage based system during three years without simulating changes in soil structure dynamics initially followed a trend similar to that of simulated runoff considering changes in soil structure dynamics (Fig. 8). However, after 633 days all treatments without simulating changes in soil structure dynamics clearly displayed higher runoff compared to those with the dynamic soil structure module activated. After three years, a decrease in the predicted runoff (about 6% under the unfertilized and 3% under fertilizer control treatments and about 12% in the unfertilized and 11% under fertilized Leucaena treatments) was found when the simulation allowed changes in soil structure. The effect of a dynamic soil structure was larger in the Leucaena treatments compared to the control without hedgerow treatments.

A comparison of soil loss scenarios for three years showed that soil loss was reduced by hedgerow systems, fertilizer application and with simulating changes in soil structure dynamics (Fig. 9). Therefore, after three years the lowest soil loss was observed in the fertilized Leucaena hedge treatment including changes in soil structure dynamics (23 Mg ha^{-1} $3yr^{-1}$). In addition, after three years, a reduction of the predicted soil loss by 4 and 6% in the unfertilized and fertilized control treatments and 15 and 16% in the unfertilized and fertilized Leucaena treatments resulted from the activated dynamic soil structure module. In the fertilized control without hedgerow treatment, the different pattern of soil loss became distinguishable very early, while in the unfertilized control and both Leucaena treatments, the different pattern of soil loss with and without simulating changes in soil structure dynamics occurred only after 633 days. Nevertheless, the effects of simulating changes in soil structure dynamics on soil loss were smaller than those on runoff. At the end, a setting where soil structure dynamic was included provided a good match between the predicted and observed runoff and soil loss.

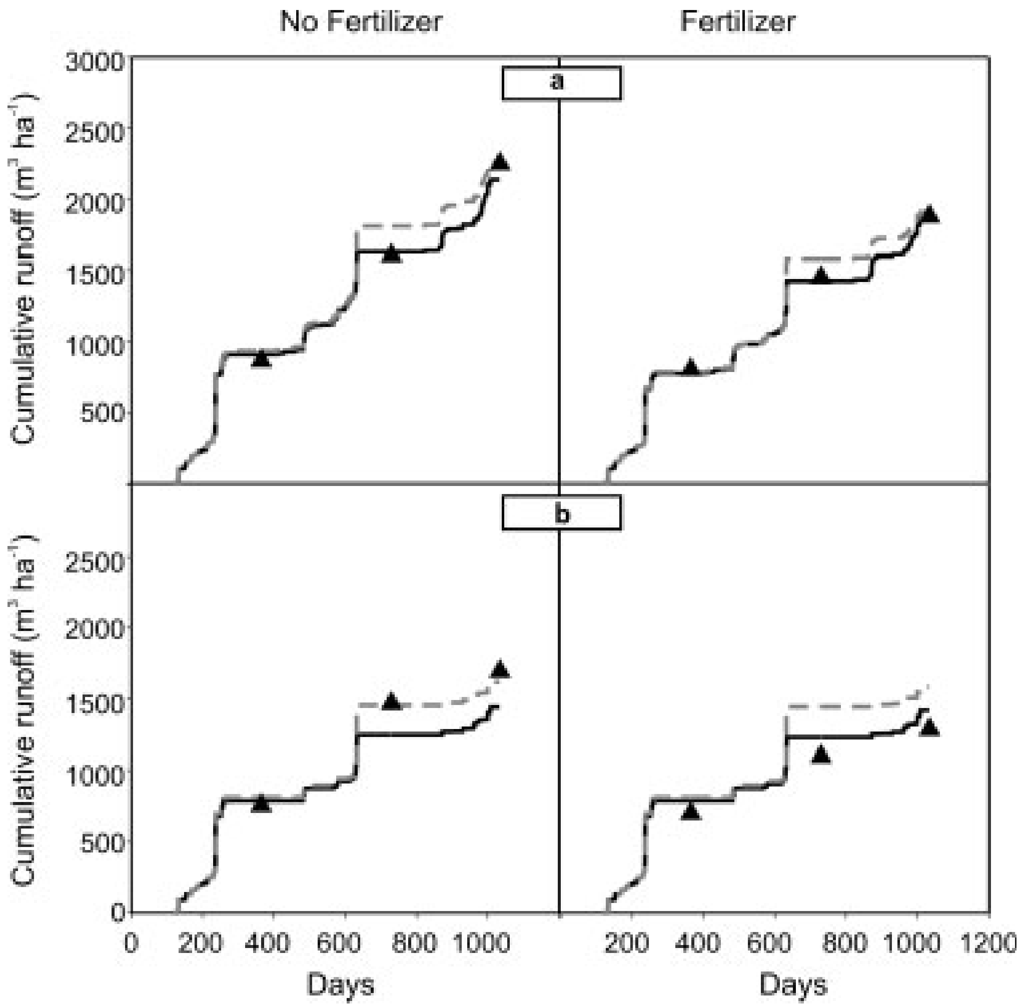


Fig. 8 Impact of soil structure dynamics on runoff: a) control without hedgerows and b) Leucaena hedgerow treatment. Solid black line represents a simulation including soil structure dynamics; dashed grey line represents a simulation excluding soil structure dynamics. Observed total runoff of each year is presented by a black triangle (▲).

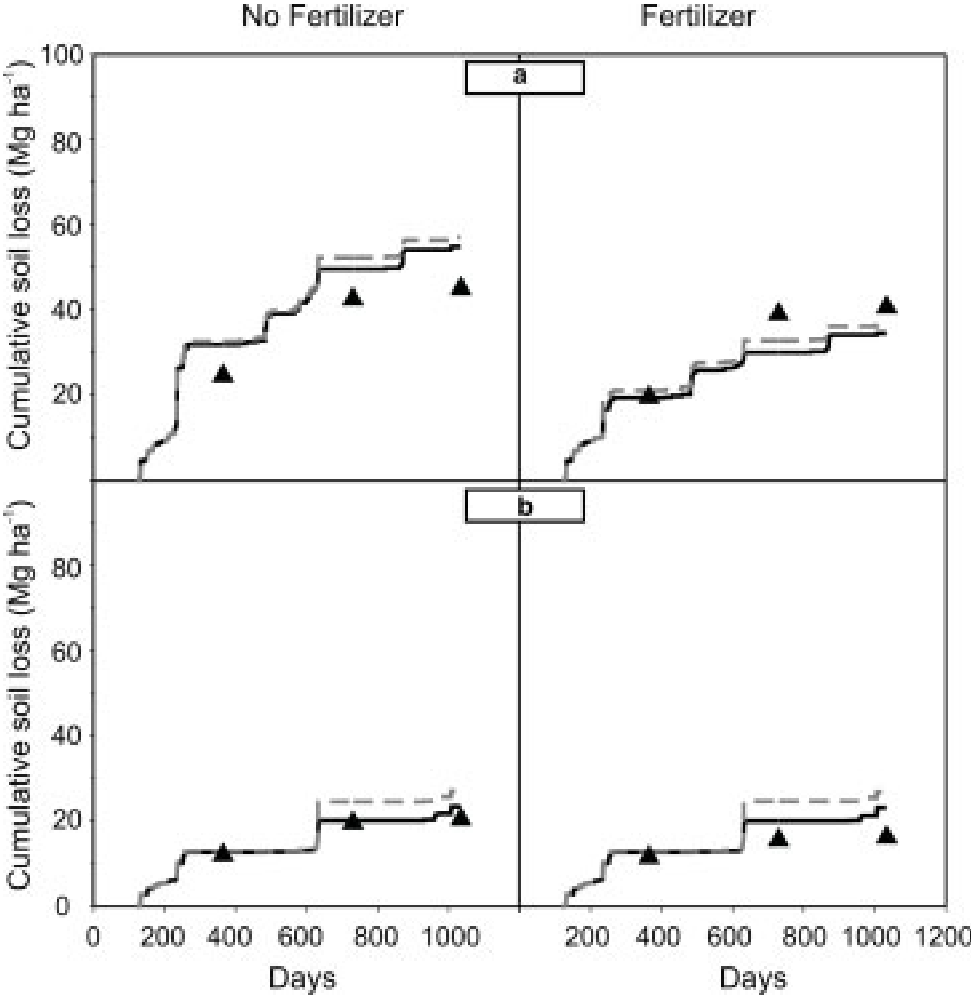


Fig. 9 Impact of soil structure dynamics on soil loss: a) control without hedgerows and b) Leucaena hedge treatment. Solid black line represents a simulation including soil structure dynamics; dashed grey line represents a simulation excluding soil structure dynamics. Observed total soil loss of each year is presented by a black triangle (▲).

4.3.4 Effect of Jack bean on runoff and soil loss

Scenario simulations of runoff and soil loss showed after three years, that the control without and with fertilizer treatments with relay cropping with Jack bean cover during the dry period reduced predicted runoff by 22% compared to the simulation without Jack bean relay cropping (Figs. 10 and 11). In contrast, no significant difference of predicted runoff was observed in the unfertilized and fertilized Leucaena hedge treatments with respect to relay cropping. The simulation results also indicated that in the control without hedgerow, fertilizer application was more effective in reduction soil loss over three years than relay cropping with Jack bean. Moreover, the predicted soil loss over three years for the unfertilized and fertilized control treatments without Jack bean, were 40 and 85% higher, respectively, than under the unfertilized and fertilized control treatments with Jack bean. After three years of simulation soil loss in the unfertilized treatments was higher than in the fertilized treatments in both, with and without, relay cropping with Jack bean. The lowest simulated soil loss was found in Leucaena hedge treatments without relay cropping with Jack bean compared to the system with relay cropping with Jack bean. Moreover, the simulation with relay cropping of Jack bean displayed the predicted runoff and soil loss close to the results of runoff and soil loss from the field experiment.

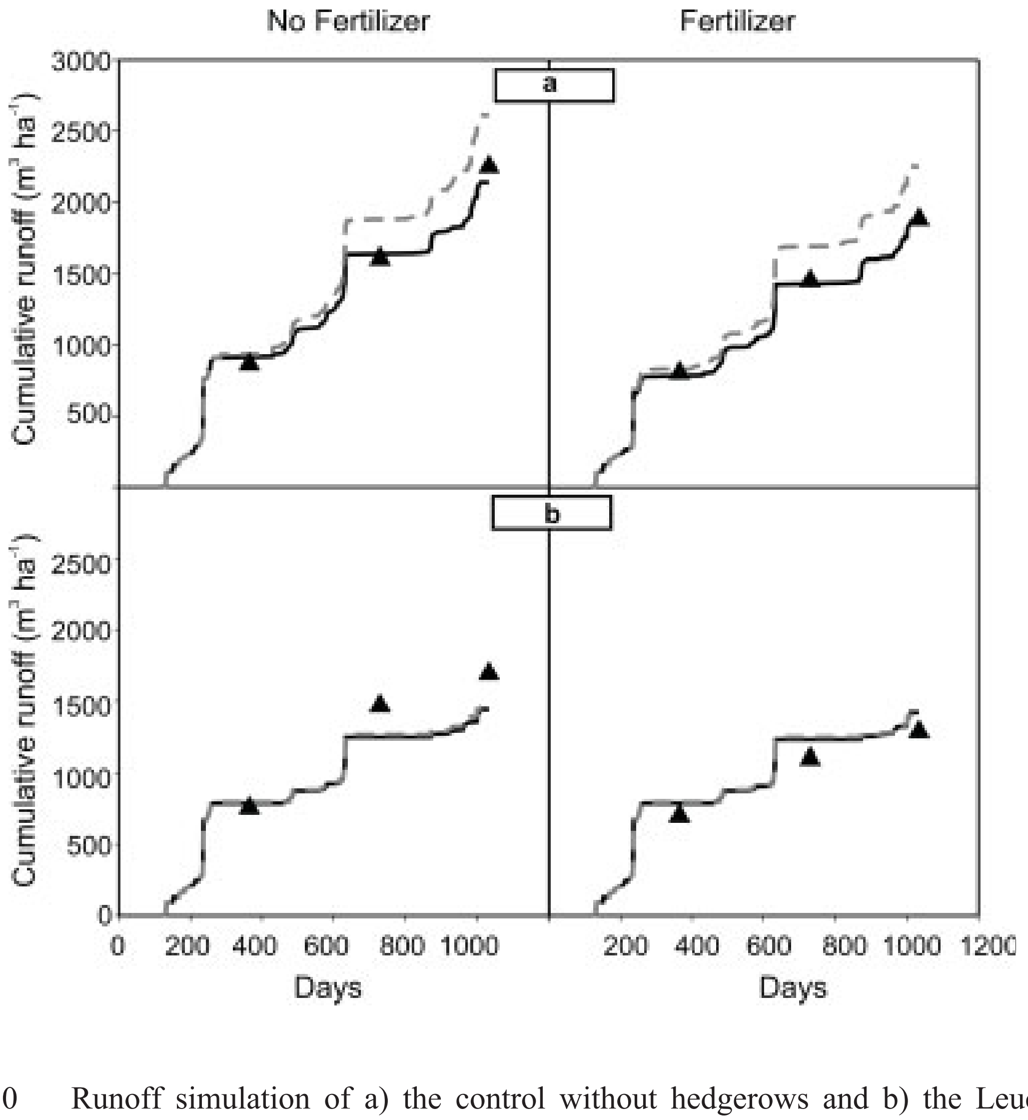


Fig. 10 Runoff simulation of a) the control without hedgerows and b) the Leucaena hedgerow treatment with (solid black line) or without (dashed grey line) Jack bean relay cropping. Observed total runoff of each year is presented by a black triangle (▲).

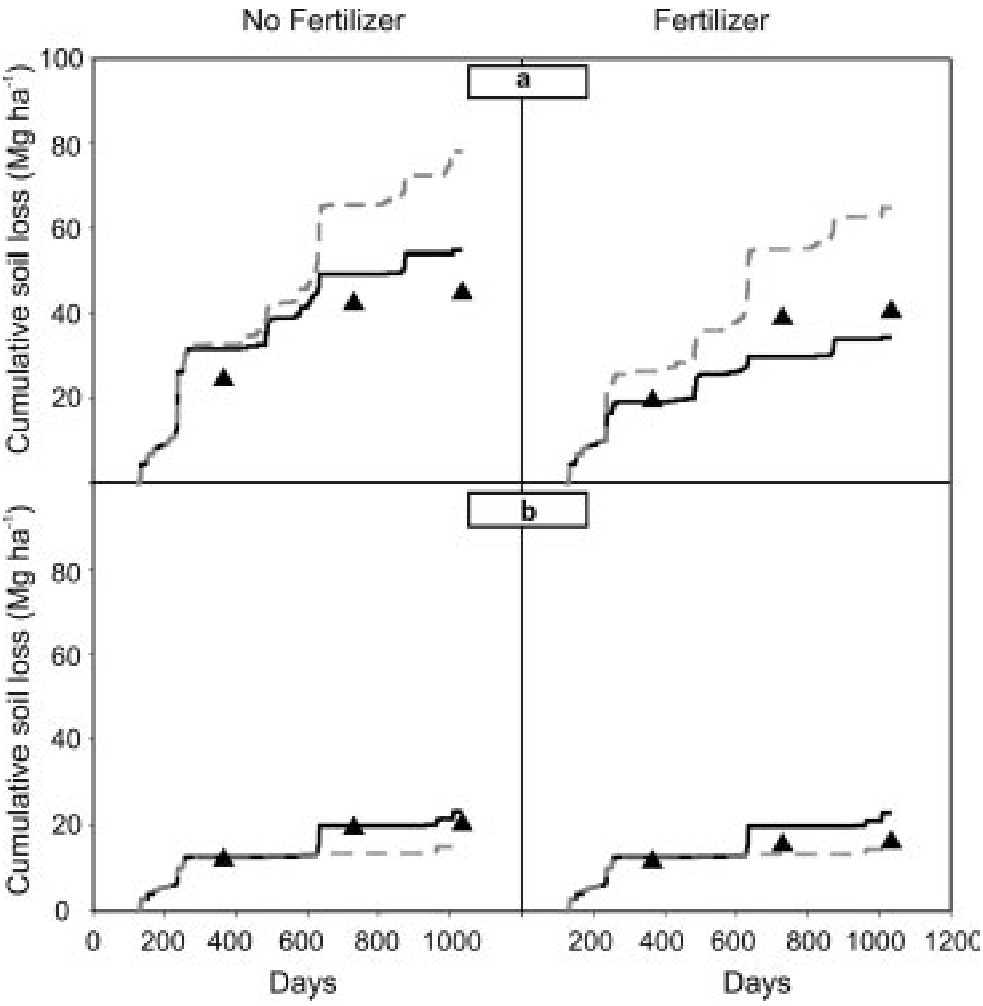


Fig. 11 Soil loss simulation of a) the control without hedgerow treatment and b) the Leucaena hedgerow treatment with (black line) or without (dashed line) Jack bean relay cropping. Observed total soil loss of each year is presented by a black triangle (▲).

4.4 Discussion

4.4.1 Evaluation of WaNuLCAS model in predicting erosion

Overprediction of runoff and underprediction of soil loss were observed in simulation runs based on site specific parameters when not considering temporal changes of soil structure. When the soil structure dynamic function was enabled in WaNuLCAS, runoff predictions strongly improved as earthworm activity represented by this function may have led to a higher formation of soil macropores with positive effects on water infiltration (Blanchart et al. 2004; Kuka et al. 2007). Reducing runoff by increasing soil water infiltration improved the performance of WaNuLCAS; however soil loss was still under-predicted. The reduction of runoff rapidly decreased the sediment concentration in the runoff represented as a function of surface contact cover. The surface contact cover is that kind of cover consisting of mulch and plant parts which are sufficiently close to the soil surface to affect overland flow. In contrast to canopy or aerial cover, contact cover is more efficient in reducing soil loss. It is very effective in protecting the soil, not only against soil detachment caused by raindrop impact, but also against soil entrainment by surface overland flow (Paningbatan et al. 1995).

The amount of soil loss can be controlled by the coefficient value of the relationship between soil loss and increase in surface contact cover. Hence, reducing the WaNuLCAS default value of 15 in the Rose equation to 5, justified by our own observations, and being in the range (5-15) as proposed by Rose (1985), improved the performance of WaNuLCAS in predicting daily soil loss. A coefficient value of 5 led to a negligible soil loss when surface contact cover was greater than 70%. Such an exponential relationship was also reported by Mati et al. (2006). For the final step of WaNuLCAS calibration, default values of crop specific parameters for maize, i.e. those having an impact on crop development, were modified to better represent juvenile growth stages of maize development when the system is most susceptible to erosion (Leihner et al. 1996). The WaNuLCAS default settings were responsible for a rapid growth of maize, leading to some unpredicted runoff and soil loss events during simulation runs. Therefore, the parameters of relative light use efficiency, harvest allocation and specific leaf area of maize were reduced. In consequence, WaNuLCAS showed an improvement of some simulated runoff and soil loss events immediately after maize planting (Fig. 5).

The validation of WaNuLCAS showed a reasonably good prediction of runoff and soil loss in a hillside cropping system of Northeast Thailand (Fig. 6) and gave good correlation coefficients under maize monocropping and hedgerow systems. The gradients of regression lines indicated that both runoff and soil loss were under-predicted by the model at larger events. This can be explained by the large variation of observed runoff between replications of the unfertilized control treatment in 2005 and the unfertilized Leucaena hedgerow treatment in 2004 which decreased slope gradients of the regression line. The gradients of regression line of soil loss were lower than the 1:1 line because the soil loss prediction of the unfertilized control treatment in 2003 and that of the fertilized control treatment in 2004 were outlying compared to the rest of the results. The over-prediction of soil loss observed in the unfertilized control treatment in 2003 was due to an extremely high rainfall event at 25th of July 2003, while soil loss of the fertilized control treatment was under-predicted in 2004 because fertilizer application increased biomass production of maize and Jack bean. This improved mulch availability and soil surface cover by maize and Jack bean and led, thus, to an under-prediction of soil loss.

4.4.2 The role of soil conservation in controlling runoff and soil loss

A scenario with modified rainfall distribution by increasing rainfall amount in the final year of simulation enhanced total runoff by 9 and 14% in the unfertilized and fertilized control treatments, respectively, and by 10 and 8% in the unfertilized and fertilized Leucaena treatments, respectively, when compared to simulation runs based on the observed rainfall pattern (Fig. 7). A comparison of the cumulative runoff and soil loss of the years 2004 and 2005 indicates that a potential increase in rainfall, achieved by substituting the 2005 rainfall pattern by that of 2004, in the last year increased runoff but had almost no effect on soil loss. This observation proved results already reported by Pansak et al. (2008), indicating a positive impact of minimum tillage and Jack bean relay cropping on soil erosion within three years of cropping. Additionally, this scenario showed that the fertilized control treatment under the modified rainfall distribution had a slightly higher increase of predicted runoff and soil loss than the unfertilized control. The explanation might be a better development of the maize cover fraction because of the higher rainfall amount. This may have hampered Jack bean growth and the development of its cover fraction due to belowground competition by maize. In the Leucaena hedgerow treatments, a higher efficiency in reducing soil loss was found in the third year when using the modified rainfall distribution instead of the observed rainfall pattern in the simulation run. The increase of rainfall in the last year of this scenario may have reduced competition for water between crop and tree, leading to a higher maize and Leucaena biomass (Imo and Timmer 2000; Pansak et al. 2007). The better growth conditions for maize and Leucaena improved soil cover and reduced, thus, soil loss more effectively compared to simulations based on the field data. The results of this scenario confirmed observations from the field experiment where lower runoff and soil loss were found in Leucaena hedgerow than in the control without hedgerows. This can be explained by the effect of hedgerow roots on the presence of macropores (Rowe et al. 2005), which enhance infiltration. Providing more mulch can be considered as an additional factor in reducing runoff and soil loss as it reduces the impact of raindrops on the soil surface (Lal 1998), increases hydraulic roughness and reduces flow velocity, and thereby decreasing soil detachment (Kiepe 1996). However, rapid reduction of soil loss in the last year was also found in the control treatment associated with minimum tillage and Jack bean relay cropping despite increasing rainfall amount in the third year. This highlights the potential of both measures in controlling erosion.

4.4.3 Importance of soil structure dynamics and relay cropping with Jack bean in controlling runoff and soil loss

The dynamic soil structure function in WaNuLCAS played a significant role in reducing runoff and soil loss and improved predicting runoff and soil loss when comparing observed and simulated data. Soil biota activity is crucial in influencing soil structure and related soil physical properties (Hairiah et al. 2006). In particular earthworms, through their burrowing and feeding activities, influence particle size distribution, organic matter content, organic matter location, soil aggregation, aggregate stability and tensile strength, soil roughness, and water infiltration (Blanchart et al. 2004). All these properties greatly influence reduction in runoff and soil loss. A simulation run over three years with disabled soil structure dynamic function produced a lower increase of runoff in fertilized compared to unfertilized treatments. This was due to the fact that not only earthworm activities increase infiltration rate, but also root development affects infiltration rate positively (Joshi et al. 2004a). The difference between disabling and enabling soil structure dynamic function on soil loss was higher in the treatments with fertilizer application. This could be explained by a higher leaf litter cover in fertilized treatments, whereas the effect by pruning and mulch material was smaller. The impact of changes in soil physical conditions with time on runoff and soil loss was stronger in the Leucaena treatments compared to treatments without hedgerows. This is a result of higher inputs to soil organic matter e.g. Leucaena litterfall, pruning of Leucaena, mulching of maize and Jack bean and decaying roots. Higher inputs of SOM in 2004 compared to 2003 may explain differences in cumulative runoff and soil loss between simulation runs using the soil structure dynamic function or not, which were observed after maize harvesting in 2004.

Increases of runoff and soil loss in the control without hedgerows and Jack bean relay cropping observed at the end of this scenario run indicated that relay cropping with Jack bean is also an important factor for reducing runoff and soil loss in the control treatment. Jack bean relay planted at the end of the rainy season and growing into the dry season can maintain soil moisture (Morgan 2005). Moreover, Jack bean applied as mulching can improve soil structure (bulk density) by increasing earthworm activities and improving soil fertility for maize in the next season; as a result, biomass and yield of maize improve in the course of time. Improved growth of maize enhances soil surface cover and, thus, improves controlling runoff and soil loss. On the other hand, no increase of runoff and the decease of soil loss were found in the Leucaena hedgerow without Jack bean during the dry season in this scenario after a 3-year simulation. The reason could be a reduction of competition between Leucaena and Jack bean, which was confirmed by the lower number of days of water stress when Jack bean was excluded from the simulation run. Therefore, in this run, WaNuLCAS showed an increase of Leucaena biomass, especially in 2005, which improved soil cover, provided by mulch, material and litterfall from maize and Leucaena, explaining the lack of response in runoff and soil loss. This points out that relay cropping with Jack bean was not necessary in the hedgerow system when hedgerows were already well established.

4.5 Conclusions

Improvements of predicting soil loss and runoff with the WaNuLCAS model were achieved during the calibration and validation process by modifying the coefficient value of the relationship between soil loss and increase in surface contact cover and modifying default values of crop specific parameters for improving crop development in the erosion module. Thereafter the model showed a good agreement between observed and predicted runoff and soil loss in maize based upland cropping systems. The WaNuLCAS model showed a high degree of flexibility as it is able to look at a wide range of soil conservation measures. Furthermore, this study proved the capability of the model to capture interactions and dynamics associated with establishing soil conservation measures in complex land use systems and improved our understanding of drivers in these systems. The model can, therefore, be well used for erosion prediction under the described boundary conditions and open new insights for adapting soil conservation in tropical mountainous regions.

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CHAPTER 5

General discussion

5.1 Evaluation of the effectiveness of soil conservation measures and fertilizer application in controlling erosion

After three consecutive years of study, the results of the experimental field at Ban Bo Muang Noi village in Loei province of Thailand on a moderate slope (21% to 28%) demonstrated that contour barriers, e.g. Vetiver (*Vetiveria zizanioides*) grass strips, *Leucaena leucocephala* hedges, or Ruzi grass (*Brachiaria ruziziensis* Germain et Evrard) barriers under minimum tillage condition in combination with relay cropping of Jack bean had a high efficiency in reducing runoff and soil loss compared to the control without hedgerow. The effectiveness of contour barriers in controlling erosion has been reported in previous studies. Xia et al. (1996) and Hu et al. (1997) reported that in China a decrease in surface runoff of 32.7–59.7% and a decrease in soil loss of 63.7–92.7% were observed when the Vetiver (*Vetiveria zizanioides*) grass strips were planted. Uri el al. (1998) further reported that zero tillage/minimum tillage and residue conservation were effective as a means of reducing soil erosion, leaching and runoff of agricultural chemicals. A previous study in Northern Thailand reported that soil loss could be reduced to less than 2 Mg ha^{-1} yr^{-1} after establishing *Leucaena leucocephala* hedges or Ruzi grass (*Brachiaria ruziziensis* Germain et Evrard) barriers based maize cropping systems (Kongkaew, 2000; Smolikowski et al., 2001). Thus, the results of this thesis reinforce that a combination of barriers and cover crop with minimum tillage seems to be particularly effective in controlling runoff and erosion. Hedges/barriers play an important role in reducing runoff and soil loss in time because hedges/barriers and trimmings provide biological barriers that help minimizing soil erosion by reducing surface runoff velocities, leading to higher deposition of soil sediment.

Alternatively, maize, even without hedgerow, but with the use of additional soil conservation measures, such as minimum tillage and mulching, also had a potential in reducing soil loss over time. For example, in the third year of the study less than 3 Mg ha^{-1} of erosion was observed in the maize-Jack bean relay system presumably because carryover of previous years' maize and Jack bean residue inputs resulted in a cumulative buildup of a protective surface soil residue cover and improved soil structure as suggested by the WaNuLCAS simulations. Experimental research elsewhere showed that surface

crop residues increased with time under no-tillage with maize due to residue carryover from year to year (Halvorson, et al., 2002). Crop residues increase soil surface roughness which reduces raindrop impact, erosivity, surface runoff of water, and promotes infiltration. In addition, the observed relationships between rainfall versus runoff and soil loss in the maize based minimum tillage plus mulching treatment from in this thesis showed that runoff was not greatly reduced after three years compared to the beginning of plot establishment but erosion was. The greater effectiveness of the hedgerow systems in controlling soil loss as compared to runoff has also been observed in other soil erosion control studies with hedgerow systems (Babalola et al., 2007; Sudhishri et al., 2008).
Maintaining a large runoff volume with a small sediment concentration is an important source for water supply, in particularly for lowland paddy fields in Southeast Asia because these fields often depend on runoff for water supply during shortages of rainfall (Sthiannopkao et al., 2007; Wang et al., 2007).
The study also demonstrated that fertilizer application enhanced the efficiency of soil conservation measures either in maize-Jack bean relay cropping system or further improving hedges/barriers performance by enhancing crop performance and by providing more mulch and thereby reducing runoff and soil loss. Improved crop growth facilitates quick soil surface cover (above ground) and increases crop and hedgerow/barrier roots (below ground) development which could reduce the impact of raindrops on the soil surface (Morgan, 2005), increase macropores (Rowe et al., 2005), and enhance water entry into the soil (infiltration rate).

5.2 Assessment of crop response under soil conservation measures and fertilizer application

The study demonstrated that the use of contour hedges/barriers 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 17% in the cropping area as compared to the value observed in the control plot without hedgerows. Such negative impacts of hedges/barriers on crop yield can be due to two main factors, e.g. terrace formation and occurrence of severe competition between crop and barrier plants. Several studies indicated that the presence of hedges or grass barriers results in a terrace formation due to sediment retention in the barrier and facilitated by downward tillage action. This reduces topsoil depth at the upper end of an alley, and in advance stages exposing subsoil, which can have a negative impact on crop response in the alley (Agus et al., 1997; Turkelboom et al., 1997; Dercon et al., 2003, 2006). Initial signs of terrace formation were also observed in this study (data not presented) which could have contributed to the observed average yield decline in the alleys. The positive crop response to fertilizer addition additionally demonstrated that direct nutrient competition effects affected crop performance. Therefore the effectiveness of the contour hedges/barriers can be reduced due to competition between crops in the alley and species forming the hedges/barriers.

In the same experimental site, the dataset from 2005 showed that maize grain yields were strongly declined in alley rows towards the hedges/barriers. The observed negative yield in the contour hedgerow treatments poses the questions about the nature of the stress, e.g. N or water stress, dominating the competition between crop and hedgerow. Maize leaf $\delta^{13}C$ values from the unfertilized and fertilized Ruzi and the unfertilized and fertilized Leucaena treatments represent growth conditions for a part of the crop cycle during which the leaf was formed. Despite the fact that one maize leaf might be a limitation for using $\delta^{13}C$ values as a tool to identify the cause of spatial variability in crop response, it was not considered forming a major constraint for its use, due to homogenous growth conditions over the entire cropping cycle.

Using of ^{13}C isotopic discrimination in combination with data on N availability and uptake in the shoot displayed that the competition was mainly for nitrogen and less for water towards the hedges/barriers. In case of Leucaena treatments, the presence of more negative $\delta^{13}C$ values in the centre of the alley suggested higher water stress at this position, as compared to the rows at the lower part of the alley, next to the barrier. Furthermore, results presented in Chapter 2, indicated that significantly lower runoff occurred on the same experimental plots when barriers were present. This could probably be linked with higher water infiltration in the lower part of the alleys. However, in combination with the high $\delta^{13}C$ values close to the barrier, it was concluded that, as was the case in the Ruzi grass plot, N deficiency was the main driver for the observed reduction in crop response. The presence of a correlation between NO_3^- and grain yield, taking into account the data from the central row and the row close to the barrier, confirmed that the yield decline towards the barrier could be related to N availability. With regards to the fertilized plots with Leucaena hedges, the most striking was the huge variation in $\delta^{13}C$ values, ranging from -10.54‰ to -11.38‰. Due to the high N availability from the fertilizer and the Leucaena prunings, the low values can be probably related with indirect water stress. The results from this study point that the competition for N between hedges/barriers and maize crop could be reduced by fertilizing the alleys, in particular in the contour hedgerow systems with Ruzi grass *(Brachiaria ruziziensis* Germain et Evrard*)*. Then, maize grain yield and stover in fertilized treatments were higher compared to the unfertilized treatments.

5.3 Evaluation of pathways of N losses and changes through time

Improving of efficiency of soil conservation measures and crop performance by fertilizer application did not result in higher N losses by runoff, soil loss and leaching. Thus, well-managed fertilizer application, e.g. by using split applications, supported contour hedgerows systems without increasing environmental pollution. This observation could be confirmed by the gradual decline of N losses by runoff and erosion and no significant difference in N losses between the unfertilized and fertilized treatments. 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).

Surprisingly, the unfertilized and fertilized treatments showed no significant difference in N losses. The lack of difference of N losses between fertilizer treatments can be explained by the better N uptake maize and hedges/barriers instead of losing N by runoff or soil loss. This agreement was supported by the better growth of hedges/barriers and high N concentration in shoot and grain of maize in the treatment with fertilizer. Mineral N losses in all treatments were only slightly lower in 2005, particularly in the treatments with fertilizer application, as compared to 2004 and 2005. The lower precipitation in the third year of observation is probably the major reason. However, the better development of the Vetiver grass and Ruzi grass barriers and Leucaena hedges suggests a higher uptake of mineral N reducing losses by leaching, and finally the jack bean relay crop probably also reduced N leaching (Aronsson, 2000). Although the hedgerow treatments shifted the main pathway of N losses towards leaching losses of mineral N, the average observed 10 kg N yr^{-1} mineral N losses by leaching at 90 cm depth was still low as compared with 112 to 115 and 50 kg N ha^{-1} yr^{-1} N leaching under vegetable and rice areas on similar sandy loamy soils in Vietnam (Trinh et al., 2007).

5.4 Assessment of performance and efficiency for predicting erosion and dynamics of key processes influencing the efficiency of soil conservation measures by using WaNuLCAS

After calibration, the validation of the WaNuLCAS model proved that the model was well suited to assess the efficiency of soil conservation measures. The WaNuLCAS model outputs of runoff and soil loss agreed well with observed runoff and soil loss based on event and yearly basis. the Water, Nutrient and Light Capture in Agroforestry Systems (WaNuLCAS) model that was developed by the World Agroforestry Center (ICRAF) to deal with a wide range of agroforestry systems with minimum parameter adjustments was used to investigate the role of soil conservation measures in controlling runoff and soil loss relatively quickly and at relatively low cost. Models are particularly useful in assessing alternatives scenarios but also in verifying the impact of varying environmental conditions. For examples, it was unclear if the observed dramatically reduced soil losses in all conservation treatments in 2005 were due to the lower rainfall recorded and the absence of extreme rainfall event in 2005. Therefore, WaNuLCAS was used to test the effect of different rainfall scenarios. In the first scenario simulation was done by the rainfall pattern of 2003 and 2004 while the low rainfall year 2005 was substituted with the higher rainfall 2004 values. The simulated result from the WaNuLCAS model confirmed the observed result from the field experiment that the control and hedgerow treatments in combination with minimum tillage, mulch and relay cropping with Jack bean can drastically reduce soil loss over time even with high total rainfall events. Additionally, in the next scenario, the role of various soil conservation measures on controlling runoff and soil loss was assessed via the effect of the dynamic soil structure module (earthworm activities). These simulation results clearly showed that hedgerow systems and fertilizer application are very important in controlling runoff and soil loss. Large organic matter inputs of plant material such as leaf litter, pruning of hedges/barriers, stover and decaying roots under hedgerow treatments with fertilizer can be linked to high earthworm activities. Then the role earthworms results in improving soil fertility and soil physical properties that directly link to macropores and infiltration (Joshi et al., 2004).

Furthermore, the role of ground cover with Jack bean during the dry season was a very important factor for maize based systems without hedgerow in reducing runoff and soil loss during subsequent rainfall events. During the dry season, after crop harvest, and prior to the cropping season, the soil was dryer, when soil was not covered by vegetation and presumably was more sensitive to soil crusting and delayed soil wetting and hence increased runoff and soil loss than the rest of the year. On the other hand runoff and soil loss patterns for the hedgerow treatments looked different from the control without hedgerow. A lack of increase in runoff and soil loss indicated that planting Jack bean during the dry season was not important in controlling runoff and soil in case of the contour hedgerow treatments. This observation might be because inputs from plant material from stover plus pruning from hedges/barriers were large enough to cover soil during the dry season. Therefore, the simulation under Leucaena treatments showed no increase runoff and soil loss after thee years. All of the above has direct implications for management. But in addition, management works to reduce erosion through fertilization, timely planting, and a whole host of farm practices that encourage vegetative growth.

5.5 Potential acceptable options for smallholders

Within this study, various soil conservation measures were tested and proved their effectiveness to control water induced erosion in maize based hillside cropping. Based on a field experiment and a model approach pros and cons of contour hedgerows, grass barriers, and minimum tillage in combination with legume relay cropping, were identified. Their acceptance by farmers, however, largely depends on the feasibility of these systems. In terms of appropriate cultivation techniques for smallholders, options need to fulfill both generate cash income and reduce agricultural risks. Soil conservation techniques are good in controlling runoff and soil erosion and they increase soil fertility by reducing N losses by erosion and without accelerating leaching.

Among all live barriers options tested in this study, Vetiver grass need more time to establish in the field compared to the Ruzi grass and Leucaena. The potential of Vetiver grass strips in reducing erosion could be observed only in the third year of the study. But its performance was similar to that of the control without hedgerows where after three years of minimum tillage and Jack bean relay cropping soil loss was also well controlled. Simultaneously, a positive maize yield response was observed in the latter. This causes difficulties for promoting Vetiver grass strips to farmers, as the area reduction for strip establishment reduced yields from second year onwards.

Results also indicate that Ruzi grass barriers and Leucaena hedges seemed to be acceptable options for smallholders on moderate slopes in tropical mountainous regions. Both species are fast to establish in the field, which could reduce erosion from the second year onwards. However, hedgerows/grass barriers have to be planted on contour lines. This, of course, requires more labour at the time the field is established before the maize is planted. It is also likely that alley cropping results in terrain changes from steep slopes to terraced fields, which are advantageous in controlling erosion and maintaining soil properties. Terraces, also called bio-terraces, can be formed gradually as contour hedgerow systems mature. Compared with engineered terraces, bio-terraces formed by hedgerow are more stable and cost less. Bio-terraces can also be established on steep slope with highly-weathered or sandy soil, and on terrain in which it is difficult to construct engineering terraces in the subhumid region (Tang et al. 2001). Furthermore pruning material peovided by either Ruzi grass barriers or Leucaena hedges may be used as fodder, mulch, green manure, and firewood depending on household needs. Ruzi grass strips and Leucaena hedges, however, started to hamper maize growth in the second year and are, thus, for economic reasons also considered to be less favourable for smallholders. In the third year, competition between hedgerows/barrier species and maize strongly affected yield in rows adjacent to hedgerows and yield declined due to competition for nitrogen. This competition is lower when fertilizer is applied at recommended rates. However, some smallholders might not be able to afford even recommended fertilizer rates.

Maize under minimum tillage and Jack bean relay cropping showed a yield increase in the course of time, even without fertilizer application. Nevertheless, soil loss and runoff were high in the first two years but Soil loss reached a very low level in the third year whereas runoff was reduced to a lesser amount. This may make the system interesting for smallholders as both environmental protection and economic interests of farmers are met.

Results from this study also suggest that maize grain yield under the Ruzi grass and Leucaena treatments show an increase from the first to the second year due to the reduction of erosion and addtional input from mulching. Therefore Ruzi grass barriers and Leucaena hedges can be particularly important at the beginning of field establishment. When hedgerows/grass barriers are combined with minimum tillage and realy cropping they become less important in the course of time, e.g. two or three years after establishment. Therefore, temporal barriers, for example a natural vegetation strip, together with minimum tillage and relay cropping (legume) seem to be an alternative option for upland cropping in tropical mountainous regions, provided they can be easily removed when the system is well established so that competition between barriers/hedges and crops can avoided.

5.6 Recommendations

- Using conservation agriculture (without hedgerows) runoff still exists but is cleaner, 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.

- A probable condition that maize based minimum tillage and mulching systems succeeds is the presence of a relatively fertile soil with good water holding capacity to allow for a fast formation of a mulch layer. Therefore, this approach would need to be tested on soils of different fertility and also with steep slopes, where the necessary protecting mulch might be washed away to lower deposition areas by heavy rainfall events (Lal, 1989).

- One disadvantage of minimum tillage is difficulty of weed control. Weed problems will increase if tillage operations are reduced. While the current study weed pressure was low for other situation, alternatives for weed control under minimum tillage accessible to smallholders in the tropics would need to be studied.

- The use of ^{13}C isotopic discrimination was shown, under field conditions, to be a promising tool for the assessment of causes for competition between hedgerows and crops grown in the alleys. Nevertheless, the use of a well structured and documented experimental frame is needed. It is suggested to extend and intensify plant sampling to further evaluate temporal and spatial variations in $\delta^{13}C$ in crop samples and related dynamics in competition for water and N.

- The results suggested that WaNuLCAS is a promising tool to study, explore potential management options for hillside cropping systems and may contribute to a better understanding of tradeoffs of upland cropping and the consequences for lowland areas. However, it requires further building up the link between nutrient loss by erosion and soil fertility function.

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CHAPTER 6

Summary

In Northeast Thailand, water-induced soil erosion is a severe problem in uplands. Soil erosion causes soil nutrient depletion, low soil productivity followed by a lower productivity of important cash and/or food crops. High amounts of fertilizer are required to compensate for nutrient losses by runoff and to mitigate soil degradation. N losses caused by soil erosion are main contributors to environmental problems. Applying integrated soil conservation systems as well as studying the dynamics of N losses is needed to achieve sustainable agriculture.

This 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.). 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, sixteen 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. In all treatments maize (*Zea mays* L.), cv. Suwan 1, was planted along the contours on a moderate slope with gradients ranging from 21 to 28% under minimum tillage conditions and relay cropped with a legume cover crop (*Canavalia ensiformis*). 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 two weeks after crop emergence, the second half was given one 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).

The objectives of this study were (i) 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. (ii) to assess the use of ^{13}C isotopic discrimination, in combination with standard methods in determining N availability and uptake, in order to better understand the competition for water and N between crops and barrier species, water and N uptake by crops under contour hedgerow systems and to derive a conceptual framework to assess relationships between crop response, N and water availability and $\delta^{13}C$. (iii) to use field experimental data to

calibrate and validate the erosion submodule of the WaNuLCAS model. (iv) to better understand the role of various soil conservation measures on controlling erosion by using the WaNuLCAS model. (v) to use the model to assess the magnitude and dynamics of key processes influencing the efficiency of soil conservation measures.

In order to study changes in the relationship between soil erosion and N loss pathways after establishing soil conservation systems in uplands of 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. After three year observation 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. 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. 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. Runoff 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.

From these observations, it is concluded that establishment of suitable contour hedgerows has an advantage in reduction of runoff and soil loss especially at the initial state of crop growth while in the later state contour hedgerows, which are combined with the use of additional soil conservation measures, such as minimum tillage and mulching, have a less important role to play in the reduction of soil loss. Decrease in maize grain yield in treatments with hedgerows/ grass barriers the tradeoff. Furthermore, soil conservation systems have significant effects on the change of N loss pathways.

Due to the negative crop response under soil conservation measures, using ^{13}C isotopic discrimination as a starting point for new insights in competition for nitrogen and water under contour hedgerow systems in tropical mountainous regions was studied for a deeper understanding of the competition leading to a decline in crop response. In this study, the aspatial variability in grain yield of maize (*Zea mays* L., cv. Suwan 1) was assessed for a *Brachiaria ruziziensis* Germain et Evrard (Ruzi grass) grass barrier and a *Leucaena leucocephala* (Lam) de Wit hedgerow systems on highlands of Northeast Thailand.

Fertilizer applications are without and with fertilizer (60 kg N ha^{-1} and 14 kg P ha^{-1}). Available NO_3^-- N was analyzed across the slope and shoot N concentration and $\delta^{13}C$ values in leaves were recorded for maize plants in the center of the alley and in the row next to and at the upper side of barriers or hedges. Results showed that $\delta^{13}C$ values were significantly ($p<0.05$) less depleted close to the barriers or hedges, except for 2 out of 16 plots. This implies that the main driver for spatial variability along the alleys was not water deficiency. The negative correlation between ^{13}C isotopic discrimination and available NO_3^- -N in the soil, with R^2 ranging from 0.5 ($p<0.10$) to 0.9 $p<0.01$) is observed indicating it assigned as a major role to N availability in the reduced crop response towards the barriers. The proposed framework of ^{13}C isotopic discrimination, together with plant and soil N data, is a new approach and was shown to be applicable to quantify N and water competition between hedgerows and crops grown in alleys under field conditions.

In the last article, assessing soil conservation strategies for upland cropping in Northeast Thailand with the Water Nutrient Light Capture in Agroforestry System model were assessed. In this study, a data set of three years (2003-2005) from this field experiment on the impact of soil conservation measures on runoff and soil loss was used for the model calibration and validation. The control without hedgerow and Leucaena hedge treatments in both with and without fertilizer were selected to test the performance of the WaNuLCAS 3.2 model simulating the impact of soil conservation measures on runoff and soil loss. The results indicated that WaNuLCAS was applicable to hillside cropping system of Northeast Thailand, as correlation coefficients of 0.82 and 0.80 were obtained between observed and predicted runoff and soil loss, respectively. Related to the scenario simulations, it can be concluded that soil conservation measures such as Leucaena hedges are important techniques to control runoff and soil loss. Soil dynamic structure had an impact on reducing runoff and soil loss via improving soil structure by time, whereas relay cropping with Jack bean played an import role in the control treatments in reducing soil loss in the third year. It was concluded that after its calibration and validation, the WaNuLCAS model can be used as a tool to study, understand and explore potential management options for this specific hillside cropping systems.

Contour barriers/hedgerows combined with minimum tillage and legume relay cropping, in terms of appropriate cultivation techniques for smallholders, provide more options for farmers to generate cash income and reduce agricultural risks due to control of runoff and soil erosion and increase in soil fertility by reducing N losses by erosion and leaching. Results also point out that the hedgerows and barriers are probably only required in the establishment phase and that thereafter maize cropping under minimum tillage combined with legume relay cropping is a viable option for the study area, at least for areas with moderate slopes.

CHAPTER 7

Zusammenfassung

Bodenerosion ist in Hanglagen von Nordostthailand ein schwerwiegendes Problem. Es führt zur Verarmung an Bodennährstoffen und einer Abnahme der Bodenproduktivität. Als Folge sinkt auch die Produktivität der angebauten Marktfrüchte und Nahrungspflanzen ab. Hohe Düngergaben werden benötigt, um die Nährstoffverluste durch Bodenabtrag und -abfluss zu kompensieren und dem Fortschreiten der Bodendegradation entgegen zu wirken. Durch Bodenabtrag verursachte N-Verluste tragen stark zu Umweltproblemen bei. Die Anwendung von integrierten Bodenschutzsystemen und Untersuchungen zur Dynamik von N-Verlusten ist notwendig, um eine nachhaltige Landbewirtschaftung zu erzielen.

Die vorliegende Studie wurde über eine Periode von drei aufeinander folgenden Jahren (2003-2005) in Ban Bo Muang Noi in Loei Provinz von Thailand (17°33' N and 101°1' O, 572 m N.N.) durchgeführt. Der Feldversuch wurde im April 2003 als Spaltenanlage mit Düngung als Hauptfaktor und Bodenschutzmaßnahme als Unterfaktor in zweifacher Wiederholung angelegt. Insgesamt wurden 16 Erosionsmessparzellen angelegt. Die Parzellengröße war 4m x 18 m (72 m^2) mit einer Auffangeinrichtung für Bodenabfluss und -abtrag am unteren Ende jeder Parzelle. In allen Behandlungen wurde Mais (*Zea mays* L.), cv. Suwan 1, entlang der Konturlinien auf einem Hang mit einer Neigung von 21 bis 28% unter Minimalbodenbearbeitung und einer Leguminose (*Canavalia ensiformis*) mit temporärer Überlappung angebaut. Die Hauptfaktorbehandlungen waren (a) keine Düngergabe und (b) 60 kg N ha^{-1} plus 14 kg P ha^{-1} auf zwei Gaben verteilt. Die Hälfte des Düngers wurde zwei Wochen nach Aufgang des Maises gegeben, die zweite Düngergabe erfolgte einen Monat später. Als >Unterfaktorbehandlungen dienten: (a) Barrierestreifen aus Vetivergras (*Vetiveria zizanioides* (L.) Nash), (b) Barrierestreifen aus Ruzigras (*Brachiaria ruziziensis* Germain et Evrard), (c) Leucaenahecken (*Leucaena leucocephala* (Lam) de Wit) und (d) eine Kontrolle ohne Hecken.

Die Ziele dieser Studie waren, (a) die kurz- bis mittelfristigen Veränderungen von Bodenabtrag und -abfluss, N-Verlusten und Ertragswirkung in einer vergleichenden Studie unter verschiedenen Bodenschutzmaßnahmen zu erfassen, (b) die ^{13}C Isotopendiskriminierungsmethode in Verbindung mit Standardmethoden zur Bestimmung N-Verfügbarkeit und –aufnahme zu testen, um ein besseres Verständnis der Konkurrenz um Wasser und Stickstoff zwischen Feldfrüchten und Barrierepflanzen, Wasser- und N-

Aufnahme bei Kulturpflanzen in Heckensystemen zu erlangen sowie ein Rahmenkonzept zur Erfassung der Beziehung zwischen Pflanze, N and Wasserverfügbarkeit und $\delta^{13}C$, (c) Verwendung der Felddaten zur Kalibrierung und Validierung des Erosionsmodules im WaNuLCAS Model, (d) ein besseres Verständnis der Rolle verschiedener Bodenschutzmaßnahmen in Hinblick Erosionskontrolle unter Anwendung des WaNuLCAS Models. (e) Verwendung des Models zur Erfassung der Größenordnung und Dynamik von Schlüsselprozessen, die Effizienz von Bodenschutzmaßnahmen beeinflussen.

Zur Untersuchung der Beziehung zwischen Bodenerosion und N-Verlusten nach Etablierung von Bodenschutzsystemen in Hanglagen von Nordostthailand wurden Bodenabtrag und -abfluss, N-Auswaschung (mit Hilfe der Harzzylindermethode) und Ertrag in Anbausystemen mit Grasstreifen (*Vetiveria zizanioides*, *Brachiaria ruziziensis*) und Hecken (*Leucaena leucocephala*) mit und ohne Düngung erfasst. Der Maiskornertrag stieg innerhalb einer dreijährigen Anbauperiode von 1.5 und 3.2 auf 3.8 und 5.5 Mg ha^{-1} in der ungedüngten und gedüngten Kontrolle an. Der Ertragsanstieg war geringer in Behandlungen mit Bodenschutz und ereichte ohne Düngung Erträge von 2.0–2.7 Mg ha^{-1} und von 3.9–4.2 Mg ha^{-1} mit Düngung. Bodenabfluss (190–264 m^3 ha^{-1}) und Bodenabtrag (0.2–1 Mg ha^{-1}) zeigte in gedüngten Parzellen mit Barrieren im Vergleich zu 2003 eine durchschnittliche Abnahme von 72% bzw. 98%, wobei die Abnahme in ungedüngten Parzellen niedriger war. Die Kontrolle hatte einen höheren Bodenabtrag im ersten Jahr (24.5 Mg ha^{-1}), zeigte aber einen starken Rückgang (1.6–2.5 Mg ha^{-1}) im dritten Jahr. Der Bodenabfluss nahm in der Kontrolle über die Jahre nicht im gleichen Umfang ab wie in Behandlungen mit Bodenschutz (Abfluss nur bei >12 mm/Tag). Der durchschnittliche, kumulierte N-Verlust über Bodenabfluss und -abtrag, und Auswaschung wurde von 55 kg N ha^{-1} in der Kontrolle auf 37–40 kg N ha^{-1} in Behandlungen mit Barrierestreifenreduziert.

Auf Basis dieser Beobachtungen wird gefolgert, dass die Etablierung von geeigneten Konturhecken einen Vorteil bei der Reduzierung von Bodenabtrag und –abfluss hat, insbesondere in frühen Entwicklungsstadien der Pflanze, während Konturhecken, in Kombination mit der Verwendung zusätzlicher Bodenschutzmaßnahmen, wie Minimalbodenbearbeitung und Mulchen, zu späteren Zeitpunkten an Bedeutung verlieren. Die Abnahme des Maisertrags in Behandlungen mit Hecken oder Grasstreifen ist ein starker Nachteil. Ferner, haben diese Systems einen signifikanten Effekt auf die Verlustwege der N-Verlagerung.

Wegen der negativen Ertragswirkung bei Anbau mit Bodenschutzmaßnahmen wurde die ^{13}C Isotopendiskriminierungsmethode als Startpunkt für neue Einsichten in Konkurrenz um N und Wasser in Konturheckensystemen verwendet, um ein tieferes Verständnis von Konkurrenz und Einfluss auf Ertragsbildung zu erzielen. In dieser Untersuchung wurde räumliche Variabilität des Kornertrages von Mais (*Zea mays* L., cv. Suwan 1) in einem *Brachiaria ruziziensis* Germain et Evrard (Ruzi grass) Grassstreifen und einem *Leucaena leucocephala* (Lam) de Wit Heckensystem mit und ohne Düngereinsatz bestimmt. Verfügbare NO_3^-- N wurden über die Hangfläche analysiert sowie die Sprossstickstoffkonzentration und die $\delta^{13}C$ Werte in Maisblättern wurde an Pflanzen im Zentrum zwischen zwei Alleen oder Streifen sowie in der Reihe nahe der Hecke und in der Reihe unmittelbar unter der oberen Hecke bzw. Grassreifens. Die $\delta^{13}C$ Werte waren mit zwei Ausnahmen nahe des Grasstreifens bzw. der Hecke signifikant ($p<0.05$) weniger stark herabgesetzt. Das impliziert, dass der Hauptfaktor für räumliche Verteilung entlang der Allee nicht mit Wassermangel im Zusammenhang steht. Die negative Korrelation zwischen ^{13}C Isotopendiskriminierung und verfügbarem NO_3^--N im Boden mit R^2 Werten von 0.5 ($P<0.10$) bis 0.9 ($P<0.01$) deutet daraufhin, dass die N-Verfügbarkeit eine Hauptrolle bei der Ertragsbildung von Mais zur Hecke oder zum Grasstreifen hin spielte. Die vorgeschlagene gemeinsame Betrachtung von ^{13}C Isotopendiskriminierung, Pflanzen- und Bodenstickstoffgehalten ist ein neuer methodischer Ansatz. Er ist geeignet, um Stickstoff- und Wasserkonkurrenz zwischen Heckenpflanzen und Nutzpflanzen in Alleesystemen unter Feldbedingungen zu quantifizieren.

In der letzten Veröffentlichung werden Bodenschutzstrategien im Ackerbau von Hanglagen in Nordostthailand mit dem *Water Nutrient Light Capture in Agroforestry System* Model bewertet. In dieser Studie wurden Daten aus dem Feldversuch (2003-2005) für die Kalibrierung und Validierung des Models verwendet. Hierzu wurde die Kontrolle ohne Hecken sowie die Behandlung mit Leucaenahecken mit und ohne Düngung ausgewählt. Die Ergebnisse zeigen, dass WaNuLCAS 3.2 geeignet ist, Anbausysteme in Bergregionen von Nordostthailand zu modellieren und zur Bewertung von Schutzmaßnahmen in Bezug auf Bodenabfluss und –abtrag verwendet werden kann. Dies wird durch Korrelationskoeffizienten von 0.82 and 0.80 zwischen beobachteten und simulierten für Bodenabfluss bzw. Bodenabtrag verdeutlicht. Im Rahmen von verschiedenen Szenarien, die mit WaNuLCAS simuliert wurden, konnte festgestellt werden, dass Bodenschutzmaßnahmen, wie z. B. die Integration von Leucaenahecken in das Anbausystem, wichtige Techniken sind, um Bodenerosion zu verhindern. Die Funktion "Dynamik der Bodenstruktur" im Model zeigte Einfluss auf die Erosionsprozesse über eine Verbesserung der Bodenstruktur mit der Zeit. Der überlappende Anbau mit *Canavalia* *ensiformis* spielte im dritten Versuchsjahr eine wichtige Rolle in der Kontrollbehandlung bei der Vermeidung von Erosion. Nach vorheriger Standortkalibrierung und –validierung erscheint daher WaNuLCAS als geeignete Maßnahme, um potentielle Managementoptionen für den Anbau in Bergregionen zu untersuchen, deren Wirkung zu verstehen und deren Anwendbarkeit bewerten zu können.

Konturgrasbarrieren und Heckenreihen in Kombination mit Minimalbodenbearbeitung und Überlappungsanbau mit Leguminosen erscheint eine geeignete Anbaumethode für Kleinbauern. darzustellen, da sie mehrere Optionen zur Generierung von Einkommen bieten und das Risiko von Erosion verhindern. Ferner können sie einen Beitrag zur Erhöhung der Bodenfruchtbarkeit leisten, da sie Stickstoffverlust über Erosion und Auswaschung minimieren können. Die Ergebnisse zeigen auch, dass Hecken und Barrieren vermutlich nur in der Etablierungsphase dieses Systems notwendig sind. Danach erscheint Maisanbau unter minimaler Bearbeitung mit Überlappungsanbau von Leguminosen, zumindest auf Flächen mit moderater Hangneigung, eine gangbare Option für Untersuchungsregion für Kleinbauern in tropischen Bergregionen zu sein.