Crop yield and fate of nitrogen fertilizer in maize-based soil conservation systems in Western Thailand

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Dedicated to

my grandmother, Yulee Ketphongchai and

my senior brother/teacher, Asst. Prof. Dr. Thanuchai Kongkaew,

wherever you may be

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Table of contents

List of figures

List of tables

Chapter 1

General Introduction

Chapter 1 General Introduction

1.1 Background

Challenges for global agriculture and food security in the coming decades are needed to increase food production in feeding more than 9 billion people by 2050 (Tilman et al., 2002; Lal, 2013). In 2020, the world demand was projected to 2.5 billion tons for cereals and 327 million tons for meat. The rate of increase in future food demand is expected to be higher in developing countries, characterized by a wide gap between actual and potential yields (Lal, 2013). In recent decades, formerly productive agricultural land has been taken away by urbanization and other human uses (Pisante et al., 2012). Both the increase in food demand and land scarcity in high-potential lowland areas, and in turn migration of people to remote hillside areas are forcing cropping intensification with a transformation of land use from subsistence to permanent agriculture in these fragile areas with their partly steep slopes (Craswell et al., 1997; Rerkasem et al., 2009). This change together with inappropriate land use is the prime cause of soil degradation by erosion, organic matter and nutrient depletion, and elemental imbalance, all of which have negatively affected productivity and sustainability of the system (Ogunlana et al., 2010; Bindraban et al., 2012; Hilger et al., 2013; Paudel et al., 2014). One millimeter of soil is indeed easily lost in one rainstorm and often unnoticed by farmers and others (Pimentel and Burgess, 2013), but between 10^5 and 10^6 years is the estimated time for the development of 25 mm of soil under various conditions (Pretorius and Cooks, 1989). Hence, soil is a finite and non-renewable resource, meaning its loss and degradation is not recoverable within a human lifespan (FAO, 2015). Globally, of the total degraded land area of 1966 million ha, 1094 million is affected by water erosion, of which 751 million ha is severely affected (Lal, 2003; Lal, 2007a). Approximately 75 billion tons of fertile soil are lost from agricultural systems each year, which accounts for about three-quarters of the total soil loss by erosion worldwide (Eswaran et al., 2001; Pimentel and Burgess, 2013). In the tropics, an estimated 500 million people practice subsistence agriculture on sloping lands (Craswell et al., 1997). On all sloping land, the impact of soil erosion accelerates with increasing steepness as more of the surface soil is carried away by the runoff, moving downhill to valleys and streams (Pimentel, 2006; Montgomery, 2007).

Erosion is not only the loss of soil. It is simultaneously the loss of water, nutrients, soil organic matter (SOM) and soil biota, resulting in the loss of valuable land due to abandonment and reduced productivity of the remaining land (Pimentel and Burgess, 2013). During the next few decades, it is estimated that 30% of the world food production is lost by degradation of agricultural land which ultimately threatens food security in future because humans worldwide obtain more than 99.7% of their food (calories) from the land and less than 0.3% from marine and aquatic ecosystems (Kendall and Pimentel, 1994; Pimentel and Burgess, 2013). Therefore, vulnerable land in sloping terrain is classified as unsuitable for continuous production of arable crops, unless effective conservation measures are introduced to stabilize the landscape (Craswell et al., 1997; Pimentel and Burgess, 2013; Montgomery, 2007). Soil conservation techniques are measures such as mulching, cover crops, zero or minimum tillage, grass strips and hedgerows, contour planting and or ploughing and various combinations of them (Pimentel and Burgess, 2013).

1.2 Geographical features and agricultural practices of mountainous regions in western Thailand

The Kingdom of Thailand is located in the tropics, between latitudes 5°27′ and 20°27′ N, longitudes 97°22′ and 105°37′ E and lies in the middle of the Indochinese Peninsula (Kuneepong, 2002). About 47% (23.9 million hectares) of its total area (51.3 million hectares) are used in agricultural production, of which the major part is occupied by paddy rice (*Oryza sativa* L.) and upland crops such as maize (*Zea mays* L.), cassava (*Manihot esculenta* Crantz) and sugarcane (*Saccharum officinarum* L.) (Office of Agricultural Economics, 2012a; Luanmanee and Paisancharoen, 2011). Since the 1960s, the increased production of these upland crops resulted in a parallel decrease in forest areas of which maize farming was especially productive in these newly cleared forestlands (Ekasingh et al., 2004).

Maize is the most important source of human food and animal feed worldwide (Ge et al., 2012). Thailand had a total production area of 1.2 million hectares or 24% of total upland crop area (5.0 million hectares) in 2011 (Office of Agricultural Economics, 2012a). Maize is recognized as an important upland crop used as food (20%) and animal feed (80%) and the Government needs to support farmer to improve their productivity as part of the effort to improve food security and farmer incomes (Attanandana and R.S.Yost, 2003; Ekasingh et al., 2004).

Thailand can be geographically divided into six regions, namely northern, north-eastern, central, eastern, western, and southern regions. The western region's physical features are mostly characterized by high mountains and valleys and include the provinces of Tak, Kanchanaburi, Ratchaburi, Phetchaburi and Prachuap Khiri Khan (Deepadung, 2003). As for Ratchaburi province, it lies between 13°32′ N to 13°54′ N latitude and 99°49′ E to 99°82′

E longitude with a total area of 0.52 million hectares of which 38% was used for crop production in 2011 (Chaiyo et al., 2011; Office of Agricultural Economics, 2012a). Mountains with an altitude ranging from 200 to 1400 m above mean sea level are located in the western part of the province, including three districts - Suan Phueng, Ban Kha and Park Tho, close to the border between Thailand and Myanmar (Chaiyo et al., 2011). According to the Köppen-Geiger classification, the climate is classified as tropical savannah (Aw) (Peel et al., 2007) in the temperature zone T3 (20-38 ºC) and the relative humidity zone H2 (41-100%) (Khedari et al., 2002). Most of the rain is blocked by the Tenassarim Range, therefore it has been considered as a “rain shadow zone”. The average annual rainfall is around 1100 mm with the wettest month in October and the driest one in January (Chaiyo et al., 2011).

Upland minorities (so-called ‘hill tribes’) living and cultivating near the Thailand-Myanmar border are Karen people. The primary agricultural production system is rain-fed and conventional tillage agriculture with major crops such as maize, pineapple and cassava as well as the vegetable crops, e. g. eggplant (*Solanum melongena* L.) and chili (*Capsicum annuum* L.) are also cultivated. Chili is an important spice crop with a high local and regional consumption by consumers and a high-value cash crop for farmers in many tropical countries (Anand et al., 2009). This is also the case for western Thailand.

The increasing circumstance of deforestation and shifting cultivation replaced by more permanent and commercialized agriculture are commonly found in Thailand's remote hillside areas (Forsyth, 2007), established on both moderate and steep slopes. The agricultural settlements had caused severe soil erosion in Thailand's mountainous regions (Forsyth, 2007), where the soils are generally shallow and infertile, formed from sandstone, shale, and granite

(Choenkwan et al., 2014). A loss of topsoil to erosion may contribute to nutrient limitation owing to a loss of inherent soil fertility levels of nitrogen, phosphorus, potassium etc. Thus, it reduces potential crop yield (Pimentel and Burgess, 2013).

In Thailand, about 34% of the area deforested for cultivation is affected by topsoil erosion and in view of that, a number of conservation measures such as grass strips, planting of fruit trees on bench terraces, cover crops and intercropping of annual food crops with trees have been proposed and promoted to farmers as crop management options on sloping land by the Land Development Department (LDD) and International Board for Soil Research and Management (IBSRAM) of Thailand (Pansak et al., 2010). Lack of knowledge about their benefits and the initial time lag in deriving positive effects of these conservation systems are major hindering factors in farmers' adoption of conservation measures (Ogunlana et al., 2010). Furthermore, Mountain agriculture in Thailand is commonly considered too marginal to warrant major research support from scientists, development workers, and various 'experts' (Rerkasem, 1998). However, Thailand does not have a specific land use planning or policy for highland agriculture because these areas are mostly considered as strictly protected areas. Hence, further research on conservation measures with understanding local conditions is crucial to improve susceptible land use management in these mountainous areas.

1.3 Nitrogen in crop production

A major soil health problem limiting productivity in the mountainous region in western Thailand is the deficiency of essential nutrients (Pisante et al., 2012). N deficient-crops with their pale yellowish-green foliage (chlorosis) forebode crop failure, financial loss, and hunger for people in all corners of the world, while excesses of certain N compounds in soils may adversely affect crops, humans, and the environment. For example, the movement of NO_3-N from soils to aquatic systems may lead to endangering the health of human infants and ruminant animals and causing eutrophication (Brady and Weil, 2000). Long-term application of NH_4-based N fertilizer can increase soil acidity leading to the development of infertile soils that do not respond well to crop yields with further application of N fertilizers (Sainju et al., 2019).

In most non-legume cropping systems, N is the most frequently deficient nutrient and, hence, crops need additional N supply (Havlin et al., 2005). In each year, the requirement of mineral N by plants in the world's agricultural systems for the production of food, animal feed, and industrial products are between 150 and 200 million tons (Unkovich et al., 2008), of which total annual N inputs to crop production include: (i) 55% from biological nitrogen fixation (BNF), recycling N from crop residues, animal manure, atmospheric deposition, irrigation water, and (ii) 45% from synthetic N fertilizer (Mosier et al., 2004; Smil, 1999). Principally, BNF, organic resources recycled within the cropping field, and mineral N fertilizers are the three main sources of N for crop production (Giller et al., 1997). Annually, the global agricultural N budget gains about 50-70 and 100 million tons of N from the plant-associated N_2 fixation and the industrial Haber Bosch process, respectively. Therefore, a vital goal for the planet's long-term sustainability is a more effective exploration and utilization of such N sources, especially fertilizer and biologically fixed N (Unkovich et al., 2008).

1.3.1 Nitrogen fertilizer use efficiency in crop production

Fertilization with N to maximize yield is routine in intensive cropping systems, while it is required to replenish the soil with N mined by the crops for sustainability in agricultural systems (Hawkesford, 2012). The application of synthetic N fertilizer made sufficient world food production possible in the past decades, and it is undoubtedly the largest source of anthropogenic reactive N worldwide (Xiaoyuan et al., 2014). Global consumption of synthetic N fertilizer increased from 31.8 Tg (1 Tg = 10^{12} g) N in 1970 (Lal, 2007a) to 104.3 Tg N in 2010 (Heffer, 2013). 55.2% of total annual N fertilizer consumption in 2010 were applied to cereals, including wheat (18.9 Tg N), maize (17.6 Tg N), rice (16.0 Tg N) and other cereals (5.0 Tg N), while, in Thailand, maize received 0.09 Tg N or 7% of total N fertilizer consumption (1.3 Tg N) (Heffer, 2013). 50 to 70% more cereal grain would be necessary to feed 9.3 billion people, and global N fertilizer demand is, hence, projected to increase to 236 Tg N in 2050 (Wood et al., 2004; Lal, 2007a), unless fertilizer use efficiency (FUE) would further increase (Dourado-Neto et al., 2010).

The agronomic nitrogen use efficiency (NUE) is defined as the amount of harvested crop biomass that is produced per unit of N supplied during the growing season (Hermanson et al., 2000; Dobermann, 2007), while the N fertilizer uptake or recovery efficiency (NFR) is defined as the percentage of fertilizer N recovered in aboveground plant biomass during the growing season, hereafter called the N fertilizer use efficiency (NFUE) (Cassman et al., 2002). Currently, only 30 to 50% of applied N fertilizer is commonly taken up by harvested crops and their residues in the first growing season. This means a significant amount of the remainder N is left in the soil as inorganic form, incorporated into the SOM or is lost from agricultural lands to other parts of the environment (Tilman et al., 2002; Cassman et al., 2002; Ladha et al., 2005; Dourado-Neto et al., 2010). Mineral fertilizer N is susceptible to several N loss processes, namely leaching, gaseous emissions, or erosion and runoff; all of them can vary far and wide depending on the ecosystem, soil characteristics, fertilizer management practices (fertilizer form, rate, time and method of application), and weather conditions (Freney et al., 1995). These N losses contribute potentially to degradation of soil and water quality and eventually lead to overall environmental degradation, any or all of which are compelling reasons of the requisite to increase NFUE (Baligar et al., 2001). Genetic, morphological and physiological plant traits and their interactions with external factors including (i) environmental conditions such as weather, soil properties and (ii) management practices, e.g., fertilization practices, tillage, cropping systems, irrigation practices, weed control and others can influence NFUE of crops (Hermanson et al., 2000; Baligar et al., 2001). Generally, NFUE declines with either increasing N rates, smaller crop N sinks, or higher indigenous N supply (Dobermann, 2007).

In the tropics, nutrient management largely relies on blanket fertilizer recommendation schemes and ill-adaptation of innovations rather than the site-specific management attuned to the real and heterogeneous world. Therefore, this contributes to the low overall nutrient use efficiencies (Van Noordwijk and Cadisch, 2002). Judicious use of mineral N fertilizers by matching it to the crop N demand and the environmental conditions as proposed under the 4R Nutrient Stewardship concept that focuses on applying the right nutrient (fertilizer) source or product at the right rate, right time, and right place in precision farming, plays a critical role for not only reducing the risk of a negative environmental impact of fertilizers but also improving the system productivity and the N use efficiency resulting in growing more on less land and better production economics (Snyder et al., 2009; Pisante et al., 2012). Achievement of synchrony between N supply and crop demand, therefore, is the key to optimize trade-offs among yield, profit, and environmental protection both in large-scale production systems in developed countries as well as smallholder systems in developing countries (Cassman et al., 2002). Management practices that fail to achieve good congruence between N supply and demand can increase access (shortage) and excess (surpass) problems of N in the systems (Van Noordwijk and Cadisch, 2002).

Apart from the 4R concept, soil conservation measures that complement best fertilizer management should also be considered in cultivation plans, such as using continuous crop rotations and cover crops to retain and recover residual inorganic N, thereby minimizing N losses and increasing N use efficiency (Snyder et al., 2009). In intercropping and agroforestry systems, the filter functions and complementarity of components are used to mop up leftover N leaving the system and may increase NFUE by enhancing nutrient capture and recycling and, in turn, decrease the conflict between the access and excess problem (Van Noordwijk and Cadisch, 2002; Cadisch et al., 2004). A meta-analysis study by Nummer et al. (2018) showed that > 50% of N and P losses via runoff and erosion from farmlands to water bodies were reduced in the systems with conservation practices such as filter strips and contour farming. Soil conservation measures are also known to improve soil fertility and physical properties, stabilize sloping lands, minimize pest and weed problems and consequently result in better crop yields and NFUE; however, the slow and occasional adoption of conservation measures, such as minimum tillage with cover crop and hedgerow systems, might be primarily attributed to insufficient attraction to farmers because of slow returns to investments and variable positive effects on crop yields combined with constraints, such as extra labor, crop area loss and competition between crops and trees (Ong et al., 2002; Dercon et al., 2006b; Hilger et al., 2013). Moreover, locally improved conservation practices need to be developed to enhance NFUE in crop plants (Cassman et al., 2002). Due to the synergistic effects of such management practices on crop yield response to N, they must be applied in an integrated manner to improve NFUE (Dobermann, 2007).

In experimental field studies, NFUE is either calculated by using the ‘difference method’ or by using ‘isotope methods’ (Dobermann, 2007). In ‘isotope methods’, NFUE is estimated as the amount of ^{15}N-labelled N recovered in fertilized crops per unit ^{15}N-labelled N applied (Harmsen, 2003). NFUE’s estimates by the isotope method have been reported with lower, similar to or even higher values compared to results of the difference method (Schindler and Knighton, 1999; Dourado-Neto et al., 2010). Lower NFUE estimated by the ^{15}N isotope method than with the difference method are generally found and mainly caused by ‘pool substitution’ and partly caused by the exclusion of any residual or ‘memory’ effect of ^{15}N fertilizer applied from the previous year in cases of long-term plots (Dourado-Neto et al., 2010; Jenkinson et al., 2004; Rao et al., 1992). The estimation of fertilizer N recovery by the difference method is lower than the isotope method can also be observed. It may be attributed to (i) high soil N availability, leading to a high N content in plant parts of unfertilized relative to fertilized plots, especially when a low rate of N fertilizer was applied (Schindler and Knighton, 1999); and/or (ii) when the amount of applied labelled N is too large for the plant to take it up (Rao et al., 1992). Both methods are subject to errors under different conditions (Rao et al., 1992). As for the difference method, plant N fertilizer recovery is based on differences in N uptake between fertilized plots and unfertilized control and calculated as:

$$NFUE\ (\%) = \frac{NF - NC}{NR} \times 100 \quad (1)$$

where *NF* and *NC* are the amounts of total N in samples in kg ha^{-1} of fertilized and unfertilized treatments, respectively, and *NR* is the amount of fertilizer N added to the fertilized treatment in kg ha^{-1} (Rao et al., 1992; Dobermann, 2007). The basic assumption of this method is that mineralization, immobilization and other soil N transformations are the same for both fertilized and unfertilized plots and unaffected by fertilizer additions, making gross misinterpretations of N recovery data possible (Schindler and Knighton, 1999). However, it is often reported that there is increased N availability and uptake in fertilized soils because of two real positive effects of added nitrogen interactions (ANI), namely: (i) the stimulation of microbial growth and thereby SOM decomposition, which is the so-called 'priming effect', and (ii) the increase of root growth in fertilized soil (Rao et al., 1992; Stevens et al., 2005). To avoid such possible errors, researchers have employed isotopic tracer techniques (Schindler and Knighton, 1999).

The mole fraction of heavy isotope relative to heavy plus light is atom fraction known as atom percent (atom %) when expressed as a percent (Glibert et al., 2019). Naturally, ^{14}N and ^{15}N are two stable isotopes of nitrogen, and their atom fraction (isotopic composition) are 99.634 and 0.366 atom percent, respectively (Halitligil, 2004). The isotopic labelling of the fertilizer N is best done during the production process by specialized firms (FAO and IAEA, 2001) by replacing specific atoms with their isotope (lighter or heavier) to produce ^{15}N depleted or ^{15}N enriched synthetic fertilizer (an isotopic tracer). NFUE can be estimated using commercially available ^{15}N labelled fertilizer either depleted (enriched ^{14}N) or enriched in ^{15}N (Chalk, 2018). Modified from

Schindler and Knighton (1999), NFUE by the isotope method when using a ^{15}N enriched fertilizer source is calculated as:

$$NFUE\ (\%) = \frac{NS \times (atom\%^{15}N_{sample} - atom\%^{15}N_{background})}{NA \times (atom\%^{15}N_{fertilizer} - atom\%^{15}N_{background})} \times 100 \qquad (2)$$

where *NS* is the amount of total N in samples in kg ha^{-1} of labelled treatments. $Atom\%^{15}N_{sample}$ and $atom\%^{15}N_{background}$ are atom% ^{15}N abundance of samples from a fertilized treatment and from a non-fertilized treatment, respectively. *NA* and $atom\%^{15}N_{fertilizer}$ are the amount (kg ha^{-1}) and atom% ^{15}N abundance of fertilizer N applied to the labelled treatment. Two primary drawbacks are: (i) the ^{15}N-labelled material is very expensive, and (ii) interpretations of N recovery are complicated by the fact that ^{15}N of labelled material undergoes a negative apparent ANI, which is the so-called 'pool substitution' including the mineralization-immobilization turnover (MIT), biological interchange processes and fixation of NH_4^+ by clay minerals when applied to the soil system (Stevens et al., 2005; Snyder et al., 2009; Rao et al., 1992; Dourado-Neto et al., 2010). A ^{15}N tracer is often used in more detailed studies to follow the flow and fate of N by detecting and quantifying applied labelled N in various sinks, namely crop, soil and N lost from the system (Dourado-Neto et al., 2010). This knowledge on N dynamics in various cropping systems can be utilized to develop sound strategies to minimize losses to environment, leading to improved soil, water and air quality and maximizes profits of farmers by enhancing crop yields and quality and reducing demand and costs for external N inputs (Freney et al., 1995; Baligar et al., 2001). To assess the fate of N in the entire system over time periods and at different scales, not only stable isotope methods but also N budgets can be employed (Dobermann, 2007).

1.3.2 Nitrogen balance

Crucial issues on the basis of general sustainability criteria in crop production are maintaining nutrient balances and compensating for nutrient export by harvest products, unavoidable losses and achieving reasonable yields per unit labor and external inputs (Hairiah et al., 2000). Nutrient balances or nutrient budgets consist of simple mass balances which are computed by the difference between nutrient inputs and outputs of a system over a certain spatial-temporal boundary (Bindraban et al., 2000), generally expressed in amount of nutrients per unit of area and time such as kg ha^{-1} $year^{-1}$ (Cobo et al., 2010). The net soil nutrient budget (NSNB) can be determined by the following equation:

$$NSNB\ (kg\ N\ ha^{-1}) = \int_{area} \int_{time} \left(\sum_{i=1}^{5} Input_i - \sum_{j=1}^{5} Output_j \right) \quad (3)$$

where *5* represents five parameters of N inputs, i.e., mineral fertilizer, organic fertilizer, deposition, N_2-fixation, and sedimentation; or N outputs, i.e., crop products, crop residues, leaching, gaseous losses and soil erosion (Stoorvogel and Smaling, 1990; Tan et al., 2005). The degree of net nutrient depletion (output > input) or enrichment (output < input) of systems can be indicated by these approaches (Oenema et al., 2006; Dobermann, 2007). Therefore, they have been useful tools: (i) for more than a century for scientists to summarize and facilitate the understanding of nutrient cycling in agroecosystems, and (ii) over the last decades for farmer as indicators of potential land degradation by nutrient depletion and for optimizing nutrient use, and (iii) for policy-makers as agro-environmental indicators and awareness raiser of nutrient use and nutrient use efficiency (Oenema et al., 2003; Cobo et al., 2010; Zingore et al., 2007; Bindraban et al., 2000). There are several ways to construct a nutrient budget and various ways to collect the information and data leading to different degrees of detail depending on the resources available to collect the information (Dobermann, 2007; Oenema et al., 2003). According to Oenema et al. (2003), nutrient budgets can be distinguished by three basic approaches: (i) farm-gate budget, (ii) soil surface budget, and (iii) soil system budget, though there are variants within each of them. Besides, nutrient balances at the field scale are simpler than those at the farm-gate and the territorial scale.

Partial budgets that do not encompass all inputs or outputs or make assumptions about those that are difficult to quantify at the scale of interest are common (Dobermann, 2007). Generally, the intensification of agricultural production leads to imbalances in nutrient budgets, especially for N and P, of which the recognition as unsustainable production in the long-term has shifted in scale from local to regional and continental dimension (Oenema et al., 2003). Agricultural systems with high external inputs likely result in a positive budget and may lead to environmental problems, while with low external inputs they likely result in nutrient depletion (Tan et al., 2005). For these reasons, the calculation of N balances is identified as a priority agro-environmental indicator needed to analyze the interactions between agriculture and the environment (OECD, 2007). Continuous cropping and inadequate replacement of nutrients removed by harvested materials or lost through erosion, leaching or gaseous emissions deplete soil fertility, especially for N. To solve such problems, conservation measures such as minimum-tillage, cover crops, residue application and mixed cropping systems together with balanced fertilizer application can help to maintain and restore soil fertility (Tilman et al., 2002).

1.3.3 N_2 fixing legumes in mixed cropping systems

Currently, plant-associated N_2 fixation contributes between 50 and 70 million tons annually to the global agricultural N budget (Unkovich et al., 2008). Mixed cropping systems with N_2 fixing leguminous trees and crops contribute to adding N to cropping systems by their BNF as well as sequestering SOM, which is a key proxy for soil fertility of tropical soils and potentially associated with increasing crop yields (Oenema et al., 2006). Jack bean (*Canavalia ensiformis*) is one of the most widely used cover crops and green manure, which can survive and grow even under poor growing conditions (Bunch, 2003). Additionally, the Jack bean is a legume crop belonging to the family Fabaceae with the ability to provide N via BNF (Mubiru and Coyne, 2009; Douxchamps et al., 2010). It can establish a root nodule symbiosis with slow-growing rhizobia, thereby exploiting the bacterial capacity for nitrogen fixation (Giller, 2001; Brewin and Kardailsky, 1997). It has a deeper rooting system than several other annual legumes; hence subsequent crops may benefit from the accumulation of N derived from deeper soil zones (Wortmann et al., 2000). Moreover, it can be managed as green manure and cover crop, yielding 2-12 Mg ha^{-1} $year^{-1}$ of dry matter and accumulating 22-400 kg ha^{-1} $year^{-1}$ of N (Wortmann et al., 2000; Ramos et al., 2001; Mubiru and Coyne, 2009; Douxchamps et al., 2010).

Nitrogen-fixing tree (NFT) legumes such as *Leucaena leucocephala* (Lam.) de Wit are increasingly incorporated into tropical farming systems (Jayasundara et al., 1997). Leucaena has its origins in Central America and the Yucatan Peninsula of Mexico and spread to most countries (covering approximately two to five million hectares worldwide) and known as the 'miracle tree' due to its great variety of uses such as firewood, forage, and human food (Shelton and Brewbaker, 1994). Environmentally, it can deliver a number of benefits, including prevention of dry-land salinity by improving the hydrological balance leading to reduction of deep drainage of water, C sequestration, enhancement of soil fertility through BNF, and maintenance of ground cover helping control weeds, preventing soil erosion, and enhancing the quality of runoff water (Shelton and Dalzell, 2007). In Australia, after large areas with considerable levels of stored salt in soils have been cleared for pasture and dry land cropping, water tables have risen, and small-scale saline discharges occurred in nearby down-slope zones. As for dry-land salinity, the returning of annual cropping land to deep-rooted perennial vegetation, such as Leucaena, in the recharge area would achieve amelioration of the problem by soaking up more moisture and decreasing deep drainage of water to the discharge area (Poole, 2003; Shelton and Dalzell, 2007). Leucaena has been used in cropping systems on steep slopes as a form of alley cropping in which its foliage is mulched to enhance yields of inter-row crops while its contour strips serve as erosion control (Shelton and Brewbaker, 1994). It is recognized to withstand repeated and drastic prunings and reported to generate large amounts of green manure from 7 to 100 Mg ha^{-1} $year^{-1}$ and large quantities of N between 300 and 600 kg ha^{-1} $year^{-1}$ in sole cropping system (Guevarra et al., 1978; Duguma et al., 1988). In alley-cropping systems, Leucaena produces between 2 and 13 Mg ha^{-1} $year^{-1}$ of green material and accumulates 40 and 300 kg ha^{-1} $year^{-1}$ of N (Duguma et al., 1988; Karim et al., 1991). Management with more frequent pruning events may reduce these dry matter yields, owing to the increased number of lag or recovery phases after cutting of Leucaena (Guevarra et al., 1978; Karim et al., 1991).

The contribution of BNF to leguminous plants can be quantified with: (i) non-isotopic methods such as N difference and C_2H_2 reduction, and (ii) N isotope methods, for instance, ^{15}N isotope dilution and ^{15}N natural abundance (Unkovich et al., 2008). ^{15}N natural abundance method is based on the principle that the ^{15}N abundance provided by the soil slightly differs from the atmosphere's ^{15}N abundance. The ^{15}N natural abundance of a sample ($\delta^{15}N$) is expressed as parts per thousand relatives to atmospheric N_2. The atmospheric N_2 has a constant abundance of 0.3663 atom% ^{15}N. Thus, $\delta^{15}N$ of any sample is obtained by the difference as follows (Unkovich et al., 2008):

$$\delta^{15}\mathrm{N}\ (‰) = \frac{1000\times\left(sample\%\ ^{15}N - 0.3663\right)}{0.3663} \quad (4)$$

where *sample%* ^{15}N is an abundance of ^{15}N atoms of a sample as a percentage of the total. For field-grown legumes, shoots are practically harvested rather than whole plants because it is not easy to recover entire root systems (Unkovich et al., 2008). Consequently, a correction of the within-plant fractionation of ^{14}N and ^{15}N between shoots and nodulated roots needs to be made using the $\delta^{15}N$ of shoots of legumes fully dependent upon N_2 fixation for growth (so-called 'B' value). Therefore, the percentage of plant N derived from atmospheric N_2 (%Ndfa) can be calculated from its $\delta^{15}N$ value using the following equation:

$$Ndfa\ (\%) = \frac{\delta^{15}N\ of\ reference\ plant - \delta^{15}N\ of\ N_2\ fixing\ legume}{\delta^{15}N\ of\ reference\ plant - B} \times 100 \quad (5)$$

where *$\delta^{15}N$ of reference plant* is the ^{15}N natural abundance (atom% ^{15}N naturally present in materials) in shoots (or entire plant) of a non-N_2-fixing reference plant deriving its entire N from the soil N, *$\delta^{15}N$ of N_2 fixing legume* is natural ^{15}N abundance in shoots of a N_2-fixing legume growing in the same soil and *B* is the $\delta^{15}N$ of shoots of legumes that fully depend on N_2-fixation for growth and hence a correction for isotopic fractionation during N_2-fixation (Unkovich et al., 2008).

The N contribution of legumes through the decomposition of its biomass added to soil varies and largely corresponds to the biomass yield of N_2 fixing plants, which in turn depends on the species, management, and site-specific factors (Nair, 1993). Jack beans used as green manure derive between 14 to 130 kg N ha^{-1} yr^{-1} from atmospheric N_2 with %Ndfa, ranging from around 56 to 74% depending on soil and environmental conditions (Wortmann et al., 2000; Douxchamps et al., 2010). Measurements of BNF in alley cropping systems show that Leucaena derived 100-300 kg N ha^{-1} yr^{-1} from atmospheric N_2 with a variation of %Ndfa from 37 to 74% (Danso et al., 1992; Sanginga et al., 1989; Sanginga et al., 1995). Even though mixed cropping systems with N_2 fixing trees and crops contribute to increasing crop yields and to sequestering organic matter in the soil, they may also run the risk of depletion of nutrients other than N from the soil (Oenema et al., 2006) due to the massive amount of nutrient removed from the field in the harvested portion of the crop. Therefore, the soils should be supplied with targeted amounts of phosphorus, potassium, and other essential nutrients to ensure long-term productivity in these mixed cropping systems (Oenema et al., 2006).

1.4 Conservation agriculture

1.4.1 Basic principles

The prevailing form of current agricultural systems is dominantly based on the 'interventionist approach' operated by human technological interventions such as conventional tillage, agrochemical uses, and synthetic fertilizer application, mostly economically and environmentally vulnerable and unsustainable. Nowadays, on the other hand, a number of production systems with a predominantly 'ecosystem approach' underpinned by healthy soils and characterized as conservation agriculture (CA) are gaining importance, providing a more effective and sustainable agricultural production (Kassam and Friedrich, 2011). The banner of CA has been addressed and promoted by the Food and Agriculture Organization of the United Nations (FAO), the European Conservation Agriculture Federation (ECAF), and others (Knowler and Bradshaw, 2007). CA is a concept for resource-saving agricultural crop production that attempts to achieve acceptable profits together with high and sustained production levels while concomitantly conserving the environment (Kassam et al., 2009) and protecting and enhancing land resources on which production depends (Dumanski et al., 2006). To make a better use of agricultural resources as compared with conventional agriculture is the overall goal of CA, and the maintenance of a permanent or semi-permanent soil cover to protect soils from sun, rain and wind and feeding soil biota is its primary feature and indeed central dogma (Knowler and Bradshaw, 2007). Three sets of intertwined principles, linked to each other should be applied simultaneously, are necessary characteristics of CA, namely: (i) continuous minimum mechanical soil disturbance, (ii) permanent organic soil cover and (iii) diversified crop rotations whereby mono-cropping is not an exclusion factor if it does not lead to pest build-up or other problems (Kassam and Friedrich, 2011; Sommer et al., 2014; Vanlauwe et al., 2014; Pisante et al., 2012). These three principles can be translated into practices such as minimum tillage, surface residue retention and rotations, cover and intercropping, which link to a number of desirable functions (Sommer et al., 2014).

Maintaining SOM, soil structure, and overall soil health are the merits of the first characteristic of CA, *minimizing soil disturbance by mechanical tillage* (Kassam and Friedrich, 2011). Minimum-tillage (MT) is commonly defined as 'the minimum soil manipulation necessary for crop production or meeting tillage requirements under the existing soil and climatic conditions' and often means any system with few tillage requirements (Kassam et al., 2009). MT retains a protective layer of mulch (crop residues), increases surface roughness, and aims to preserve the topsoil, saving fuel, labor, and equipment costs (Kassam et al., 2009). This comes with maintaining soil structure and SOM by limiting/minimizing the mechanical soil disturbance known as an accelerator of SOM oxidation and consequent CO_2 loss back to the atmosphere (Kassam and Friedrich, 2011; Singh et al., 2018). However, the benefits of MT on erosion control, water conservation, and soil fertility enhancement are directly attributed to the amount of crop residue mulch and application of other biomass (dung/manure) as soil amendments (Lal, 2007b). In sustainable production, therefore, MT is a need, but insufficient condition and other complementary techniques including mulch cover, cover crops, crop rotations and legume crops are also required (Kassam and Friedrich, 2011).

Using cover crops or crop residues addresses the second CA characteristic, *enhancing and maintaining SOM in the soil,* which protects soil surface, conserves water and nutrients, promotes soil biological activity and contributes to integrated weed and pest management (Kassam and Friedrich, 2011; Singh et al., 2018). SOM has long been used as a key indicator of cropping systems' sustainability and can be increased by applying organic N materials to soils, as indicated by many long-term cropping system studies (Dourado-Neto et al., 2010). Most CA specialists generally recommend sowing a cover crop after the commercial crop. But in many parts of the tropical zone where the rainy seasons are too short for such a crop succession, sowing cover crops right before the harvest of the cash crop in a relay cropping system is an alternative (Baldé et al., 2011).

Relay cropping refers to a technique where crops are planted at different times in the same field, and both (or all) crops spend, at least, part of their growing season together in the field (Nafziger, 2009). In case that crop residues are returned to the land, Wilhelm et al. (2007) revealed that this did not only control soil erosion but also replenished soil organic carbon (SOC), being responsible for favorable soil properties such as retaining and recycling nutrients, improving soil physical properties, and sustaining microbial life. They also reported that estimates of the amount of maize straw needed to maintain SOM (5.25 to 12.50 Mg ha^{-1}) and thus productivity are greater than those required to control water (0.65 to 7.98 Mg ha^{-1}) or wind (0.14 to 2.74 Mg ha^{-1}) induced erosion in cropping systems.

The combination of MT and soil surface cover is an obvious and increasingly popular alternative in place of conventional agricultural practices, especially tillage of soils by ploughs, disks, or hand-held tillage tools (Knowler and Bradshaw, 2007; Kassam et al., 2009). A meta-analysis study using 176 field studies by Liu et al. (2014) reported that soil organic carbon concentration in bulk soil (up to 50 cm depth) increased around 13% following crop straw (stubble/residue) return to the fields. In another recent meta-analysis study using 154 studies with a minimum of 4 years of observation, yield stability on average did not differ between no-tillage and conventional tillage indicating that a transition to no-tillage generally does not affect yield stability (Knapp and van der Heijden, 2018). Based on data from 264 studies published worldwide, additionally, conservation tillage with residue retention increased soil saturated hydraulic conductivity and available water capacity compared with conventional tillage (Li et al., 2019).

The last characteristic of CA - *diversification of species* - using both annuals or perennials, in associations, sequences and rotations that can include trees, shrubs, pastures and crops may contribute to an enhanced crop nutrition by recycling nutrients and bringing in N through biological fixation when legumes are included, potentially break pest and disease cycles that under continuous sole cropping inevitably jeopardize plant health and crop yields and improve system's resilience thereby (Kassam and Friedrich, 2011; Sommer et al., 2014). Multispecies agroecosystems are widespread in the tropics. A multispecies system with appropriate management such as appropriate species selection and spatial arrangement of plant components promise the following benefits for farmers: (i) enhanced productivity, (ii) improved stability, and (iii) increased sustainability (Ong et al., 2004).

Intercropping systems, namely cultivating two or more crops together on the same field and at the same time, may, therefore, utilize agricultural resources more effectively, both in time and in space, particularly under intensive crop management (Gao et al., 2009; Raseduzzaman and Jensen, 2017). In comparison to monoculture, the productivity can be higher due to the following mechanisms: (i) a denser and longer green canopy may allow to increase light capture and reduce weed competition, and water loss by evaporation directly from the bare soil and (ii) a deeper and denser rooting system may allow exploring the soil better, increase the potential for water and nutrient uptake, improve soil physical properties, reduce runoff, conserve water and soil, enhance soil biological activity and nutrient cycling (Ong et al., 2004). The second potential benefit is an increased stability, i.e., in multispecies systems, the level of production risk or sensitivity to short-term fluctuations can be reduced by decreasing and spreading the risk of harsh climate and pest or disease outbreaks through species diversity and consequently reducing the chance of total crop failure caused by those risks (Craswell et al., 1997; SUSTAINET, 2010; Ong et al., 2004). The last potential, sustainability, can also be fostered as long-term productivity is maintained by the protection of the resource base, including reduced erosion, the addition of N through biological nitrogen fixation (BNF), retrieval of subsoil nutrients and/or reduction of nutrient losses by reduced leaching (Ong et al., 2004). A global meta-analysis using 33 articles covered a wide range of agroecological conditions reported that cereal-grain legume intercropping systems reduced the yield variability and enhanced yields and the stability of yields compared with sole crops (Raseduzzaman and Jensen, 2017).

Agroforestry, according to the definition suggested by the World Agroforestry Centre/the International Centre for Research in Agroforestry (ICRAF), is a collective name for land use systems and technologies where woody perennials, such as trees, shrubs, palms, bamboos, are deliberately used on the same land management units as agricultural crops and/or animals, in some forms of spatial arrangement or temporal sequence in which there are both ecological and economical interactions between the different components (Nair, 1993). In both developing countries and the industrialized world, agroforestry offers sustainable solutions to several serious issues such as food security, environmental protection, on-farm biodiversity enhancement, climate-change mitigation, microclimate improvement, erosion prevention, and alternate source of income (Nair, 2014; Dumanski et al., 2006; Shi et al., 2018). Agroforestry has been used as an alternative for sustainable agriculture, particularly in situations where fallow periods were shortened in shifting cultivation, and forest encroachment by farmers grew due to an increase in population (Oenema et al., 2006). Without a doubt, its potential as a land use system, capable of yielding both wood and food as well as conserving and rehabilitating ecosystems, especially for soil improvement and conservation, is generally accepted and recognized worldwide (Nair, 1993). A meta-analysis of 427 soil carbon stock data has shown that average soil carbon stocks in agroforestry systems of around 126 Mg C ha^{-1} were 19% higher than in cropland or pasture areas, and these systems could globally store 5.3 x 109 Mg additional carbon in soil on 944 M ha with most being located in the tropics and subtropics (Shi et al., 2018). Across ecological conditions in sub-Saharan Africa under 1106 observations, agroforestry practices significantly increased crop yield, soil organic carbon, and total soil nitrogen as well as decreasing runoff and soil loss compared to non-agroforestry practices (Kuyah et al., 2019).

In alley cropping, a promising zonal agroforestry subsystem for humid and sub-humid tropics, crops are grown in the alleys between trees, consisting of regularly pruned hedgerows of planted, usually N-fixing, shrubs or trees (Nair, 2014; Nair, 1993; Kang et al., 2008; Pansak et al., 2010; Kang, 1997). Several terms are used to describe alley cropping, e.g., contour hedgerow farming (in the Philippines), avenue cropping (in Sri Lanka) and hedgerow intercropping (by ICRAF) (Ogunlana et al., 2010). The presence of woody species in the alley cropping system has been shown to contribute to (i) nutrient recycling, (ii) reduction in soil nutrient leaching losses, (iii) soil erosion control, (iv) soil fertility improvement, (v) weed suppression, (vi) stimulation of higher soil fauna, and (vii) sustained levels of crop production (Kang, 1997; Nair, 1993). Farms on which contour hedgerow intercropping system under appropriate land management measures for particular locations have been adopted, therefore, are able to meet the multifaceted requirement of sustainable land use management, i.e., protecting soil and water resources and being productive, stable, viable and acceptable to farmers (Craswell et al., 1997). In a long-term experiment in China, the land equivalent ratios (LER) were higher than 1.0 after the trees produced fruit, and the apple trees made a significant contribution to the land use advantage in apple-peanut, apple-millet, and apple-maize alley cropping systems (Xu et al., 2019).

Apart from the practices translated directly from the three principles of CA, several good agronomic practices shall be added to achieve sustainable and productive systems, i.e., timely planting, optimal plant spacing, choice of cultivars and definitely rational use of mineral fertilizer (SUSTAINET, 2010; Sommer et al., 2014). The appropriate use of mineral fertilizer is required to enhance crop productivity and produce sufficient crop residues being essential for smallholder farmers to engage in CA, especially true in an area with the lack of alternative organic resources to provide adequate surface mulch because minimum tillage without mulch commonly results in yield declines (Vanlauwe et al., 2014).

'Appropriate' refers to the application of the 4R Nutrient Stewardship concept with the right source of fertilizer at the right rate, time and place as those, leading to the economic, social and environmental benefits desired by stakeholders (Vanlauwe et al., 2014; Zingore and Johnston, 2013; Bruulsema et al., 2009). A study in Zimbabwe revealed that maize yield benefits of CA could only be realized when mineral fertilizer is applied as well (Nyamangara et al., 2012). On the other hand, fertilizer use efficiency is also affected by the three principles of CA (Vanlauwe et al., 2014; Rusinamhodzi et al., 2012). In an on-farm experiment in Mozambique, maize yields in a system under a combination of all the three CA principles. As well as N and P fertilization were five times higher than yields when only N and P fertilization was done (Rusinamhodzi et al., 2012). Efficiency in the use of fertilizers can also be substantially increased under alley cropping as compared with no-alley-cropping (Nair, 1993). Tailoring/adapting CA to fit particular local needs is an additional supplementary key strategy to augment adoption by farmers worldwide (Knowler and Bradshaw, 2007). Hence, appropriate land management practices based on sound research need to be developed, depending on a complex set of social, economic, and biophysical factors of each particular location (Craswell et al., 1997).

1.4.2 Spread and uptake of conservation agriculture

CA has been practiced for several decades and demonstrated to be beneficial for sustainable agroecosystem management and intensification of agriculture and is used on all continents on an area of more than 117 million hectares (Kassam et al., 2009; Kassam and Friedrich, 2011). A greater tendency to adopt CA can mostly be found in regions with steep slopes and soils susceptible to erosion (Knowler and Bradshaw, 2007). According to Friedrich et al. (2012), farmer-led transformations of agricultural production systems based on CA gather momentum globally as a new paradigm for the 21st century. CA is even gaining acceptance as an alternative to both conventional and organic agriculture in many parts of the world, notably, Brazil and Argentina, with full CA being practiced on a large scale, e.g., North America with zero tillage and Africa and Asia with technologies such as agroforestry (Dumanski et al., 2006). A number of benefits of CA are recognized worldwide, including improving water conservation and infiltration, increasing SOM content with associated C sequestration, reducing runoff of pesticides and fertilizer, decreasing wind and water erosion, reducing consumption of fuel and lessening labor and investment in equipment (Pisante et al., 2012; Singh et al., 2018). However, diverse results for CA under various practices are found with both being promising for some aspects and disappointing for others (Govaerts et al., 2006; Govaerts et al., 2007; Mupangwa et al., 2012; Pansak et al., 2007; Pansak et al., 2008; Paudel et al., 2014; Paul et al., 2013; Craswell et al., 1997; Kang et al., 2008; Lienhard et al., 2013; Mando et al., 2005; Pisante et al., 2012; Rusinamhodzi et al., 2012; Sommer et al., 2014; Thierfelder et al., 2013a). For example, in the literature (Paudel et al., 2014), both higher (Lienhard et al., 2013; Thierfelder et al., 2012) or no changes or even decreasing crop yields were reported (Paul et al., 2013; Mando et al., 2005) during the initial years of practicing CA. A study under maize-pigeon pea intercropping in Mozambique founded that full application of all three principles of CA without fertilization yielded significantly better than only no-tillage systems that received N and P fertilizers (Rusinamhodzi et al., 2012). After four cropping seasons in Zambia, a direct-seeded CA treatment using a dibble stick and cowpea in the rotation increased by up to 8% maize yields compared to a conventional control using a ridge and furrow system (Thierfelder et al., 2013b).

In some countries, CA has been adopted, managed, and maintained reluctantly by farmers due to various constraints (Bayard et al., 2007; Hilger et al., 2013). Although long-lasting research studies in Asia and Africa presented positive results on CA, the area of adoption is still less than 1% of arable cropland (Friedrich et al., 2012). There are a number of factors influencing the adoption of CA, which can be separated into two groups as follows: (i) endogenous factors, i.e., farmer and farm household characteristics (e.g., age, education, health, experience and gender), farm biophysical characteristics (e.g., farm size, the area planted, erosion rate and slope level), farm financial and management characteristics (e.g., tenure, labor, income, profitability and equipment) and (ii) exogenous factors such as input and output prices, membership in organizations and extension/technical assistance (Knowler and Bradshaw, 2007). In fact, resource-poor farmers in developing countries are fully aware of the benefits of crop residues and animal wastes as a soil amendment and of the severe problem of soil degradation. However, the desperate need for using biomass either as a fuel source for cooking and heating or as fodder for livestock leading to the lack or complete absence of crop residues mulch and other biomass on the soil surface is still the most important constraints, limiting adoption of CA practices (Lal, 2007b).

In an alley-cropping system, a cost-benefit analysis revealed that the slow and sporadic adoption might be mainly attributed to insufficient attraction to farmers because of slow returns to investments and unpredictable positive effects on crop yields (Ong et al., 2002; Nelson et al., 1996). Various features of this system actually counterbalance its advantages and hinder its widespread adoption consisting of additional skill requirement for hedgerow pruning and mulch application, difficulty in mechanizing agricultural operations, the potential of hedgerow species to become a weed and/or an alternative host for pests and pathogens or harbor grain-eating birds and possibilities for increased termite activity, especially under dry conditions (Nair, 1993). Moreover, even though contour hedgerow systems can stabilize sloping lands, they also have not been widely adopted by farmers, owing to various constraints, such as extra labor, crop area loss and crop-tree competition (Craswell et al., 1997; Dercon et al., 2006b; Hilger et al., 2013; Pansak et al., 2007; Pansak et al., 2008).

1.4.3 Interactions at tree-crop interface in alley cropping systems

The success of agroforestry relies greatly on the exploitation of component interactions that refer to the influence of one component of the system on the performance of the other components and the whole system. These component interactions are treated as both: (i) positive or beneficial or complementary interaction such as microclimate amelioration and water/nutrient conservations, and (ii) negative or harmful interaction such as competition for light, water and/or nutrients that occur at the tree-crop interface (TCI), and the balance of both interactions determines the overall effect of a given agroforestry combination (Nair, 1993). Tree-crop interactions are inconstant and may be influenced by several factors such as species combination, their planting densities, soil conditions, climatic characteristics and management regimes (Imo and Timmer, 2000). Biologically, therefore, the improvement by alley cropping system depends on (i) the right choice of woody species, (ii) successful hedgerow establishment and (iii) efficient hedgerow and crop management (Kang, 1997).

Sound species selection and spatial arrangement of plant components can commonly limit intimacy and thereby reduce competition and increase complementarity at the TCI (Kang, 1997; Ong et al., 2002; Ong et al., 2004). The component species' root distribution has been frequently used as a direct indication of below-ground competition and complementarity in mixed cropping system (Wahid, 2001; Van Noordwijk and Cadisch, 2002). In sequential and simultaneous agroforestry systems, extensive tree root development probably increases nutrient capture and transfer to subsequent crops via organic pools in former such as improved fallows, whereas tree root development in the crop root zone leads to competition for resources in the latter, as observed in an alley-cropping system where plant components are spatially zoned (Van Noordwijk and Purnomosidhi, 1995). Deep-rooted trees can act in the sequential system as ‘nutrient pumps’ by bringing nutrients to the soil surface via litterfall and in the simultaneous system as ‘safety-nets’ by capturing nutrients that have currently leached beyond the range of crop roots (Rowe et al., 1999; Van Noordwijk and Purnomosidhi, 1995). Usually, deeper rooting trees are better candidates for use in simultaneous agroforestry systems because they have less competition with crops (Akinnifesi et al., 1998; Rowe et al., 2001). Competition between trees and companion crops is likely to occur in every plant association, including alley-cropping systems, if they utilize the same reservoir of growth resources, i.e., light, nutrients and water (Nair, 1993). Competitive interactions between components are exerted on both aboveground competitions for growth factors absorbed/intercepted through leaves, which mainly is radiant energy and below-ground for others absorbed through roots such as nutrients and water (Monteith et al., 1991; Ong et al., 2002; Ong et al., 2004; Nair, 1993; Leihner et al., 1996).

Usually, hedgerows are periodically pruned to minimize shading and reduce light competition of the companion crops during the cropping period and to supply biomass for mulching and other purposes (Kang, 1997; Sun et al., 2008). Pruning trees may have positive effects, owing to a drop of below-ground competition due to a reduction of tree nutrient and water demand and an increase in soil fertility because of root dieback and turnover. Conversely, it may also be of adverse effects enhancing below-ground competition due to more but thinner superficial roots due to a lower height of stems pruned (Van

Noordwijk and Purnomosidhi, 1995; Bayala et al., 2004). Moisture competition is a major problem in semi-arid tropics and low rainfall areas (Kang, 1997) because the competitive effects of hedgerows on crops generally exceed the benefits gained by preventing the small and infrequent amount of run-off commonly found (Ong et al., 2002). Below-ground nutrient competition between woody hedgerows and associated crops can become a main problem in acid and low fertility soils where both species tend to have restricted root growth (Kang, 1997). A shallower soil where tree roots may be forced to develop in the crop root zone can exacerbate such below-ground competitions (Kho, 2000). Moreover, some plants can produce secondary metabolites and secrete them from roots (root exudates) affecting (inhibitory and/or stimulatory) other organisms namely animals, bacteria, viruses, fungi, and neighboring plants in their vicinity (Makoi and Ndakidemi, 2012). For example, black walnut produces a phenolic compound called juglone (5-hydroxy-1,4-naothoquinone) that has inhibitory effects on survival, growth, and yield of several plants such as barley, alfalfa, wheat, and maize (Bertin et al., 2003). Nevertheless, management intervention, such as root barriers, trenching or disking and planting and managing the companion species during early establishment of black walnut, may help sustain the production potential in crops-black walnut alley cropping by alleviating the adverse effects of juglone (Jose and Holzmueller, 2008).

Obviously, the interspecific competition is one of the main disadvantages proved by lower yields and biomasses, especially for the crop located adjacent to hedgerows (Dercon et al., 2006b; Pansak et al., 2007; Guo et al., 2008; Kinama et al., 2007). In view of the above information, competition for growth resources may mask a number of advantages that trees may provide for the sustainability of long-term agroforestry systems and hamper their acceptance by rural communities in mountainous areas (Van Noordwijk and Purnomosidhi, 1995; Pansak et al., 2007).

1.4.4 Monitoring below-ground resource use competition in mixed cropping system

The magnitude of below-ground interactive (competitive) effects relies not only on the root systems but also on management operations by the land-user which can be grouped as (i) growth-enhancing manipulations such as fertilization, application of mulch and manure, and irrigation and (ii) growth-reducing manipulations such as shoot and root pruning, herbicide application and grazing/browsing (Lose et al., 2003; Nair, 1993). At the moment, to develop effective management solutions that can lessen yield loss due to competition are regularly based on trial and error rather than understanding the importance of each competitive mechanism (Clay et al., 2005). Additionally, it is difficult to separate and quantify the mechanisms (water/nutrients) responsible for competition-induced yield loss by traditional experimental techniques, which normally require either a huge number of treatments or a modelling effort (Pansak et al., 2007; Clay et al., 2005; Nair, 1993). A ^{13}C discrimination (Δ) approach based on a plant's physiological response to the environment can be used to solve that difficult problem in identifying and quantifying the effects of water and nutrients both in C_3 and C_4 plants (Clay et al., 2005; Clay et al., 2001a; Clay et al., 2001b).

Naturally, there are two stable isotopes of carbon (C), i.e., ^{12}C (98.9%) and ^{13}C (1.1%), and the overall abundance of ^{13}C relative to ^{12}C in plant tissue is commonly less than in the C of atmospheric carbon dioxide (CO_2) indicating that carbon isotope discrimination occurs in the incorporation of CO_2 into plant biomass (Farquhar et al., 1989). Isotope ratio mass spectrometry (IRMS) is a specialized technique usually used to accurately and precisely measure variation in the abundance ratio of the minor (heavier isotope) of the element to the major (lighter isotope) such as $^{15}N/^{14}N$ and $^{13}C/^{12}C$ (Muccio and Jackson, 2009). To eliminate any bias or systematic error in the measurements, the ratios of these isotopes are always measured relative to an isotopic standard, internationally recognized standards or reference materials for C such as Pee Dee Belemnite (PDB), Vienna Pee Dee Belemnite (VPDB) and NBS 19 calcium carbonate and for N such as IAEA-N-1 ammonium sulfate and laboratory air for N (Qi et al., 2003; Muccio and Jackson, 2009; Brand et al., 2009). The international Atomic Energy Agency (IAEA) and the National Institute of Standards and Technology (NIST) supply a range of other natural abundance standards (Muccio and Jackson, 2009). For example, USGS40 ($\delta^{13}C$ = -26.24‰ and $\delta^{15}N$ = -4.52‰) and USGS41 ($\delta^{13}C$ = +37.76‰ and $\delta^{15}N$ = +47.57‰) are two L-glutamic acid enriched in ^{13}C and ^{15}N which are prepared and utilized as the reference materials due to the exhaustion of the original materials such as PDB and VPDB (Qi et al., 2003; Brand et al., 2009). Isotope ratios of samples of interest are reported in the delta notation (δ). The units of $\delta^{13}C$ are 'per mil' (‰) and it is calculated according to the following equation:

$$\delta^{13}C_{sample}\ (‰) = \left(\frac{R_{sample}}{R_{standard}} - 1\right) \times 1000 \quad (6)$$

where R_{sample} and $R_{standard}$ are the abundance $^{13}C/^{12}C$ ratio of a sample and a reference material, respectively (Muccio and Jackson, 2009; O'Leary, 1988; Pansak et al., 2007). Analyzed samples are mostly depleted in the heavier isotope as compared with the standard and consequently have negative $\delta^{13}C$ values (Muccio and Jackson, 2009). C3 plants have $\delta^{13}C$ values of approximately -28‰ (ranging between around -35 to -21‰), whereas C4 plants are of approximately -14‰ (ranging between around -20 to -9‰). The $\delta^{13}C$ can be related to carbon-isotope discrimination (Δ) by:

$$\Delta = \frac{(\delta^{13}C_{air} - \delta^{13}C_{sample})}{(1 + \frac{\delta^{13}C_{sample}}{1000})} \qquad (7)$$

where $\delta^{13}C_{air}$ and $\delta^{13}C_{sample}$ are the stable carbon isotope ratio of air and sample material, respectively (O'Leary, 1988; Farquhar et al., 1989; Henderson et al., 1992). The $\delta^{13}C_{air}$ is -8‰ in the absence of industrial activity.

The mathematical equations to solve for the relationship between water stress and Δ are well documented for C_3 and C_4 plants. The Δ values of C_3 plants are related to diffusional fractionation (a = 4.4‰) and discrimination against $^{13}CO_2$ by ribulose diphosphate carboxylase or Rubisco (b = 30‰) and the ratio of intercellular to ambient partial pressure of CO_2 (p_i/p_a) and is expressed as:

$$\Delta_{C_3} = a + (b - a)\,\frac{P_i}{P_a} \qquad (8)$$

where parameters a and b are constants, whereas p_i/p_a is controlled by genetic factors and environmental constraints such as soil compaction and drought (Farquhar et al., 1982; Dercon et al., 2006a). The significance of this equation is that when for example, soil moisture decreases and plants close their stomata to reduce water loss, leading to (i) small stomata conductance relative to the capacity for CO_2 fixation, and (ii) small p_i due to reduction of the CO_2 diffusion from the air outside to the air inside the leaf (Dercon et al., 2006a; Farquhar et al., 1989). This reduction of CO_2 concentration inside the leaf will cause the decrease of Δ towards 4.4‰ or a higher ^{13}C abundance of the fixed CO_2. On the contrary, when stomata conductance is comparatively large, it will cause the increase of p_i approaching p_a and the increase of Δ towards 30‰ or approaching *b* (Farquhar et al., 1989). For example, Shangguan et al. (2000) observed that the C isotope discrimination (Δ) of wheat (C_3 plant) is reduced by the increase of drought intensity and increased by N deficiency.

Farquhar (1983) and Henderson et al. (1992) described the discrimination occurring in photosynthesis of C_4 plants by an expression:

$$\Delta_{C_4} = a + [b_4 + \emptyset\,(b_3 - s) - a]\,\frac{P_i}{P_a} \quad (9)$$

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‰), Ø (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 is the ratio of intercellular to ambient partial pressure of CO_2. Observed Δ data in C4 plants such as maize can be used as an alternative tool to estimate water-use efficiency (WUE) that is indirectly linked to water stress and to evaluate the impact of water stress at low to high N availability on crop performance. Higher N supply causes the CO_2 diffusion from the air across the leaf being insufficient fast to keep up with CO_2 demand needed to maintain plant productivity. This ^{13}C discrimination value increases even more if the high N supply occurs together with low availability of soil water (Dercon et al., 2006a; Pansak et al., 2007). In summary, increasing Δ values (equal to a decrease of δ or more negative δ) in C_4 plants and conversely decreasing Δ values (equal to an increase δ or less negative δ) in C_3 plants are the response of an increase in water stress (Clay et al., 2001a). The simultaneous use of Δ and δ is confusing since the Δ values are usually positive, while the δ values are usually negative when VPDB is the reference. Thus, it is preferable to use the δ values only as intermediates in the calculation of isotope effects (O'Leary, 1988). ^{13}C discrimination in plants is affected by many factors, including especially nutrients and water (Clay et al., 2001a; Dercon et al., 2006a). Therefore, additional measurements of water availability are crucial to assist in separating water and nutrient competition in mixed cropping systems.

Physical, chemical and biological processes such as plant growth, solute transport, runoff and erosion are controlled by soil water content (SWC), of which spatial and temporal variability is governed by the variability of soil properties and heterogeneity of the boundary conditions (Beff et al., 2013). A good example is contour hedgerow intercropping, a system along with the potentially high spatial variability of soil moisture due to complex spatial arrangements of plant components (Garré et al., 2013a).

Electrical resistivity tomography (ERT) is a non-invasive technique for spatially resolved monitoring of SWC distribution with a high spatial resolution, which aids in getting more understanding of water conditions in such complex systems (Garré et al., 2012). ERT is a geophysical technique for imaging subsurface structures based on electrical resistivity differences between different subsurface materials (Hauck and Scheuermann, 2005). Soils are a porous medium consisting of non-conductive solid particles that contain electrolyte solution that can conduct electric current by the movement of the free ions in the bulk solution and ions adsorbed at the matrix surface (Michot et al., 2003). The measurement of electrical resistivity (ρ) is done by applying an electrical current through a set of electrodes and reading the resulting differences in electric potential on separate conductors (Garré et al., 2012). Apparent electrical resistivity in multiple soil volumes arranged in two-dimensional or three-dimensional sections can be generated by using multi-electrode arrays along lines or grids (Rossi et al., 2011). Changes with space and/or time of several variables such as root biomass, soil texture and structure, stone content, soil temperature and soil moisture and soil water salinity have an impact on the measured apparent electrical resistivity. Performing resistivity measurements at several places and/or times can follow changes of these variables and thereby provide a good calibration relationship between electrical resistivity and the variable under consideration (Garré et al., 2012). An estimate of SWC through repeated resistivity measurements can be obtained by using the relation between the resistivity of a material and its pore fluid described by Hauck and Scheuermann (2005). Adjusted pedo-physical relationships of soil temperature data from temperature probes, SWC data from time domain reflectometer (TDR) probes and soil resistivity (conductivity) data from ERT electrodes installed in a calibration pit can be used for temperature correction of other measured bulk electrical conductivity values and for converting them to SWC under field conditions (Garré et al., 2013a; Garré et al., 2012). During the last few decades, ERT has been used in observation of transient state phenomena in the soil-plant continuum, SWC distribution and dynamics in cropped field, water uptake of garden trees and natural forests and water use of agricultural crops under different systems

(Michot et al., 2003; Beff et al., 2013; Garré et al., 2012). ERT has been proved as a valuable technique providing SWC distributions in various systems and thus it can be used as a complementary tool to study below-ground resource use competitions in mixed cropping systems.

1.5 Hypotheses

Diverse cropping systems under conservation agriculture may improve nitrogen fertilizer use efficiency and nitrogen balances on sloping land, thereby improving productivity and reducing negative environmental impacts. Nevertheless, soil conservation systems with hedgerows are frequently stated to have adverse effects on crops' productivity planted close to them. A better understanding of nitrogen cycling processes and crop-soil-hedge interactions is thus essential for designing sound soil conservation systems and enhancing farmers' acceptance. Therefore, the main hypotheses addressed in this thesis are:

(i) Maize-chili intercropping systems with or without conservation measures (minimum tillage and legume relay cropping or both together with contour hedgerows) increase nitrogen fertilizer use efficiency by reducing N losses, providing filter functions to capture and recycle N fertilizer and improving crop growth.

(ii) Legume-based mixed cropping systems instead of maize monoculture improve nitrogen balance by increasing nitrogen inputs through a high proportion of atmospheric N_2 fixation and raising the nitrogen budget by decreasing nitrogen losses and improving nitrogen use efficiency, and thereby increasing crop yields.

(iii) Maize-chili intercropping systems give higher returns to farmers than maize sole cropping due to the high price of fresh chili fruit and decreasing production risk by increasing diversification.

(iv) Identification of the driving forces (nutrients or water) of below-ground competition between crops and hedgerows at the crop-soil-hedgerow interface is possible by combining stable isotope discrimination, electrical resistivity tomography and time domain reflectometry methods.

1.6 Goal and objectives

The expansion and intensification of agriculture accompanied by land misuse and poor soil management often exacerbates soil degradation processes such as soil loss and nutrient depletion, especially nitrogen (N). Conservation agriculture based on either minimum tillage and cover crops or contour hedgerow intercropping systems or a combination of both have been developed and recommended to improve nitrogen use efficiency (NUE), N balance and crop yield. However, hedgerows' presence may negatively impact crops grown close to them due to competition that occurs aboveground for light and belowground for nutrients and water. This study's overall goal was to develop a sound cropping system and practice for farmers on sloping terrain in Southeast Asia. The overall objective was to better understand the use efficiency of fertilizer N, its translocation and fate, and crop performance at plot level and resource use competition between crops and hedgerows affected by conservation agriculture. The specific objectives were:

(i) To evaluate nitrogen use efficiency, nitrogen recovery and yield performance of crops under monoculture, maize-chili intercropping, minimum tillage with legume relay cropping, and alley cropping and their combination in tropical uplands, representing locally recommended conservation agriculture techniques (Section 3.1).

(ii) To examine the fate (flows) of nitrogen fertilizer using the ^{15}N isotope technique and to quantify nitrogen budgets at plot level over two cropping seasons for the traditional maize monoculture and the alternative maize-chili intercropping under conventional tillage or minimum tillage and relay cover crop, with or without Leucaena hedgerows (Section 3.2).

(iii) To use combined data of stable isotope discrimination, electrical resistivity tomography and time domain reflectometry to improve the understanding of competition at the crop-soil-hedge interface (Section 3.3).

1.7 Structure of the thesis

This thesis is divided into four chapters. The research topic is yield and fate of nitrogen fertilizer in maize-based soil conservation systems in Western Thailand. The contextual information of the thesis and the objectives of the research are addressed in Chapter 1. Chapter 2 presents materials and methods used in this research. Chapter 3 contains three sections, including (i) Section 3.1 describing maize yields and aboveground recovery of ^{15}N-labelled urea under conservation agriculture, (ii) Section 3.2 presents the residual effects and fate of ^{15}N-labelled fertilizer and nitrogen balances in maize-based soil conservation systems, and (iii) Section 3.3 discusses the benefits of combining $\delta^{13}C$ measurements and ERT imaging to improve our understanding of competition at the Crop-Soil-Hedge interface. The thesis continues with a general discussion (Chapter 4). Summaries in English and German languages and references are subsequently included.

Chapter 2

Materials and Methods

Chapter 2 Materials and Methods

2.1 Study site

The experiment was carried out at the Queen Sirikit research station (13°28’N, 99°16’E), Ratchaburi Province, Thailand, on a hillside with a slope of around 20%. The climate is a tropical savannah climate (Peel et al., 2007) with a temperature of 20-38 ºC and relative humidity of 41-100% (Khedari et al., 2002). Total rainfall and reference evapotranspiration (ET_0) were 1370 and 1137 mm during the first cropping season (June 29th 2010 to June 25th 2011) and 895 and 630 mm during second cropping season (June 26th 2011 to January 8th 2012), respectively, with rain falling mostly between May and October (Figure 1). Soils were classified in the range between an endoleptic Alisol and hyperskeletic Leptosol (IUSS Working Group, 2006). The topsoil (0-15 cm depth) had a loamy texture (38.8% sand, 40.2% silt and 21.0% clay), an organic matter content of 2.2%, an available P (Bray II) of 12.5 mg kg^{-1}, an available K of 220 mg kg^{-1} (NH_4OAc, pH 7), a total N of 0.16%, and a pH (1:1=soil: water) of 5.8. The trial was established in 2009 after clearing low-performing bamboo cultivation that was invaded by natural vegetation.

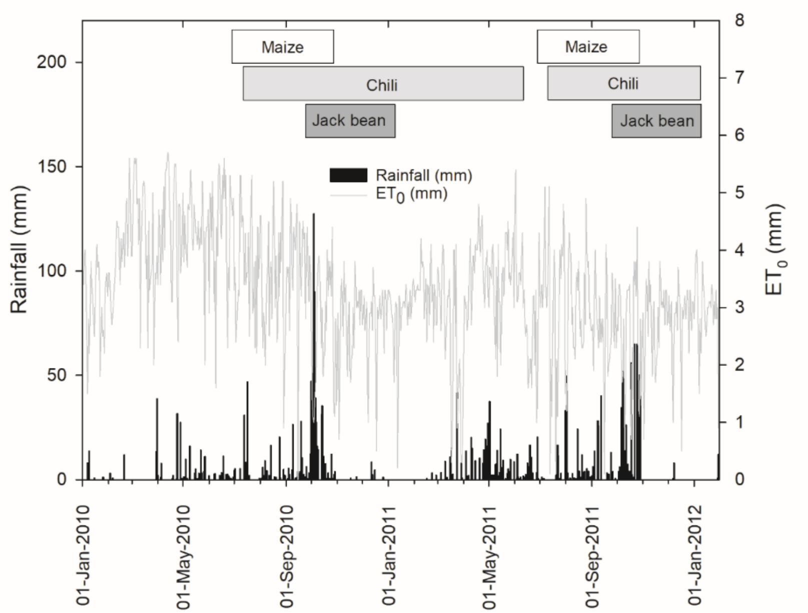

Figure 1 Daily rainfall distributions and reference evapotranspiration (ET_0) for the monitored period of 2 growing seasons at the experimental site. Boxes show planting times of maize, chili, and Jack bean.

2.2 Experimental design and data collection

The trial was established as a randomized complete block design (RCBD) with three replicates and the following treatments: (T1 or MM or control) maize (*Zea mays* L.) mono-crop under tillage and fertilization, (T2) maize intercropped with chili (*Capsicum annuum* L.) under tillage and fertilization, (T3) maize intercropped with chili, application of minimum tillage plus Jack bean (*Canavalia ensiformis* (L.) DC) relay cropping and fertilizer application, (T4 or MHF^+) maize intercropped with chili, application of minimum tillage with Jack bean relay cropping and fertilizer application plus an additional perennial hedges of *Leucaena leucocephala* (Lam.) de Wit, (T5) as T3 but without fertilization, and (T6 or MHF^-) as T4 but without fertilization (Figure 2). There was an additional plot of chili sole cropping to calculate the land equivalent ratio (LER). The plot size was 4 m x 13 m.

Before planting, land preparation by plowing using hand hoes (the usual farmer practice) was done in conventional tillage treatments (T1 and T2). In contrast, only hand weeding was applied in minimum tillage treatments (T3, T4, T5, and T6).

Maize variety Pacific 999 was sown on June 29th 2010, and June 26th 2011, at the spacing of 25 cm in the row and 75 cm between rows. Eight weeks old Chili seedlings of the high-value variety 'Super-hot' were transplanted 15 days after maize seeding with a plant spacing of 100 x 100 cm. There were four plants per chili row. Each alley consisted of two rows of maize or chili. Leucaena hedges were planted in February 2009 using non-inoculated seeds, 1 m wide and spaced 6 m apart according to recommendations of the Land Development Department (LDD) and International Board for Soil Research and Management (IBSRAM) of Thailand (Pansak et al., 2008). Non-inoculated Jack bean seeds were sown 30 days before maize harvest between crop rows at an intra-row spacing of 25 cm as relay crop in minimum tillage treatments.

Maize received an application of 62 kg N ha^{-1} as urea, split-applied at equal dosages at 30 and 60 days after sowing (DAS), as well as 11 kg P ha^{-1} as triple superphosphate and 36 kg K ha^{-1} as potassium chloride at 30 DAS according to site-specific nutrient demand calculations (Attanandana and R.S.Yost, 2003). According to local farmers' practice, fertilizers were applied in a 5 cm wide band at a soil depth of 5-10 cm, 5-10 cm away from the maize row. In 2010, equivalent amounts of ^{15}N-labelled urea (10 atom% ^{15}N) in powder form were applied in a band like normal urea fertilizer to the first maize row in T4 and the second maize row in T1, T2, and T3 counted from the top of the plots to monitor the fate of fertilizer N. No ^{15}N-labelled urea was applied in 2011 to allow observing of residual effects of N fertilization. In T2, T3 and T4, chilies received a basal-dressing of 92 kg N ha^{-1} (urea) at transplanting and a top dressing of 92 kg N ha^{-1} 75 days after transplanting (DAT). After maize harvest, chilies received 72-32-60 kg N-P-K ha^{-1} using a granular compound fertilizer (fertilizer grade; 16-16-16 kg N-P_2O_5-K_2O) by split-applied at equal dosages 150, 225, and 300 DAT. Leucaena hedges and Jack beans were not fertilized.

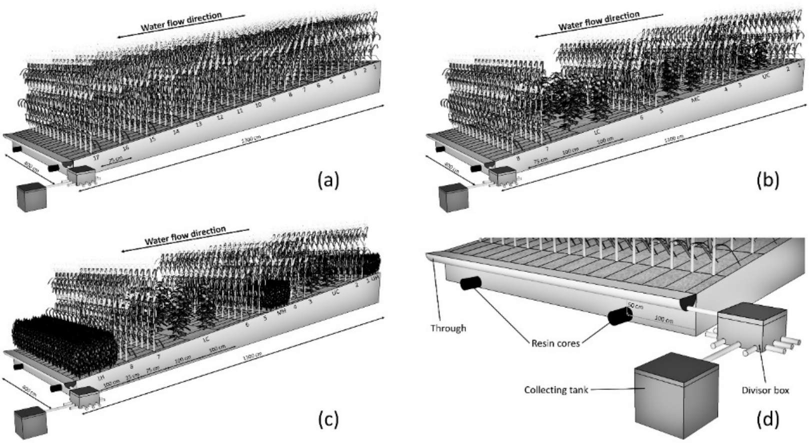

Figure 2 Schematic representation of the experimental plots at Queen Sirikit's demonstration farm, Ratchaburi Province, West Thailand, (a) maize monoculture (T1 or MM or control) (b) maize-chili intercropping (T2, T3, and T5) (c) maize-chili intercropping with L. leucocephala hedgerows (T4 or MHF^+ and T6 or MHF^-), and (d) runoff water and sediment collecting devices and resin core installation positions. Figures under plants show maize row number and capital letters under plants show upper (UC), middle (MC), and lower (LC) chili alley positions, respectively, and upper (UH), middle (MH), and lower (LH) *L. leucocephala* hedgerow positions, respectively.

During the maize growing period, Leucaena hedges were regularly pruned to a height of 50 cm to minimize light competition, starting just before maize planting. Prunings were spread uniformly over the soil surface and left as mulch. All plots were hand weeded three times, at land preparation, the second N fertilizer top-dressing, and two months after maize harvesting time. In the second season (June 26th 2011-January 8th 2012), the field experiment was managed as in the first season (June 29th 2010-June 25th 2011). However, in the second season, chili growth performance was poor due to severe pests and disease attack (Garré et al., 2013b). Hence, chilies were pulled out in the second year already in January 2012. Therefore, fertilized chili plots received only a basal-dressing of 92 kg N ha^{-1} (urea) at transplanting and a top dressing of 92 kg N ha^{-1} 75 DAT.

Maize was harvested at physiological maturity (around 120 DAS) on October 27th 2010, and October 17th 2011. From each row, eight maize plants were randomly collected, discarding border plants. Before weighing, maize samples were separated into leaf, grain, shank-husk-cob core, and stems. For chilies, fresh fruits were collected seven times in season 1 and four times in season 2. At the last fruit harvest, whole chili plants were harvested, separated, and weighed in the first season on June 10th 2011 and the second season on January 8th 2012. Leucaena prunings of each hedgerow from upper, middle, and lower slope position and from all pruning events after ^{15}N-labelled fertilizer application were collected and weighed separately in all hedgerow treatments. A composite weed sample per plot was collected after every hand weeding following the ^{15}N-labelled fertilizer application. A sampling of Jack bean occurred four months after planting from 1-m^2-quadrants in the upper, middle, and lower slope positions of T3-6. The sample was separated into pods and shoot and weighed separately. After Jack bean harvest, the remaining plants were cut and left on the soil surface as a mulch. From all plant samples, a subsample was taken, oven-dried at 70ºC until a constant weight was reached and reweighed to obtain the fresh/dry weight conversion factor for each part. All plant samples were coarsely ground in a rotary mill to pass a 2 mm sieve. A composite sample of maize straw was formed by proportional mixing of the ground leaf, stem, and shank-husk-cob core material according to the weight of each part.

After each maize harvest, soil samples were taken at depths of 0-5, 5-15 and 15-45 cm. Soil samples were collected from four positions between maize rows along the slope by an auger (diameter 8 cm) in T2, T3, and T4. Whereas, in T1, four soil samples were collected between maize rows at corresponding slope positions. Each soil sample was bulked and thoroughly mixed from two subsamples taken from two points in each sampling line. Soil samples were air-dried at room temperature around 25-28 ºC (Ketrot and Wisawapipat, 2021) and coarsely ground by hand to pass a 2-mm-sieve. Bulk densities were determined by core method at three soil depths, i.e., average (3 replications) 1.69 g cm^{-3} for 0-5 cm, 1.73 g cm^{-3} for 5-15 cm, and 1.80 g cm^{-3} for 15-45 cm and used to calculate the soil mass of the plots.

From each erosive rainfall event after application of ^{15}N-labelled urea, soil loss and runoff samples were collected at the bottom of each plot and measured as described by Pansak et al. (2008). Collecting devices consisted of collecting tanks indirectly connected to the erosion plots through one of twelve channels of a divisor box located between plot and tank (Figure 2). Sediment (soil loss) samples were collected, air-dried, coarsely ground, sieved through a 2-mm-mesh sieve, and carefully stored for later ^{15}N stable isotope analyses. NO_3^--N and NH_4^+-N in runoff water was determined by the steam distillation method (Mulvaney, 2001). After mineral-N determination, many distillates were found to contain less than 40 µN, a quantity too small for ^{15}N enrichment analysis with a Euro Elemental Analyzer coupled to Finnigan Delta IRMS. Hence, 40 µg N of unlabelled urea (know natural ^{15}N abundance) were added in solution to the samples (spiking) and then oven-dried at 50 ºC.

N subsurface flow was assessed by the resin core method (Pansak et al., 2008). Resin cores were made from polyethylene pipes (diameter: 14 cm; length: 10 cm). These cores were filled with a mixture (9 cm) of one volume of Amberlite MB 20 (a combined cation-anion exchange resin) and four volumes of sand and covered on top (1 cm) by a thin sand-layer. After filling, the bottom and top side of the cores, they were wrapped with a 100-mesh (sieve size=0.149 mm) nylon net to protect leakage of the resin-sand mixture. Resin cores were buried before maize planting in both years. Two resin cores per plot were installed at the bottom position of each plot, 50 cm below, and parallel to the soil surface by facing the top of the slope at a distance of 100 cm from either side of the plot border (Figure 2). The installation was done by digging a small trench to 50 cm depth and excavating a fitting hole into the wall to host the resin cores. Subsequently, resin cores were gently inserted into the hole. The remaining space was filled with soil, and the trench was closed. At the end of each maize growing season, all resin cores were carefully excavated. Each core's resin-sand mixture was separated into three layers, 0-3, 3-6 and 6-9 cm. To avoid interference by water from outside the plot at the bottom of the resin-sand layer (6-9 cm), only the two upper layers (0-3 cm; 3-6 cm) were used to determine the NO_3^--N and NH_4^+-N concentration by extraction with 2 M KCl and distillation with MgO and Devarda alloy (Mulvaney, 2001). Distillates of the resin core after mineral-N determination were prepared in the same way as distillates of runoff water for ^{15}N content. ^{15}N enrichment of the original distillates from runoff water and resin core exudates was calculated using the quantity of mineral-N in the distillates and the ^{15}N enrichment of the unlabelled urea and the known amount of added N (40 µg N) (Boddey et al., 1995).

Before ^{15}N stable isotope analysis, portions of all samples were finely ground to powder in a piston mill and oven-dried. Pulverized samples were packed into tin capsules and analyzed for their $^{15}N/^{14}N$ ratio and total N concentration using a Euro Elemental Analyzer coupled to a Finnigan Delta IRMS at the University of Hohenheim Laboratory. Acetanilide (HEKAtech GmbH, Germany) with an atom % ^{15}N of 0.3659 was used as an analytical standard. In all cases, samples with an expected lower ^{15}N enrichment were prepared first and analyzed, followed by samples with higher ^{15}N enrichments to reduce the likelihood of cross-contamination.

2.3 Yield and land equivalent ratio calculations

Area corrected yields present crop yields as influenced by the actual planting density on biomass and were computed as follows:

$$Area\ corrected\ yield\ (kg\ ha^{-1}) = Y_{absolute} \times Plant\ density_{actual} \quad (10)$$

where $Y_{absolute}$ is the average yields of grains/fruits or straw for maize and chili per square meter (m^{-2}) regardless of the differences of plant components in various treatments, and $Plant\ density_{actual}$ is the actual crop density of the cropping systems. A maize row comprised of 16 plants; thus, the total plant density was 53333 plants ha^{-1} in T1, 21333 plants ha^{-1} in T2, T3 and T5, and 28810 plants ha^{-1} in T4 and T6. There were four plants per row for chili, giving a density of 5333 plants ha^{-1} in T2, T3, and T5 and 3333 plants ha^{-1} in T4 and T6. For Leucaena prunings, Jack bean and weed aboveground biomass (AGB), the actual plot area occupied by the respective plants was used to convert yields from square meter to area corrected values on a hectare basis. The total number of 4 m^2-Leucaena hedgerows was 417 rows ha^{-1}. Jack bean's actual plant density was 46155 plants ha^{-1} in T3 and T5 and 43077 plants ha^{-1} in T4 and T6. As for area corrected aboveground biomass calculation, Jack bean plants were assumed to cover 100% of the plot in T3 and T5 and only 79% of the plot in T4 and T6 due to the occupation of Leucaena hedgerows. Weeds were expected to invade 100% of the plot in all treatments.

The land equivalent ratio (LER) was used to assess the performance of intercropping. It is the most frequently used index, being applied to any form of intercropping (Guo et al., 2008). An LER higher than one indicates an advantage of intercropping, showing that interspecific facilitation or complementarity is higher than the interspecific competition (Li et al., 1999). The LER was calculated according to equation 11.

$$LER = \left(\frac{Y_{im}}{Y_{sm}} + \frac{Y_{ic}}{Y_{sc}}\right) \quad (11)$$

where Y_{im} and Y_{sm} are the area corrected marketable grain yields (kg ha^{-1}) of intercropped and sole cropped maize, respectively, and Y_{ic} and Y_{sc} are the area corrected marketable fresh fruit yields (kg ha^{-1}) of intercropped and sole cropped chili.

2.4 Fate of fertilizer-^{15}N calculation

The percentage of total N derived from applied ^{15}N-labelled fertilizer (Ndff) and the percentage of ^{15}N-labelled fertilizer recovery (^{15}NFR) in each pool of a cropping system was calculated according to the following equations adapted from Stevens et al. (2005):

$$Total\ N\ content\ (kg\ N\ ha^{-1}) = \frac{DW_{sample}\ (kg\ ha^{-1}) \times Nconc_{sample}\ (\%)}{100} \quad (12)$$

$$Fertilizer\ N\ fraction\ (N_f) = \frac{(atom\%^{15}N_{sample} - atom\%^{15}N_{background})}{(atom\%^{15}N_{fertilizer} - atom\%^{15}N_{background})} \quad (13)$$

$$Ndff\ (\%) = N_f \times 100 \quad (14)$$

$$Fertilizer\ N\ \text{recovery}\ (kg\ N\ ha^{-1}) = N_f \times Total\ N\ content\ (kg\ N\ ha^{-1}) \quad (15)$$

$$Fertilizer\ N\ recovery\ (\%) = \frac{Fertilizer\ N\ \text{recovered}\ (kg\ N\ ha^{-1})}{Fertilizer\ N\ applied\ (kg\ N\ ha^{-1})} \times 100 \quad (16)$$

where DW_{sample}, $Nconc_{sample}$ and $atom\%^{15}N_{sample}$ are dry weight (based on absolute yields on a hectare basis), nitrogen concentration and atom%^{15}N abundance of samples from a fertilized treatment, respectively. $Atom\%^{15}N_{background}$ is atom%^{15}N abundance of samples from a non-fertilized treatment, and $atom\%^{15}N_{fertilizer}$ and *fertilizer N applied* are atom%^{15}N abundance and the rate of ^{15}N-labelled urea applied to maize in the first season. In this paper, ^{15}N based fertilizer N recovery data of each pool are illustrated on the total plot area per cropping season.

2.5 Biological nitrogen fixation and its calculation

The percentage of Leucaena and Jack bean N derived from atmospheric N_2 (%Ndfa) was assessed using the ^{15}N natural abundance method (Shearer and Kohl, 1986; Ojiem et al., 2007; Unkovich et al., 2008). This method is based on the principle that the ^{15}N abundance provided by the soil slightly differs from the atmosphere's ^{15}N abundance. Hence, %Ndfa can be calculated using equation 17:

$$\%Ndfa = \frac{(\delta^{15}N_{ref} - \delta^{15}N_{fix})}{(\delta^{15}N_{ref} - B)} \times 100 \tag{17}$$

where $\delta^{15}N_{ref}$ is the ^{15}N natural abundance of shoots of a non-N_2-fixing reference plant that derives its entire N from the soil N, $\delta^{15}N_{fix}$ is the ^{15}N natural abundance of shoots of an N_2-fixing legume plant growing in the same soil, and B is the $\delta^{15}N$ of shoots of a legume, fully dependent upon N_2-fixation for growth and acts as a correction for isotopic fractionation during the N_2-fixation. As mentioned by Unkovich et al. (2008), cereals or other broad-leafed crops are grown in 'alleys' between tree-legume hedgerows that can be used as non-fixing references. Therefore, in this study, maize plants grown in the same field as the legumes and collected before application of ^{15}N-labelled fertilizer, were used as reference plants for %Ndfa calculation. The B values were obtained from Boddey et al. (2000) for Leucaena (0.34 $^{0}/_{00}$), and for Jack beans (1.26 $^{0}/_{00}$) from Douxchamps et al. (2010).

Due to the ^{15}N-labelled fertilizer application in T3 and T4, these systems were contaminated with enriched ^{15}N materials. Therefore, the %Ndfa of Leucaena and Jack bean from T5 and T6 were used as estimates of maximum %Ndfa value for T3 and T4 as most sites with N fertilizer applications reduce N_2 fixation by decreasing nodulation and/or delaying the establishment of a functioning symbiosis (Unkovich et al., 2008). Avoiding soil disturbance in minimum tillage treatments, only Leucaena pruning and aboveground material of Jack bean (without belowground materials) were used to calculate the amounts of N_2 fixed by legume plants, which provided estimates of the minimum contribution of fixed N into the systems.

Table 1 presents the average $\delta^{15}N$ of maize seedlings, Leucaena prunings, and Jack bean aboveground biomass (AGB) and the average percentages of nitrogen derived from biological N_2 fixation (%Ndfa) of Leucaena prunings and Jack bean AGB of this study.

Table 1 Average $\delta^{15}N$ of reference plant (maize seedlings) and leguminous plants (Leucaena pruning and Jack bean) and %Ndfa in each season.

Plant	Season 1		Season 2	
	$\delta^{15}N$	%Ndfa[1]	$\delta^{15}N$	%Ndfa
Maize seedling (reference plant)				
T5[2] (n = 24)	6.5 (0.9)[6]	--	7.5 (0.9)	--
T6[3] (n = 24)	6.3 (0.8)	--	7.0 (1.4)	--
Leucaena pruning (T6; n = 54)[4]	4.1 (0.6)	34.1 (9.4)	4.3 (0.7)	36.6 (9.6)
1st pruning (n = 9)	3.9 (0.6)	36.5 (8.3)	4.6 (0.5)	32.6 (6.3)
2nd pruning (n = 9)	4.2 (0.7)	32.2 (9.7)	4.6 (0.4)	33.44 (6.3)
3rd pruning (n = 9)	4.0 (0.7)	34.5 (10.8)	4.4 (0.6)	35.9 (8.7)
4th pruning (n = 9)	3.9 (0.5)	35.8 (7.4)	4.5 (0.7)	35.0 (9.1)
5th pruning (n = 9)	4.2 (0.6)	31.4 (9.5)	4.1 (0.9)	40.4 (11.7)
6th pruning (n = 9)	4.1 (0.6)	33.3 (9.6)	4.0 (0.8)	40.7 (10.4)
Jack bean AGB[5]				
T5 (n = 9)	5.1 (0.6)	18.3 (7.3)	5.5 (0.7)	23.0 (7.8)
T6 (n = 9)	4.8 (0.6)	19.7 (8.3)	5.1 (0.8)	23.0 (9.3)

[1] %Ndfa = nitrogen derived from atmospheric N_2 via biological N_2 fixation.
[2] T5 = maize and chili intercropping under minimum tillage with relay crop and no fertilizer application.
[3] T6 = as T5 but additionally with hedgerows.
[4] The averaged value of all six pruning times
[5] AGB = aboveground biomass
[6] Standard deviation is given in parenthesis

2.6 Nitrogen budget

The N budget was estimated for all treatments and both years by using the following equations (Douxchamps et al., 2010):

$$N_{budget}(kg\ N\ ha^{-1}) = N_{input} - N_{output} \quad (18)$$

mineral fertilizer N, seed N, symbiotically fixed N, and wet deposition N were summed up as the nitrogen input and estimated as:

$$N_{input}(kg\ N\ ha^{-1}) = N_{deposition} + N_{fertilization} + N_{seed} + N_{fixation} \quad (19)$$

where $N_{deposition}$ is the quantity of N deposited by rainfall, it was roughly estimated based on rainfall amount recorded by a weather station at the field site (Figure 1). Average mineral N concentrations in rainwater (0.53 mg L^{-1}) for rural areas of Thailand were obtained from Paramee et al. (2005). $N_{fertilizer}$ is the mineral N fertilization of maize (N_{Mfert}) and chili (N_{Cfert}), calculated for each treatment based on the amount of fertilizer applied to the plots and the N concentration of the fertilizers. N_{seed} was accounted for maize (N_{Mseed}), Jack beans (N_{Jseed}), and chili seedlings ($N_{Cseedling}$), computed as the product of N concentration and plant density. $N_{fixation}$ is the contribution of the biological N_2 fixation of Leucaena (N_{Lfix}) and Jack bean (N_{Jfix}) and was calculated as the product of %Ndfa calculated as mentioned above in equation (17), N concentration and area corrected biomass of Leucaena prunings and Jack bean.

Nitrogen export by harvested products (crop removal) and N losses was added up to the nitrogen output, calculated as follows:

$$N_{output}(kg\ N\ ha^{-1}) = N_{Mgrain} + N_{Cfruit} + N_{losses} \quad (20)$$

where N_X is the amount of N (kg ha^{-1}) in each of the mentioned plant materials X (*Mgrain* = maize grain, and *Cfruit* = chili fruit) and was obtained from its N concentration multiplied by its area corrected biomass production (kg ha^{-1}). N_{losses} was the amount of N (kg ha^{-1}) in the runoff, soil loss, and subsurface flow and estimated as:

$$N_{losses}(kg\ N\ ha^{-1}) = N_{RO} + N_{SL} + N_{SF} \quad (21)$$

where N_X is the amount of N (kg ha^{-1}) in each of the mentioned material X (*RO* = runoff, *SL* = soil loss, and *SF* = subsurface flow) and was obtained from its N concentration multiplied by its mass.

N recycled is the amount of N in maize, and chili residues, Leucaena prunings and Jack bean aboveground biomass and was calculated as:

$$N_{recycled}(kg\ N\ ha^{-1}) = N_{Mr} + N_{Cr} + N_{Lp} + N_{Jb} \quad (22)$$

where N_X is the amount of N (kg ha^{-1}) in each of the mentioned plant material X (*Mr* = maize residue, *Cr* = chili residue, *Lp* = Leucaena prunings and *Jb* =

Jack bean aboveground biomass) and was obtained from its N concentration multiplied by its area corrected biomass production (kg ha^{-1}).

2.7 Leaf area index

The leaf area index (LAI) was measured with a Sunscan Canopy Analyser (Delta-T Devices, UK), consisting of a 1 m long probe with 64 photodiodes equally spaced on the probe length and an external beam fraction sensor (BFS) III to calculate the LAI based on zenith angle, ellipsoidal leaf angle distribution parameter (ELADP), time and location coordinates. For LAI monitoring, eight measurements were taken below canopy in-between every two rows of maize and chili by means of the Sunscan probe while the attached BFS simultaneously measured above canopy incident light against each below canopy measurement outside of the plot. In a single LAI measuring campaign 64, 56 and 56 measurements were taken in maize monocrop, hedge intercrop with and without fertilizer, respectively, for assessing the LAI distribution within a plot. This practice was carried out five times during the maize growing season. Eight out of 16 maize plants per row were marked and monitored for plant height five times during the season. Plant height was measured from all rows and in all treatments on the same day during a single campaign. An automatic weather station (Campbell Sci., UK) was installed at the experimental site to monitor maximum and minimum air temperature, relative humidity, solar radiation, and rainfall (Figure 3).

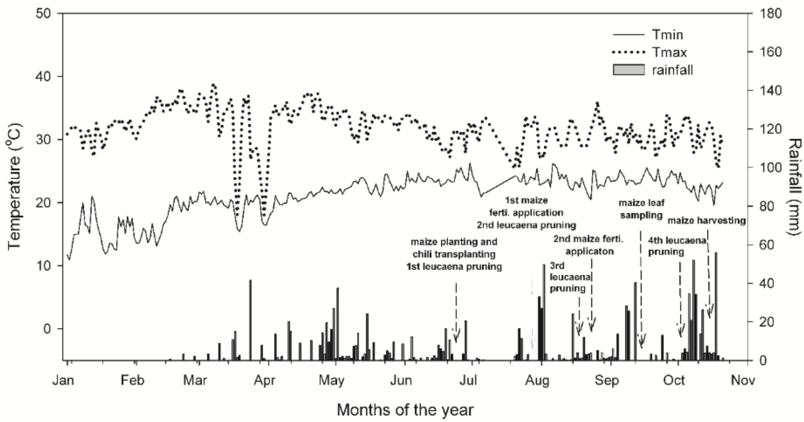

Figure 3 Temperature, rainfall and crop management at the experimental site. Data were recorded during 2011 at Queen Sirikit Research Farm, Ratchaburi province, Thailand.

2.8 Root length density

End of September 2011, soil core samples were taken to measure the root length density of maize and Leucaena. Therefore, a 2 m long and 1m deep trench on one side of maize monocrop (T1 or MM) and both hedgerow treatments (T4 or MHF^+, T6 or MHF^-) was dug along the slope in the same block where ERT measurements were carried out. In MM, five core samples were taken at the middle slope position of the plot, while eleven samples were taken in both MHF^+ and MHF^- treatments covering the central hedgerow and four maize rows, two above and two below this central hedgerow (Figure 4). For collecting root samples, a core volume of 101.3 cm^3 was horizontally inserted into the trench at depths of 5 and 20 cm. After drying samples were sieved and separated into soil, maize, and Leucaena roots.

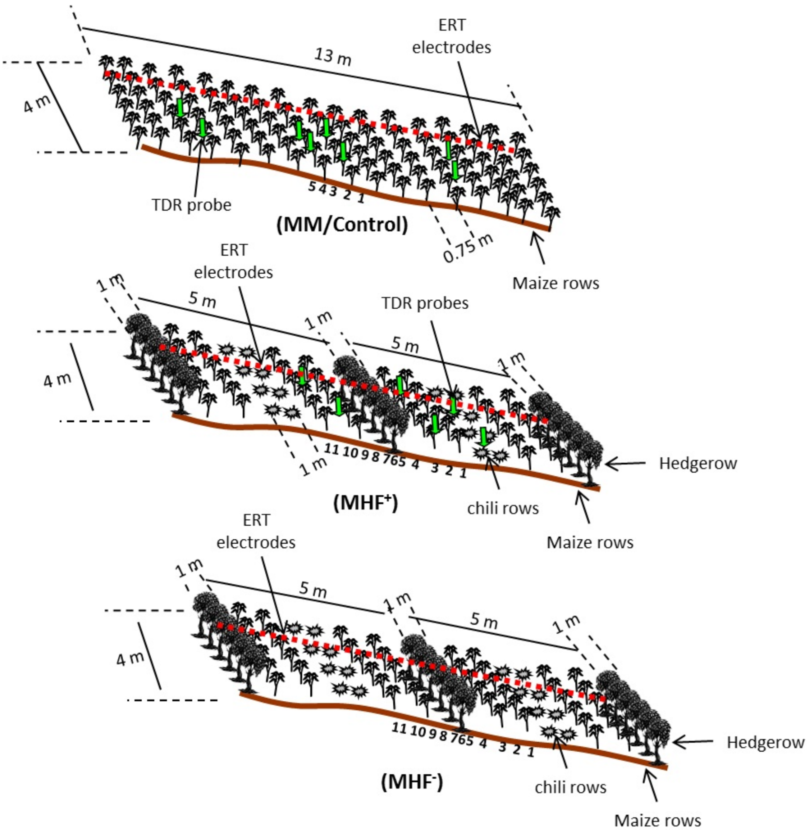

Figure 4 Planting scheme of the selected maize-based cropping systems and position of time domain reflectometry (TDR) probes and electrical resistivity tomography (ERT) electrodes within each plot, Queen Sirikit Research Farm, Ratchaburi province, Thailand.

2.9 Soil water monitoring

Electrical resistivity tomography (ERT) measurements were made in the 3rd replicate (block) from July 25th (28 DAS) to September 15th, 2011 (80 DAS) with the help of a ten-channel Syscal Pro resistivity meter (IRIS, France). In total, 54 electrodes were permanently installed in each plot at three depths, i.e., 36 electrodes at 5 cm, 9 at 25 cm and 9 at 50 cm with a horizontal distance of 33, 132, 132 cm in MM, MHF^+, and MHF^-. The electrodes were stainless steel rods insulated using heat-shrink tubing leaving the 5-cm bottom sharpened ends free as electrodes. A combination of dipole-dipole and Wenner measurements were carried out in each plot consisting of 1694 distinguished quadruples with a measuring time of 1 hour per plot per day. A corresponding calibration trench (1-m depth) in an area just below the ERT measured plots was made. The resistivity data was corrected for temperature by using the following equation (Campbell et al., 1949):

$$EC_{b,25} = \frac{EC_b}{1+\alpha(T-25)} \quad (23)$$

where $EC_{b,25}$ (Sm^{-1}) is the electrical conductivity at 25°C, α the empirical coefficient equal to 0.02 °C^{-1} and T (°C) is the soil temperature.

The bulk electrical conductivity was converted to water content after a calibration procedure by using the following simplified Waxman and Smits (W-S) model (Waxman and Smits, 1968):

$$WC = \left\{\frac{(EC_{b,25}-b)}{\alpha}\right\}^{1/n} \quad (24)$$

where *WC* is volumetric water content (m^3m^{-3}), $EC_{b,25}$ the bulk soil electrical conductivity at 25°C (Sm^{-1}) and *a, b, n* the fitting parameters. The complete ERT measurement procedure, calibration, conversion of EC to WC and various factors affecting ERT measurements can be found in Garré et al. (2013b). The results of this study highlighted some constraints of the ERT method for soil moisture monitoring in the field, such as the difficulty of defining a relationship between electrical conductivity and soil moisture in very heterogeneous soils as the test site, but the accuracy lies in the range of other works (Garré et al., 2012; Vanderborght et al., 2013). Hence, absolute values have to be used with caution on shallow soils. Relative changes and their spatial-temporal patterns, however, are registered very well, being impossible with conventional soil moisture sensors. We, therefore, used average soil water content (ΔWC) in this study. The ΔWC of August 2nd, 2011 was set as zero soil moisture depletion and initial soil moisture content to measure the soil moisture depletion of a specific date thereafter.

Time domain reflectometry (TDR) was also used to monitor soil moisture. We used 2-pin TDR sensors (0.25 m) and an automated setup consisting of coaxial multiplexers, a TDR-100 measurement device and a CR-1000 data logger (Campbell Sci., UK). The volumetric water content was calculated from the TDR-measured dielectric constant using the Topp et al. (1980) calibration equation:

$$\theta_v = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} K_a - 5.5 \times 10^{-4} {k_a}^2 + 4.3 \times 10^{-6} {k_a}^3 \qquad (25)$$

where θ_v (m^3m^{-3}) is the volumetric water content, and k_a is the apparent dielectric constant (ratio of capacitance of soil to the capacitance of air, which is a function of the soil moisture content). The volumetric water contents were measured at three similar slope positions in maize monocrop and hedge intercrop with fertilizer (Figure 4). The probes were installed vertically from the surface to a depth of 0.25 m. TDR probes were disconnected during the ERT measurement to avoid current loss through multiplexers. The TDR data presented here are from the same replicate as the ERT measurements.

2.10 Carbon stable isotope evaluation

For determination of carbon isotopic ratios, leaf samples of the third youngest leaf counted from the top of a maize plant at around 100 DAS and maize grain at harvest were collected. Carbon isotopic ratios of maize leaves and grains were determined per maize row. Therefore, for grain samples, all cobs of a row excluding border plants were collected at harvest. Grains were separated from the cob and kept separately. In hedgerow intercrop treatments, all maize rows were sampled, while in the maize monocrop treatment, eight maize rows at a similar slope position as in the two hedgerow treatments were used for analysis. Leaf and grain samples were oven-dried at 70 °C until a constant weight was achieved, thereafter ground finely with a ball mill and again oven-dried at 70 °C overnight. Finally, well-mixed subsamples of these fine maize leaf and grain flour samples were analyzed using a Euro elemental analyzer coupled to a Finnigan Delta IRMS to determine leaf and grain $^{13}C/^{12}C$ ratios. $\delta^{13}C$ was calculated by expressing these measured ratios (R_{sample}) against the Vienna Peedee belemnite (VPDB) standard (R_{VPDB}):

$$\delta^{13}C_{sample}(‰) = \left\{\left[{}^{R_{sample}}\!/_{R_{VPDB}}\right] - 1\right\} \times 10^3 \quad (26)$$

IAEA, Vienna standards USGS-40 and USGS-41 have been used for internal calibration.

2.11 Nitrogen concentration and response of maize grains

The nitrogen concentration in maize grains was determined by the dry combustion method. The combustion system was coupled with a mass spectrometer.

The natural log of the response ratio for nitrogen ($LnRR_N$) was calculated to quantify the effects of Leucaena hedges on maize total grain nitrogen concentration by modifying the formula given by Gross et al. (2010):

$$LnRR_N = In\left(\frac{\text{grain total N concentration with hedges}}{\text{grain total N concentration without hedge (control)}}\right) \quad (27)$$

In the control, only maize rows at corresponding position along the slope to that of maize under hedgerow treatments were used to calculate $LnRR_N$. A $LnRR_N$ less than zero indicates a negative hedge effect on resource availability, while a $LnRR_N$ equal to or greater than zero indicates no or a positive hedge effect, respectively.

2.12 Data analyses

All data were compared by an analysis of variance (ANOVA) for a randomized complete block design using the Statistical Analysis System (SAS) version 9.2 (SAS Institute Inc., Cary, NC, USA) with PROC GLM or PROC MIXED to test the effect of cropping system and slope position. Comparisons of means were performed with Tukey's HSD test for multiple comparisons or Fisher's LSD test for pairwise comparisons when the ANOVA F-test indicated significant ($p < 0.05$) differences among the factors' means such as treatments and seasons. Additionally, REG PROCEDURE was used to model the relationships between various dependent and independent or explanatory variables and to check their levels of significance at $\alpha = 0.05$.

Chapter 3

Results and Discussion

Chapter 3 Results and Discussion

3.1 Maize yields and aboveground recovery of ^{15}N-labelled urea under conservation agriculture

3.1.1 Results

3.1.1.1 Yield, aboveground biomass production, and N uptake of maize-based cropping systems at plot-level

The cropping system significantly affected area corrected yields of maize, ranging from 2.6 to 6.7 Mg ha^{-1} (Table 2). The general crop management of Thai farmers (T1) had the highest maize grain yield among all treatments, being significantly ($p < 0.0001$) higher than those of T2, T3 and T4. Maize straw ($p < 0.0001$) and total aboveground biomass (AGB) ($p < 0.0001$) followed approximately the same trend as maize grain yields. The replacement of maize rows by either chilies and/or Leucaena hedgerows in intercropping and soil conservation systems was the main cause for the decrease of maize yields at plot level.

Chili fresh fruit yields ranged from 2.3 to 3.3 Mg ha^{-1}, being significantly higher ($p = 0.019$) in T2. Chili dry fruit ($p = 0.025$), straw ($p = 0.0024$) and AGB ($p = 0.0004$) followed the same trend but straw and AGB of T3 and T4 showed significant differences ($p < 0.0024$ and 0.0004, respectively). Dry chili straw and AGB significantly increased in the order: T4 < T3 < T2. Both T3 and T4 illustrate the detrimental effect of minimum tillage and/or hedgerow systems on chili yields. Total Leucaena prunings from six cutting events of T4 were 1.6 Mg ha^{-1}. Jack bean AGB of T3 and T4 was 1.6 and 1.1 Mg ha^{-1}, respectively, with no significant difference. Cumulative weed AGB of three hand weeding ranged from 2.0 to 4.8 Mg ha^{-1}, being significantly ($p = 0.0012$) greater in T1.

Total N uptake of maize differed among treatments significantly and followed similar trends as found for area corrected maize yields (Table 2). Maize N uptake ranged from 46 to 118 kg ha^{-1} in grains ($p = 0.0003$) and 27 to 63 kg ha^{-1} in straw ($p = 0.002$) and was highest in T1. N content of chili fruits of T2 was significantly ($p = 0.0007$) higher as compared to T3 and T4, whereas N content of straw ($p = 0.0007$) and AGB ($p = 0.0002$) significantly decreased in the order T2 > T3 > T4. N uptake by Leucaena prunings was 83 kg N ha^{-1}. N uptake by AGB of Jack beans in T4 (39 kg N ha^{-1}) was lower than in T3 (59 kg N ha^{-1}) without showing significant differences. N uptake by weeds followed the trend of weed AGB, being significantly ($p = 0.0008$) higher in T1.

Table 2 Area corrected yields and N uptake of maize, chilies, *L. leucocephala*, Jack beans, and weeds as affected by cropping systems. Data were collected at Queen Sirikit's demonstration farm, Ratchaburi Province, West Thailand, during June 2010 and June 2011.

Parameter	Treatment[1]				*P value*
	T1	T2	T3	T4	
Maize (Mg ha^{-1})					
Grain	6.7 a[2]	3.1 b	2.6 b	3.3 b	< 0.0001
Straw	7.9 a	3.8 b	3.0 b	3.4 b	< 0.0001
AGB[3]	14.6 a	6.9 b	5.6 b	6.7 b	< 0.0001
N uptake (kg N ha^{-1})					
Grain	118 a	55 b	46 b	58 b	0.0003
Straw	63 a	34 b	27 b	27 b	0.0020
AGB	181 a	89 b	73 b	85 b	0.0004
Chilies					
Fruits, fresh (Mg ha^{-1})	-	3.3 a	2.4 b	2.3 b	0.0186
Fruits, dry (kg ha^{-1})	-	614 a	469 b	451 b	0.0245
Straw, dry (kg ha^{-1})	-	945 a	689 b	480 c	0.0024
AGB, dry (kg ha^{-1})	-	1559 a	1158 b	931 c	0.0004
N uptake (kg N ha^{-1})					
Fruit	-	17 a	12 b	12 b	0.0007
Straw	-	30 a	22 b	14 c	0.0007
AGB	-	47 a	34 b	26 c	0.0002
Leucaena					
Prunings (Mg ha^{-1})	-	-	-	1.6	-
N uptake (kg N ha^{-1})	-	-	-	83	-
Jack beans					
AGB (Mg ha^{-1})	-	-	1.6 a	1.1 a	ns[4]
N uptake (kg N ha^{-1})	-	-	59 a	39 a	ns
Weeds					
AGB (Mg ha^{-1})	4.8 a	2.5 b	2.0 b	2.5 b	0.0012
N uptake (kg N ha^{-1})	116 a	44 b	42 b	52 b	0.0008

[1] T1 = maize monocropping under conventional tillage, T2 = maize and chili intercropping under conventional tillage, T3 = as T2 but under minimum tillage with relay crop, T4 = as T3 but additionally with hedgerows.
[2] Values within the same row annotated with the different letters were significantly different among treatments at $p < 0.05$.
[3] Total aboveground biomass.
[4] Not significant difference at $p < 0.05$.

3.1.1.2 Yield, aboveground biomass production, N concentration, and N uptake and of maize based cropping systems at the row-level

A different view is obtained from row-based yields as compared to area corrected yields. Absolute maize grain yield (p = 0.042), straw yield (p = 0.0223), and AGB (p = 0.025) of the ^{15}N-labelled fertilizer application row were highest in T2, followed by T1, T3 and T4; however, significant differences were only observed between T2 and T4 (Table 3). Grain, straw, and total AGB of T2 were 32, 103, and 65% higher than that of T4, respectively. N concentration of maize grains (p = 0.029) and straw (p = 0.039) and N uptake by maize grains (p = 0.022), straw (p = 0.0303) and AGB (p = 0.022) at the application row of ^{15}N-labelled fertilizer was highest in T2 with significant differences when compared with T4.

Except for straw yield and AGB of T1, ANOVA analysis detected significant effects of slope positions on grain, straw, and AGB of maize in all treatments (Figure 5). The highest grain, straw, and AGB yields of T2, T3, and T4 were found at distances equal to 675, 1125, and 975 cm counted from the application row, respectively, whereas the lowest values were observed at distances equal to -75 cm in all of these treatments. In T1, the highest and lowest straw yields were found at 450 and 825 cm, respectively. In T4, absolute maize grain, straw, and AGB of rows located close to hedgerows were lower than those of rows distant to the hedgerows.

The location of the chili alley had only a minor effect on chili yields. Absolute straw yield at the lower position of T2 was significantly (p = 0.041) higher compared to the middle and upper positions, and AGB of chili of the upper alley was significantly (p = 0.0181) higher than that of the lower alley in T4 (Table 4). Comparing intercropping treatments, chili dry fruit significantly (p = 0.0002) decreased in the order T4 > T2 > T3, straw was significantly (p =

0.0071) higher in T2 than in T3 and T4, and AGB of T3 was significantly (p = 0.003) lower compared to T2 and T4. Sole cropped chili, however, did not significantly differ when compared to T2. Cropping systems and position along the slope had no effect on N concentration of chilies but treatment effects were found for N uptake by fruits ($p < 0.0001$), straw ($p = 0.0042$) and AGB ($p = 0.0012$) (Table 4). N uptake decreased in the order T4 > T2 > T3 for chili fruits, T2 > T3, T4 for straw, and T2, T4 > T3 for AGB.

Leucaena prunings of T4 ranged from 733-1092 g m^{-2} and were significantly lower in the hedgerow at the middle of the plot, similar to N uptake (p = 0.0347) (Table 5). Jack bean AGB was 137-177 g m^{-2} in T3 and 123-153 g m^{-2} in T4. AGB, N concentration, and uptake of Jack beans showed no significant effects of cropping systems and slope positions. Absolute AGB of weeds ranged from 195 to 478 g m^{-2} and was highest ($p = 0.0012$) in T1. N uptake by weeds was higher in T1 than in T2, T3 and T4.

Table 3 Absolute yield, N concentration, N uptake, and percentage of N derived from ^{15}N-labelled fertilizer (Ndff) of maize at the row of ^{15}N-labelled fertilizer application as affected by different maize based cropping systems. Data were collected at Queen Sirikit's demonstration farm, Ratchaburi Province, West Thailand, during June 2010 and June 2011.

Parameter	Treatment[1]				*P value*
	T1	T2	T3	T4	
Maize yield (g m^{-2})					
Grain	645 ab[2]	652 a	604 ab	493 b	0.0415
Straw	747 ab	849 a	698 ab	419 b	0.0223
AGB[3]	1392 ab	1501 a	1302 ab	912 b	0.0246
N concentration in maize (%)					
Grain	1.67 ab	1.83 a	1.73 ab	1.58 b	0.0288
Straw	0.78 ab	0.89 a	0.83 ab	0.77 b	0.0387
N uptake by maize (g N m^{-2})					
Grain	10.8 ab	12.1 a	10.5 ab	7.8 b	0.0215
Straw	5.8 ab	7.8 a	5.9 ab	3.3 b	0.0303
AGB	16.6 ab	19.9 a	16.4 ab	11.1 b	0.0218
Ndff of maize (%)					
Grain	18.6 b	19.2 b	18.7 b	28.3 a	0.0075
Straw	16.1 b	17.3 b	16.6 b	28.4 a	0.0127
AGB	17.7 b	18.4 b	17.9 b	28.1 a	0.0117

[1] T1 = maize monocropping under conventional tillage, T2 = maize and chili intercropping under conventional tillage, T3 = as T2 but under minimum tillage with relay crop, T4 = as T3 but additionally with hedgerows.
[2] Values within the same row annotated with the different letters were significantly different among treatments at $p < 0.05$.
[3] Total aboveground biomass.

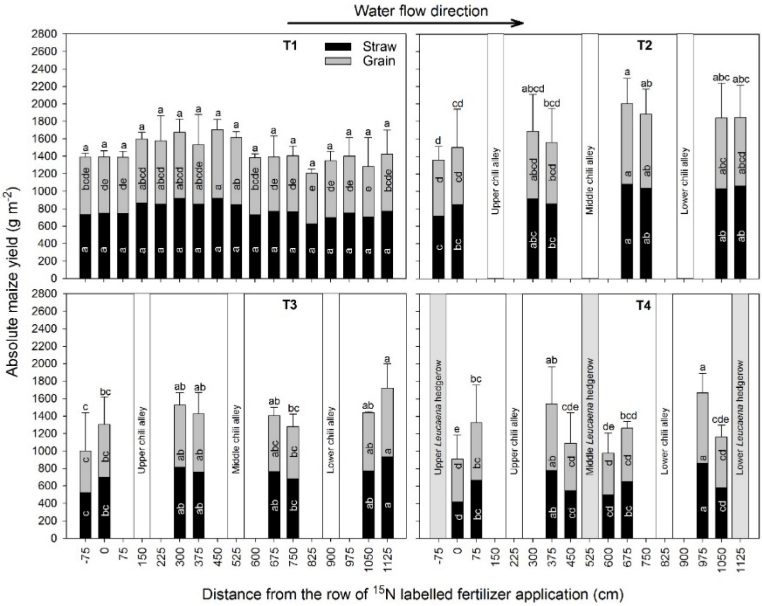

Figure 5 Absolute maize yields in different maize based cropping systems at a range of distances from ^{15}N applied row (distance = 0 cm). Error bars indicate standard deviation. Data were collected at Queen Sirikit's demonstration farm, Ratchaburi Province, West Thailand, during June 2010 and June 2011. Distances within the same treatment that differed significantly (p < 0.05) in each absolute maize yield component (straw, grain, and aboveground biomass) are indicated with different letters. Treatments are shown as follows: T1 = maize monocropping under conventional tillage, T2 = maize and chili intercropping under conventional tillage, T3 = as T2 but under minimum tillage with relay crop, T4 = as T3 but additionally with hedgerows.

Table 4 Absolute yield, N concentration, N uptake, and percentage of N derived from ^{15}N-labelled fertilizer (Ndff) of chilies as affected by different alley positions and maize based cropping systems. Data were collected at Queen Sirikit's demonstration farm, Ratchaburi Province, West Thailand, during June 2010 and June 2011.

Parameter	Treatment[1]			*P value*	Treatment[1]			*P value*	Treatment[1]			*P value*	Treatment[1,2]			*P value*	Treatment[1,2]		*P value*
	T2				T3				T4				T2	T3	T4		T2	Chili monocropping	
	Alley position				Alley position				Alley position										
	Upper	Middle	Lower		Upper	Middle	Lower		Upper	Middle	Lower								
Chili yield (g m^{-2})																			
Fruit	117 a[3]	111 a	117 a	ns[4]	85 a	85 a	95 a	ns	142 a	-	129 a	ns	115 b	88 c	135 a	0.0002	115 a	116 a	ns
Straw	168 b	170 b	193 a	0.0407	120 a	136 a	132 a	ns	157 a	-	131 a	ns	177 a	129 b	144 b	0.0071	177 a	146 a	ns
AGB[5]	285 a	281 a	310 a	ns	205 a	221 a	226 a	ns	299 a	-	260 b	0.0181	292 a	217 b	279 a	0.0025	292 a	262 a	ns
N concentration in chili (%)																			
Fruit	2.80 a	2.70 a	2.70 a	ns	2.67 a	2.67 a	2.60 a	ns	2.70 a	-	2.67 a	ns	2.73 a	2.64 a	2.68 a	ns	-	-	-
Straw	3.27 a	3.33 a	3.00 a	ns	3.07 a	3.43 a	2.83 a	ns	2.67 a	-	3.07 a	ns	3.20 a	3.11 a	2.87 a	ns	-	-	-
N uptake by chili (g N m^{-2})																			
Fruit	3.2 a	3.0 a	3.1 a	ns	2.2 a	2.3 a	2.5 a	ns	3.8 a	-	3.4 a	ns	3.1 b	2.3 c	3.6 a	<0.0001	-	-	-
Straw	5.5 a	5.7 a	5.7 a	ns	3.7 a	4.7 a	3.7 a	ns	4.2 a	-	4.0 a	ns	5.6 a	4.0 b	4.1 b	0.0042	-	-	-
AGB	8.7 a	8.7 a	8.8 a	ns	5.9 a	7.0 a	6.2 a	ns	8.0 a	-	7.4 a	ns	8.7 a	6.3 b	7.7 a	0.0012	-	-	-
Ndff of chili (%)																			
Fruit	0.09 a	0.04 b	0.03 b	0.0305	0.12 a	0.04 b	0.03 b	0.0088	0.13 a	-	0.03 b	0.0225	0.05 a	0.06 a	0.08 a	ns	-	-	-
Straw	0.22 a	0.03 b	0.01 b	0.0211	0.18 a	0.02 b	0.02 b	0.0464	0.15 a	-	0.01 b	0.0376	0.09 a	0.07 a	0.08 a	ns	-	-	-
AGB	0.16 a	0.03 b	0.02 b	0.0244	0.15 a	0.02 b	0.02 b	0.0254	0.14 a	-	0.02 b	0.0304	0.07 a	0.07 a	0.08 a	ns	-	-	-

[1] T2 = maize and chili intercropping under conventional tillage, T3 = as T2 but under minimum tillage with relay crop, T4 = as T3 but additionally with hedgerows.
[2] The average values of all alley positions in each treatment.
[3] Values within the same row annotated with the different letters were significantly different among alley positions or treatments at $p < 0.05$.
[4] Not significant difference at $p < 0.05$.
[5] Total aboveground biomass.

Table 5 Absolute yield, N concentration, N uptake, and percentage of N derived from ^{15}N-labelled fertilizer (Ndff) of *L. leucocephala*, Jack beans, and weeds as affected by different slope positions and maize based cropping systems. Data were collected at Queen Sirikit's demonstration farm, Ratchaburi Province, West Thailand, during June 2010 and June 2011.

Parameter	Treatment[1]			*P value*	Treatment[1]			*P value*	Treatment[1,2]				*P value*
	T3				T4								
	Position[3]				Position[3]				T1	T2	T3	T4	
	Upper	Middle	Lower		Upper	Middle	Lower						
Leucaena													
Pruning yield (g m^{-2})	-	-	-	-	1051 a[4]	733 b	1092 a	0.0001	-	-	-	-	-
N concentration (%)	-	-	-	-	5.45 a	5.32 a	5.19 a	ns[5]	-	-	-	-	-
N uptake (g N m^{-2})	-	-	-	-	54 a	40 b	56 a	0.0347	-	-	-	-	-
Ndff (%)	-	-	-	-	0.46 a	0.02 b	0.01 b	<0.0001	-	-	-	-	-
Jack bean													
AGB[6] (g m^{-2})	173 a	177 a	137 a	ns	152 a	143 a	123 a	ns	-	-	162 a	139 a	ns
N concentration (%)	3.67 a	3.72 a	3.74 a	ns	3.30 a	3.45 a	3.71 a	ns	-	-	3.70 a	3.47 a	ns
N uptake (g N m^{-2})	6.1 a	6.3 a	5.2 a	ns	5.2 a	4.9 a	4.5 a	ns	-	-	5.9 a	4.9 a	ns
Ndff (%)	0.51 a	0.02 b	0.01 b	0.0015	0.74 a	0.03 b	0.01 b	0.0321	-	-	0.18 a	0.26 a	ns
Weeds													
AGB (g m^{-2})	-	-	-	-	-	-	-	-	478 a	254 b	195 b	251 b	0.0012
N concentration (%)	-	-	-	-	-	-	-	-	2.43 a	1.75 a	2.16 a	2.12 a	ns
N uptake (g N m^{-2})	-	-	-	-	-	-	-	-	11.6 a	4.4 b	4.2 b	5.2 b	0.0008
Ndff (%)	-	-	-	-	-	-	-	-	0.43 a	0.07 b	0.14 b	0.05 b	0.0003

[1] T1 = maize monocropping under conventional tillage, T2 = maize and chili intercropping under conventional tillage, T3 = as T2 but under minimum tillage with relay crop, T4 = as T3 but additionally with hedgerows.
[2] The average values of all slope positions for Jack bean and composite sample for weeds in each treatment.
[3] The alley positions for Leucaena in T4 and slope positions for jack bean in T3 and T4.
[4] Values within the same row annotated with the different letters were significantly different among alley positions or treatments at $p < 0.05$.
[5] Not significant difference at $p < 0.05$.
[6] Total aboveground biomass.

3.1.1.3 Recovery of ^{15}N-labelled fertilizer in plants across the slope

In all treatments, ^{15}N-labelled fertilizer recovery (^{15}NFR) along the slope followed a similar pattern: ^{15}NFR of maize was always highest (46-54%, Table 6) at the application position of ^{15}N-labelled urea and dropped thereafter rapidly with distance from that position (Figure 6). This was mainly because the percentage of total N derived from ^{15}N-labelled fertilizer (Ndff) of maize was largest in the ^{15}N application row (18-28%, Table 3) and decreased thereafter rapidly, while N uptake varied less strongly along the slope.

Apart from the application row, ^{15}NFR rates above 1% were only found in maize located within +/-75 cm away from the ^{15}N-labelled fertilizer application row (T1: 1.3% above and 3.3% below the application row; T2: 2.6%; T3: 1.7%; and T4: 3.4%) and in Leucaena prunings of T4 (3.8%) (Figure 6). These recovery values point to nutrient scavenging by neighbouring plants in the root interference zone at the application area of ^{15}N-labelled urea. Downward movement of labelled fertilizer during rainfall events further led to ^{15}NFR at lower slope positions. Within downslope distances of 150-1125 cm from the application row, recovery of ^{15}N-labelled fertilizer by plants along the slope was very small, ranging between 0.31-0.02% in T1, 0.22-0.02% in T2, 0.30-0.02% in T3, and 0.21-0.03% in T4. Significant differences of ^{15}NFR were observed for T2 and T4 with a higher recovery by upslope plants (a distance equal to -75 cm) as compared to downslope plants (distances from 150 cm to 1125 cm). ^{15}NFR of maize at a distance equal to 75 cm was significantly higher than those of other rows downslope (at distances between 150 and 1125 cm) in T1 and T4 (Figure 6).

Positions of chili alley also significantly affected the percentage of Ndff in chili fruits straw and AGB in all maize-chili intercropping treatments. Ndff of upper chili alley (0.09-0.22%) was higher than at the middle and lower alleys

(0.01-0.04%) (Table 4). ^{15}NFR by chili fruits of maize-chili intercropping systems (T2, T3, and T4) mostly showed similar spatiotemporal trends based on seven harvest times (Figure 7). The upper alley positions tended to be higher ^{15}NFR than the middle (T2 and T3) or lower alley positions (T2, T3, and T4) throughout from the first to the seventh harvest. For temporal variability, ^{15}NFR declined gradually from the first to the third harvest in all alleys. ^{15}NFR increased sharply at the fourth harvest and drop from the fifth to the seventh harvest, excepting the upper alley of T4 at the sixth harvest.

Ndff of Leucaena prunings was very low, being highest in the upper hedgerow (0.46%, $p < 0.0001$, Table 5). Spatiotemporal ^{15}NFR by Leucaena prunings based on six events was much higher at the upper position than the middle and lower hedgerows and decreased over time (Figure 8a). ^{15}NFR of middle and lower hedgerows were low and remained constant throughout the observation period. For the upper hedgerow, there was a substantial decrease in ^{15}NFR from the first to fourth pruning, followed by a slight increase at the fifth pruning and declined again at the sixth pruning. Jack beans relay cropped with maize in T3, and T4 showed a similar trend of ^{15}NFR along with the slope positions. Ndff and ^{15}NFR of Jack bean were low, being highest in the upper slope position in T3 and T4 (Table 5, Figure 8b).

Table 6 ^{15}NUE (%) by maize, chilies, *L. leucocephala*, weeds, Jack beans, agronomic pool, and system pool as affected by different maize based cropping systems. Data were collected at Queen Sirikit's demonstration farm, Ratchaburi Province, West Thailand, during June 2010 and June 2011.

Parameter	Treatment[1]				*P value*
	T1	T2	T3	T4	
Maize row of ^{15}N labelled urea application[5]					
Grain	32.1 ab	34.6 a	30.6 b	32.7 ab	0.0231
Straw	14.9 b	18.9 a	14.9 b	13.0 b	0.0004
AGB	47.0 b	53.5 a	45.5 b	45.7 b	0.0013
Upper maize row[2] (AGB[3])	1.3 b[4]	2.6 a	1.7 ab	-	0.0139
Lower maize rows[6] (AGB)	4.6 a	0.4 b	0.6 b	4.0 a	0.0002
Total maize[7] **(AGB)**	52.9 ab	56.5 a	47.8 c	49.7 bc	0.0024
Total chilies[8] **(AGB)**	-	0.3 a	0.2 a	0.2 a	ns[13]
Total Leucaena[9] **(prunings)**	-	-	-	4.0	-
Total weeds[10] **(AGB)**	0.8 a	0.1 b	0.1 b	0.1 b	0.0017
Total Jack beans[11] **(AGB)**	-	-	0.5 a	0.6 a	ns
System pool[12]	53.7 a	56.8 a	48.6 b	54.5 a	0.0036

[1] T1 = maize monocropping under conventional tillage, T2 = maize and chili intercropping under conventional tillage, T3 = as T2 but under minimum tillage with relay crop, T4 = as T3 but additionally with hedgerows.
[2] Maize row no. 1 in T1, T2, and T3.
[3] Total aboveground biomass.
[4] Values within the same row annotated with the different letters were significantly different among treatments at $p < 0.05$.
[5] Maize row no. 2 in T1, T2, and T3 and maize row no. 1 in T4.
[6] Maize row no. 3 to 17 in T1, maize row no. 3 to 8 in T2 and T3 and maize row no. 2 to 8 in T4.
[7] Upper row + row of ^{15}N labelled urea application + lower rows.
[8] Sum of three chili alleys and seven harvesting times.
[9] Sum of three *Leucaena* hedgerows and six pruning times.
[10] Sum of three weeding times.
[11] Sum of three slope positions.
[12] Total maize + total chilies+ total *Leucaena* + total Jack beans + total weeds
[13] Not significant difference at $p < 0.05$.

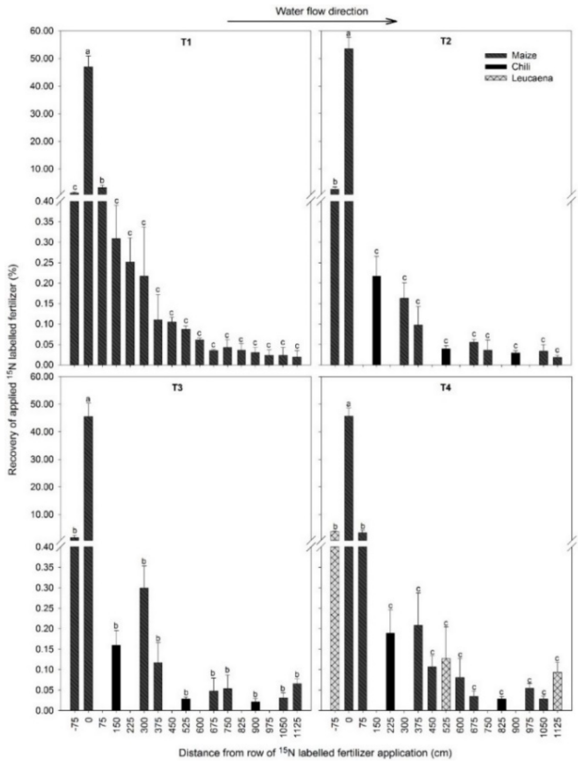

Figure 6 Recovery of ^{15}N applied as urea by maize, chili and *L. leucocephala* prunings in different maize-based cropping systems at a range of distances from application row (distance = 0 cm). Error bars indicate standard deviation. Data were collected at Queen Sirikit's demonstration farm, Ratchaburi Province, West Thailand, during June 2010 and June 2011. Distances within the same treatment that differed significantly ($p < 0.05$) in ^{15}N-labelled urea recovery by plants are indicated with different letters. Treatments are shown as follows: T1 = maize monocropping under conventional tillage, T2 = maize and chili intercropping under conventional tillage, T3 = as T2 but under minimum tillage with relay crop, T4 = as T3 but additionally with hedgerows.

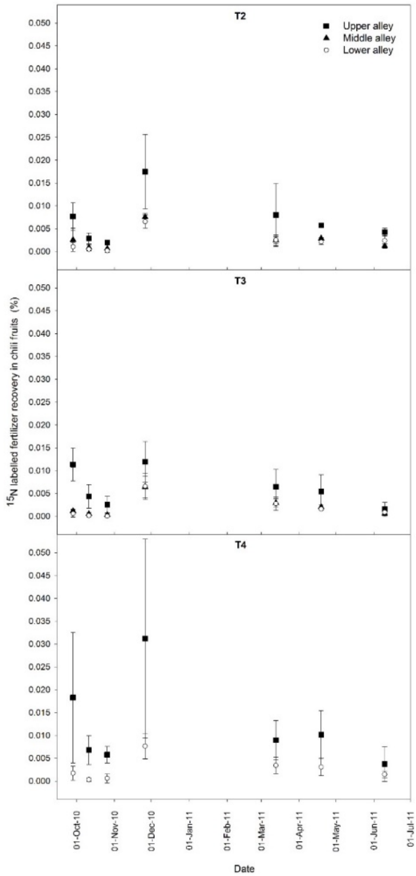

Figure 7 ^{15}NFR by chili fruits at seven harvesting times on September 28th, October 11th, October 26th and November 26th 2010 and March 13th April 19th and June 10th 2011 and three alley positions under different treatments. Error bars indicate standard deviation. Data were collected at Queen Sirikit's demonstration farm, Ratchaburi Province, West Thailand. Treatments are shown as follows: T2 = maize and chili intercropping under conventional tillage, T3 = as T2 but under minimum tillage with relay crop, T4 = as T3 but additionally with hedgerows.

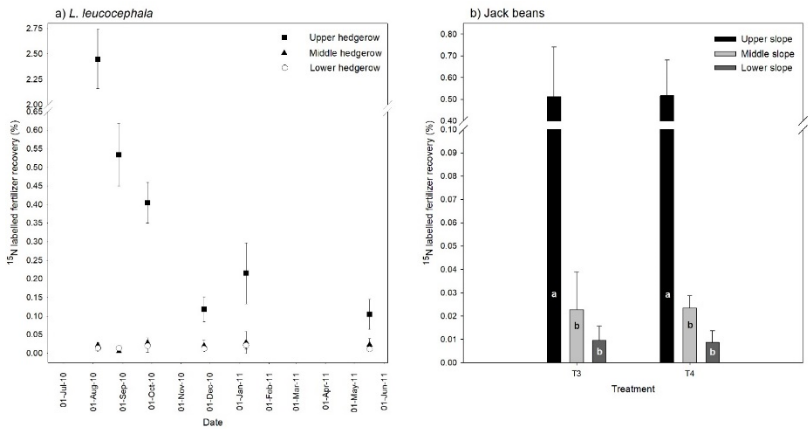

Figure 8 ^{15}NFR by (a) *L. leucocephala* prunings at six pruning events on August 6th, August 28th, September 27th and November 25th 2010 and January 8th and May 17th 2011 and three hedgerow positions and (b) by Jack bean in different maize-based cropping systems and at three slope positions under different treatments. Error bars indicate standard deviation. Slope positions within the same treatment that differed significantly ($p < 0.05$) in ^{15}NFR by Jack bean are indicated with different letters. Treatments are shown as follows: T3 = maize and chili intercropping under minimum tillage with relay crop, T4 = as T3 but additionally with hedgerows. Data were collected at Queen Sirikit's demonstration farm, Ratchaburi Province, West Thailand.

3.1.1.4 Nitrogen fertilizer use efficiency of maize based cropping systems

The N fertilizer recovery of maize at the application row reflects the direct N fertilizer use efficiency based on the application of ^{15}N-labelled fertilizer to target maize plants. Besides, the percentage of ^{15}NFR of all plant species was summed up for each treatment to expose the ^{15}N-labelled fertilizer use efficiency (^{15}NUE) on a plot basis.

The majority of the applied ^{15}N labelled urea was used by maize at the application row with ranges of 30.6-34.6% in grain, 13.0-18.9% in straw, and 45.5-53.5% in AGB (Table 6). The ^{15}NUE of maize grains was significantly ($p = 0.0231$) higher in T2 as compared to T3 while ^{15}NUE by maize straw ($p = 0.0004$) and AGB ($p = 0.0013$) of T2 were higher when compared to T1, T3 and T4.

Significant differences of ^{15}NUE among treatments were found for total AGB of maize and weeds and system pools but not for the total AGB of chilies and Jack beans. ^{15}NUE of total maize AGB ranged from 47.8 to 56.5%, being significantly higher ($p = 0.0024$) in T2 than in T3 and T4. Overall ^{15}NUE of weeds was less than 1% (ranging from 0.1 to 0.8%), being significantly ($p = 0.002$) higher in T1 than the other treatments. Only small amounts of ^{15}N labelled urea were taken up by chilies (0.2 to 0.3 %) and Jack beans (0.5 to 0.6%).

The proportion of ^{15}N-labelled urea recovered by all plants (system pool) was significantly ($p = 0.004$) different between T3 and the other treatments, with T2 having an 8% larger ^{15}NUE than T3. In contrast to total maize, system pool ^{15}NUE of T2 did not differ significantly from T4 due to the additional 4.0% of ^{15}NUE of Leucaena prunings (Table 6).

3.1.2 Discussion

3.1.2.1 Impact of cropping systems on crop yields and N uptake

The area corrected maize yield of the control (T1, 6.9 Mg ha^{-1}; Table 2) was above the world average (4.5 Mg ha^{-1}) and the one for Southeast Asia (5.8 Mg ha^{-1}) for the 1997-2006 period (Setiyono et al., 2010). Maize yields declined strongly as soon as mixed, and alley cropping was involved. In T2, T3 and T4, maize yield declines were associated with reduced maize cropping area due to the integration of chilies and Leucaena into the systems. This area and yield reduction is a major adoption constraint for farmers unless additional economic benefits are provided by these systems (Hilger et al., 2013; Tuan et al., 2014a). Moreover, area corrected maize grain yield decreases of T3 and T4 were slightly larger than those caused by area reduction. There are several explanations for that, e.g., a lag period during the establishment phase of minimum tillage delaying beneficial effects of minimum tillage on soil structure (Pansak et al., 2010) or N competition between crops and trees in hedgerow systems (Pansak et al., 2007). Area corrected yields revealed highly significant ($p < 0.001$) treatment effects on N uptake by maize (Table 2), confirming that crop management caused variations in N uptake associated with planting density or species arrangement.

Absolute maize (row-based) yields helped identifying direct impacts of neighbouring species on maize, unbiased by area correction. Hence, we found that the maize yield of T2 was significantly higher than that of T1 (Table 3). This better yield points to a positive effect of chili intercropping on maize growth due to a lower planting density and different growth rates of the involved species fostering maize growth (Black and Ong, 2000). Hussain (2015) observed within the same trial that maize-chili intercropping had a higher radiation use efficiency (RUE) than the other treatments. Wider spacing between maize and chili and a lower chili canopy enabled maize to use radiation more efficiently due to better vertical light penetration and capture. Additionally, a low level of competition between both species facilitated resource use by maize (Li et al., 1999), which fostered its growth and leading to higher maize yields per row in T2.

The yield reductions of T3 and T4 when compared to T2 (Table 3) can be mainly attributed to the adverse effects of minimum tillage during the establishment phase (Ghuman and Sur, 2001; Franzluebbers, 2004). During the initial adoption of minimum tillage, soil immediately below the surface may become compacted, and higher initial fertilizer expenditures than under conventional tillage can be required because of nutrient fixation by organic matter (Franzluebbers, 2004). From India, Ghuman and Sur (2001) reported that minimum tillage with residue mulch application required a 2-year-lag period to adjust to the new management conditions but gave higher maize grain yields than under conventional tillage thereafter.

Fluctuations of row-based maize yields across the slope in all treatment (Figure 5) are probably due to the soil variability, commonly found for different slope positions on hills (Fu et al., 2004). This is confirmed by the observed spatial variability of the soil apparent conductivity (ECa) measured by electromagnetic induction (EMI) sensors in our trial (Rudolph et al., 2016). Maize located close to Leucaena hedgerows, however, had lower yields (Figure 5) and N concentration (data not shown) than maize growing distant to Leucaena hedgerows. Maize and hedges strongly compete for light, water and nutrients in their vicinity (Dercon et al., 2006b; Pansak et al., 2007) may probably be the critical reasons for the lower N concentration and yields of maize. In this study, competition for light was low because hedges were regularly pruned to reduce the shading of maize. Water was also not a cause of competition as soil moisture measurements revealed equal or even slightly higher values in T4 compared to the control (Hussain et al., 2015).

Pruning of trees has potentially positive effects owing to a drop of belowground competition associated with a reduced nutrient and water uptake by trees. It also increases soil fertility due to root dieback and decomposition of pruning material, which was frequently applied to the soil as mulch. On the other hand, it may have enhanced belowground competition due to producing more shallow roots due to a lower height after stem pruning (Van Noordwijk and Purnomosidhi, 1995; Bayala et al., 2004). In this study, overall N was still the limiting factor for maize yield decline in rows close to hedgerows, confirmed by low N concentrations and uptake of maize grown in rows adjacent to hedgerow as shown by Hussain et al. (2015). Similar observations were reported by Pansak et al. (2007) on a moderate slope in Northeast Thailand where Leucaena hedges and maize strongly competed for N, leading to yield decline in maize rows close to the hedge. Although N stress and competition between Leucaena and maize are still controversially discussed (Imo and Timmer, 2000; Akinnifesi et al., 1996), the N demand and rooting pattern of Leucaena are the most obvious reasons for severe belowground competition occurring in these cropping systems (Pansak et al., 2007).

The soil at the study site was shallow (45 cm depth), and maize roots extended to the 15-45 cm soil layers, where they interfered with Leucaena roots (Hussain et al., 2015). These do not only point to the limited role of Leucaena as a safety-net for nutrients (Cadisch et al., 2004) but also indicated the likelihood of competition between Leucaena and maize for N in this system. At least during the 2010 cropping season, the impact of N competition was more robust than the positive effect of N addition by hedgerows.

Although absolute chili yields did not differ between sole and mixed cropping (Table 4), comparing the production of T3 and T2, however, indicated that an initial lag period associated with minimum tillage occurred. These had a negative effect on both the area corrected and the absolute yields (Tables 2 and Table 4). Surprisingly, area corrected chili yields in T4 were similar to T3 despite having fewer chili plants (38%) in the former (Table 2) because of the additionally established Leucaena hedges. These results demonstrate that the reduced chili area was offset by higher absolute yields in T4 when compared to T3 (Table 4). These can be attributed to the beneficial effects of hedgerows reducing overland flow and thereby decreasing runoff nutrient losses and/or recycling of N as well as inputs via biological nitrogen fixation as described by Mathuva et al. (1998). In this study, chili plants could get some benefits of N release from Leucaena prunings because Leucaena hedgerows were pruned and spread uniformly over the soil surface including chili's area. Further information on losses, recycling, and biological fixation of N in each season under different maize-based cropping systems can be found in Section 3.2.

3.1.2.2 Cropping systems effects on aboveground fertilizer N use of maize

In our study, N fertilizer uptake by maize was relatively high, with 46-54% of the applied ^{15}N-labelled fertilizer recovered in the AGB at the row of application (Table 6). These rates are comparable to ranges reported in other studies (Dourado-Neto et al., 2010; Xu et al., 1992). However, they are higher than those of some ^{15}N tagged fertilizer experiments (Akinnifesi et al., 1996; Rowe et al., 2005; Dourado-Neto et al., 2010). Rimski-Korsakov et al. (2012) found that recovery of ^{15}N-labelled urea by maize varied from 48 to 62%, whereby lower N dressings resulted in a higher uptake. A similar variation (24-79%) was found by Xu et al. (1992) for Leucaena alley cropping with maize, which largely depended on the fertilizer dressing and residue management.

In our study, ^{15}N-labelled urea was split-applied in a band near the maize plants at a relatively low rate of 62 kg N ha^{-1} at 30 and 60 DAS and well covered with soil at a soil depth of 5 cm depth as farmers' practice at crop stages when maize N demand was very high. These minimized N losses and led to a high ^{15}NUE of maize despite maize cropping on a moderately steep slope of around 20%, being prone to erosion. These results suggest that a well-managed N fertilization by applying an adequate rate and matching temporal and spatial N supply with crop N demand fosters NUE (Rowe et al., 2005).

Akinnifesi et al. (1996), furthermore, observed that maize N uptake derived from fertilizer (Ndff) decreased when Leucaena prunings were mulched. According to these authors, a priming effect may lead to an exchange between fertilizer N and N derived from the soil or prunings. It is in contrast to our findings where the Ndff (%) of maize at the application row of ^{15}N-labelled urea was significantly higher in T4 than in all other treatments, indicating no significant priming or pool substitution effect (Table 3). Hence, the maize in T4 depended stronger on fertilization than in the other treatments due to competition for soil/residue mineralized N by the scavenging neighbouring hedge.

The contribution of N derived from the soil (Ndfs = 100 - Ndff) to the AGB of maize at the application row of ^{15}N-labelled urea, i.e., residual mineral N, mineralized organic N and displaceable clay fixed NH_4-N, was 82.3% in T1, 81.6% in T2, 82.1% in T3 and 71.9% in T4 of the total N assimilated by maize at the application row of ^{15}N-labelled urea (Table 3) representing 13.7, 16.3, 13.5 and 8.1 g N m^{-2} respectively. Our results are consistent with maize ^{15}N fertilizer recovery studies of Stevens et al. (2005), Dourado-Neto et al. (2010) and Rimski-Korsakov et al. (2012), in which the majority of plant N was from the soil. These underline the importance of SOM as an N source for crop production. It also implies that agricultural practices with residue mulch and cover crop and intercropping systems (as in T3) that conserve or even increase SOM are crucial for tropical hillside agriculture.

Lower values of ^{15}NUE of maize straw but similar ones in grains at the application row of ^{15}N-labelled urea in T4 (Table 6) are partially the results of higher N fertilizer partitioning to the grain fraction (Ciampitti and Vyn, 2013). These may also be a result of ^{15}N mineralization and release from decomposed Leucaena prunings and roots, which coinciding with the grain filling of maize in T4. The increase of ^{15}NFR in prunings at the upper Leucaena hedge from the fourth to the fifth pruning may be due to N releases from maize harvest residue, which remained on the plot (Davidson and Janssens, 2006; Tu et al., 2013). A similar trend was found for ^{15}NFR in chili fruits (Figure 7). Combining these spatiotemporal observations on ^{15}NFR of chilies and Leucaena prunings (Figure 7 and Figure 8a) may indicate that maize residues decomposed relatively fast and released ^{15}N from the previous uptake around the fourth chili harvest and fifth Leucaena pruning leading to increases of their ^{15}NFR at such specific times. That means the applied ^{15}N-labelled urea in maize straw, being partly available for other plants.

3.1.2.3 Cropping systems effect on the recovery of N fertilizer applied to maize across the field

In contrast to our expectations, ^{15}NUE results do not support our first hypothesis that intercropping under conservation agriculture with minimum tillage and legume relay cropping or both together with contour hedgerows increase N fertilizer use efficiency as compared to maize monocropping when taking into account all recoveries across the field. This hypothesis was based on the assumptions that (i) conservation practices decrease soil erosion and runoff and thereby reduce N fertilizer loss, (ii) intercropping and hedgerow systems through their filter functions, capture and recycle N fertilizer along the slope as it is moving downwards, and (iii) conservation measures improve soil fertility and physical properties, minimize pest and weed problems and consequently result in better crop growth and NUE.

Incorporating fertilizer to the soil and low rainfall at the beginning of the growing season (Figure 1) were reasons for very low downslope translocation of fertilizer N. Thereby, minimizing positive effects of lateral filters functions, which are supported by a maximum of only 1-5% of ^{15}N recovery downslope and high recovery at the application point. Furthermore, minimum tillage combined with relay cover crops may have led to temporal retention of ^{15}N at the application point due to immobilization associated with higher organic inputs, thereby further limiting lateral movement. Despite the relatively low ^{15}N recoveries downslope, Leucaena hedges were most effective in capturing and recycling lateral-moving N fertilizer in this system, as well as reducing soil erosion (data shown in Section 3.2). These confirm the results of Rowe et al. (2005). They also reported that lateral flows of N fertilizer could be intercepted by crop plants or trees along the slope (a filter function or lateral 'safety-net'). A study on N flows in agroforestry systems using unbounded plots similarly found that lateral movement of ^{15}N-enriched materials and their uptake by maize and tree roots were small beyond a distance of 1 m and negligible after a radius of 4 m from the application point (Rowe and Cadisch, 2002).

Improvement of crop growth under conservation practices did not occur in our study. The absolute maize yield declined in T3 and T4 compared to T2 (Table 3) and consequently reduced ^{15}NUE of total maize AGB under minimum tillage combined with relay cover crops with/without Leucaena hedgerow (Figure 6, Table 6). In the overall system pool where ^{15}NUE Leucaena prunings contributed 4%, therefore, significant differences ($p < 0.05$) were only found between T3 and all other treatments. This pool (total ^{15}NUE Leucaena) was recyclable N that returns to the soil and can be used by crops in the system. All other components of this pool had only marginal effects of 0.1-0.6% and hence were negligible.

3.1.2.4 Systems based return evaluation

Remarkably, even though maize return was reduced under the maize-chili intercropping with/without hedgerows (Table 2), the farmers could get equal or even higher economic returns from the sale of chilies as compared to maize sole cropping. The average prices of fresh and dry marketable chili fruit in 2010 in Thailand were 1.3 and 2.3 USD kg^{-1}, respectively. For maize grain, it was around 0.3 USD kg^{-1} (Office of Agricultural Economics, 2011). Hence, total returns for T1, T2, T3, and T4 were 1,914, 5,129, 3,829, and 3,900 USD ha^{-1}, respectively, when chilies were sold fresh and 1,914, 2,289, 1,815, and 1,974 USD ha^{-1}, respectively, when dried chilies were sold. Extra costs in establishing and managing intercropping systems, e.g., labour costs for transplanting, fertilizing, and harvesting chili and pruning Leucaena, were not considered in calculation due to lack of data. The extra costs, particularly for growing and maintaining additional crops, can be huge, being between two or three times the costs of monocropping (Whitmore, 2000). The average capital for maize production in Thailand was around 686 USD ha^{-1} during 2010-11 (Office of Agricultural Economics, 2012b). Therefore, rough estimates of costs for maize intercropping are between 1,372 to 2,058 USD ha^{-1}. On the other hand, intercropping decrease labour and costs by shading of weeds that would otherwise have to be controlled by hand or herbicides (Whitmore, 2000). Despite lower maize prices, farmers favor maize grains as animal feedstuff while producing chilies are valuable cash products being marketed either fresh or dry. Therefore, our hypothesis that maize-chili intercropping give higher returns than maize sole cropping is supported when chili fruits are sold fresh. Furthermore, field observations showed that the chili canopies were not massive and did not compete with maize due to their surface cover. It implies that there is potential for increasing the planting densities by reducing the distance between chilies and maize rows and between chili rows with a positive impact on farmers' returns.

3.2 Residual effects and fate of ^{15}N-labelled fertilizer and nitrogen balances in maize-based soil conservation systems

3.2.1 Results

3.2.1.1 Plant production

3.2.1.1.1 Marketable yields of maize and chili

Maize grain yield of intercropping treatments (T2, T3, T4, T5 and T6) ranged from 2.5 to 3.3 Mg ha^{-1} in season 1 and 2.3 to 3.8 Mg ha^{-1} in seasons 2, all of which were significantly lower than that of the maize monocropping system (T1) (Figure 9). Grain yields decreased in the order T1 > T4, T6 > T2 > T3, T5 and T1 > T4 > T6 > T2, T3 > T5 in first and second season, respectively. There was no statistically significant yield difference between the two seasons.

Total chili fresh fruit yields in the first season were between 1.5 and 3.3 Mg ha^{-1} and in the second season ranged from 0.4 to 0.7 Mg ha^{-1}. Significant differences among treatments were only found in season 1, decreasing in the order T2 > T3 > T4 > T5 > T6. The first season resulted in a much higher fruit yield than the second season, mainly due to fungal diseases and insect attacks on chili plants in the second season.

The Land Equivalent Ratio (LER) was used to assess the utilization of plant growth factors under different maize-based cropping systems. The LER values varied between 0.73 and 1.01 in the first season but increased in the second season between 0.89 and 1.22 (Figure 9). T2 in season 1 and T2, T3 and T4 in season 2 showed some advantage in terms of marketable yield because LER values were greater than 1.00. In contrast, the LER values of T3 and T4 in season 1 and T5 and T6 in both seasons were less than 1.00, indicating a less efficient resource use.

3.2.1.1.2 Other yield components

Maize straw biomass varied between 2.6 and 7.9 Mg ha^{-1} in season1 but was lower in the second season (1.8 and 5.4 Mg ha^{-1}) (Figure 10). Straw yields were significantly different among treatments in both seasons, decreasing in the order T1 > T2 > T4, T6 > T3 > T5 in the first season, and T1 > T4, T6 > T2, T3 > T5 in the second season.

Chili straw yields ranged from 0.5 to 0.9 Mg ha^{-1} in season 1 to only 0.2 to 0.4 Mg ha^{-1} in season 2. Significant differences among intercropping treatments in each season and between seasons in each treatment were observed for chili straw biomass (Figure 10). Chili straw yields decreased in the order T2 > T3 > T4, T5, T6 in season 1 and T2 > T3 > T4 > T5, T6 in season 2.

Total Leucaena pruning yields were not significantly different between T4 and T6 in each season and between seasons in each treatment, being 1.5 and 2.0 Mg ha^{-1} in T4 and 1.6 and 1.7 Mg ha^{-1} T6 in the first and second season, respectively (Figure 10). Aboveground biomass (AGB) of Jack bean varied between 1.1 and 2.2 Mg ha^{-1} in season 1 and between 3.0 and 4.6 in season 2 (Figure 10). Jack bean in T5 yielded significantly higher AGB than the other treatments in season 2 but not in season 1. Weeds AGB ranged from 2.0 to 4.8 Mg ha^{-1} in season 1 and significantly decreased to 0.2 and 0.4 Mg ha^{-1} in season 2. In the first season, AGB of weeds significantly decreased in the order T1 > T6 > T2, T4, T5 > T3, while statistically significant differences among treatments were not observed in season 2 (Figure 10).

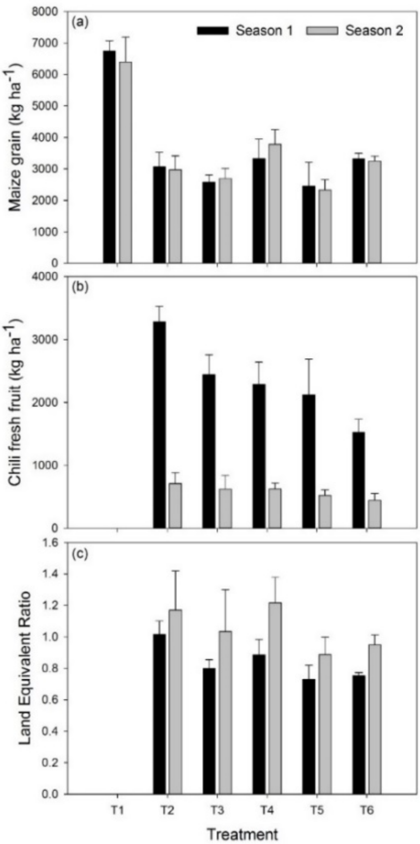

Figure 9 Maize grain and chili fresh fruit yields (kg ha^{-1}) and Land Equivalent Ratio (LER) expressed as means and standard deviations. T1: maize monocropping under conventional tillage and fertilizer application; T2: maize and chili intercropping under conventional tillage and fertilizer application; T3: as T2 but under minimum tillage with relay crop; T4: as T3 but additionally with hedgerows; T5: as T3 but no fertilizer application; T6: as T4 but no fertilizer application.

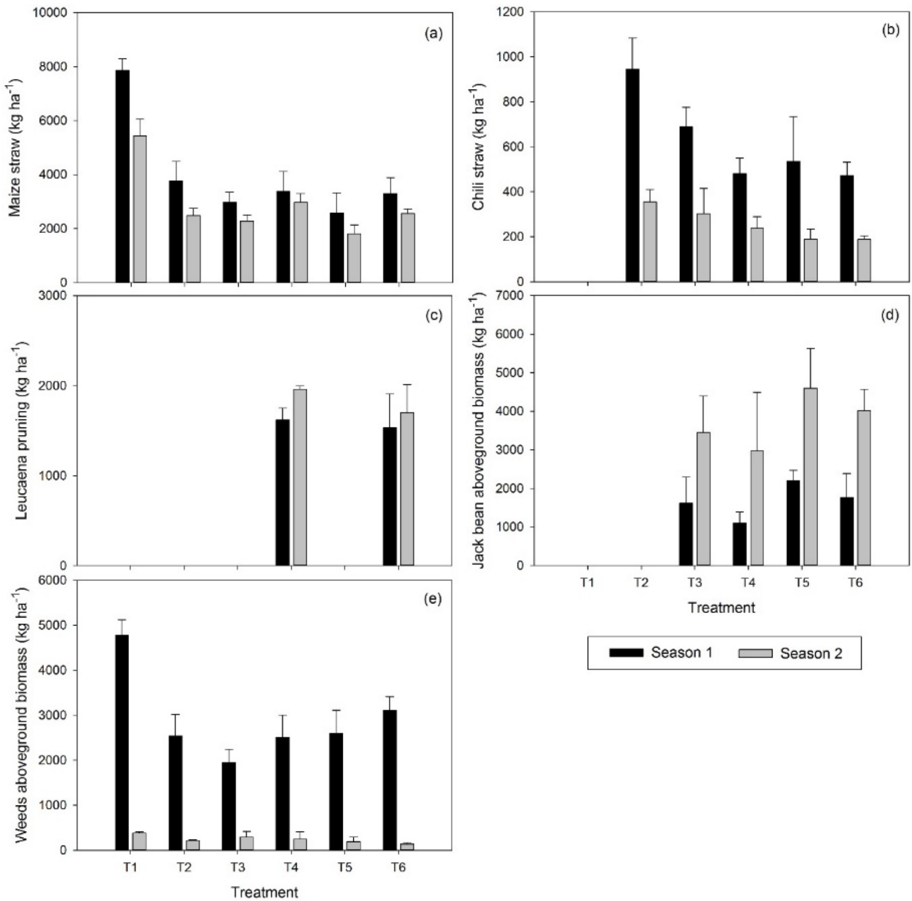

Figure 10 Maize straw (a), chili straw (b), Leucaena prunings (c), Jack bean (d), and weed (e) aboveground biomass (kg ha^{-1}) expressed as means and standard deviations. T1: maize monocropping under conventional tillage and fertilizer application; T2: maize and chili intercropping under conventional tillage and fertilizer application; T3: as T2 but under minimum tillage with relay crop; T4: as T3 but additionally with hedgerows; T5: as T3 but no fertilizer application; T6: as T4 but no fertilizer application.

3.2.1.2 N recycled via plant residues in cropping systems

The amount of N recycled ($N_{recycled}$) and its source for all treatments is presented in Table 7. Between 20.8 and 63.5 kg N ha^{-1} and 15.7 and 39.0 kg N ha^{-1} were recycled through maize residues (N_{Mr}) in the first and second season. Averaging across all treatments, N_{Mr} represented 32-38% in season 1 and 29-34% in season 2 of the overall maize N uptake. After the last chili harvest, 13.4 to 30.0 kg N ha^{-1} in season 1 and 3.5 to 7.7 kg N ha^{-1} in season 2 were recycled with chili residues (N_{Cr}) on respective plots, which were equal to 53-64% (season 1) and 54 -64% (season 2) of the overall chili N uptake. N_{Cr} decreased in the order T2 > T3 > T4, T5, T6 in season 1 and T2, T3 > T4, T5, T6 in season 2. Leucaena prunings (N_{Lp}) under T4 and T6 contributed 83.5 and 77.7 kg N ha^{-1} in season 1 and 93.1 and 79.4 kg N ha^{-1} in season 2 (Table 7). $N_{recycled}$ via Jack bean (N_{Jb}) in season 1 and season 2 ranged from 38.6 to 77.6 kg N ha^{-1} and 38.6 to 77.6 kg N ha^{-1}, respectively. N_{Jb} decreased in the order T5 > T3, T6 > T4 in the first season, and T5, T6 > T3 > T4 in the second season. The amount of $N_{recycled}$ through weeds (N_W) in each treatment was influenced by year and significantly higher in season 1 (43.6-115.6 kg N ha^{-1}) as compared to season 2 (4.2-8.6 kg N ha^{-1}). Moreover, significant differences among treatments were only found in season 1, decreasing in the order T1 > T6 > T2, T3, T4, T5.

When plant residues were not removed and burnt from the plots, the average N amounts recycled in plots ranged from 108 and 246 kg N ha^{-1} in season 1 and 31 and 220 kg N ha^{-1} in season 2. $N_{recycled}$ for both seasons was influenced by the treatments, significantly decreasing in the order T4, T6 > T1, T3, T5 > T2 in season 1 and T4, T6 > T3, T5 > T1, T2 in season 2.

Table 7 Nitrogen recycled (kg ha^{-1}) of each treatment and cropping season.

Treatment[1]	$N_{recycled}$ (kg ha^{-1})					
	N_{Mr}	N_{Cr}	N_{Lp}	N_{Jb}	N_W	**Total**[2]
Season 1 (June 29th 2010 – June 25th 2011)						
T1	63.5 a, A[3]	-	-	-	115.6 a, A	**179.2 b, A**
T2	34.1 b, A	30.0 a, A	-	-	44.1 c, A	**108.2 c, A**
T3	27.0 bc, A	21.5 b, A	-	58.8 ab, B	42.0 c, A	**149.3 b, A**
T4	27.0 bc, A	13.6 c, A	83.5 a, A	38.6 b, B	51.8 c, A	**214.5 a, A**
T5	20.8 c, A	15.6 c, A	--	77.6 a, B	43.6 c, A	**157.6 b, A**
T6	26.7 bc, A	13.4 c, A	77.7 a, A	62.5 ab, B	65.4 b, A	**245.7 a, A**
Season 2 (June 26th 2010 – January 8th 2012)						
T1	39.0 a, B	-	-	-	8.6 a, B	**47.5 c, B**
T2	18.7 b, B	7.7 a, B	-	-	5.1 a, B	**31.4 c, B**
T3	16.7 b, B	6.8 a, B	-	102.0 ab, A	8.4 a, B	**133.9 b, A**
T4	22.7 b, A	4.3 b, B	93.1 a, A	76.4 b, A	6.5 a, B	**203.0 a, A**
T5	15.7 b, A	3.7 b, B	-	131.8 a, A	4.2 a, B	**155.4 b, A**
T6	22.6 b, A	3.5 b, B	79.4 a, A	111.7 a, A	3.0 a, B	**220.2 a, A**

[1] T1 = maize monocropping under conventional tillage and fertilizer application, T2 = maize and chili intercropping under conventional tillage and fertilizer application, T3 = as T2 but under minimum tillage with relay crop, T4 = as T3 but additionally with Leucaena hedgerows, T5 = as T3 but without fertilizer application and T6 = as T4 but without fertilizer application.
[2] Total $N_{recycled}$ = N from maize residues (N_{Mr}) + N from chili residues (N_{Cr}) + N from Leucaena prunings (N_{Lp}) + N from Jack bean AGB (N_{Jb}) + N from Weeds AGB (N_W)
[3] Values followed by different small letters indicate significant differences ($p < 0.05$) of the treatments in each season, while values followed by different capital letters indicate significant differences ($p < 0.05$) of two seasons in each treatment.

3.2.1.3 Runoff and soil loss

Total runoff in season 2 and total eroded sediment in season 1 showed significant differences among treatments (Figure 11). Total runoff significantly decreased in the order T2, T3 > T1, T5 > T4, T6 in the second season. In the first season, runoff was substantially higher in all treatments, with associated higher total soil loss which decreased significantly in the order T1, T2, T5 > T3 > T6 > T4.

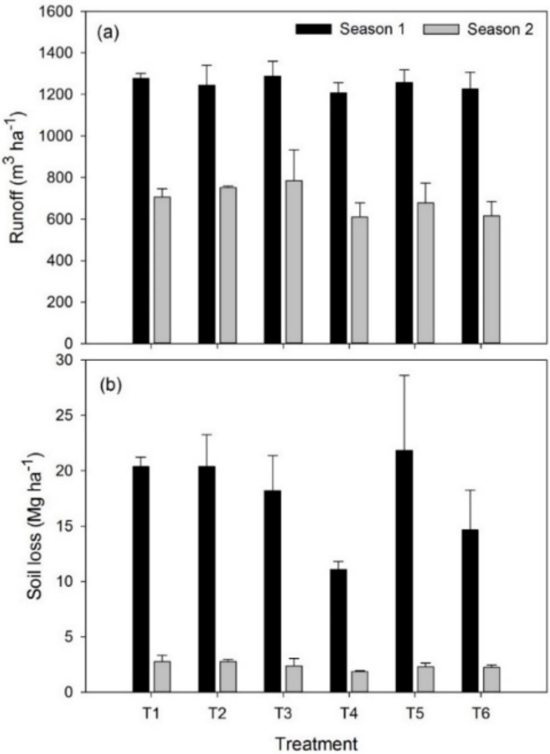

Figure 11 Annual runoff (m^3 ha^{-1}) and soil loss by erosion (kg ha^{-1}) for each treatment and cropping season expressed as means and standard deviations. T1: maize monocropping under conventional tillage and fertilizer application; T2: maize and chili intercropping under conventional tillage and fertilizer application; T3: as T2 but under minimum tillage with relay crop; T4: as T3 but additionally with hedgerows; T5: as T3 but no fertilizer application; T6: as T4 but no fertilizer application.

3.2.1.4 Fate of ^{15}N labelled fertilizer applied to maize

3.2.1.4.1 ^{15}N output

The total cumulative recovery of ^{15}N labelled urea (^{15}NFR) applied in the year 2010 at the rate of 62 kg N ha^{-1} to maize on an entire plot basis ranged from 31.6 to 36.5% by maize grain to around 0.1% by chili fruits, in season 1 (the season of application) (Table 8). ^{15}NFR by maize grain in T2 was higher than in T3 but not significantly differed to T1 and T4 in season 1. Only 1.3 to 3.6% of fertilizer N were recovered by maize grain in season 2 (the subsequent season), decreasing in the order T1 > T2 > T3 > T4. Less than 0.05% of ^{15}N labelled urea was found in chili fruits in season 2. Likewise, the fertilizer N losses estimated by the N isotopic method in runoff, soil loss, and subsurface pools monitored at a distance of 1175 cm downslope from the application point of ^{15}N labelled urea were less than 0.05% in both seasons. N outputs (N export), the sum of recoveries by maize grain, chili fruit, and losses (runoff + soil loss + subsurface), ranged from 31.7 to 36.6% in season 1 and residual recovery in season 2 ranged from 1.3 to 3.6%, following similar trends as ^{15}NFR by maize grain. More than 99% of the total ^{15}N outputs were accounted for by N exported in maize grain and less than 1% was exported in chili fruit or lost via runoff, soil loss, and subsurface flow.

3.2.1.4.2 ^{15}N recycled and ^{15}N soil

In season 1, ^{15}NFR by maize straw was significantly higher in T1 (18.7%) and in T2 (20.0%) when compared with T3 (15.3%) and T4 (14.5%) (Table 8). T1 had greater ^{15}NFR by maize straw than T2, T3 and T4 in the second season. Only small amounts of ^{15}N labelled urea were recovered by chili straw (< 0.05

to 0.2%) and Jack bean aboveground biomass (AGB) (0.1 to 0.5%); and they did not significantly differ among treatments in both seasons. Between 0.6% and 0.4% of ^{15}N fertilizer were taken up by Leucaena pruning after soil sampling in the first and second seasons, respectively. A large portion of the applied ^{15}N recovered by Leucaena prunings (3.5% in season 1 and 1.0% in season 2) occurred before soil sampling in each season. ^{15}NFR by weeds after soil sampling was small, being overall highest in T1 (0.9%) in the first season. Before soil sampling in both seasons, weeds recovered less than 0.05% of ^{15}N fertilizer with no significant differences among treatments. For N balance calculations, ^{15}N fertilizer recovered by weeds and Leucaena pruning before soil sampling was expected to have been decomposed to organic matter and thus being part of soil N. Overall, 6.2-28.1% and 7.7-28.6% of the applied ^{15}N remained in the soil (0-45 cm) at the end of both maize growing seasons, respectively (Table 8). ^{15}NFR in soil decreased in the order T3 > T4 > T2 > T1 in both seasons. ^{15}NFR of each plant pool was higher in season 1 than season 2, whereas ^{15}NFR in the soil of T1, T2 and T3 was slightly increased in season 2 relative to season 1. For season 1, the major part of ^{15}NFR that could carry over (N recycled pool + N soil) to the following season (season 2) as residual N for T1 and T2 was maize straw, while for T3 and T4 was soil. N soil also accounted for the majority of ^{15}NFR in the N recycled pool for all treatments in season 2 (Table 8).

3.2.1.4.3 Total ^{15}N recovery and unaccounted for

Significant differences in total recovery (N output + N recycled + N soil) among treatments were found for both seasons (Table 8). In season 1, the percentage of labelled fertilizer N found within the plant-soil system ranged from 60 to 76%, being significantly higher in T3 compared to T1.

Additionally, the fertilizer N deficit of T1 was greater than that of T3 in the first season. In total, 12.7 to 31.3% of labelled N were recovered in season 2, being significantly higher in T3 than other treatments. If all of the ^{15}N urea in N recycled and N in soil pools of season 1 remain in the system and they were carried over to season 2 as residual N fertilizer. Therefore, unaccounted N losses in the following season were the difference between residual N fertilizer (N recycled + N soil) of season 1 and total recovery of season 2. Based on these calculations, 12.9 to 16.1% were not accounted for in the systems at the end of season 2, but differences among treatments were not significant. The main pool accounting for the total ^{15}N recovery of T1, T2 and T4 was N export in season 1 and residual N fertilizer in season 2, while for T3, it was residual N fertilizer in both seasons (Table 8).

Table 8 Recovery of N fertilizer (^{15}NFR, %) applied in season 1, N recycled and losses by different plant, soil, and water pools as affected by maize-based soil conservation systems during two cropping seasons.

Pool	^{15}N labelled fertilizer recovery (%)											
	Season 1 (June 29th 2010 – June 25th 2011)				Season 2 (June 26th 2010 – January 8th 2012)				Total (June 29th 2010 – January 8th 2012)			
	T1[1]	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4
N export[2]	**34.2 ab[9]**	**36.6 a**	**31.7 b**	**36.1 ab**	**3.6 a**	**2.4 b**	**1.8 bc**	**1.3 c**	**37.8 ab**	**39.0 a**	**33.5 b**	**37.4 ab**
Maize grain	34.2 ab	36.5 a	31.6 b	36.0 ab	3.6 a	2.4 b	1.8 bc	1.3 c	37.8 ab	38.9 a	33.4 b	37.3 ab
Chili fruit	-	0.1 a	0.1 a	0.1 a	-	< 0.05	< 0.05	< 0.05	-	0.1 a	0.1 a	0.1 a
Losses[3]	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Runoff	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Soil loss (erosion)	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Subsurface (lateral flow)	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
N recycled[4]	**19.6 a**	**20.2 a**	**16.1 b**	**15.7 b**	**1.3 a**	**0.9 b**	**0.9 b**	**1.0 ab**	**-**	**-**	**-**	**-**
Maize straw	18.7 a	20.0 a	15.3 b	14.5 b	1.3 a	0.8 b	0.7 b	0.5 b	-	-	-	-
Chili straw	-	0.2 a	0.1 a	0.1 a	-	< 0.05	< 0.05	< 0.05	-	-	-	-
Leucaena pruning[5]	-	-	-	0.6 (3.5)	-	-	-	0.4 (1.0)	-	-	-	-
Jack bean AGB	-	-	0.5 a	0.5 a	-	-	0.1 a	0.1 a	-	-	-	-
Weeds AGB[6]	0.9 a (< 0.05)	0.1 b (< 0.05)	0.1 b (< 0.05)	0.1 b (< 0.05)	- (< 0.05)	- (< 0.05)	- (< 0.05)	- (< 0.05)	-	-	-	-
N soil (0-45 cm)	**6.2 c**	**12.9 bc**	**28.1 a**	**17.6 b**	**7.7 b**	**13.6 b**	**28.6 a**	**16.2 b**	**-**	**-**	**-**	**-**
Total N recovery[7]	**60.0 b**	**69.8 ab**	**76.0 a**	**69.4 ab**	**12.7 b**	**17.0 b**	**31.3 a**	**18.5 b**	**-**	**-**	**-**	**-**
Unaccounted N losses[8]	**40.0 a**	**30.2 ab**	**24.0 b**	**30.6 ab**	**13.1 a**	**16.1 a**	**12.9 a**	**14.8 a**	**-**	**-**	**-**	**-**

[1] T1 = maize monocropping under conventional tillage and fertilizer application, T2 = maize and chili intercropping under conventional tillage and fertilizer application, T3 = as T2 but under minimum tillage with relay crop, T4 = as T3 but additionally with Leucaena hedgerows

[2] Maize grain + Chili fruit + Losses

[3] Runoff + Soil loss (erosion) + Subsurface (lateral flow)

[4] Maize straw + Chili straw + Leucaena pruning + Jack bean AGB + Weeds AGB

[5] Season 1 = ^{15}NFR of Leucaena pruning after soil sampling at maize harvesting time of season 1 until maize sowing of season 2 (^{15}NFR of Leucaena pruning before soil sampling at maize harvesting time of season 1) and Season 2 = ^{15}NFR of Leucaena pruning after soil sampling at maize harvesting time of season 2 until chili plant pulling out (^{15}NFR of Leucaena pruning before soil sampling at maize harvesting time of season 2)

[6] Season 1 = ^{15}NFR of Weeds AGB after soil sampling at maize harvesting time of season 1 until maize sowing of season 2 (^{15}NFR of Weeds AGB before soil sampling at maize harvesting time of season 1) and Season 2 = ^{15}NFR of Weeds AGB after soil sampling at maize harvesting time of season 2 until chili plant pulling out (^{15}NFR of Weeds AGB before soil sampling at maize harvesting time of season 2)

[7] N export + N recycled + N soil (0-45 cm)

[8] Season 1 = 100 - Total N recovery of season 1 and Season 2 = N recycled of season 1 + N soil (0-45 cm) of season 1 - Total N recovery of season 2

[9] Values followed by different small letters indicate significant differences ($p < 0.05$) of the treatments in each season

3.2.1.5 N budgets

The soil surface N budget components are presented in Table 9, and the resulting N balances with and without N fertilizer unaccounted for (unrecovered fertilizer N) are shown in Figure 12 and Table 10, respectively.

3.2.1.5.1 N inputs

Estimated N inputs (N_{input}) from wet deposition ($N_{deposition}$) were 7.3 and 4.7 kg N ha^{-1} in season 1 and 2, respectively (Table 9). The amount of mineral fertilizer application to maize (N_{Mfert}) and chili (N_{Cfert}) varied depending on cropping systems and fertilization in each treatment and season. Thereby, the total N fertilizer ($N_{Mfert} + N_{Cfert}$) applied to plants in T1, T2, T3, and T4 were 62, 161.3, 161.3, and 118.8 kg N ha^{-1} in season 1 and 62, 122.9, 122.9, and 94.8 kg N ha^{-1} in season 2, respectively. Total N_{seed} ($N_{Mseed} + N_{Jseed} + N_{Cseedling}$) in both seasons varied from 0.4 to 4.8 kg N ha^{-1}. The observed differences of N in seed (N_{seed}) were due to plant types and the planting density of each treatment.

N_{input} from biological nitrogen fixation ($N_{fixation}$) through Leucaena prunings (N_{Lfix}) under T4 and T6 (maize-based cropping systems with leguminous plants), were 28.3 and 26.2 kg N ha^{-1} in season 1 and 33.4 and 28.5 kg N ha^{-1} in season 2, respectively (Table 9). Significant differences between both treatments and seasons were not observed. As for Jack bean, 10.7, 7.6, 14.2 and 12.3 kg N ha^{-1} in the first season and 23.4, 17.6, 30.3 and 25.7 kg N ha^{-1} in the second season were derived from $N_{fixation}$ (N_{Jfix}) under T3, T4, T5 and T6, respectively.

3.2.1.5.2 N outputs

Nitrogen output (N_{output}) via exported maize grain (N_{Mgrain}) and chili fruit (N_{Cfruit}) ranged from 41.4 to 117.6 kg N ha^{-1} and 7.7 to 16.7 kg N ha^{-1}, respectively, in season 1; while in season 2, they ranged from 30.8 to 95.8 kg N ha^{-1} and 2.5 to 4.4 kg N ha^{-1}, respectively (Table 9). Significant differences of N_{Mgrain} among the treatments were found in both seasons, decreasing in the order T1 > T4 > T2, T3, T6 > T5 and T1 > T4 > T2 > T3, T6 > T5 in the first and second season, respectively. N export via chili fruits (N_{Cfruit}) significantly decreased in the order T2 > T3, T4 > T5 > T6 and T2 > T3 > T4 > T5 > T6 in season 1 and 2, respectively. N_{Cfruit} in season 1 was greater than season 2 in all treatments.

The total plot level of N losses in the first season ranged from 5.5 to 7.1 kg N ha^{-1} by runoff (N_{RO}), 29.0 to 50.2 kg N ha^{-1} by soil loss (N_{SL}), and 0.06 to 0.09 kg N ha^{-1} by subsurface flow (N_{SF}) (Table 9). In the second season, N_{RO} N_{SL} and N_{SF} ranged from 2.2 to 3.2 kg N ha^{-1}, 6.8 to 9.5 kg N ha^{-1} and 0.16 to 0.24 kg N ha^{-1}, respectively. N_{RO} significantly increased in the order T4 < T1 < T5, T6 < T2, T3 in season 1, and T4, T5, T6 < T2, T3 < T1 in season 2. N_{SL} was only significantly different among treatments in season 1, decreasing in the order T1, T2, T5 > T3 > T6 > T4. Comparing between seasons, N_{SF} of all treatments was higher in season 2 than season 1, while N_{RO} and N_{SL} of all treatments were greater in season 1 relative to season 2 in T1.

3.2.1.5.3 N balances

T2, T3, and T4 showed positive N balances of +42, +76 and +62 kg N ha^{-1} in the first season and of +65, +100 and +84 kg N ha^{-1} in the second season, respectively, without considering the portion of unaccounted for of N fertilizer applied to maize and chili ($NB_{withoutUnaccounted}$) (Figure 12). In contrast, T1 and T5 resulted in negative balances with N depletions of -103 and -82 kg N ha^{-1} and -42 and -3.9 in season 1 and season 2, respectively. For T6, the N balance was -53.8 kg N ha^{-1} in the first season and +4.5 kg N ha^{-1} in the second season. Significant differences between seasons in each treatment were found in N balances, being higher in season 2 than season 1.

Table 10 shows the potential unaccounted N losses via volatilization, denitrification, and leaching process based on the assumption that unlabelled-N fertilizer applied to maize in season 2 and chili in both seasons was lost at the same proportion as that of labelled-N fertilizer applied to maize in season 1. Thus, 24.8 kg N ha^{-1} in T1, 7.5 kg N ha^{-1} in T2, 6.0 kg N ha^{-1} in T3 and 10.2 kg N ha^{-1} in T4 of N fertilizer applied to maize in each cropping season were unaccounted for. Whereas, unrecovered N of fertilizer applied to chili under T2, T3, and T4 was 41.3, 32.8, and 26.1 kg N ha^{-1} in season 1 and 29.7, 23.6, and 18.8 kg N ha^{-1} in season 2, respectively. If these unaccounted N losses were included in the calculation of fertilized treatments (T1, T2, T3, and T4), lower N balances values (estimated full N balance; $NB_{withUnaccounted}$) relative to $NB_{withoutUnaccounted}$ were obtained. For example, the negative N balances in T1 increased to -127.4 and -66.3 kg N ha^{-1} in season 1 and 2, respectively, and that of T2 in season 1 became negative with -6.5 kg N ha^{-1}. However, the full balances ($NB_{withUnaccounted}$) of T3 and T4 remained positive with +37.7 and 25.3 kg N ha^{-1} in season 1, and +70.4 and +54.5 kg N ha^{-1} in season 2, respectively (Table 10).

The fertilizer N applied in the first season but lost in the subsequent season (residual fertilizer N losses) varied between 3.2 and 8.2 kg N ha^{-1} for N fertilizer applied to maize, and between 12.6 and 22.1 kg N ha^{-1} for N fertilizer applied to chili (Table 10). Additionally, considering this portion of N fertilizer losses, the overall total N balances ($NB_{withUnaccounted}$) over the 2-year cropping season were -201.9 kg N ha^{-1} in T1, -4.8 kg N ha^{-1} in T2, +87.2 kg N ha^{-1} in T3, +62.2 kg N ha^{-1} in T4. Hence, the total estimated N balances over the two consecutive seasons significantly decreased in the order T3, T4 > T2 >T6 > T5 > T1 (Table 10).

Table 9 Nitrogen inputs and outputs (kg ha^{-1}) of different cropping system treatments during two cropping seasons.

Treatment[1]	N_{input}[2] (kg ha^{-1})								N_{output}[3] (kg ha^{-1})				
	$N_{deposition}$	$N_{fertilizer}$		N_{seed}			$N_{fixation}$		N_{Mgrain}	N_{Cfruit}	N_{losses}		
		N_{Mfert}	N_{Cfert}	N_{Mseed}	N_{Jseed}	$N_{Cseedling}$	N_{Lfix}	N_{Jfix}			N_{RO}	N_{SL}	N_{SF}
Season 1 (June 29th 2010 – June 25th 2011)													
T1	7.3	62.0	-	0.4	-	-	-	-	117.6 a, A[4]	--	5.8 bc, A	48.8 a, A	0.07 a, B
T2	7.3	24.8	136.5	0.1	-	1.1	-	-	55.6 bc, A	16.7 a, A	7.1 a, A	48.1 a, A	0.09 a, B
T3	7.3	24.8	136.5	0.1	3.6	1.1	-	10.7 ab, B	45.9 bc, A	12.5 b, A	6.8 a, A	42.5 ab, A	0.08 a, B
T4	7.3	33.5	85.3	0.2	3.4	0.7	28.3 a, A	7.6 b, B	58.0 b, A	12.0 b, A	5.5 c, A	29.0 c, A	0.08 a, B
T5	7.3	-	-	0.1	3.6	1.1	--	14.2 a, B	41.4 c, A	10.3 c, A	6.6 ab, A	50.2 a, A	0.06 a, B
T6	7.3	-	-	0.2	3.4	0.7	26.2 a, A	12.3 a, B	52.1 bc, A	7.7 d, A	6.6 ab, A	37.3 bc, A	0.09 a, B
Season 2 (June 26th 2010 – January 8th 2012)													
T1	4.7	62.0	--	0.4	-	-	-	-	95.8 a, A	-	3.2 a, B	9.3 a, B	0.23 a, A
T2	4.7	24.8	98.1	0.1	-	1.1	-	-	46.7 bc, A	4.4 a, B	3.0 ab, B	9.5 a, B	0.16 a, A
T3	4.7	24.8	98.1	0.1	3.6	1.1	-	23.4 b, A	41.1 cd, A	3.9 ab, B	2.5 ab, B	8.1 a, B	0.21 a, A
T4	4.7	33.5	61.3	0.2	3.4	0.7	33.4 a, A	17.6 c, A	58.0 b, A	3.7 abc, B	2.4 b, B	6.8 a, B	0.24 a, A
T5	4.7	-	-	0.1	3.6	1.1	-	30.3 a, A	30.8 d, A	2.9 bc, B	2.2 b, B	7.5 a, B	0.20 a, A
T6	4.7	-	-	0.2	3.4	0.7	28.5 a, A	25.7 c, A	45.3 cd, A	2.5 c, B	2.4 b, B	7.1 a, B	0.23 a, A

[1] T1 = maize monocropping under conventional tillage and fertilizer application, T2 = maize and chili intercropping under conventional tillage and fertilizer application, T3 = as T2 but under minimum tillage with relay crop, T4 = as T3 but additionally with Leucaena hedgerows, T5 = as T3 but without fertilizer application and T6 = as T4 but without fertilizer application.
[2] N input (N_{input}) = [N from wet depositions ($N_{deposition}$) + N from fertilizers (N_{fert}) applied to maize (N_{Mfert}) + N from fertilizers applied to chili (N_{Cfert}) + N from maize seed (N_{Mseed}) + N from Jack bean seed (N_{Jseed}) + N from chili seedlings ($N_{Cseedling}$) + N from BNF ($N_{fixation}$) in Leucaena prunings (N_{Lfix}) + N from BNF in Jack bean AGB (N_{Jfix})].
[3] N output (N_{output}) = N exported via maize grain (N_{Mgrain}) + N exported via chili fruits (N_{Cfruit}) + N losses (N_{losses}) via runoff (N_{RO}) + N losses via soil loss (N_{SL}) + N losses via subsurface flow (N_{SF})
[4] Values followed by different small letters indicate significant differences ($p < 0.05$) of the treatments in each season, while values followed by different capital letters indicate significant differences ($p < 0.05$) of two seasons in each treatment.

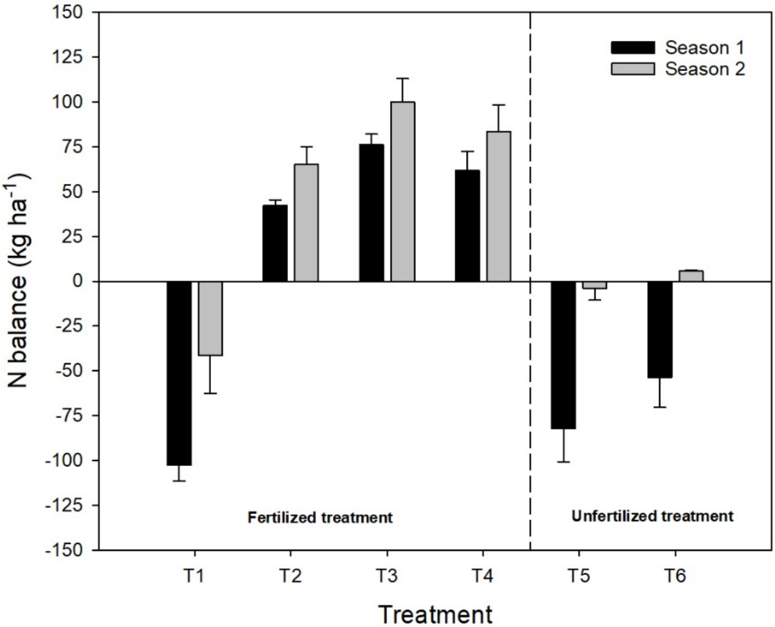

Figure 12 Partial N balance (kg ha^{-1}) for each treatment and cropping season expressed as means and standard deviations based on inputs and outputs of Table 9 (without considering the fate of ^{15}N labelled urea applied to maize). T1: maize monocropping under conventional tillage and fertilizer application; T2: maize and chili intercropping under conventional tillage and fertilizer application; T3: as T2 but under minimum tillage with relay crop; T4: as T3 but additionally with hedgerows; T5: as T3 but no fertilizer application; T6: as T4 but no fertilizer application.

Table 10 Estimated full N balances (kg ha^{-1}) based on partial N balance and taking into consideration the unaccounted proportional losses (leaching, gaseous losses) of ^{15}N labelled urea applied to maize.

Treatment[1]	N balance[2] (kg ha^{-1})	Unaccounted N fertilizer losses (kg ha^{-1})				**Estimated full N balance[5]** (kg ha^{-1})
		Maize fertilizer[3]		Chili fertilizer[4]		
		Season of application	Subsequent season	Season of application	Subsequent season	
		Season 1 (June 29th 2010 – June 25th 2011)				
T1	-102.7	24.8	-	-	-	**-127.4 e**[6]
T2	42.3	7.5	-	41.3	-	**-6.5 b**
T3	76.4	6.0	-	32.8	-	**37.7 a**
T4	61.6	10.2	-	26.1	-	**25.3 a**
T5	-82.4	-	-	-	-	**-82.4 d**
T6	-53.8	-	-	-	-	**-53.8 c**
		Season 2 (June 26th 2010 – January 8th 2012)				
T1	-41.5	24.8	-	--	-	**-66.3 d**
T2	65.0	7.5	-	29.7	-	**27.9 b**
T3	100.0	6.0	-	23.6	-	**70.4 a**
T4	83.5	10.2	-	18.8	-	**54.5 a**
T5	-3.9	-	-	-	-	**-3.9 c**
T6	5.6	-	-	-	-	**5.6 bc**
		Total (June 29th 2010 – January 8th 2012)				
T1	-144.2	49.6	8.2	-	-	**-201.9 d**
T2	107.3	15.0	4.0	71.0	22.1	**-4.8 b**
T3	176.4	12.0	3.2	56.4	17.7	**87.2 a**
T4	145.1	20.4	5.0	44.9	12.6	**62.2 a**
T5	-86.2	-	-	-	-	**-86.2 c**
T6	-48.2	-	-	-	-	**-48.2 bc**

[1] T1 = maize monocropping under conventional tillage and fertilizer application, T2 = maize and chili intercropping under conventional tillage and fertilizer application, T3 = as T2 but under minimum tillage with relay crop, T4 = as T3 but additionally with Leucaena hedgerows.

[2] N balance calculated without consideration of the fate of ^{15}N labelled urea applied to maize as partly showed in Figure 12

[3] Unaccounted losses (kg ha^{-1}) of N fertilizer applied to maize of Season 1 (Season of application) = Unaccounted N losses (%) of Season 1 from Table 8 x Amount of N fertilizer applied to maize (N_{Mfert}) of Season 1 from Table 9, Season 2 (Season of application) = Unaccounted losses (%) of Season 1 from Table 8 x Amount of N fertilizer applied to maize (N_{Mfert}) of Season 2 from Table 9 (calculation based on the assumption that N fertilizer applied in the second season to maize lost at the same proportion as N fertilizer applied in the first season), and Total = Season 1 (Season of application) + Season 2 (Season of application) + Season 1 (Subsequent season = Unaccounted losses (%) of Season 2 from Table 8 x Amount of N fertilizer applied to maize (N_{Mfert}) of Season 1).

[4] Unaccounted losses (kg ha^{-1}) of N fertilizer applied to chili of Season 1 (Season of application) = Unaccounted N losses (%) of Season 1 from Table 8 x Amount of N fertilizer applied to chili (N_{Cfert}) of Season 1 from Table 9, Season 2 (Season of application) = Unaccounted losses (%) of Season 1 from Table 8 x Amount of N fertilizer applied to chili (N_{Cfert}) of Season 2 from Table 9 (calculation based on the assumption that N fertilizer applied in the second season to chili lost at the same proportion as N fertilizer applied in the first season), and Total = Season 1 (Season of application) + Season 2 (Season of application) + Season 1 (Subsequent season = Unaccounted losses (%) of Season 2 from Table 8 x Amount of N fertilizer applied to chili (N_{Cfert}) in each treatment of Season 1); all calculation based on the assumption that N fertilizer applied to chili lost at the same proportion as N fertilizer applied to maize.

[5] Estimated full N balance = N balance – Unaccounted N fertilizer losses of N fertilizer applied to maize – Unaccounted N fertilizer losses of N fertilizer applied to chili

[6] Values followed by different small letters indicate significant differences ($p < 0.05$) of the treatments in each Season.

3.2.2 Discussion

3.2.2.1 Effect of maize-based cropping systems on the fate and residual effect of ^{15}N-labelled fertilizer

The observation that maize intercropped with chili (T2) had a slightly higher total plant system ^{15}NUE (56.8%) of fertilizer applied to maize than farmers' practice (T1) with maize mono-crop (53.8%) confirmed our initial hypothesis that intercropping systems improve N fertilizer use efficiencies (Table 8). This improved NUE may be explained by the fact that a higher light use efficiency (LUE), growth, and maize yield in T2 compared with T1 have been observed by Hussain et al. (2020) due to a low interspecific competition by chili. In both systems, the majority of the fertilizer N was recovered by maize, whereas the added filter function of chili to catch slope downward-moving N accounted only for around 0.3%, while alterations in N losses via runoff, erosion and subsurface lateral movement were below the detection limit. Our initial hypothesis of a higher NUE in intercropping was further confirmed as there was a reduction of total unaccounted N losses in maize-chili intercropping (46.4%) as compared to the maize sole cropping system (53.2%).

However, the addition of conservation measures in T3 and T4 in which minimum tillage and relay cropping with Jack bean with or without Leucaena hedgerows were implemented did not increase ^{15}N fertilizer use efficiency of maize or the total plant system compared to farmers practice. This is contrary to our initial hypothesis. The most plausible explanation for this finding is that farmers practice already included an appropriate fertilizer application at the right place (banded next to plants) and time according to the 4R nutrient stewardship concept (Pisante et al., 2012; Snyder et al., 2009). Secondly, low rainfall during juvenile maize growth (Figure 1) avoided a major runoff and erosion events causing a very low downslope translocation of fertilizer N and thereby minimize potential positive effects of the filter functions in intercropping and agroforestry systems. This is confirmed by the observed high ^{15}N-labelled urea recoveries by maize (^{15}NFR) of 46.9% to 56.5% in the first season (Table 8). These values compare well with the 49.6% ^{15}N-fertilizer recovery by maize in a Leucaena alley cropping system in Australia observed by Xu et al. (1993). Tuan et al. (2014b) also observed relatively high N recoveries when the ^{15}N-labelled urea was band applied and incorporated into the topsoil near the maize plant (Tuan et al., 2014b), while (Rowe et al., 2005) stressed the need for fertilizer application at the time of peak maize N demand. Nevertheless, under less favorable management and environmental conditions, much lower N fertilizer recoveries by maize are commonly found in tropical ecosystems, for example, 8-16% in Nigeria (Akinnifesi et al., 1996) and12-21% in Nepal (Pilbeam et al., 2002) 20-34% in three diverse tropical agroecosystems (Dourado-Neto et al., 2010).

There are several known reasons for reduced crop growth, especially within two or three years after conversion from conventional tillage to minimum tillage, such as N deficiency under high immobilization by plant residues (Lal, 2015). Lower LUE and growth of maize under conservation measures in this trial (Hussain et al., 2020) further caused the ^{15}NUE reduction in maize and the total plant system (maize grain + chili fruit + N recycled) in T3 (46.9 and 47.8%, respectively) and T4 (50.5 and 51.8%, respectively) as compared to T2. This finding is also in agreement with Rowe et al. (2005). They found that hedgerows adversely affect crop growth through competition, and hence the mixed-species system (22-33%) did not improve the combined plant NUE as compared to the maize monocropping system (42%). Further information on ^{15}NFR and crop yields across the field within the ^{15}N-labelled urea application season can be found in Section 3.1.

At maize harvest, the recovery of ^{15}N-labelled fertilizer (^{15}NFR) from the 45 cm soil profile range from 6.2 to 28.6% during the two consecutive years, which was lower than observed in previous studies in maize-based cropping systems. For example, Pilbeam et al. (2002) found that an average of 58% of the applied fertilizer ^{15}N was recovered in the 0-60 cm soil layer at maize harvest, which increased to 76% by the subsequent millet harvest. An average of 37% of fertilizer ^{15}N persisted in the soil after three successive seasons in 12 tropical sites, reported by Dourado-Neto et al. (2010). Nevertheless, the highest ^{15}NFR in T3 (28.1 and 28.6%) was similar to the value observed in maize (22-34%) hillside cropping systems in Vietnam (Tuan et al., 2014b). Low ^{15}NFR in the soil of this study may be related to the observed high ^{15}N recoveries by plants and partly by the soil sampling method as soil samples were collected between maize rows and 20-30 cm away from the ^{15}N-labelled urea application point (Tuan et al., 2014b).

There were very low ^{15}N signals in runoff, subsurface and soil loss in this experiment, implying a minor surface N translocation along the slope as also found in a similar study in Vietnam (Tuan et al., 2014b). Total N losses by those three ways (< 0.05%) seem not of economic importance. However, the ^{15}N-labelled urea was applied at a distance of 1175 cm upslope from collecting points of soil and subsurface losses (Figure 7). Thus, these observed fertilizer N losses may not reflect general plot fertilizer N losses because crops in rows following the application point intercepted most of the translocated ^{15}N before reaching the collecting points (Tuan et al., 2014b).

Some of the fertilizer ^{15}N in this study could not be accounted for in the plants, 0 to 40 cm soil layer at maize harvest in each season and losses (runoff + soil loss + subsurface). It was presumed lost (denitrification or volatilization or leaching) or in the soil below 45 cm and beyond the sampling points (Pilbeam et al., 2002; Tuan et al., 2014b). The moderately acid soil (Xu et al., 1992) and fertilizer immediately incorporated into topsoil would not favor ammonia volatilization under this experimental condition. Therefore, it is suggested that denitrification or leaching was the primary loss mechanism. The cumulative unaccounted N losses at maize harvest over two consecutive seasons ranged from 37 to 53% (Table 8). This finding supports a study of maize with the Leucaena alley cropping system in Australia in which approximately 38% of fertilizer ^{15}N was apparently lost from the soil-plant system, mostly during the first two years (Xu et al., 1993).

Furthermore, lower total unaccounted N losses over two years were found when minimum tillage with legume relay cropped with (T4; 45.4%) or without (T3; 37.0%) hedgerows were added into the systems. The lowest total unaccounted N losses and highest N soil recovery of T3 imply a high retention of fertilizer N in soil organic matter under minimum tillage because of high organic inputs (Mupangwa et al., 2020).

The increase in total unrecovered ^{15}N and maize ^{15}N recovery in T4 compared with T3 may have been caused by repeated additions of Leucaena prunings (Akinnifesi et al., 1996). This pool acts as recyclable N that is easier used by plants or lost than N bounded to SOM.

Although 25.8-44.2% of ^{15}N-labelled urea applied in season 1 could potentially be carried over to the next season, recovery of residual ^{15}N-labelled fertilizer by subsequent plants was less than 5% (Table 8). This result also accords with the general recovery of residual N fertilizer in a second crop under various cropping systems (Dourado-Neto et al., 2010; Pilbeam et al., 2002; Smith and Chalk, 2018). The low residual fertilizer N recovery indicated that immobilized fertilizer N's turnover rate is commonly low and contributes little to the subsequent crop N uptake (Pilbeam et al., 2002; Sieling et al., 2006; Meisinger et al., 2008; Rocha et al., 2019). A microplot study of maize-Leucaena alley cropping in Australia reported that in the second, third, and fourth maize crop recovered only 0.7%, 0.4% and 0.3% of the residual fertilizer ^{15}N, respectively (Xu et al., 1993). The higher residual ^{15}N-labelled recovery in plants under conventionally tilled soil (T1 and T2) than minimum tilled soil (T3 and T4) may indicate that the higher the soil disturbance, the higher the rate of net mineralization of organic N and release of N from residues (McConkey et al., 2002). Whereas, pool substitution processes between labelled and unlabelled N for plant uptake might occur more when a high unlabelled-N fertilizer rate was applied to chili in the maize-chili intercropping system (T2); thus, lower residual ^{15}N-labelled recovery in plants was found in T2 compared with T1 (Jenkinson et al., 1985). Moreover, the primary source of N for maize in this experimental site was native soil N (> 70%), as explained in Section 3.1.

These results demonstrate the significant potential to improve utilization of residual fertilizer N bounded to SOM and reduced N losses through better N management (Tuan et al., 2014b) and the need for additional N fertilizer application to each crop to maintain or achieve high yields (Rocha et al., 2019).

3.2.2.2 Interpretation of the nitrogen balances of maize-based cropping systems

Current farmers' practice (T1) under the conventional tillage with fertilizers induced a negative partial N balance ($NB_{withoutUnaccounted}$) in both seasons (Figure 12). In T1, N export by maize grain yield (N_{Mgrain}) and N loss by erosion (N_{SL}) were major total N output (N_{output}) pathways, while mineral fertilizers applied to maize (N_{Mfert}) were major total N input (N_{input}) pathways (Table 9). N_{Mgrain} brought $NB_{withoutUnaccounted}$ to be negative in both years. Due to lower N_{Mgrain}, a less negative N balance in season 2 (-41.5 kg N ha^{-1}) compared to season 1 (-103 kg N ha-1) of T1 was observed; however, this does not imply that the system is better because lower crop yield means lower or no income (Douxchamps et al., 2010). Similarly, N_{output} by crop removal (N_{Mgrain} + chili fruit (N_{Cfruit})) under all maize-based intercropping systems also declined in season 2 compared to season 1. The slightly lower maize grain yield (Figure 9) and N_{Mgrain} (Table 9) of T1, T2, T5 and T6 in season 2 compared to season 1 were probably caused by gradually nutrient depletion in soils due to low fertilizer rate (62-11-36 kg N-P_2O_5-K_2O ha^{-1} season^{-1}), bringing about the annual total nutrient deficit (Tan et al., 2005). A more extended period of conservation measures (Pansak et al., 2008) combined with mineral fertilizer application tended to increase maize grain yield of T3 and T4 and maintain N_{Mgrain} of T4 in season 2 compared with season 1 (Figure 9 and Table 9). Vanlauwe et al. (2014) concluded that conservation agriculture (CA) strategies have to integrate the appropriate use of fertilizer to increase farmers' benefits such as crop productivity and the availability of crop residues. Poor growth performance because of pest and disease attack (Garré et al., 2013b) induced lower chili fruit yield and N_{Cfruit} in season 2 than in season 1. Moreover, in each season, the higher maize grain yield and N_{Mgrain} acquired in maize sole cropping system (T1) were reasonably predictable, mainly due to lower maize density in the mixed cropping systems. Further information on crop yields in each season and the reasons behind yield variations under different maize-based cropping systems can be found in Section 3.1 (season 1) and Section 3.3 (season 2).

Current amounts of mineral N fertilizers do not compensate for N_{output} as detected in T1. Thus, more sound cropping systems with (i) higher N_{input} (additional mineral N fertilizers and symbiotic N_2 fixation by legumes) and (ii) higher NUE and lower N losses (soil conservation practices) are required for total N balance improvement. When high amounts of mineral fertilizer were applied to chili (N_{Cfert}), the partial N balances became positive for all fertilized intercropping systems (T2, T3 and T4) in both seasons. N_{Cfert} in T2, T3 and T4 accounted for 80, 74 and 51% in season 1 and 76, 63, and 40% in season 2 of N_{input}. Whereas, N_{Mfert} represented only 15 and 19% in T2, 14 and 16% in T3, 20 and 22% in T4 for season 1 and season2, respectively. Lack of mineral fertilizer application was the main reason for the negative N balances in both non-fertilized treatments (T5 and T6) in season 1 and only T5 in season 2. The slightly positive N balance (6 kg N ha^{-1}) under T6 in season 2 was mostly because of higher N added by symbiotic N_2 fixation of legumes ($N_{fixation}$), especially from Leucaena pruning. The above results confirm that mineral N fertilizer is the main contributing factor in maintaining or improving yield and N balance in maize-based cropping systems either with or without soil conservation measures, as also observed in previous studies (Xu et al., 1992; Akinnifesi et al., 1996; Pilbeam et al., 2002; Rowe et al., 2005; Douxchamps et al., 2010; Dourado-Neto et al., 2010; Hussain et al., 2015; Tuan et al., 2014b; Lin et al., 2016; Rocha et al., 2019; Mupangwa et al., 2020; Lundy et al., 2015).

Likewise, N supplement from symbiotic N_2 fixation by legumes under conservation-based intercropping (T3, T4, T5 and T6) positively impacted the N budgets. Our results confirm the hypothesis that legumes in relay cropping with or without hedgerows leading to higher N inputs through biological N fixation (BNF). Total N from symbiotic N_2 fixation of legumes ($N_{fixation}$) in T3, T4, T5 and T6 represented 6, 22, 54 and 77% in season 1 and 15, 33, 76 and 86% in season 2 of N_{input}. Consistent with finding under organic crop rotation and agroforestry systems by Lin et al. (2016), we discovered that symbiotic N_2 fixed was the essential N_{input} for the non-fertilized treatments (T5 and T6). The 31-41%Ndfa of Jack bean AGB in our study (Table 1) was lower than the range of the 57-69% reported by Giller (2001) and 64-74% described by Douxchamps et al. (2010). Similarly, Leucaena prunings (18-23%) also had a lower %Ndfa than the 64-72% range in Leucaena sole cropping and 73-83% in

Leucaena mixed with grass in a study on N fixing potential of tree legumes (Jayasundara et al., 1997). These findings highlight that both legumes were grown for the first time in this region and not inoculated with rhizobia. Thus, higher %Ndfa and biomass of both legumes in this experiment in season 2 compared with season 1 were as expected, which has also been found for many tropical green manure legumes after the year of establishment (Douxchamps et al., 2010; Giller, 2001). The variation of %Ndfa (Table 1), biomass production (Figure 10) and N concentration (Table 5) of each legume affected the discrepancy of fixed N in our trial (Table 9). Previous studies reported that the amount of fixed N by legumes in tropical areas was mainly determined by the difference in biomass production (Thomas et al., 1997; Douxchamps et al., 2010).

Additionally, the N fixation of legumes in this trial was underestimated because Leucaena's trunk and belowground biomass (root and nodule) of Jack bean and Leucaena were not considered. Unkovich et al. (2008) proposed a multiplication factor of 2.0 for pasture/fodder legumes (assuming 50% belowground N); hence total Jack bean (aboveground + belowground) in our field would potentially provide 15-28 kg N ha^{-1} in the first season and 35-61 kg N ha^{-1} in the second season. On average of Leucaena leucocephala, which was always pruned to 50 cm height in Sri Lanka, the pruning, trunk, and roots percentages were about 82%, 9% and 9% of the total N yield, respectively (Jayasundara et al., 1997). By applying this N partition and assuming similar total N_2 fixed among plant parts, the N fixed by Leucaena (pruning + trunk + root) that would possibly raise fixation to 31-33 and 34-39 kg N ha^{-1} in the systems in season 1 and 2, respectively. If we include these additional N contributions from both legumes, the N balances of the systems with legumes would be improved. Taken together, these results show that legumes can increase soil N via biological N fixation, but they may also accelerate other nutrients' (like P, K) exhaustion leading to low N use efficiency and large N losses to the environment in the long-term period (Whitmore, 2000; Oenema et al., 2006). Nevertheless, Pansak et al. (2008) concluded that these systems with well-managed fertilizer applications boost up the efficiency of soil conservation measures in reducing runoff and soil loss by improving crop and hedgerow performance and do not per se cause an intensification in environmental pollution.

In comparison, N from wet deposition ($N_{deposition}$) and changes of N from seed and seedling of plants (N_{seed}) affected by different plant density in cropping systems made a minor impact on N budgets in fertilized treatments (T1, T1, T3 and T4), but had a more pronounced effect in non-fertilized treatments (T5 and T6). Higher impacts of $N_{deposition}$ and N_{seed} in non-fertilized systems compared to fertilized systems are generally founded in the low-external-input cropping systems (De Jager et al., 2001). However, these impacts in T5 and T6 were lower in season 2 compared to season 1. It seems possible that these results are due to the better performance of legumes; thus, expected higher $N_{fixation}$ was added to both systems in season 2 compared to season 1. In season 2, therefore, the impact of $N_{fixation}$ obscured $N_{deposition}$ and N_{seed} on N budgets of T5 and T6.

Another key influencing factors of N_{output} was N loss via erosion (N_{SL}) (Table 9). In contrast, the alterations in N losses via runoff (N_{RO}) and subsurface (N_{SF}) by mixed cropping systems made only a minor impact on N budgets. During season 1, erosion caused large N losses in the systems without conservation practices (T1 and T2) (Figure 11 and Table 10). Our results confirm the initial hypothesis that intercropping with soil conservation measures improve the N budget by decreasing N losses because minimum tillage plus Jack bean relay cropping and fertilizer application with (T3) or without Leucaena hedges (T4) could decrease N_{SL}. A similar study on a relatively fertile soil with good water holding capacity and moderate slopes in Thailand by Pansak et al. (2008) confirmed that contour hedgerows combined with minimum tillage, mulching and relay cropping were important in reducing runoff and soil loss. In season 1, lack of mineral fertilizer application in non-fertilized systems (T5 and T6) increased N_{SL} of both treatments compared to fertilized systems (T3 and T4). This finding further supports the idea that the efficiency of soil conservation measures in improving crop and hedgerow performance can be enhanced by fertilizer application, in this manner reducing runoff and soil loss (Pansak et al., 2008). N_{SL} represented from 28-35% and 9-17% of N_{output} in season 1 and season 2, respectively. Reduced erosion

(1.9-2.8 Mg ha^{-1}) and N_{SL} (6.8-9.5 kg ha^{-1}) in season 2 (Figure 11 and Table 9) may have been partly caused by reduced rainfall with good distribution (no massive rainfall event) in season 2 (Figure 1) and the positive effect of plant residue mulches from season 1 (Figures 10). Reducing rain impact on soil and providing increased roughness that slows soil loss is the advantage of mulches (Kinama et al., 2007). Generally, soil conservation programs consider soil-loss tolerance values to be 5-12 Mg ha^{-1} year^{-1}, against which to evaluate "acceptable" soil erosion rates (Montgomery, 2007). Therefore, the amount of soil loss by the erosion of T4 and T6 in season 1 and all treatments in season 2 were within an acceptable rate. If the plant residues in this trial would have been disposed of by open burning in the fields, as frequently occurring in mountainous agricultural lands in Thailand (Sirithian et al., 2018), it may lead to potentially severe soil erosion, air pollution and N losses via gas emission equal up to 108-246 kg N ha^{-1} in season 1 and 31-220 kg N ha^{-1} in season 2 (Table 7).

The "the partial N balance" in this study ($NB_{withoutUnaccounted}$) overestimated the true (full) N budget because unaccounted N losses of applied mineral fertilizer, such as downward leaching and gaseous losses, were not included in the estimation. Therefore, the fate of ^{15}N-labelled fertilizer data (Table 8) was integrated into $NB_{withoutUnaccounted}$ (Figure 12) for constructing "the labelled N budget" or "full N balance" in this experiment ($NB_{withUnaccounted}$) (Table 10) for a greater understanding of ^{15}N-labelled fertilizers cycling (Meisinger et al., 2008) and a more precise N balance estimate. When considering N fertilizer's unaccounted losses applied to crops, $NB_{withUnaccounted}$ became a lower value than $NB_{withoutUnaccounted}$ in all fertilized systems. Accumulated over the two seasons, $NB_{withUnaccounted}$ of different maize-based systems varied between -202 and +87.2 kg N ha^{-1}. $NB_{withUnaccounted}$ could clearly explain the general trend of decreasing maize grain yield with negative balances under T1, T2, T5 and T6 and increasing maize grain yield with positive balances under T3 and T4 in season 2 compared with season 1 (Figure 9 and Table 10). Radersma et al. (2004) observed that the measured maize yield decline over time was related to negative N balances under the alley-cropping system in Kenya.

Comparing between two N balance calculations, $NB_{withUnaccounted}$ enables us to better understand the positive relationship between maize yield and N balance, especially in T2. However, the direct measurements of N losses were commonly less than the unaccounted for of fertilizer N (Bandyopadhyay and Sarkar, 2005). Therefore, further research is needed to investigate the short-term and long-term effects of maize-based cropping systems on N_{output} via gaseous losses and leaching processes under tropical sloping land conditions. The differences in N balances among the different cropping treatments in this study implied that treatments could affect the N dynamics. Negative N balance leads to N exhaustion, while positive N balance increases soil N, of which mineralized N may promote not only crop growth and support yield formation but also N losses (Sieling et al., 2006).

3.2.2.3 Crop productivity and production risk of maize-based cropping systems

Intercropping of maize and chili with NPK fertilization showed some advantage in terms of marketable yields, i.e., maize grain and fresh chili fruit (Figure 9), because the LER was higher than 1.0 in both seasons under T2 (1.01 and 1.17, respectively) but only in season 2 under T3 and T4 (1.03 and 1.22, respectively). The Land Equivalent Ratio (LER) greater than 1.0 indicates a better utilization of the environment resources by the intercrop crops compared to the sole crops (Guo et al., 2008), or interspecific facilitation (or complementarity) is more robust than the interspecific competition (Li et al., 1999). These results imply that there is the requirement of extra land of 1, 17, 3 and 22%, respectively, by sole cropping system to get yields equal to those maize-chili intercropping with or without conservation measures.

The total returns from commercial maize and chili yields in intercropping systems were obviously higher than maize sole cropping in the first season, as explained in Section 3.1. These higher returns were mainly due to the high price of fresh chili fruit (1.3 USD kg^{-1}), while the price of maize grain was low at only 0.3 USD kg^{-1}. Based on the first season's price and yield of crops, farmers may prefer to cultivate chili in monocropping

(7,641 USD ha^{-1} in season 1) instead of maize-chili intercropping to get the next season's highest returns. However, due to pest and disease attack, chili growth and yield were extremely low in the second season. Total returns for T1, T2, T3, T4, T5, and T6 were 1,918, 1,818, 1,612, 1,946, 1,378 and 1,550 USD ha^{-1}, respectively, which were higher than chili sole cropping (1,321 USD ha^{-1}). These results are fascinating and indicate the crucial role of intercropping systems that decrease production risk by increasing diversification and reducing the chance of overall yield losses by pests and diseases (Craswell et al., 1997).

3.3 Combining $\delta^{13}C$ measurements and ERT imaging: improving our understanding of competition at the Crop-Soil-Hedge interface[1]

3.3.1 Results

3.3.1.1 Maize aboveground biomass development, grain yield, and $\delta^{13}C$

The hedge intercrop with fertilizer (T4 or MHF^+) treatment produced on average the highest maize aboveground biomass (AGB) per row (1251 g m^{-2}) which was statistically similar to the production of the control under monocropping (T1 or MM, 1166 g m^{-2}) (Table 11). Maize AGB was significantly lower in the hedge intercrop without fertilizer treatment (T6 or MHF^-) than in the same treatment with fertilization (MHF^+). In the hedgerow treatments, maize in rows distant from Leucaena hedges produced 46% and 73% higher AGB than maize in rows close to the hedgerow ($p \leq 0.01$) in MHF^+ and MHF^- treatments, respectively. Chili fresh fruits were harvested four times during the growing period of maize. The MHF^+ treatment produced a higher amount of total chili fruits (170 g m^{-2}) than MHF^- (141 g m^{-2}) (data not shown).

The hedge intercrop with fertilizer (MHF^+) treatment produced on average the highest maize grain yield (GY) per row (701 g m^{-2}) which was statistically similar to the grain yield production of control under monocropping (MM, 641 g m^{-2}). Maize GY was significantly lower in the hedge intercrop without

[1] This section is published as Hussain, K., Wongleecharoen, C., Hilger, T., Vanderborght, J. Garré, S., Onsamrarn, W. Sparke, M., Diels, J. Kongkaew, T., Cadisch, G. 2015. Combining δ13C Measurements and ERT Imaging: Improving our Understanding of Competition at the Crop-Soil-Hedge Interface. Plant and Soil 393(1):1-20

fertilizer treatment (MHF^-) than in the same treatment with fertilization (MHF^+). In the hedgerow treatments, maize in rows distant from Leucaena hedges produced a 41% and 63% higher grain yield than maize in rows close to the hedgerow ($p \leq 0.01$) in MHF^+ and MHF^-, respectively (Table 11).

Plant growth and development was monitored by measuring plant height and LAI at biweekly intervals during the growing period of maize. Significant differences in maize plant height ($p \leq 0.001$) were observed between all treatments; maximum height (110 DAS) was gained by maize plants under monocropping (control) while the lowest plant height was observed in MHF^-. Maize in rows distant to a hedgerow gained significantly higher plant heights than maize in rows close to a hedgerow in MHF^+ and MHF^- (Table 11). Maize LAI of all treatments steadily increased during the season, reaching maxima 60 DAS with 2.95 in MM, followed by MHF^+ with 2.48 and 2.30 in MHF^- (Figure 13). Thereafter LAI declined in all treatments to around 1.6 ($p \leq 0.05$) at 100 DAS. Chili LAI development remained low in both hedge intercrop treatments (MHF^+ and MHF^-). In chilies, cercospora leaf spot (*Cercospora capsici*) was observed 15-20 days after transplanting which created defoliation, reducing its LAI.

Grain $\delta^{13}C$ was significantly less negative in maize rows close to hedgerows (-10.33‰, $p \leq 0.001$) than in maize rows distant to hedge (-10.64‰) in MHF^+ (Table 11). In MHF^-, grain $\delta^{13}C$ was also less negative in maize close to hedges (-9.21‰) than in distant maize rows (-9.43‰). Maize rows within MM showed no significant difference among each other. Mean grain $\delta^{13}C$ was significantly less negative in MHF^- (-9.32‰) as compared to MHF^+ (-10.49‰) and MM (-10.55‰). Mean leaf $\delta^{13}C$ was significantly less negative in MHF^- as compared to MHF^+ and MM treatments at 100 DAS while there were no significant differences in leaf $\delta^{13}C$ signals between the rows of each treatment.

3.3.1.2 Maize and Leucaena root length densities

In MM, maize plants developed a higher root length density (RLD) near the soil surface (5 cm depth) as compared to 20 cm depth (Figure 14). In MHF^+, RLD measurements at 5 and 20 cm depth showed that Leucaena roots expanded horizontally into the soil area above and below hedges being predominantly found in the topsoil on the downhill side of hedgerows. Maize roots remained dominant just below their planting position. At the 20-cm-soil-depth, RLD of both, Leucaena and maize, decreased as compared to the layer near the soil surface Hedgerow roots, however, were significantly present at this depth. RLD data showed that Leucaena developed much more roots in MHF^- than in its corresponding fertilized treatment independent of soil depth. These Leucaena roots also extended into nearby maize rows above and below the hedge, strongly intercepting with maize roots. At the 20-cm-soil-layer, Leucaena roots were quite dominant in the maize growing area.

Table 11 Maize aboveground biomass (AGB), grain yield (GY), plant height and grain & leaf $\delta^{13}C$ signals in maize rows at corresponding positions as affected by maize monocropping (T1 or MM), maize hedge intercropping with fertilizer (T4 or MHF^+) and without fertilizer (T6 or MHF^-). In the control, maize rows correspond with slope positions of rows of both hedge intercrop treatments (MHF^+ and MHF^-). Data were recorded during the 2011 growing season at Queen Sirikit Research Farm, Ratchaburi province, Thailand.

		MM (Control)	**MHF^+**	**MHF^-**
AGB (g m^{-2})				
Position	Close to hedge (n=12)	1110	1018 *b*[#]	790 *b*
	Distant from hedge (n=12)	1222	1483 *a*	1363 *a*
		ns	*$p \leq 0.001$****	*$p \leq 0.01$***
	Average row AGB (n=24)	1166 *AB*[#]	1251 *A*	1077 *B*
		*$p \leq 0.05$**		
GY (g m^{-2})				
Position	Close to hedge (n=12)	629	582 *b*[#]	457 *b*
	Distant from hedge (n=12)	653	820 *a*	746 *a*
		ns	*$p \leq 0.01$***	*$p \leq 0.01$***
	Average row GY (n=24)	641 *AB*[#]	701 *A*	602 *B*
		*$p \leq 0.05$**		
Plant height (mm)				
Position	Close to hedge (n=12)	1519	1298 *b*	1163 *b*
	Distant from hedge (n=12)	1562	1450 *a*	1304 *a*
		ns	*$p \leq 0.001$****	*$p \leq 0.001$****
	Average row plant height (n=24)	1540 *A*	1374 *B*	1234 *C*
		*$p \leq 0.01$***		
Grain $\delta^{13}C$ (‰)				
Position	Close to hedge (n=12)	-10.54	-10.33 *a*	-9.21 *a*
	Distant from hedge (n=12)	-10.56	-10.64 *b*	-9.43 *b*
		Ns	*$p \leq 0.001$****	*$p \leq 0.01$***
	Average row $\delta^{13}C$ (n=24)	-10.55 *B*	-10.49 *B*	-9.32 *A*
		*$p \leq 0.01$***		
Leaf $\delta^{13}C$ (‰)				
Position	Close to hedge (n=12)	-11.63	-11.63	-11.47
	Distant from hedge (n=12)	-11.64	-11.67	-11.32
		ns	*ns*	*ns*
	Average row $\delta^{13}C$ (n=24)	-11.64 *B*	-11.65 *B*	-11.40 *A*
		*$p \leq 0.01$***		

ns = non-significant; *, **, *** are significant at $p \leq 0.05$, 0.01, 0.001%, respectively.
[#]Figures followed by different small letters indicate significant differences within a treatment while capital letters indicate significant differences among treatments using a Tukey test.

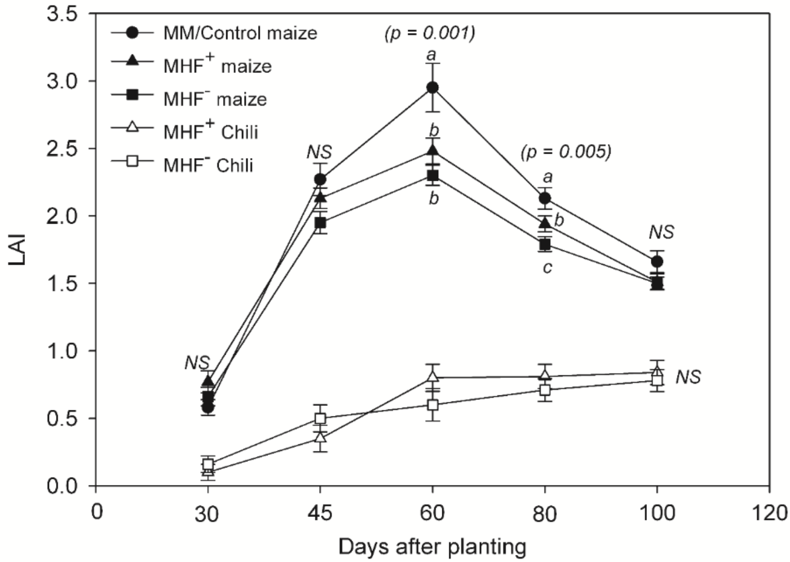

Figure 13 Leaf area index (LAI) of maize and chili as affected by maize monocrop (T1 or MM), hedge intercrop with fertilizer (T4 or MHF^{+}) and without fertilizer (T6 or MHF^{-}). Different letters indicate significant while NS shows non-significant differences between the treatments at $p < 0.05$. Bars indicate the standard error. LAI values are means of 12 individual measurements. Data were recorded during the 2011 growing season at Queen Sirikit Research Farm, Ratchaburi province, Thailand.

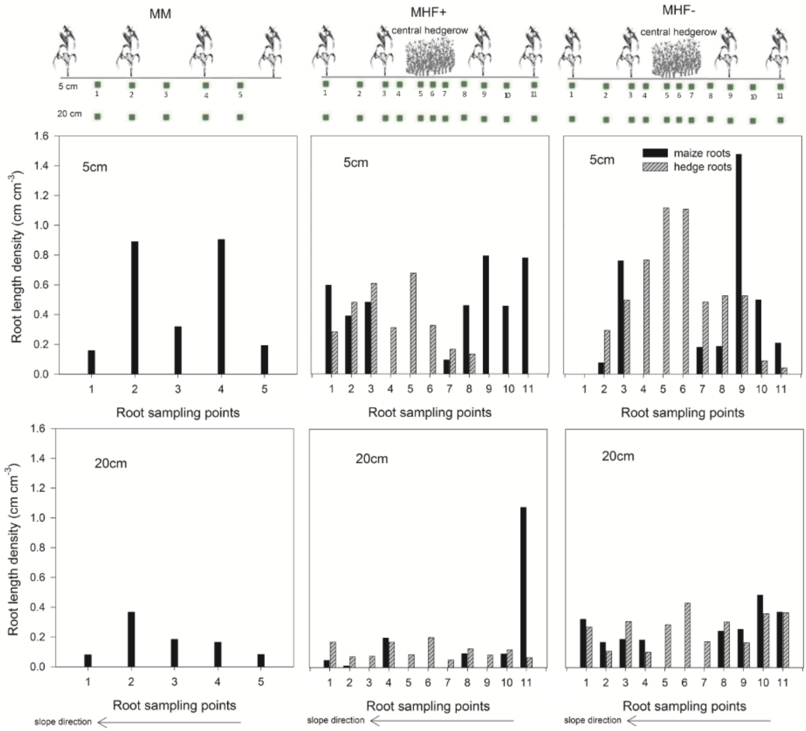

Figure 14 Root length density (cm cm^{-3}) of maize and hedgerow at 5 and 20 cm soil depth in maize monocrop (T1 or MM), hedge intercrop with fertilizer (T4 or MHF^{+}) and hedge intercrop without fertilizer (T6 or MHF^{-}) treatments. Upper portion of the graph is showing the exact root sampling positions at central position within a plot. Data were recorded in September 2011 at Queen Sirikit Research Farm, Ratchaburi province, Thailand.

3.3.1.3 Volumetric water contents by TDR

Before maize planting, soil moisture was higher than during the cropping period and showed almost equal temporal patterns in MM and MHF^+. From June to August, soil moisture between maize rows of MM was higher than in maize rows of MHF^+ but decreased thereafter reaching the same level as MHF^+. Comparisons of soil volumetric water contents of TDR probes installed between maize rows before and after the Leucaena hedgerow in MHF^+ treatment showed that soil moisture conditions were mostly similar at both positions, but soil moisture was higher before planting maize as compared to the period thereafter (Figure 15).

The TDR probes installed in-between chili rows in the MHF^+ treatment indicated higher volumetric water contents during whole measuring period than probes installed at similar slope position between maize rows of the MM treatment, indicating less soil moisture depletion by chili rows.

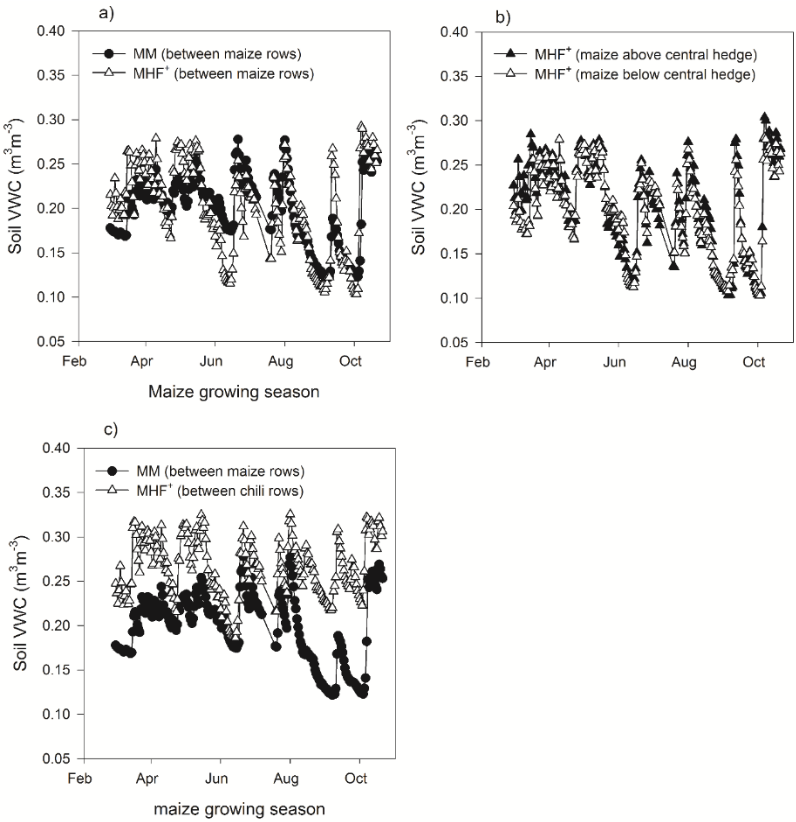

Figure 15 Volumetric water content (m^3m^{-3}) at a soil depth of 0-25 cm measured with TDR probes March to end October, 2011. Data were recorded at Queen Sirikit Research Farm, Ratchaburi province, Thailand.

3.3.1.4 ERT imaging and its relationship to plant growth

The ERT data revealed that maize generally caused the strongest soil moisture depletion followed by maize rows beside the Leucaena hedges in August 2011 (Figure 16). Chilies induced only moderate soil moisture depletion during the monitoring period. Maize monocrop (MM/control) showed the highest soil moisture depletion pattern over time and along the slope. Hedge intercrop with fertilizer (MHF^{+}) treatment presented a lower soil moisture depletion pattern than the maize monocrop, mainly due to the low water use in the chilli cropping area. In the hedge intercrop without fertilizer application (MHF^{-}) depletion of soil moisture was even less. Soil moisture depletion patterns among maize rows were more variable within both hedge intercrop treatments than in the maize monocrop. Moreover, in MHF^{+}, ERT soil moisture depletion patterns showed a stronger depletion in maize rows close to hedgerows compared to maize in rows distant to the hedges. Differences, however, were quite small. In the non-fertilized hedge intercrop treatment, the maize rows just after chili rows mostly utilized more water compared to other maize rows. Soil moisture depletion increased with increase of LAI from July 29th to August 29th, 2011 in all treatments (Figure 17). Variations in soil moisture depletion and LAI were lower among treatments on July 29, while they increased from August 13th to 29th. Maximum soil moisture depletion was observed in maize rows under monocropping (MM/control) where the highest LAI was observed. Soil moisture depletion was lowest in maize rows under MHF^{-} treatment with lowest LAI.

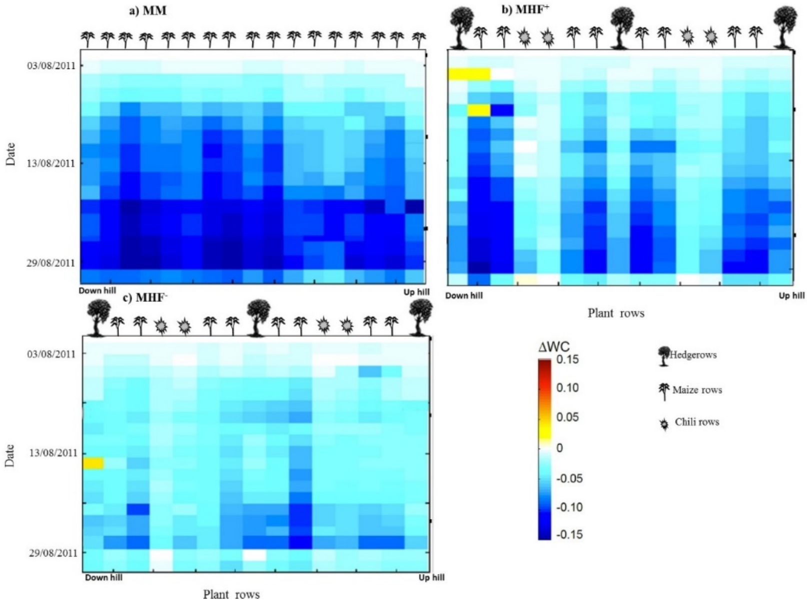

Figure 16 Relative soil moisture depletion (ΔWC) trends of maize based cropping systems along the slope in a soil depth of 0-80 cm based on electrical resistivity tomography (ERT) imaging: a) maize monocrop (T1 or MM), b) hedge intercrop with fertilization (T4 or MHF$^+$), c) hedge intercrop without fertilization (T6 or MHF$^-$). Data presented were recorded between August 2nd and 31st, 2011 at Queen Sirikit Research Farm, Ratchaburi province, Thailand (adapted from Garré et al. (2013b)). ΔWC of August 2nd, 2011 was set as zero soil moisture depletion and initial soil moisture content.

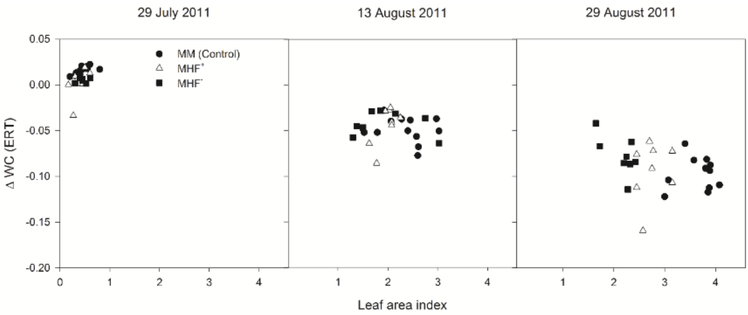

Figure 17 Relationships between actual water contents minus initial water contents (ΔWC (ERT)), and LAI of maize rows as affected by monocropping (T1 or MM), maize hedge intercropping with fertilizer (T4 or MHF^+) and without fertilizer (T6 or MHF^-) on 29 July, 13 and 29 August 2011. Data were recorded during the 2011 growing season at Queen Sirikit Research Farm, Ratchaburi province, Thailand.

3.3.1.5 Nitrogen response ratio in maize grains

A significantly positive correlation was observed in hedge-based systems between maize aboveground biomass (AGB) and N concentration (%N) in grains with moderate to strong linear relationships in hedge intercrop treatments with (MHF^+: R^2=0.80, $p \leq 0.001$) and without (MHF^-: R^2=0.68, $p \leq 0.01$) fertilization (Figure 18). In hedge intercrop treatments, maize rows close to the Leucaena hedgerow showed lower aboveground biomass with lower N concentration while maize in rows distant from Leucaena showed higher aboveground biomass with higher N concentrations in grains. In maize monocropping, eight maize rows at similar slope positions to hedge intercropping with and without fertilizer (MHF^+ and MHF^-) were selected for comparison but no such relationship was found (R^2=0.28; p =0.17). The resource response ratio ($LnRR_N$) in maize grains of the hedge-intercrop treatment with fertilization (MHF^+) was zero or slightly positive in maize rows distant to hedgerows while maize rows close to Leucaena hedgerows showed a negative response ratio (Figure 19). In the hedge-intercrop treatment without fertilization (MHF^-), all maize rows showed negative $LnRR_N$ values except one.

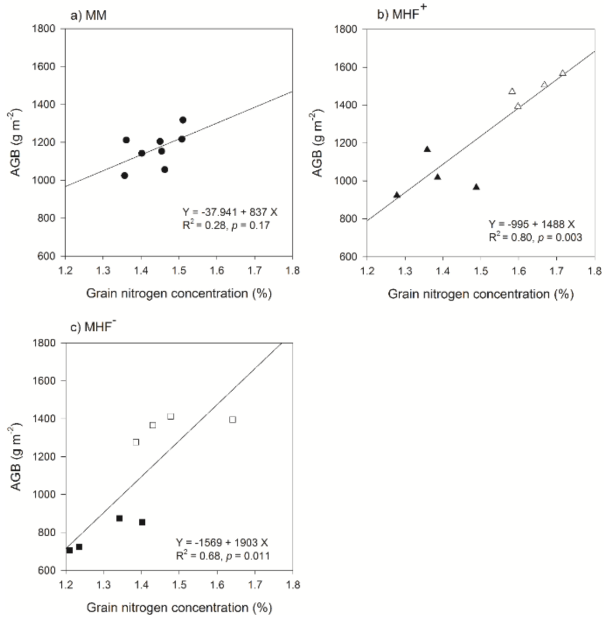

Figure 18 Relationship between maize aboveground biomass and total nitrogen concentration (%N) in maize grains planted as a) maize monocrop (T1 or MM), b) hedge intercrop with fertilizer (T4 or MHF^+) and c) hedge intercrop without fertilizer (T6 or MHF^-). Data were recorded during the 2011 growing season at Queen Sirikit Research Farm, Ratchaburi province, Thailand. The filled and unfilled symbols in MHF^+ and MHF^- are showing the maize rows present close and distant to hedgerows respectively.

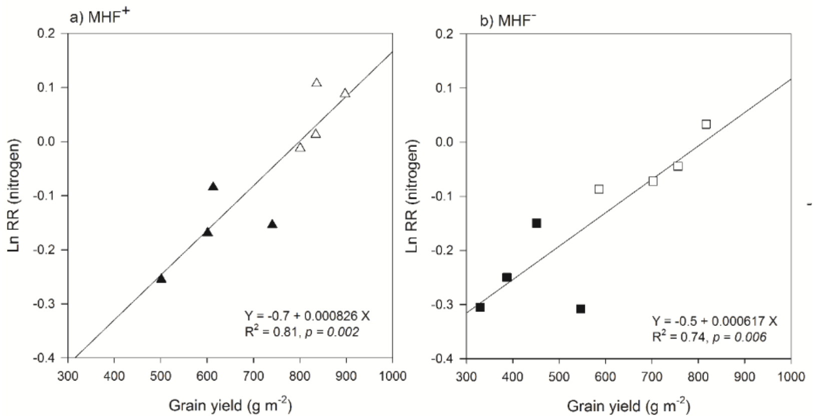

Figure 19 Comparisons of natural log response ratio of grain total nitrogen concentration (LnRRn) and grain yield in various maize rows in a) hedge intercrop with fertilizer (T4 or MHF^+) and b) hedge intercrop without fertilizer (T6 or MHF^-). Data were recorded during the 2011 growing season at Queen Sirikit Research Farm, Ratchaburi province, Thailand. The filled and unfilled symbols are showing the maize rows present close and distant to hedgerows, respectively.

3.3.1.6 Behaviour of $\delta^{13}C$ and its relationship with N concentration in maize grains and ERT soil moisture depletion

Spatial variation in grain $\delta^{13}C$ was observed in all treatments (Figure 20). All maize rows of fertilized treatments (MM and MHF^{+}) showed more negative grain $\delta^{13}C$ signals compared to hedge intercrop treatment without fertilizer (MHF^{-}). However, in fertilized hedge intercrop treatment maize rows close to Leucaena hedgerows showed less negative $\delta^{13}C$ signals compared to the distant maize rows. Least negative $\delta^{13}C$ signals were observed in case of hedge intercrop treatment without fertilization (MHF^{-}).

A negative correlation was observed between grain $\delta^{13}C$ and N concentration in maize grains in hedgerow treatments only (Figure 21); i.e., $\delta^{13}C$ signals decreased with increasing N concentrations in maize grains of different rows with R^2=0.76 (p = 0.005) to 0.89 (p = 0.001) in maize hedge intercrop without and with fertilization, respectively. This relationship resulted from the fact that maize grown in rows close to Leucaena hedgerows at upper, middle and lower slope positions, had a low %N with less negative values of $\delta^{13}C$, whereas maize grown in rows distant from the hedgerow showed a higher %N with more negative values of $\delta^{13}C$, again making two distinct data sets for maize in rows close and distant to hedges in both MHF^{+} and MHF^{-} treatments.

$\delta^{13}C$ signals in maize grains were less negative associated with lower soil moisture depletion based on ΔWC (ERT) on August 29, 2011 and vice versa, showing a significant correlation with each other (r = 0.66 and $p \leq 0.001$; Figure 22). A similar but not significant trend was observed with $\delta^{13}C$ signals in maize leaves collected at 100 DAS (data not presented).

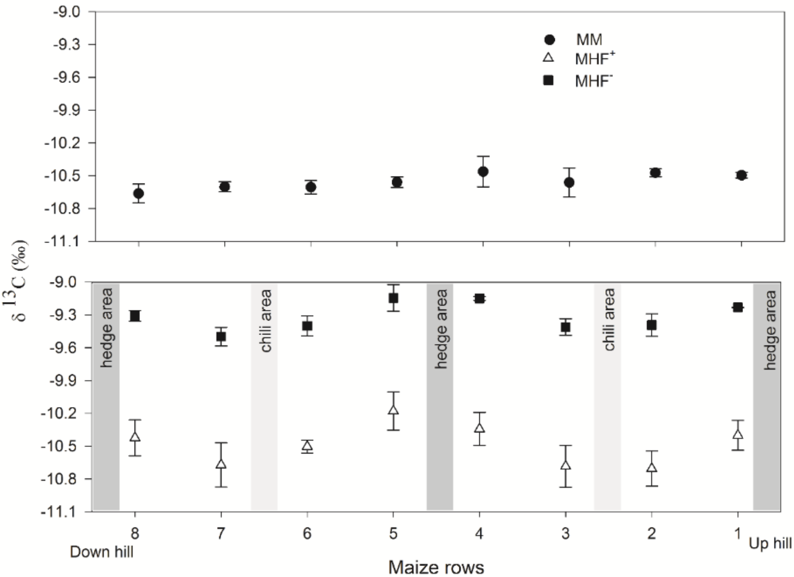

Figure 20 Spatial variability of grain $\delta^{13}C$ signals in various maize rows in maize monocrop (T1 or MM) (upper figure), hedge intercrop (lower figure) with fertilizer (T4 or MHF^{+}) and hedge intercrop without fertilizer (T6 or MHF^{-}). Bars are showing the standard error. Data were recorded during the 2011 growing season at Queen Sirikit Research Farm, Ratchaburi province, Thailand. Note: high $\delta^{13}C$ signals means less negative $\delta^{13}C$ values, and low $\delta^{13}C$ signals means more negative $\delta^{13}C$ values.

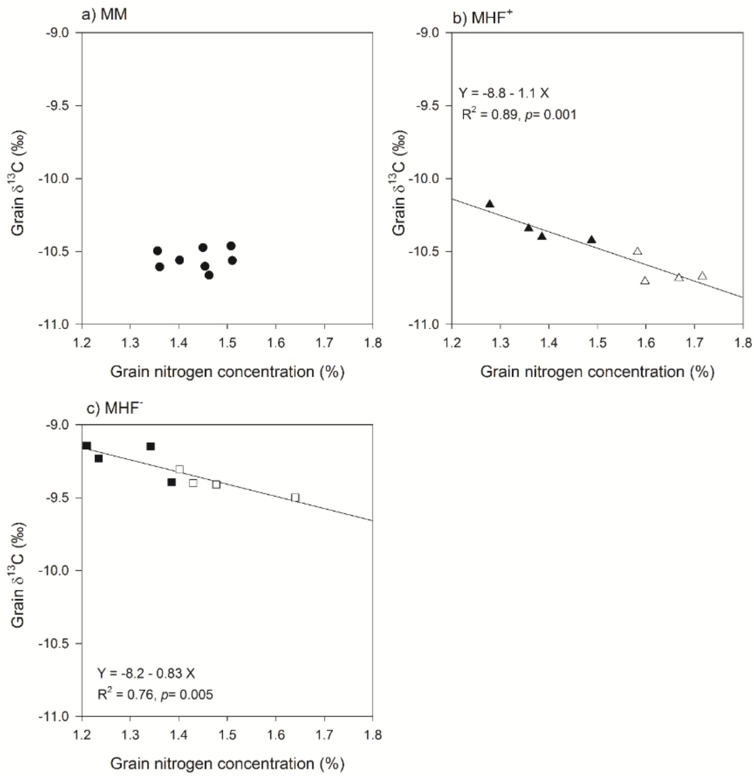

Figure 21 Relationships between $\delta^{13}C$ and total nitrogen concentration (%N) in maize grains planted as a) maize monocrop (T1 or MM), b) hedge intercrop with fertilizer (T4 or MHF^{+}), and c) hedge intercrop without fertilizer (T6 or MHF^{-}). Data were recorded during the 2011 growing season at Queen Sirikit Research Farm, Ratchaburi province, Thailand. The filled and unfilled symbols in MHF^{+} and MHF^{-} are showing the maize rows present close and distant to hedgerows, respectively. Note: high $\delta^{13}C$ signals means less negative δ13C values, and low δ13C signals means more negative δ13C values.

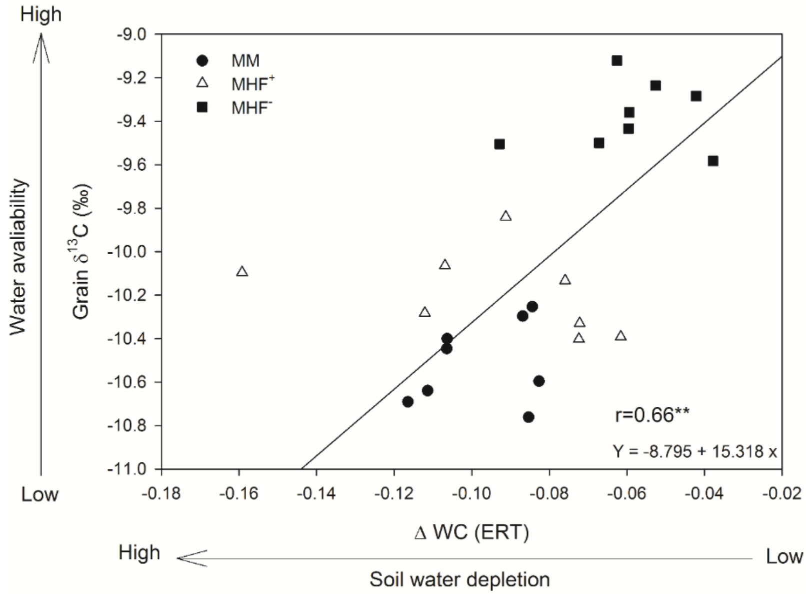

Figure 22 Relationship between grain stable carbon isotope discrimination and ΔWC (ERT) measured on 29th August 2011 (here Δ WC is the difference between actual water contents on 29th August 2011 and initial water contents, which was set zero to calculate soil moisture depletion of a specific date). Data were recorded during the 2011 growing season at Queen Sirikit Research Farm, Ratchaburi province, Thailand.

3.3.2 Discussion

Contour hedgerow and alley cropping systems maintain and improve crop production on relatively fertile soils (Mugendi et al., 1999), while on low fertile soils hedges may affect crop production negatively as shown by our results despite inputs from biological N_2 fixation and recycling of nutrients from deeper soil layers (Rowe et al., 1999). Hedges often compete for light, nutrients and water with crop rows close to them. In principle, tree roots may have access to water in deeper soil layers which matters in water limited environments (Ong et al., 2002). Light was mentioned as an important factor in reducing yields of maize plants close to trees due to shading (Everson et al., 2004). In our study, hedges were pruned four times at 0.5 m height during the maize growing season. Competition for light and shading effects, especially between hedges and maize rows adjacent to them, can therefore be excluded; hence, we focused on water and N competition. The other point which we planned to consider before setting up the experiment was to assess the interaction between maize and chili. Chilies, however, were infested by Cercospora leaf spot at around 15-20 days after transplanting, which even later created defoliation of chili plants. Adjacent maize rows benefitted from the disease infestation of chilies without profound interaction with each other.

3.3.2.1 Water competition

The results of our study did not confirm that competition for water between species was a driving force for yield formation in this study. This was supported by the observation that over the whole plot water use was highest in the maize monocrop system as confirmed by the ERT spatial results as well as the TDR moisture patterns. This was due to a higher number of maize rows and, therefore, the total number of maize plants in the monocropping treatment with a higher mean LAI and plant height, inducing strong soil moisture depletion while in the MHF^+ treatment mean LAI was reduced due to poor plant development in maize rows growing close to the hedgerows. In MHF^+, maize growing next to chili rows apparently depleted soil water content to a lower extend compared to maize monocrop at a similar position along the slope. This was because of the lower soil water demand by poorly developing chilies nearby, resulting in an associated sparing effect leading to enhanced total soil moisture under these maize rows. In contrast, in case of maize growing in rows close to the hedge soil moisture depletion was larger than under maize next to chili (Figure 16). Soil moisture depletion at the crop-hedge interface was not only due to water use by maize but also by Leucaena hedges, as their roots intercepted with maize roots in maize rows close to them. However, combined soil water use in the hedge system was still lower compared to the maize monocrop. Hence, it seems unlikely that the observed decrease of maize dry matter production in rows next to the hedges was due to severe water deficiency induced by competition from water scavenging Leucaena roots (Figure 14). Heterogeneous soil moisture depletion patterns in both hedge intercrop treatments with and without fertilization were found due to mixed cropping with various root architectures. This induced heterogeneity in water uptake or depletion as shown by the ERT images. Pansak et al. (2007) indicated the existence of such a spatial impact of hedges on water and nutrient uptake but were not able to show its impact over time.

In MHF^+, maize in rows close to hedges had lower AGB and GY as well as less negative grain $\delta^{13}C$ or equal leaf $\delta^{13}C$ values than maize grown in rows distant to hedges (Table 11, Figure 20), indicating that water availability was not the cause of poorer maize performance. This was supported by $\delta^{13}C$ signals and ΔWC (ERT) of the unfertilized hedge-intercrop treatment (MHF^-), i.e., MHF^- showed least negative $\delta^{13}C$ signals with lowest soil

moisture depletion. Fertilizer application was the only difference between MHF^+ and MHF^-; hence, we concluded that the lack of fertilizer in MHF^- induced less negative $\delta^{13}C$ signals. The objective of using MHF^- treatment was further to separate the effect of N on $\delta^{13}C$ to that of water effect. Therefore, we concluded that water was not a major factor reducing maize growth and AGB and GY production in maize rows close to hedge in MHF^+. This is in accordance to the studies of Clay et al. (2001a) and Pansak et al. (2007).
In contrast, mean maize grain $\delta^{13}C$ signals were significantly more negative in MM (Table 11), pointing to drier soil conditions (Clay et al., 2001a; Dercon et al., 2006a; Pansak et al., 2007; Wang et al., 2012) with larger soil moisture depletion. (Figure 16). On the other hand, the lower moisture contents and higher soil moisture depletion in maize MM treatments than MHF^+ as shown by TDR and ERT data may also be partly due to soil tillage effects. In MM, the soil was tilled, reducing the soil's capacity to conserve the moisture to some extent while minimum tillage associated with Jack bean relay cropping and subsequent mulching may have improved the soil structure (Pansak et al., 2010). Another point lowering depletion of soil moisture in MHF^+ by maize was probably due to a better moisture conservation by hedgerows slowing down water runoff, additionally facilitating water infiltration (Pansak et al., 2008).

3.3.2.2 Nutrient competition

Pansak et al. (2007) proposed a framework to distinguish between nutrient and water competition based on a relationship between ^{13}C isotopic discrimination and NO_3^-–N availability for maize and mentioned that both factors were inversely proportional to each other. To apply this concept, we examined the $\delta^{13}C$ behaviour in the unfertilized hedge intercrop treatment (MHF^-) to evaluate the changes in $\delta^{13}C$ as affected by nutrient unavailability. Grain $\delta^{13}C$ signals of MHF^- treatment were significantly less negative with a lower maize production than those of the fertilized hedge intercrop treatment (MHF^+) (Table 11). As fertilization was the only difference between both treatments the less negative grain $\delta^{13}C$ values associated with a poor maize biomass production points to a lack of nutrients which limited maize growth. Furthermore, ERT data revealed the lowest soil moisture depletion pattern in MHF^- indicating higher soil moisture availability than even under the productive MM and central rows of MHF^+ suggesting that water stress was not likely a major factor of reduced maize growth in MHF^-. Hence, these results indicated that a reduced fertilization induces less negative grain $\delta^{13}C$ signals. In MHF^+, maize rows close to hedgerows also had significantly less negative grain $\delta^{13}C$ values with lower biomass production than maize rows grown distant to the hedge, showing similar grain $\delta^{13}C$ and production behaviour as observed under unfertilized conditions. This is another indicator for nutrient limitation between hedges and maize rows grown close to them. These results were in accordance with Pansak et al. (2007), who studied hedgerows and grass barrier effects on ^{13}C isotopic composition of maize. Their study also pointed to N deficiency as a major reason of maize yield declines in rows close hedgerows and grass barriers. Moreover, maize rows close to hedgerows produced less aboveground biomass with lower total N concentrations in grains also indicating low N availability in these rows. On the other hand, higher total grain N concentration of maize grown in rows distant to hedgerows in MHF^- as compared to maize grains from MM was possibly due to scavenging of N from the chili area and also due to Leucaena hedgerow prunings left on the soil surface as green manure. Thus, $\delta^{13}C$ signals are influenced by both water and nitrogen availability, with nitrogen being the main driver of changes in carbon isotopic signatures in our case. Furthermore, the fact that leaves taken at 100 DAS did not show yet significant $\delta^{13}C$ effects between rows close/distance to hedge suggests that nutrient limitation increased particularly during later stages of maize development, with grain $\delta^{13}C$ values being a cumulative stress indicator. The natural log response ratio of nitrogen ($LnRR_N$) also indicated a negative impact of hedges on maize in rows close to it by competing for nitrogen in MHF^+ (Figure 19). Hence, the absence of fertilizer, especially nitrogen, was most likely the reason of less negative grain $\delta^{13}C$ signals in the MHF^- treatment, which also led to lower water use by maize proved by ΔWC (ERT) soil moisture depletion patterns. Many studies pointed out negative effects of reduced nitrogen availability on plant growth, especially on LAI development (Muchow, 1988; McCullough et al., 1994). Lack of nitrogen will ultimately decrease LAI in maize (McCullough et al., 1994). This was the main reason for a reduced LAI development in the unfertilized hedge intercrop treatment, which in consequence, reduced plants ability to use the water efficiently as well as reducing their water demand. On the other hand, grain nitrogen concentration depends on the crop grown (Lemaire and Gastal, 2009), particularly on its source and sink relationship. Plant vegetative parts act as source for grain nitrogen and large amounts of nitrogen are stored in these vegetative parts just before grain filling stage (Barbottin et al., 2005; Schiltz et al., 2005). So, any positive or negative change in the source sink relationship will ultimately affect grain nitrogen concentration. As plant growth was restricted by nutrient (e.g., N) limitations in all maize rows of unfertilized hedge intercrop treatment and also of maize in rows close to hedgerows in fertilized hedge intercrop treatment, this reduced the source of nitrogen to be transferred to grains (Lhuillier-Soundélé et al., 1999) in these treatments. That is why grain nitrogen concentrations were quite low in maize rows close to hedges with lower aboveground biomass compared to distant maize rows in MHF^+ and MHF^- treatments (Figure 18).

3.3.2.3 Carbon isotopic discrimination and electrical resistivity tomography imaging

Carbon isotopic discrimination and ERT imaging results showed a significant correlation to each other. Although the correlation was not too strong, the results showed that maize rows with low soil moisture depletion had less negative grain $\delta^{13}C$ signals. The trend also showed that the unfertilized hedge intercrop treatment depleted soil moisture least, which was clearly supported by grain carbon isotopic discrimination ($\delta^{13}C$) having least negative signal in all MHF^- maize rows, while maize monocrop depleted soil moisture strongly resulting in more negative grain $\delta^{13}C$ signals. Several issues affected the correlation between both methods. First, ERT soil moisture depletion patterns were measured by the electrodes installed along the slope having electrodes on one side of the rows while grain $\delta^{13}C$ samples were collected from eight out of sixteen plants per row. Second, ERT soil moisture depletion was monitored from 28 to 80 DAS of maize, while $\delta^{13}C$ measured from maize grains at harvest represented the entire maize growth period. Third, ERT soil moisture depletion showed that within MHF^+, maize rows close to hedgerows depleted soil water content most strongly, but this zone was not only used by maize. Leucaena roots were found below maize rows adjacent to the hedge (Figure 14). Consequently, the less negative grain $\delta^{13}C$ of these maize rows allowed distinguishing nutrient from water competition. The two methods may show an even stronger correlation if both $\delta^{13}C$ and ERT soil moisture depletion measurements would be taken from same plants at the same time, hence holding great promise for future investigation in such crop-soil-tree interfaces.

Chapter 4

General Discussion

Chapter 4 General Discussion

The demand for low cost animal fodder and biofuels (Shiferaw et al., 2011) have been increasing together with food demand of a growing population (Rerkasem et al., 2009) are active drivers of land-use change in Southeast Asia. Hence, traditional shifting cultivation with long fallow periods has been widely replaced by permanent maize monocropping systems in Southeast Asia's mountainous mainland. Combined with inappropriate land use, this is one of the leading causes of negative impacts on agricultural productivity due to soil degradation processes such as soil loss and nutrient depletion, especially nitrogen (N) (Ogunlana et al., 2010; Hilger et al., 2013; Bindraban et al., 2012). Conservation agriculture based on either minimum tillage and cover crops or contour hedgerow intercropping systems or a combination of both have been developed and recommended to improve nitrogen use efficiency (NUE), N balance and crop yield. However, hedgerows' presence may negatively impact crops grown close to them due to competition that occurs aboveground for light and belowground for nutrients and water. Therefore, there is the need to understand better the use efficiency of fertilizer N, its translocation and fate, and crop performance at plot level and resource use competition between crops and hedgerows affected by conservation measures for designing sound soil conservation systems and practices and enhancing farmers' acceptance on sloping terrain in Southeast Asia.

4.1 Does soil conservation agriculture improve N fertilizer use efficiency and economic returns?

The initial hypothesis that intercropping systems, with or without conservation measures, increase nitrogen fertilizer use efficiency by reducing

N losses, providing filter functions to capture and recycle N fertilizer and improving crop growth was partly supported as maize intercropped with chili (T2) had a slightly higher total plant system ^{15}NUE (56.8%) of fertilizer applied to maize than farmers' practice (T1) with maize mono-crop (53.8%). This improved NUE may be further explained by the fact that a higher light use efficiency (LUE), growth, and maize yield in T2 compared with T1 have been observed by Hussain et al. (2020) in this trial due to a low interspecific competition by chili. In both systems, the majority of the fertilizer N was recovered by maize at the application position of ^{15}N-labelled fertilizer, being 47% in T1 and 53.5% in T2. Downward movement of ^{15}N-labelled fertilizer around 4.6% was recovered by maize located at lower slope positions in T1. In comparison, chili and maize in T2 were not able to exert a major filter slope function to catch downward-moving N, accounting only for around 0.3% and 0.4%, respectively. Alterations in N losses via runoff, erosion, and subsurface later movement were below the detection limit. Further confirmation of a higher NUE in intercropping was a reduction of total unaccounted N losses in maize-chili intercropping (46.4%) as compared to the maize sole cropping system (53.2%).

The addition of conservation measures in T3 and T4 in which minimum tillage and relay cropping with Jack bean with or without Leucaena hedgerows were implemented did not increase ^{15}N fertilizer use efficiency of maize or that of the total plant system compared to farmers practice. This is contrary to our initial hypothesis. The most reasonable explanation for this finding is that farmers practice already included an appropriate fertilizer application at the right place (banded next to plants) and time (Pisante et al., 2012; Snyder et al., 2009). Secondly, low rainfall during juvenile maize growth led to a very low downslope translocation of fertilizer N and thereby minimized potential positive effects of the filter functions in intercropping and agroforestry systems. This is confirmed by the observed high ^{15}N-labelled urea recoveries by maize (^{15}NFR) at the row of ^{15}N-labelled fertilizer application of 45.5% to 53.5% in the first season. These values compare well with the 49.6% ^{15}N-fertilizer recovery by maize in a Leucaena alley cropping system in Australia observed by Xu et al. (1993). Under less favorable management and environmental conditions, much lower N fertilizer recoveries by maize are commonly found in tropical ecosystems, for example, 8-16% in Nigeria (Akinnifesi et al., 1996) and 12-21% in Nepal (Pilbeam et al., 2002). Lower LUE and growth of maize under conservation measures in this trial (Hussain et al., 2020) further caused a ^{15}NUE reduction in maize and the total plant system (maize grain + chili fruit + N recycled) in T3 (46.9 and 47.8%, respectively) and T4 (50.5 and 51.8%, respectively) as compared to T2. This finding is also in agreement with Rowe et al. (2005). They observed that hedgerows adversely affected crop growth through competition, and hence the mixed-species system (22-33%) did not improve the combined plant NUE as compared to the maize monocropping system (42%). Although fertilizer N was applied, the primary source of N for maize was the soil. N derived from the soil (Ndfs = 100 - Ndff) to the AGB of maize was 82.3% in T1, 81.6% in T2, 82.1% in T3 and 71.9% in T4 of the total N assimilated by maize at the application row of ^{15}N-labelled urea. Our results are consistent with maize ^{15}N fertilizer recovery studies of Stevens et al. (2005), Dourado-Neto et al. (2010) and Rimski-Korsakov et al. (2012), in which the majority of plant N was from the soil. Moreover, they revealed that the N's proportion from the soil was related to the N fertilizer dose and soil N fertility. These underline the importance of SOM as an N source for crop production. It also implies that agricultural practices with residue mulch, cover crop and legume mixed intercropping systems that can conserve or even increase SOM are crucial for tropical hillside agriculture.

In the first cropping season, the total ^{15}N-labelled fertilizer recovery (^{15}NFR) by Leucaena prunings from six pruning events was 0.13% for the middle and 0.09% for the lower hedgerows. Low ^{15}NFR was also observed by maize (0.09% and 0.02%) in T1, by chili (0.04%) and maize (0.01%) in T2, and by chili (0.03%) and maize (0.07%) in T3 at the similar slope positions with the middle and the lower hedgerows, respectively. Incorporating fertilizer to the soil and low rainfall at the start of the growing season were reasons for very low downslope translocation of fertilizer N. Leucaena hedges; despite showing potential for filter functionality in capturing and recycling downward-moving N, its positive impacts were offset by their strong competition with maize for N, causing low absolute yields and N uptake of maize. Absolute maize aboveground biomass (AGB) and N uptake of the ^{15}N-labelled fertilizer application row increased in the order T4 < T3 < T1 < T2, being 912, 1,302, 1,392 and 1,501 g m^{-2} and 11.1, 16.4, 16.6 and 19.9 g N m^{-2}, respectively. Possible strategies to improve this hedgerow cropping system, therefore, are (i) extending the space between maize and hedges, (ii) using other hedge species with lower nutrient (N) demand, or (iii) applying site-specific nutrient management, which increases fertilizer supply to maize in rows close to hedgerows. Imo and Timmer (2000), using vector competition analysis comparing three between-alley spacings (2, 4 and 8 m) in maize-Leucaena hedgerows systems in Kenya, revealed the greatest competition for moisture and/or light in 2 m alleys and for N in 8 m alleys, causing a lower maize yield as compared to sole crop maize. On the other hand, the highest maize productivity and N uptake were observed in 4 m alleys with fertilization (N and P), reflecting the synergistic effects of the trees (Leucaena), possibly due to increased N mineralized from the mulch added as pruning. The Simulation runs with the Water, Nutrient, Light Capture in Agroforestry Systems model by Hussain (2015) using a data set from this study indicated that small targeted N and P dressings to maize in rows close to the hedgerows helped to overcome nutrient competition at the crop-soil hedge interface. Results support the idea that tree density, spacing and fertilizer application can be optimized to balance facilitation and competition effects in alley cropping designs (Imo and Timmer, 2000). These are key for fostering the adoption of alley cropping on tropical hillsides to sustain maize production.

The hypothesis that maize-chili intercropping systems give higher economic returns to farmers than maize sole cropping due to the high price of fresh chili fruit was supported since the total returns from commercial maize and chili yields in intercropping systems were higher than those of maize sole cropping in the first season, being 1,914, 5,129, 3,829, 3,900, 3,494, and 2,976 USD ha^{-1}, for T1, T2, T3, T4, T5 and T6 respectively. These higher returns were mainly due to the high price of fresh chili fruit (1.3 USD kg^{-1}), while the price of maize grain was low at only 0.3 USD kg^{-1}. Therefore, farmers benefit from higher returns of maize and chili products in the intercropping system already in the short run.

4.2 Are intercropping systems effective in improving N balances and decreasing production risks?

The study presented in Section 3.2 was designed to evaluate the effect of maize-based cropping systems on the fate of fertilizer ^{15}N and plot N balances. Overall fertilizer ^{15}N recovery of plants was 47.8-56.8% over the first season, while residual fertilizer ^{15}N recovery of plants was only 2.3-4.9% over the subsequent season. The residual fertilizer ^{15}N recovery by plants was relatively small, indicating that the labelled portion of the organic N pool had begun to stabilize and become more resistant to mineralization after one year (Stevens et al., 2005). The quantities of applied labelled N remaining in the soil at the end of season 1 and season 2 ranged from 6.2-28.1% and 7.7-28.6%, respectively. The applied fertilizer ^{15}N accounted for within the plant-soil system was 60.0-76.0% in season 1 and 12.7-31.3% in season 2. Consequently, 24.0-40.0% and 12.9-16.1% of labelled fertilizer N were not accounted for at the end of season 1 and season 2, respectively.

The overall total labelled N balances, as indicators of agricultural production's sustainability, were -201.9 kg N ha^{-1} in T1, -4.8 kg N ha^{-1} in T2, +87.2 kg N ha^{-1} in T3, +62.2 kg N ha^{-1} in T4, -86.2 kg N ha^{-1} in T5, and -48.2 kg N ha^{-1} in T6 over the 2-year cropping season. The most severe soil N depletion was found under maize sole cropping with conventional tillage and low N fertilizer rate (current farmers' practice or T1) and maize-chili intercropping under conservation measures without N fertilization (T5 and T6). Despite an increased N fertilizer use efficiency (56.8%), reduced unaccounted N losses (30.2%) and a high N fertilizer application rate for chili were noticed in the maize-chili intercropping with conventional tillage (T2), the labelled N balance over two years was still slightly negative. Negative N balances, especially those in T1, T5 and T6, pose a major challenge in developing sustainable agricultural production and call for alternative approaches to improve N balances. Tilman et al. (2002) recommended that conservation measures such as minimum-tillage, cover crops, residue application and mixed cropping systems together with balanced fertilizer application can help to maintain and restore soil fertility. In this study, the observed positive labelled N balances of maize-chili intercropping with conservation measures and fertilization (T3 and T4) were mainly associated with (i) the increase of N input via additional N fertilizer applied to chili and symbiotic N_2 fixation of legumes, and (ii) the reduction of N losses by soil erosion and unaccounted fertilizer N.

Maize-chili intercropping with fertilization showed a Land Equivalent Ratio advantage (LER > 1.0) relative to sole species cropping as found in T2, T3, and T4 (1.17, 1.03, and 1.22, respectively) but only in the second season. In contrast, a relative disadvantage of intercropping was observed in a field experiment in subtropical China where LER values of the soybean-false indigo and soybean-vetiver hedgerow systems were 0.96 and 0.99, respectively (Guo et al., 2008). On the other hand, similar to our observations, positive intercropping effects for maize-faba bean were detected in China's field experiments, with LER values of 1.13–1.34 based on grain yield. A Land Equivalent Ratio (LER) greater than 1.0 indicates a better utilization of the environment resources by the intercrop crops compared to the sole crops (Guo et al., 2008), or interspecific facilitation (or complementarity) is more robust than the interspecific competition (Li et al., 1999). A low interspecific competition with higher LUE, growth, and yield (Hussain et al., 2020) was possibly the main reason for some yield advantage in maize-chili intercropping with fertilization relative to sole cropping.

Based on the first season's price and yield of crops explained above (Section 4.1), farmers may prefer to cultivate chili in monocropping (7,641 USD ha^{-1} in season 1) instead of maize-chili intercropping to get the next season's highest returns. But chili growth and yield were extremely low in the chili monocrop system due to pest and disease attack in the second season. Thus, total returns for T1, T2, T3, T4, T5, and T6 were 1,918, 1,818, 1,612, 1,946, 1,378 and 1,550 USD ha^{-1}, respectively, which were higher than chili sole cropping (1,321 USD ha^{-1}). These results indicate the crucial role of intercropping systems that decrease production risk by reducing the chance of yield losses by pests (Craswell et al., 1997) as observed in chili plants under monocropping system (83% yield reduction). As for crop rotation, it is the agronomic practice of growing a series of crops sequentially over time on the same land and being considered as an environmentally friendly approach for sustainable agriculture with several benefits such as lower incidence of weeds and pests as well as improvement of soil properties (Zhao et al., 2020). “Never plant the same crop in the same place twice” is the basic form of crop rotation resulting in naturally breaking the cycles of insects and diseases that damage food crops (Chaddad, 2016). Therefore, an alternative practice for farmers in our field site is a maize-chili rotation that may potentially give greater yield benefits and mitigate insect and pathogen pressure. However, intercropping with Leucaena hedgerows is still a good choice because it can additionally provide many advantages that trees may provide for the sustainability of long-term agroforestry systems in mountainous areas such as soil loss and runoff reductions (Van Noordwijk and Purnomosidhi, 1995; Pansak et al., 2007).

In this study, the isotope technique using ^{15}N enriched fertilizer (urea) proved to be a novel tool for the spatiotemporal observations of fertilizer N recovery, upward- and downward-movements, and losses under maize-based cropping systems. The N budgets using ^{15}N labelling described in this experiment provide useful information to farmers and policymakers on soil N fertility on Thailand's sloping lands. However, the different N flows that need to be quantified to estimate soil N balances are specific to every spatiotemporal pattern (Stoorvogel and Smaling, 1998). Moreover, visualizing a positive effect on crop productivity and soil fertility depends on the time needed to develop the systems governed by the site's biophysical conditions and the farm management done by the farmers (Douxchamps et al., 2010). Hence, further research needs to involve an in-depth study on soil N fluxes, including (i) N losses via denitrification, leaching, and gaseous emissions, (ii) belowground N contribution of the legumes, and (iii) soil N mineralization rate, to allow better estimates of N balance on sloping arable lands.

Taken together, these results suggest that there are significant positive interactions between mineral N fertilizer cycling, intercropping systems, and soil conservation measures in maintaining or improving crop yields and N balances in Thailand’s hillside agriculture. Therefore, sustainable agriculture might be achieved if farmers in Thailand combine intercropping with soil conservation measures and N fertilizer's appropriate use.

4.3 Is nitrogen or water the driving force of belowground competition in hedgerow intercropping?

The study shown in Section 3.3 was intended to identify the driving forces (nutrients or water) of below-ground competition between crops and hedgerows at the crop-soil-hedgerow interface. Observed ^{13}C discrimination data is affected by soil water availability and N levels (Clay et al., 2001a; Dercon et al., 2006a). In C_4 plants, decreasing $\delta^{13}C$ (more negative values) is the response of an increase in water stress while increasing $\delta^{13}C$ (less negative values) are the response of a decrease in N availability because N stress reduces the photosynthesis capacity of plants (Clay et al., 2001a; Hussain, 2015). In this study, under Leucaena hedgerows intercropping with (T4) and without (T6) fertilizer application in which grain $\delta^{13}C$ values in the maize rows planted closed to hedgerows (-10.33 in T4 and -9.21 in T6) were higher (less negative) as compared with maize rows planted distant to hedgerows (-

10.64 in T4 and -9.43 in T6). Moreover, higher $\delta^{13}C$ values were observed in T6 than T4 and maize monocropping (T1). These results suggested that a lack of fertilizer application inducing higher $\delta^{13}C$ values and supported the statement that nutrient competition led to an increase in maize grain $\delta^{13}C$ values. Electrical resistivity tomography (ERT) is a non-invasive technique for monitoring the spatiotemporal distribution of soil water content in a wide range of cropping systems (Garré et al., 2012), which cannot be simply achieved by other soil moisture measurements. Soil moisture depletion patterns measured by ERT revealed lower water depletion under unfertilized treatment (T6) as nutrients constraint hindered plant water uptake. These observations support the report that higher $\delta^{13}C$ indicated higher water availability (Clay et al., 2005). Thus, water was not a primary limiting factor for reducing the growth, and biomass production of maize in rows planted close to hedgerows in T4.

Eventually, combining the results of $\delta^{13}C$ and ERT measurements was possible to show that the reduced maize yield in rows close to hedgerows was due to a lack of N and not due to a lack of water. This argument was confirmed by time domain reflectometry (TDR) soil moisture data of lower soil moisture contents and higher soil moisture depletion in T1 than T4. Moreover, the natural log response ratio of N ($LnRR_N$) further indicated a negative impact of hedgerows on maize in rows located close to them by competing for N (Hussain, 2015). N concentrations in grain were also relatively low in maize rows planted close to hedgerows with lower aboveground biomass than distant maize rows in both T4 and T6. Therefore, nutrient competition, especially for N, was most likely the reason for higher $\delta^{13}C$ values, poor growth and yield performance of maize in rows close to hedgerows in T4 (Vanlauwe et al., 2001). The proposed framework by Pansak et al. (2007), using a relationship between ^{13}C isotopic discrimination and soil N availability to distinguish between nutrient and water competition, also pointed to N competition between maize and hedgerows in their experiment.

The results showed that having only $\delta^{13}C$ values is not sufficient because both water and nutrient deficiency affect ^{13}C discrimination in plants. It requires additional water availability measurements to aid the separation of water and nutrient stress in mixed cropping systems. Therefore, the combination of carbon isotopic discrimination and ERT imaging proved to be valuable tools in understanding and distinguishing water competition from N competition at this complex interface.

Such experiments would help fine-tune crop management of hedgerow-based soil conservation systems to alleviate nutrient competition by developing specific fertilizer recommendations to conquer the nutrient gap close to tree hedges. Successful solutions to overcome these constraints may foster farmers' adoption of hedgerow-based soil conservation measures, which are needed for reducing soil erosion, leading to more sustainable land use in tropical hillside agriculture in the long run. Data of such studies are also required for validating spatially explicit agroforestry models in terms of nutrient and water competition, such as the Water, Nutrient, Light Capture in Agroforestry Systems model (Van Noordwijk and Lusiana, 1998). For contour hedgerows in Thailand, Howeler et al. (2004) concluded that the keys to adoption included (i) the use of a farmer participatory approach for technology development and dissemination and (ii) a combined package of suitable practices and technologies adapted to local conditions that may produce immediate financial benefits such as new varieties and cash crops together with fertilizers applications for reducing nutrient competitions between hedges and crops. Moreover, lack of knowledge about alley cropping systems is a major hindering factor in adopting this method; hence, more soil scientists and researchers should effectively disseminate information on the benefits and practices used to establish alley farms to Thai farmers.

4.4 Outlook

The calculated negative to positive N budgets using ^{15}N labelling described in this experiment provide useful information to farmers and policymakers for maintaining and restoring soil nitrogen fertility in Thailand's sloping lands. However, the different N flows that need to be quantified to estimate soil N balances are specific to every spatiotemporal pattern (Stoorvogel and Smaling, 1998). Moreover, visualizing a positive effect on crop productivity and soil fertility depends on the time needed to develop the systems governed by the site's biophysical conditions and the farm management done by the farmers (Douxchamps et al., 2010). Hence, further research needs to involve an in-depth study on soil N fluxes, including (i) N losses via denitrification, leaching and gaseous emissions, (ii) belowground N contribution of the legumes and (iii) soil N mineralization rate, to allow better estimates of N balance on sloping arable lands. Findings of carbon isotopic discrimination and ERT imaging trends supported each other, but their correlation was low. The following issues should be considered during such types of experiments: $\delta^{13}C$ samples should be collected from the maize plants growing next to the ERT electrode to account for spatial heterogeneity. $\delta^{13}C$ samples should also be collected simultaneously to ERT soil moisture measurement. Field experiments with soil conservation measures preferentially should be conducted for more extended periods for reliable broadcasting of these fine-tuned management practices to the farming community for long term sustainable agriculture. However, such long-term experiments are expensive and time consuming to obtain the necessary knowledge. Therefore, an alternative method for conquering this lack of real information is exploiting current improved process knowledge to develop better models such as the Water, Nutrient, Light Capture in Agroforestry Systems model (WaNuLCAS) to test more effective management solutions in the short- and long-run (Hussain et al., 2015a).

Summary

The increase in food demand and land scarcity in high-potential lowland areas have forced cropping intensification with a transformation of land use from subsistence to permanent agriculture in remote hillside in Southeast Asia. This change and inappropriate land use are the prime cause of soil degradation by erosion, which have negatively affected the agricultural system's productivity and sustainability in Thailand. Therefore, vulnerable land in sloping terrain is classified as unsuitable for continuous production of arable crops unless conservation measures are introduced to stabilize the landscape. Even though conservation practices can stabilize sloping land, farmers have not been widely adopted the measures due to various constraints, such as crop area loss and crop-tree competition. To improve land use management, a two-year study (2010-2011) was conducted at the Queen Sirikit research station (13°28’N, 99°16’E), Ratchaburi Province, Thailand, on a hillside with a slope of around 20%. The treatments consisted of (T1) maize (*Zea mays* L.) mono-crop under tillage and fertilization, (T2) maize intercropped with chili (*Capsicum annuum* L.) under tillage and fertilization, (T3) maize intercropped with chili, application of minimum tillage plus Jack bean (*Canavalia ensiformis* (L.) DC) relay cropping and fertilizer application, (T4) maize intercropped with chili, application of minimum tillage with Jack bean relay cropping and fertilizer application plus perennial hedges of *Leucaena leucocephala* (Lam.) de Wit, (T5) as T3 but without fertilization, and (T6) as T4 but without fertilization. There was an additional plot of chili sole cropping to calculate the land equivalent ratio (LER).

The first part of the study evaluated yield performance and nitrogen use efficiency (NUE) of crops using the ^{15}N isotope technique under diverse

fertilized cropping systems during the first year. Maize grain yields were lower in T2 (3.1 Mg ha^{-1}), T3 (2.6 Mg ha^{-1}) and T4 (3.3 Mg ha^{-1}) than in the control (T1) (6.7 Mg ha^{-1}). The total returns from maize and chili yields were 1,914, 5,129, 3,829, 3,900, 3,494, and 2,976 USD ha^{-1}, for T1, T2, T3, T4, T5 and T6, respectively. Higher economic returns in mixed crop systems, by selling both maize and chilies, compensated for the maize area loss by intercropping. Maize ^{15}NUE was highest in T2 (53.5%), being significantly higher than in T1 (47.0%), T3 (45.5%), and T4 (45.7%). Overall system's NUE in T2 (56.8%) was comparable to T1 (53.8%) and T4 (54.5%) but significantly lower in T3 (48.6%). Minimum tillage and hedgerows (despite their positive filter effect) did not increase NUE but adversely affected maize growth during the establishment phase.

The second part of the study examined nitrogen fertilizer's fate and quantified partial nitrogen budgets at plot level over two cropping seasons for various maize-based cropping systems with or without fertilizer application. Overall plant uptake of fertilizer ^{15}N applied to maize was 48.6-56.8% over the first season, while residual fertilizer ^{15}N recovery of plants was only 2.3-4.9% over the subsequent season. The quantity of applied labelled N remaining in the soil at the end of season 1 and season 2 was 6.2-28.1% and 7.7-28.6%, respectively. Thus, 60.0-76.0% in season 1 and 12.7-31.3% in season 2 of the applied fertilizer ^{15}N were accounted for within the plant-soil system. Consequently, 24.0-40.0% and 12.9-16.1% of labelled fertilizer N were not accounted for at the end of season 1 and season 2, respectively. The derived N balance over two years revealed severe soil N depletion under T1 (-202 kg N ha^{-1}), T5 (-86 kg N ha^{-1}) and T6 (-48 kg N ha^{-1}), and a slightly negative N budget under T2 (-5 kg N ha^{-1}). In contrast, T3 (87 kg N ha^{-1}) and T4 (62 kg N ha^{-1}) had positive N balances. The increase of N input via additional N fertilizer applied to chili and symbiotic N_2 fixation of legumes, and the reduction of N losses by soil erosion and unaccounted fertilizer N (probably lost via leaching, volatilization and denitrification) were the main factors of the positive N balances under maize-chili intercropping systems with conservation measures and fertilization (T3 and T4). Maize yield decline under T1, T2, T5 and T6 in season 2 was related to negative N balances, while maize yield increase under T3 and T4 was related to positive N balances. However, maize-chili intercropping with fertilization had some advantage (LER > 1.0) relative to sole species cropping. Moreover, total returns from crop yields in season 2 of all maize-chili intercroppings (1,378-1,818 USD ha^{-1}) were higher than chili sole cropping (1,321 USD ha^{-1}), which pointed to its crucial role in decreasing production risk by reducing yield loss by pests and diseases observed in chili plants.

The third part of the study used combined data of stable isotope discrimination and electrical resistivity tomography (ERT) to improve understanding of competition at the crop-soil-hedge interface. Hedges significantly reduced maize grain yield and aboveground biomass in rows close to hedgerows. ERT revealed water depletion was stronger in T1 than in T4 and T6, confirming time domain reflectometry (TDR) and leaf area data. In T4, water depletion was higher in maize rows close to the hedge than rows distant to hedges and maize grain $\delta^{13}C$ was significantly less negative in rows close to the hedge (-10.33‰) compared to distant ones (-10.64‰). Lack of N increased grain $\delta^{13}C$ in T6 (-9.32‰, $p \leq 0.001$). Both methods were negatively correlated with each other (r= 0.66, $p \leq 0.001$). Combining ERT with grain $\delta^{13}C$ and %N allowed identifying that maize growth close to hedges was limited by N and not by water supply.

In conclusion, the results suggested a significant positive interaction between mineral N fertilizer, intercropping systems and soil conservation measures in maintaining or improving crop yields and N balances in Thailand's hillside agriculture. Simultaneously, combining ERT imaging and ^{13}C isotopic discrimination approaches improved the understanding of spatial-temporal competition patterns at the hedge-soil-crop interface and pointed out that competition in maize-based hedgerow systems was driven by nitrogen rather than water limitation. Therefore, sustainable agriculture might be achieved if farmers in Thailand combine soil conservation measures with appropriate and targeted N fertilizer use.

Zusammenfassung

Der steigende Nahrungsmittelbedarf und die Landknappheit in fruchtbaren Tieflandgebieten haben zu einer Intensivierung des Anbaus in abgelegenen Berggebieten in Südost Asien geführt. Dieser Wandel und die unangemessene Landnutzung durch annuelle Monokulturen sind die Hauptursache für die vorherrschende Bodendegradation durch Wassererosion, die sich negativ auf die Produktivität und Nachhaltigkeit des landwirtschaftlichen Systems in Thailand ausgewirkt hat. Daher wird gefährdetes Land in Hanglagen als ungeeignet für den kontinuierlichen Anbau von Ackerfrüchten eingestuft, es sei denn, es werden Erhaltungsmaßnahmen zur Stabilisierung der Landschaft eingeführt. Obwohl Naturschutzmaßnahmen die Hanglage stabilisieren können, werden sie von den Landwirten aufgrund verschiedener Einschränkungen, wie z.B. Verlust von Anbauflächen und Konkurrenz zwischen Pflanzen und Bäumen, nicht in großem Umfang angenommen. Um das Landnutzungsmanagement zu verbessern, wurde eine zweijährige Studie (2010-2011) an der Queen Sirikit Forschungsstation (13°28'N, 99°16'E), Provinz Ratchaburi, Thailand, an einem Hang mit einer Neigung von etwa 20 % durchgeführt. Die Behandlungen bestanden aus (T1) Mais (*Zea mays* L.) als Monokultur unter traditioneller Bodenbearbeitung und mineralischer Düngung, (T2) Mais mit Chili (*Capsicum annuum* L.) als Zwischenfrucht unter traditioneller Bodenbearbeitung und Düngung, (T3) Mais mit Chili als Zwischenfrucht, Anwendung von minimaler Bodenbearbeitung sowie Gründungung mit Jack Bean (*Canavalia ensiformis* (L.) DC) und mineralischer Düngung, (T4) Mais mit Chili als Zwischenfrucht, minimaler Bodenbearbeitung mit Jack Bean als Gründungung und mineralischer Düngung und zusätzlich mehrjährige Hecken aus *Leucaena leucocephala* (Lam.) de Wit, (T5) wie T3, aber ohne mineralische Düngung, und (T6) wie

T4, aber ohne mineralische Düngung. Eine zusätzliche Parzelle mit Chili-Alleinkultur diente dazu um das Landäquivalentverhältnis (LER) zu berechnen.

Der erste Teil der Studie bewertete die Ertragsleistung und die Stickstoffnutzungseffizienz (NUE) der Nutzpflanzen unter Verwendung der ^{15}N-Isotopentechnik unter den verschiedenen gedüngten Anbausystemen im ersten Jahr. Die Kornerträge von Mais waren in T2 (3,1 Mg ha^{-1}), T3 (2,6 Mg ha^{-1}) und T4 (3,3 Mg ha^{-1}) niedriger als in der Kontrolle (T1) (6,7 Mg ha^{-1}). Die gesamten Einnahmen aus Mais- und Chili-Erträgen betrugen 1.914, 5.129, 3.829, 3.900, 3.494 und 2.976 USD ha^{-1} für T1, T2, T3, T4, T5 bzw. T6. Höhere wirtschaftliche Erträge in Mischkulturen, durch den Verkauf von Mais und Chili, kompensierten den Maisflächenverlust durch den Zwischenfruchtanbau. Die Mais-NUE war in T2 (53,5%) am höchsten und damit signifikant höher als in T1 (47,0%), T3 (45,5%) und T4 (45,7%). Die NUE des Gesamtsystems in T2 (56,8%) war vergleichbar mit T1 (53,8%) und T4 (54,5%), aber signifikant niedriger in T3 (48,6%). Minimale Bodenbearbeitung und Hecken (trotz ihrer positiven Filterwirkung) erhöhten die NUE nicht, beeinträchtigten aber das Maiswachstum während der Etablierungsphase.

Der zweite Teil der Studie untersuchte den Kreislauf von Stickstoffdünger und quantifizierte partielle Stickstoffbudgets auf Parzellenebene über zwei Anbausaisons für die untersuchten maisbasierten Anbausysteme mit oder ohne Düngerausbringung. Die Gesamtaufnahme des bei Mais ausgebrachten ^{15}N-Düngers durch die Pflanzen betrug 48,6-56,8 % in der ersten Saison, während sie in der folgenden Saison nur 2,3-4,9 % betrug. Die Menge des ausgebrachten markierten N, die am Ende der 1. bzw. 2. Saison im Boden verblieb, betrug 6,2-28,1% bzw. 7,7-28,6%. Somit konnten 60,0-76,0 % in

Saison 1 und 12,7-31,3 % in Saison 2 des ausgebrachten ^{15}N-Düngers im System Pflanze-Boden nachverfolgt werden. Folglich wurden 24,0-40,0 % und 12,9-16,1 % des markierten N-Düngers am Ende der Saison 1 bzw. der Saison 2 nicht verbucht. Die erlangte N-Bilanz über zwei Jahre zeigte einen starken N-Entzugvom Bodenpool unter T1 (-202 kg N ha^{-1}), T5 (-86 kg N ha^{-1}) und T6 (-48 kg N ha^{-1}) und ein leicht negatives N-Budget unter T2 (-5 kg N ha^{-1}). Im Gegensatz dazu hatten T3 (87 kg N ha^{-1}) und T4 (62 kg N ha^{-1}) positive N-Bilanzen. Die Erhöhung des N-Eintrags durch zusätzliche N-Düngung von Chili und die symbiotische N_2-Fixierung von Leguminosen sowie die Verringerung der N-Verluste durch Bodenerosion und nicht bilanzierten Dünger-N (Auswaschung, Verflüchtigung und Denitrifikation) waren die Hauptfaktoren der positiven N-Bilanzen unter Mais-Chili-Zwischenfruchtsystemen mit konservierenden Maßnahmen und Düngung (T3 und T4). Der Rückgang des Maisertrages unter T1, T2, T5 und T6 in Saison 2 war mit negativen N-Bilanzen verbunden, während der Anstieg des Maisertrages unter T3 und T4 mit positiven N-Bilanzen verbunden war. Allerdings hatte der Mais-Chili Zwischenfruchtanbau mit Düngung einen gewissen Vorteil (LER > 1,0) im Vergleich zum Anbau der alleinigen Art. Darüber hinaus waren die Gesamterträge in der Saison 2 aller Mais-Chili-Zwischenfrüchte (1.378-1.818 USD ha^{-1}) höher als beim Chili-Alleinanbau (1.321 USD ha^{-1}), was auf die entscheidende Rolle des Mais-Chili-Anbaus bei der Verringerung des Produktionsrisikos durch die Reduzierung von Ertragsverlusten durch Schädlinge und Krankheiten der Chili-Pflanzen hinweist.

Im dritten Teil der Studie wurden kombinierte Daten aus stabiler Kohlenstoff-Isotopendiskriminierung und elektrischer Widerstands-Tomographie (ERT) verwendet, um das Verständnis für die Konkurrenz an der Schnittstelle zwischen Kulturpflanze, Boden und Hecke zu verbessern. Hecken reduzierten signifikant den Kornertrag und die oberirdische Biomasse von Mais in Reihen nahe an Hecken. ERT Daten zeigten, dass der Wasserentzug in T1 stärker war als in T4 und T6, was die Resultate der Zeitbereichsreflektometrie (Time Domain Reflectometry, TDR) und der Blattfläche bestätigte. In T4 war der Wasserentzug in heckennahen Maisreihen höher als in heckenfernen Reihen und das $\delta^{13}C$ Signal des Maiskorns war in heckennahen Reihen signifikant weniger negativ (10,33‰) als in heckenfernen (10,64‰). N-Mangel erhöhte das Korn $\delta^{13}C$ in T6 (9,32‰, $p \leq 0{,}001$). Beide Methoden waren negativ miteinander korreliert ($r = 0{,}66$, $p \leq 0{,}001$). Die Kombination von ERT mit Korn $\delta^{13}C$ sowie %N Daten ergab, dass das Maiswachstum in der Nähe von Hecken durch N und nicht durch die Wasserversorgung begrenzt wurde.

Zusammenfassend deuten die Ergebnisse auf eine signifikante positive Wechselwirkung zwischen mineralischem N-Dünger, Zwischenfruchtsystemen und Bodenschutzmaßnahmen bei Aufrechterhaltung oder Verbesserung von Ernteerträgen und N-Bilanzen in Thailands Bergregionen hin. Gleichzeitig verbesserte die Kombination von ERT-Bildgebung und ^{13}C-Isotopendiskriminierung das Verständnis von räumlich-zeitlichen Konkurrenzmustern an der Schnittstelle Hecke-Boden-Kultur und wies darauf hin, dass die Konkurrenz in Mais-basierten Hecken-Systemen eher durch Stickstoff- als durch Wasser-Limitierung angetrieben wird. Daher könnte eine nachhaltige Landwirtschaft erreicht werden, wenn Landwirte in Thailand Bodenschutzmaßnahmen mit einem angemessenen und platzierten N-Düngereinsatz kombinieren.

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