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Measuring and modelling resource use competition at the crop-soil-hedge interface on a hillside in Western Thailand

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List of abbreviations

ACPAR: Above canopy photsynthetically active radiation

AGB: Above ground biomass

ANOVA: Analysis of variance

B: Biomass

BCPAR: Below canopy photsynthetically active radiation

BFS: Beam fraction sensor

BNF: Biological nitrogen fixation

°C: Degree Celsius

CD: Coefficient of determination

CRM: Coefficient of residual mass

DAP: Days after planting

DM: Dry matter

EC: Electrical conductivity

EF: Modelling efficiency

ELADP: Ellipsoidal leaf angle distribution parameter

ERT: Electrical resitivity tomography

ƒPAR: Fraction of photosynthetically active radiation interception

g m^{-2}: gram per square meter

GLM: Generalized linear model

GOF: Goodness of fit

GY: Grain yield

HI: Harvest Index

IBSRAM Thailand: International Board for Soil Research and Management Thailand

IFPRI: International Food Policy Research Institute

IPAR: Intercepted photsynthetically active radiation

IRMS: Isotope Ratio Mass Spectrometry

k: Canopy extinction coefficient

LAI: Leaf area index

LDD Thailand: Land development department Thailand

LER: Land equivalent ratio

$LnRR_N$: Natural log of nitrogen response ratio

LUE: Light use efficiency

LUE_{AGB}: Light use efficiency for above ground biomass production

LUE_{GY}: Light use efficiency for grain yield production

MAS: Month after sowing

ME: Maximum Error

MJ: Mega Joule

mm: Millimeter

N: Nitrogen

NS: Not significant

Ng: Grain nitrogen concentration

NW: Northwest

P: Phosphorous

PAR: Photsynthetically active radiation

PDB: Pee Dee Belemnite

Qs: Solar radiation

RMSE: Root mean square error

TDR: Time domain reflectometry

WaNuLCAS: Water, Nutrient and Light Capture in Agroforestry Systems Model

WC: Water content

Chapter 1

General Introduction

Chapter 1 General Introduction

1.1 Background of the study

Humans obtain about 99.7% of their food calories from land and around 0.3% from aquatic ecosystems, worldwide, so crop land conservation and maintaining soil fertility for food production should be given highest importance as human welfare (Pimentel and Burgess, 2013). World's two billion hectares of agricultural land is already affected by soil degradation (Hillel et al., 2005) and each year around 10 million hectares of world's crop land are being lost due to soil erosion which directly reduces world food production (Pimentel and Burgess, 2013). Thailand is an agricultural country with a population of around 64 million estimated in 2007 and an approximately country area of 514 thousand square kilometres, of which 41% is used for agricultural purposes and around 31% is under forest while 28% of total area is considered as unclassified land. Around 39% of the total population is directly or indirectly dependent on or engaged in agriculture. The share of agriculture in country's gross domestic production is 9%. Thailand's agricultural products are not only being utilized within the country but are also exported to various countries around the world (Thailand country update report, 2010).

Rice, cassava, maize, sugarcane, oil crops and fruit trees are considered as major field crops not only for food security but also for income generation and export. Latest projections by the International Food Policy Research Institute (IFPRI) indicated that the demand for maize will overtake the demand for wheat and rice in all developing countries by 2020, with Asia accounting for 60% of the global demand for maize due to increasing population (IFPRI, 2003). Maize occupies a major portion of Asia's cropping area; in Thailand it is cultivated on about 33% of its upland area (Ekasingh et al., 2004), mostly on recently cleared forests. This newly cleared forest land often remains productive for few years of cultivation only but is highly prone to soil degradation. In Thailand almost 34% of cultivated land is already degraded by soil erosion (Pansak et al., 2010). Various governmental agricultural institutions and departments of Thailand are educating and promoting famers to use soil conservation measures, especially on uplands facing problems of erosion on moderate to steep slopes. Agroforestry with intercropping is considered effective in maximizing benefits from available resources and have greater potential to maximize the outcome while conserving soils on slopes under tropical conditions. But the viability of such systems depends on their efficiency under limited soil resource conditions, which in turn makes them acceptable among the farming community. Agroforestry systems such as alley or hedge cropping have the potential to reduce soil loss and runoff, to enhance soil fertility, and to improve water quality (Garrity, 2004; Nair et al., 2007; Garrett et al., 2009). Despite many successful stories of these hedgerow based agroforestry systems in conserving soil and water in sloping terrain, most farmers are reluctant to adopt them because hedges occupy space which is then not available for crop production and compete for water and nutrient with crops growing adjacent to them under already often limited resource conditions. Kang et al. (1981) observed that periodical pruning of hedges provides nutrients to the plants intercropped with trees. Agroforestry practices were addressed as soil fertility enhancement factors as well (Schroth and Sinclair, 2003). But including hedgerows or grass barriers in annual cropping systems can have various negative impacts on the crop in the alley due to competition (Agus et al., 1997; Dercon et al., 2003; 2006b). This competition is possible above ground for light and below ground for nutrients, water and interference of crop roots with tree roots (Kang et al., 1981; Karim et al., 1991; Hauser, 1993). Therefore, experiments emphasizing on fine-tuning of crop management with hedgerow- or grass barriers-based soil conservation systems is useful to identify options fostering farmers' adoption of soil conservation measures which are need of the time for reducing soil erosion, leading to a more sustainable land use in tropical hillside agriculture on a long-term basis.

1.2 Western mountainous region of Thailand

Thailand is one of the most important and progressing countries of Southeast Asia, located in the Indochina peninsula. Geographically, the country can be divided into six regions, i.e central, northern, north-eastern, eastern, western and southern regions. The Ratchaburi province is located (13°28'N, 99°16'E) in the western region of Thailand. This province has an area of 52 km^2, partly with high mountains (Suan Pueng district, Khing Amphoe Ban Kha and Park Tho district) located in the western part of the province close to the Thai-Myanmar border with altitudes between 200-1400 m a.s.l. (Chaiyo et al., 2011).

These areas are considered as a 'rain shadow zone' because most of the rains are blocked by the Tanowsri Mountains. April is often the hottest month while December is mostly the coldest month of the year (Pimentel and Burgess, 2013). The rainy season lasts from end of May to end of September or occasionally end of October. Maize (*Zea mays L.*) is commonly grown in this area. Other major crops are cassava (*Manihot esculenta*) and chili (*Capsicum annuum*). Both, maize and chili are also considered as cash crops among the smallholder farmers of the region. Maize growing season starts just after the onset of rains and it is mostly harvested at the end of September until mid of October. Most of the cultivation is carried out on recently cleared forests which often covered sloping land and shallow soils. Such recently deforested upland areas are prone to soil degradation which directly reduces the fertility of these soils. On the other hand, most of the farmers have poor access to fertilizers because of limited farm capital. Soil erosion and low soil fertility are, therefore, the main problems of upland areas and sloping lands and major constrains of crop production.

Furthermore, farmers prefer to work off-farm than crop cultivation due to low yields, high input cost, labour scarcity for crop management and disease and pest infestation, but job opportunities are rare. Some farmers abandon old deforested land after few years of cultivation and start clearing the forest on another mountain. This continuous deforestation of sloping land affects not only the environment negatively but also decreases the fertility of upland due to soil degradation.

1.3 Cropping systems under practice

Farmers' choice of cultivation depends on two main points; the first focus is to cultivate a crop to secure food for his household and the second focus is market demand of a specific crop. Most of the smallholders grow maize as household food while some also focus on growing cash crops like chili due to its high market value. In both cases, however, the cultivation is often done on just deforested uplands with various degrees of slope which encourages soil erosion (Forsyth, 2007). Therefore, soil degradation is a common problem of uplands, mostly due to inappropriate cultivation practices while slope length, rainfall erosivity, steepness, soil erodibility, conservation practices and crop management are considered as main factors influence soil erosion (Krishna Bahadur, 2009); however not only in Thailand but also in other parts of Asia.

The average rainfall of the area is around 1134 mm per year with maximum rainfall in September-October. Rainfall data from 1984-2005 showed that 1996 was the year with maximum rainfall 1910 mm and 2004 was the year with minimum total rainfall of 607 mm (Pok, 2006). Heavy rains at the time of crop harvest or just after harvest cause maximum soil erosion and reduce the soil fertility year by year basis due to removal of top fertile soils from these moderate to steep slope cultivated lands. Slopes of the area vary between 25 and 30% with natural forest dominated with bamboo plants. This area had been used for mining before World War II but mining completely stopped during 1994-1995 (Pok, 2006). Land degradation of the area has already affected the well-being of the rural population and crop cultivation problems in here have led the farmers to think about substitute income generating activities instead of farming. Most of the farmers of area quitted farming and started various kinds of off-farm jobs in factories, mills and institutions.

1.4 Conservation agriculture

Conservation agriculture is a set of soil management practices used to minimize the disruption of the soil's structure, composition and natural biodiversity. The concern about maintaining soil productivity is growing with time in many regions of the world. This not only motivated the governments but also farmers to explore and adapt conservation methods in agriculture that maintain the soil structure and productivity (Knowler and Bradshaw, 2007). Monocropping offers little opportunity for stable agricultural production especially under degraded soil configuration with fragile and whimsical nature of weather (Banik et al., 2000). Intercropping have several advantages such as yield stability (Lithourgidis et al., 2011), improving soil conservation, efficient use of above and below ground resources (Javanmard et al., 2009), increasing productivity and land use efficiency (Dhima et al., 2007) and improving weed and pest control (Vasilakoglou et al., 2008). In addition, mixed cropping systems blended with conservation methods are more stable and less risky for farmers because these reduce risks of simultaneous crop failure. Intercropping with conservation methods plays a pivotal role in increasing land use efficiency on long-term basis and has gained interest because of its potential advantages of yield enhancement with efficient reduction of soil degradation risks on various degrees of slopping lands. Intercropping with soil conservation methods include alley cropping, contour hedgerows, and grass barriers with integrated fruit trees. Several studies reported that hedgerows and grass barriers are very effective for conserving agricultural production on steep slopes (Durán Zuazo et al., 2006; Pansak et al., 2008; Quinkenstein et al., 2009). According to FAO (2001) and García-Torres et al. (2003), the main objective of conservation agriculture is to make use of available agricultural resources judiciously with proper management which directly minimize external inputs. Farm and farmhouse characteristics (such as age, gender, education, experience), biophysical farm characteristics (such as farm size, area planted, farm fragmentation, yield per hectare, slope), farm management and financial characteristics (e.g. tenure, family labour, hired labour, income) and exogenous factors (like input and output prices, interest rates, sources of information) are factors influencing the adaptation of conservation practices during cultivation of crops (Knowler and Bradshaw, 2007). Agroforestry is an approach of land use with inclusion of trees into farming systems which allows production of trees and crops or livestock from same piece of land to get ecological, cultural, economic and environmental benefits (Thevathasan et al., 2004). Agroforestry systems originated from developing countries with high population densities and limited land resources. These systems differ from traditional forestry due to their social and economic benefits while maintaining soil and water sustainability and acting as buffer to climatic extremes. Agroforestry systems have the potential for carbon sequestration by trees and in soils, allowing to maintain sustainable productivity over time. Pansak et al. (2008) and Hilger et al. (2013) mentioned that hedgerows are very effective in reducing soil loss on uplands. Various studies investigated several woody species as hedgerows in different ecological conditions with results showing variable degrees of success (Guo et al., 2009; Quinkenstein et al., 2009) but despite all these benefits, most of the famers are reluctant to adapt such methods.

1.5 Why farmers are reluctant to adopt agroforestry systems?

Agroforestry systems can contribute to sustainable land use only if such systems can be adopted by the farming community. Conservation agroforestry systems are basically more complex systems than traditional 'slash and burn' agriculture because it requires a new input-output mixture of annual, perennial, green manure and other components combined with new conservation methods such as alley cropping and contour hedgerow cropping (Rafiq et al., 2000). Few months are required to evaluate an annual cropping system while it takes three to six years to see the benefits of a conservation agroforestry system (Franzel and Scherr, 2002). Most researchers indicated that decisions to adopt any conservation practice is largely driven by its expected contributions in increasing productivity, risk reduction, output stability and economic viability compared to alternative practices (Salam et al., 2000; Scherr, 2000). Success in adaptation of such systems depends on costs and benefits associated with them (Giller et al., 2011). Most reviews of agroforestry in tropical areas concluded that yield increase is rare in alley cropping on slope because of lager competition effect of trees on crops for nutrient and water (Sanchez, 1995; Rao et al., 1998). Planting of trees as contour hedges are highly effective in reducing soil erosion on hill slopes as compared to alley cropping on flatter lands (Young, 1997). Agroforestry researchers have already examined the interactions between crop production and water management (Lefroy and Stirzaker, 1999) and also crop yield and environmental functions (Wallace et al., 2000). Nelson et al. (1996) explained that slow return of contour hedgerows is the explanation why farmer are reluctant to adapt contour hedgerows in their cropping systems. Farmers are keen to adopt in most cases low cost technologies like natural vegetative strips for controlling erosion which is essential for long-term productivity on the slopes (Garrity et al. 1999). Ong et al. (2002) also concluded from his review on tree crop interactions that soil loss can substantially be reduced by inclusion of trees in cropping systems but their beneficial effect on crops is often unpredictable and insufficient to attract the adoption of contour hedges. Competition for resources between contour hedges and crops is low and not significant when below ground resources are abundant (Ong et al., 2000) but as depletion of below ground resources occurs with colonizing aging systems, tree growth happens with time at the expense of crop production (Lott et al., 2000); however pruning, mulching and minimum tillage actually improves the situation (Oteng'i et al., 2007). These studies also confirmed that the nature and extent of the tree-crop interaction changed greatly with maturity of systems (Lott et al., 2000; Ong et al., 2000; Oteng'i et al., 2007). The intensity of these interactions depends on environmental and management conditions. Kinama et al. (2005) reported high water losses by evaporation from soils while studying crops with contour hedgerow agroforestry in semi-arid Kenya. Other studies indicated pattern and overlapping roots between maize and hedges (*Senna siamea*) which caused yield decrease in maize rows planted close to hedges (Umaya et al., 1999; Mungai et al., 2001). Moreover, Dercon et al. (2006b) pointed out that competition for soil moisture and nutrient occurred between crops of the alley and hedgerows which influenced crop productivity negatively, while studying contour hedgerow systems in Ecuador. Odhiambo et al. (2001) described a similar story of tree roots, soil water, and crop yield interactions from a field experiment. They concluded that crop yield depression was prominently higher in plants grown close to trees and that there was very little evidence of complimentary interaction for resource sharing between crops and trees but overall trees competed for resources with crops. Therefore, most of the farmers are reluctant to invest in any soil conservation measure, which they feel is not improving their crop yields and reducing their cultivated land, even with negative impacts on crop productivity due to erosion on the long run.

1.6 Techniques to monitor resource use competition at plant soil hedge interface

Understanding above and below ground interactions at the plant-soil-hedge interface is important for planning and establishing of any kind of soil conservation measure. Crop species planted close to each other on the same piece of land follow a spatio-temporal pattern of interactions for water, nutrient below ground and light above ground. Above ground interactions between crops and hedgerows may be visually estimated by farmers and researchers and managed by pruning the hedges, spacing and arrangement of crops and trees used as hedgerows but this is also not easy specially under field condition with various canopy structures and spatio-temporal patterns of light capture.

Below ground interactions are invisible, thus more difficult to understand and manage. Knowledge about below-ground competition, its spatial pattern and impacts on crop performance is still limited, particularly when looking at water. Water availability to plants is influenced by several factors that vary spatially such as micro-topography influencing soil water distribution after rainfall, depth of ground water table, soil texture and soil compaction, under field conditions. The spatial variability of such factors generates conditions under which some plants face water stress while others do not.

These spatio-temporal patterns of above and below ground resource use interactions request novel approaches, e.g. combinations of various techniques not only to understand these interaction but also to quantify these interaction and to suggest management options for improving these systems in terms of yield performance. A combination of stable carbon isotopic discrimination ($\delta^{13}C$ measurements) and electrical resistivity tomography techniques (ERT imaging) was used to understand and distinguish below ground competition for water and nutrient at crop-soil-hedge interface in maize based agroforestry systems.

The production efficiency of maize based cropping systems in harvesting solar radiation and the spatial variability of light capture was evaluated by monitoring the fraction of intercepted PAR (F), intercepted PAR (IPAR) and RUE with the help of Sunscan canopy analyser systems and various statistical procedures.

The spatially explicit Water, Nutrient, Light Capture in Agroforestry Systems model Version 4.01 was used to investigate and distinguish resource use competition at the crop-soil-hedge interface on long-term basis, sustainability of maize based agroforestry systems, strategies to mitigate the competition and management options for agroforestry systems improvement.

1.6.1 Stable carbon isotope and electrical resistivity tomography

Isotopes are atoms having the same number of protons and electrons but a different number of neutrons. An isotope is considered to be stable when it has similar number of neutrons (N) and protons (Z). There are around 300 stable isotopes, more than 1200 radioactive isotopes, and 21 elements that have only one isotope (Hoefs, 1997). Earlier, geochemists and pale-oceanographers used stable isotopes to develop a rigorous empirical and theoretical basis for integration of isotopes into studies of past climatic conditions, global element cycles and tracing rock sources. Similarly, environmental chemists, ecologists and plant biologists also developed empirical database and theoretical framework for the use of isotopes in plants and animals studies. Moreover, use of stable isotopes of carbon, nitrogen, oxygen, and hydrogen has increased in the past three decades to study physiological processes in plants. Harmon Craig, was a geochemist and pioneer of natural abundance stable isotopes who first measured isotopic values of plant materials in 1953-54 (Michener and Lajtha, 2008). Later, ecologists identified isotopic signatures based on different photosynthetic pathways, water use efficiency (WUE) and also water and nitrogen effects on plants isotope natural abundance.

Carbon isotope discrimination showed big environmental and genetic variations in plants (Monneveux et al., 2007). ^{12}C and ^{13}C are two naturally occurring stable isotopes of carbon, most of which is ^{12}C (98.9%) while 1.1% is ^{13}C (Farquhar et al., 1989). This is an alternative technique to assess the impact of water and nitrogen on plant growth. Many studies proved the usefulness of carbon isotope discrimination in assessing the effect of water limitation and nitrogen uptake on crop performance (Farquhar, 1983; Clay et al., 2001; Condon et al., 2002; Dercon et al., 2006a; Pansak et al., 2007). IRMS (isotope ratio mass spectrometry) was used for analysis of carbon isotopic discrimination in maize plant samples.

Electrical resistance tomography (ERT) is a geophysical technique that calculates the subsurface distribution of electrical resistivity from a large number of resistance measurements from electrodes (Daily et al., 2004). Electrical resistivity is actually measured by the application of an electrical current through a set of electrodes and reading the resulting differences in electric potential on separate electrodes (Garré et al., 2012). Soil electrical resistivity is a function of soil texture and structural characteristics and is also sensitive to its water content (Sheets and Hendrickx, 1995). Soils are a porous medium with nonconductive solid particles, containing electrolytes solution. Movement of free ions in the bulk solution and ions adsorbed at the matrix surface can conduct electric current. ERT is not only a valuable technique for monitoring water uptake by planted trees and in natural forests (Celano et al., 2011) but also to monitor changes in soil moisture and water use in crop stands (Michot et al., 2003; Amato et al., 2009; Garré et al., 2011; Garré et al., 2013) non-invasively. Interpretation of field measured electrical resistivity for water contents is quite difficult because of its sensitivity to many other physical factors. However, many studies mentioned ERT, a valid method to understand water fluxes under various crop management options (Michot et al., 2003; Garré et al., 2013). The details about stable carbon isotope discrimination and electrical resistivity measurements are given in Chapter 2.

1.6.2 Light interception and light use efficiency

Ecosystems are supplied with energy from an external source, the sun, in thermodynamic terms (Monteith, 1972). According to Kahle et al. (2003), approximately 50% of the radiant energy emitted from the sun lies in the infrared region (>0.7 µm), about 40% in the visible region (0.4-0.7 µm), and about 10% in the UV region (<0.4 µm). Solar radiation provides energy for carbon assimilation of plant canopies and their water loss to atmosphere. It maintains heat balance of agricultural surfaces and is a major environmental factor controlling development of crops, livestock, forests and pastures (Stanhill and Cohen, 2001). The ability of plants to transform the radiant energy absorbed in the form of photoactive radiation into biomass is referred to as light use efficiency (LUE). Long et al. (2006) mentioned that changes in the efficiency of light interception as well as light utilization can improve photosynthesis and yield potential up to 50%. Crop biomass production depends on light interception by plant leaves and the efficiency of converting intercepted light into dry matter production while the fraction of incoming photosynthetic active radiation absorbed by crop canopies mainly depends on the leaf area index (LAI) and cropping geometry (Plénet et al., 2000). Various simple polynomial and linear phytomass production models were developed to investigate effects of radiation interception by crop canopies and plants ability to convert this intercepted radiation into biomass, under field conditions (Monteith and Moss, 1977; Purcell et al., 2002). Many field experiment results pointed to a linear and positive relationship between total dry matter and the amount of radiation intercepted by crops planted under various planting systems such as monocropping, intercropping and agroforestry systems (Monteith and Moss, 1977; Sivakumar and Virmani, 1984; Kiniry et al., 1989; Edwards et al., 2005; Liu et al., 2012). Various factors were reported as influential for estimating radiation use efficiency (Sinclair and Muchow, 1999). LUE estimations depend on whether the radiation measured as total solar radiation or estimated on the basis of photosynthetic active radiation (PAR), as PAR is considered as half of the total solar radiation coming from sun (Sinclair and Muchow, 1999). Moreover, RUE of crop can vary not only with crop growth and leaf area development but also the radiation intercepted by the crop canopy. Cop canopy can intercept 85% PAR only when crop has large leaf area index (Bonhomme, 2000). LAI is the total one sided area of the leaf tissue per unit ground area and is considered as key parameter in eco-physiology (Bréda, 2003). LAI is dimensionless quantity and is also very important component of biogeochemical cycles because it determines and controls many crop growth functions such as radiation extinction, canopy water interception for gas exchange, radiation interception, radiation absorption and LUE estimation. So any change in LAI of a crop canopy may change and modify stand productivity. Crop LAI can be measured by both direct and indirect methods. Direct method of LAI measurements involves using either a leaf area meter or specific dimension relationship to area via a shape coefficient but is mostly destructive by harvesting the plants and is the most accurate method used for crops and pastures. Leaf area is measured on a sub-sample of harvested leaves as specific leaf area (SLA, cm^2 g^{-1}) related to its dry mass. Finally total dry mass of the leaves of known harvested area is converted into LAI by multiplying total leaf dry mass with SLA (Bréda, 2003).

For indirect LAI measurement, recently, a range of new instruments has been developed to indirectly assess LAI of plant canopies. Among these, some calculate LAI by comparing differential light measurements above and below canopy such as Accupar, Demon, Licor LAI-2000, Sunscan Canopy Analyzer etc. while others incorporate canopy image analysis techniques (Digital Plant Canopy Imager CI 100, MVI). We used indirect measurement of LAI, intercepted PAR with the help of Sunscan canopy analyser coupled with beam fraction sensor (BFS-III). For complete procedure of LAI measurements, PAR interception and LUE calculation and evaluation of maize planted under various maize based cropping systems please see Chapter 3.

1.6.3 Modelling approach and its importance

Conservation agriculture is considerably more complex than traditional agriculture because it includes systms such as alley cropping, contour hedgerow cropping and enriched fallows (Rafiq et al., 2000). Therefore, continuous experimentation, modification and even more important farmers' education are key factors for developing and further improving these conservation systems (Barrett et al., 2002). Multicomponent and product nature of these tree based conservation techniques may also limit their adoption by farmers, especially due to continuous management, long-term testing and modification requirements (Mercer, 2004). Such conservation agroforestry systems more likely take two to three or even more years to show beneficial impacts compared to any annual crop which just take few months to harvest and evaluate (Franzel and Scherr, 2002). Long-time field experiments for testing the sustainability and interaction between components of such systems are quite expensive, laborious and time consuming. Therefore, dynamic crop modelling can be useful for long term testing of such complex systems. Crop modelling can provide better understanding of processes at crop-soil-hedge interface and also interactions between the components of the system on long-term basis and also reduce the cost of long-term field experiments by reducing cost of experiment, labour and time. Various models are being used for crop growth simulation with soil conservation such as WaNuLCAS (Walker et al., 2007; Pansak et al., 2010), DSSAT (Jones et al., 2003; Saseendran et al., 2007; Liu et al., 2011), APSIM (Mohanty et al., 2012; Chauhan et al., 2013) etc.

WaNuLCAS is a model suitable to simulate the dynamics processes at tree-soil-crop interface in a spatial, plot and or field scale (Van Noordjik and Lusiana, 1999). Recently, many studies used various versions of WaNuLCAS model to assess tree crop interactions, soil loss and runoff, impact of improved fallow technology on maize yield under various soil and environmental conditions by using various intercropping scenarios with timber trees (Walker et al., 2007; Bayala et al., 2008; Martin and Noordwijk, 2009; Pansak et al., 2010). The model was developed in STELLA (Systems thinking for education and research) environment with special emphasis on above and below ground interactions between the components of the system. WaNuLCAS model have two types of files, a WaNuLCAS.stm file and WaNuLCAS.xls file interlinked to each other. WaNuLCAS.stm file is used basically for dynamics simulations while WaNuLCAS.xls is the workbook used for model input and management parameters.

1.7 Guiding hypotheses

The guiding hypotheses addressed in this thesis are:

- Competition for water between crops and hedgerows is a driving force for crop production reduction.
- Soil conservation systems with hedgerows and intercropping will induce spatial patterns of resource use which can be linked to competition at the crop-soil-hedge interface.
- Combining stable carbon isotope discrimination, electrical resistivity tomography and time domain reflectometry will allow the identification of the driving resource (water or nutrient) competition factor at the crop-soil-tree interface in hedgerow systems.
- Planting patterns have an impact on canopy characteristics and vertical and lateral PAR distributions responsible for radiation interception and finally maize production.
- WaNuLCAS being able to identify various sources and degrees of competition is well-suited to capture the water and nutrient dynamics at the crop-soil-hedge interface and copes with a wide range of crop management options suitable for mitigation strategies.

1.8 Goal and objectives

Intercropping with hedgerows or grass barriers conservation system are complex systems due to multiple interactions between the components of system. Soil conservation systems with hedgerows are often reported having negative impacts on crops' productivity planted close to them. Understanding these above and below ground interaction at the crop-soil-hedge interface is important for a better planning of soil conservation systems and improving acceptance by farmers. The overall goal of this study was to better understand and quantify interactions between crop and hedgerows and resource use competition at crop-soil-tree interface by using various techniques including modelling approach. The more specific objectives were:

- To improve understanding of competition at the crop soil hedge interface by combining stable isotope discrimination, electrical resistivity tomography and time domain reflectometry.
- To identify the effects of intercropping and hedgerows on maize above ground biomass (AGB) accumulation, leaf area index (LAI), grain nitrogen concentration (N_g), canopy photosynthetic active radiation interception (IPAR), light use efficiency (LUE) and land equivalent ratio (LER).
- To evaluate the resource use competition between hedge and maize rows planted close to each other by using WaNuLCAS model.
- To identify possible crop management options for mitigating competition at crop-soil-tree/hedge interface and production sustainability of maize intercropping with agroforestry system by using modelling approach.

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Chapter 2

Combining $\delta^{13}C$ measurements and ERT imaging: improving our understanding of competition at the crop-soil-hedge interface

Chapter 2 Combining $\delta^{13}C$ measurements and ERT imaging: improving our understanding of competition at the crop-soil-hedge interface*

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2.1 Abstract

Background and aims

Hedgerow cropping decreases erosion in hillside agriculture but also competes for water and nutrients with crops. This study combined two methods for an improved understanding of water and nutrient competition at the crop-soil-hedge interface.

Methods

$\delta^{13}C$ isotopic discrimination in plants and soil electrical resistivity tomography (ERT) imaging were used in a field trial with maize monocropping (MM) *vs*. leucaena hedgerow intercropping with and without fertilizer (MHF^+ and MHF^-) in Thailand.

Results

Hedges significantly reduced maize grain yield and aboveground biomass in rows close to hedgerows. ERT revealed water depletion was stronger in MM than in MHF^+ and MHF^- confirming time domain reflectometry and leaf area data. In MHF^+, water depletion was higher in maize rows close to the hedge compared to rows distant to hedges and maize grain $\delta^{13}C$ was significantly less negative in rows close to hedge (-10.33‰) compared to distant ones (-10.64‰). Lack of N increased grain $\delta^{13}C$ in MHF^- (-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.

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Conclusion

Combining ERT imaging and ^{13}C isotopic discrimination approaches improved the understanding of spatial-temporal patterns of competition at the hedge-soil-crop interface and allowed distinguishing between water and N competition in maize based hedgerow systems.

Keywords: Alley cropping; competition; ERT imaging; N; soil water; stable isotope discrimination; Thailand

2.2 Introduction

Contour hedgerows are very effective in reducing soil loss (Pansak et al. 2008; Hilger et al. 2013). They enhance water infiltration but also increase water demand which may lead to competition at the crop-soil-hedge interface, particularly on shallow soils in hilly terrain. Until now many woody species have been tested as hedgerows under different ecological conditions with varying degrees of success (Guo et al. 2009; Quinkenstein et al. 2009). Success in adaptation of such systems depends on costs and benefits associated with them (Giller et al. 2011). Kang et al. (1981) observed that crops grown in alleys between hedges receive nutrients from the hedges due to their periodical pruning. On nutrient-poor Ultisols, alley cropping improved nitrogen recycling and increased food crop yields without fertiliser application but it was less effective as compared to sole or intercropping under fertilisation (Akondé et al. 1997). The presence of hedgerows, however, can have negative impacts on crops grown in rows next to them due to competition (Dercon et al. 2006a, 2006b; Pansak et al. 2007). This competition occurs above ground for light and below ground for nutrients and water at the interference zone of crop and tree roots (Kang et al. 1981; Hauser and Kang 1993). The magnitude of below ground competition depends on the rooting pattern of the used tree species and the way trees are arranged (Lose et al. 2003). Shading effects by hedges on crops growing adjacent to them can easily be avoided when trees are pruned regularly, e.g. twice to three times a year (Leihner et al. 1996). Such kind of tree management also has below-ground impacts and decreased fine root development of trees (Bayala et al. 2004).

Our understanding of below-ground competition, its spatial pattern, and its impact on crop performance is still limited, particularly when looking at water. Under field conditions, the water available to plants is influenced by several factors that vary spatially such as micro-topography influencing soil water distribution after rainfall, depth of ground water table, soil texture and soil compaction. Bazié et al. (2012) studied tree–soil–crop interactions by additions of water and nutrients using the separation method. Such kinds of studies are also useful to identify competition but are somehow artificial as the competing factors are monitored in separate plots. Recently, various studies showed that electrical resistivity tomography (ERT) is a valuable technique to monitor water uptake by planted trees as well as in natural forests (Celano et al. 2011) but also to monitor changes in soil moisture and water use in crop stands (Michot et al. 2003; Amato et al. 2009; Garré et al. 2011, 2012). ERT is a non-invasive, spatially integrated multiple electrode technique being used to monitor soil water fluxes over a period of time. However, the interpretation of field measured electrical resistivity is quite difficult, as it is not only sensitive to water contents but also to physical factors such as temperature, soil solution (Besson et al. 2008), soil minerals, pore connectivity, soil particle size, and percent clay (Samouëlian et al. 2005). Nevertheless, most of results showed that ERT is a valid method to understand water fluxes under various crop management options. Michot et al. (2003) pointed out that this technique has the potential in improving hydrological studies in soil science and agronomy. Garré et al. (2013) working at the same experimental site as the one described in this study used ERT at field scale on a shallow soil under tropical conditions in a moderately hilly terrain and found spatio-temporal soil moisture depletion patterns which varied among tested cropping systems.

Another option to discover water and nutrient interactions at the plant-soil interface is the ^{13}C stable isotope discrimination method. This is an alternative technique to assess both the impact of water and nitrogen on plant growth. Pansak et al. (2007) provided a conceptual framework for assessing relationships between crop response, nitrogen and water availability, and stable carbon isotopic discrimination in an alley cropping system which allows differentiating competition for nitrogen and water.

Water stress influences photosynthesis-induced ^{13}C isotopic discrimination, i.e. plants close stomata partly or entirely to reduce water loss which limits CO_2 exchange between leaf and atmosphere. This reduces the ratio of intercellular to ambient partial pressure of CO_2 (p_i/p_a) and in this way affects ^{13}C discrimination. Farquhar (1983) and Henderson et al. (1992) described the ^{13}C isotopic discrimination in C_4 plants by the equation:

$$^{13}C_4 \text{ fractionation} = a + \left(b_4 + b_3\phi - a\right)\rho_i / \rho_a \quad (1)$$

where a is the fractionation due to diffusion in air (4.4‰), b_4 is the fractionation of gaseous CO_2 to HCO_3^- by PEP carboxylase (-5.7‰ at 30°C), b_3 is the ^{13}C discrimination due to RuBisCo (30‰), ϕ (leakiness) is the fraction of CO_2 released in bundle sheath cell and leaks to the mesophyll cell, where it may be fixed by PEP carboxylase or released to atmosphere, and ρ_i/ρ_a is the ratio of intercellular to ambient partial pressure of CO_2. Equation 1 shows that ^{13}C isotopic discrimination in C_4 plants, such as maize, is not only due to changes in p_i/p_a ratio but also depends on variation in leakiness (ϕ) of the bundle sheath cells. Like p_i/p_a, bundle sheath cell leakiness also depends on several factors, i.e. genetic variation, light intensity, water and nutrient stress (Buchmann et al. 1996; Meinzer and Zhu 1998). Leakiness can increase with reduced N supply (Meinzer and Zhu 1998), leading to depleted $\delta^{13}C$ signals. Measurements of the carbon isotopic discrimination in C_4 plants show a variable response to soil water availability (Ghannoum 2009) and plant N levels. N stress decreases the $\delta^{13}C$ (high signals as less negative values) because N stress reduces the photosynthetic capacity of plants. This does not only diminish the total CO_2 fixed but also the amount of $^{13}CO_2$ fixed which in turn reduces $\delta^{13}C$ in plant tissues (Clay et al. 2005). Dercon et al. (2006a) studied the use of ^{13}C isotopic discrimination in maize to signal water stress at low to high nitrogen (N) availability and showed that changes in $\delta^{13}C$ values in maize could be related to soil moisture and N availability. Additionally, any change in ^{13}C isotopic discrimination due to N availability is indirectly linked to water stress. If N supply is high and is not in equilibrium with soil water availability, carbon isotopic discrimination will increase resulting in ^{13}C depletion because CO_2 diffusion from air across the leaf membrane is not sufficiently fast to keep up with CO_2 demand needed to maintain plant productivity (Dercon et al. 2006a). Wang et al. (2012) imposed nitrogen and irrigation treatments on field-grown maize and observed that an increase in bundle-sheath cell leakiness went hand in hand with higher ^{13}C discrimination and reduced photosynthetic capacity. Clay et al. (2005) also mentioned that the effect of nitrogen on^{13}C discrimination can be separated from water by including some selected treatments in the field experiments.

We hypothesized that soil conservation systems with hedgerows and intercropping will induce spatial patterns of resource use which can be linked to competition at the crop-soil-hedge interface. The intention of this study was to combine stable isotope probing, ERT imaging and standard methods for plant growth and performance, nitrogen/water availability and uptake under tropical conditions (i) to improve our understanding of competition at the crop-soil-hedge interface, (ii) to identify effects of intercropping and hedgerows on maize (Zea mays L.) growth and performance, and (iii) to determine the link between ERT soil moisture depletion patterns, stable isotopic discrimination and total nitrogen uptake of maize as affected by cropping pattern, plant growth and development.

2.3 Materials and methods

2.3.1 Study site

The field experiment was carried out in 2011, two years after trial establishment, at the Queen Sirikit research farm, close to Ban Bo Wi village, Suan Phueng district, Ratchaburi province of Thailand (13°28´ N and 99°15´ E). In 2011, the annual precipitation was 1200 mm, falling mostly between May and October. The mean air temperature of 2011 was 28 °C with a maximum of 38 °C in Februrary and a minimum of 10 °C in January (Fig. 1). The soil at the study site ranges between an endoleptic Alisol and a hyperskelettic Leptosol (Garré et al. 2013) being prone to surface erosion (Land Development Department, 2011). The top soil (0-15 cm depth) had an organic matter content of 2.2%, an available P (Bray II) content of 12.5 mg kg^{-1}, an available K of 220 mg kg^{-1} (NH_4OAc, pH 7), a total N concentration of 0.16% and a pH (1:1=soil: water) of 5.8.

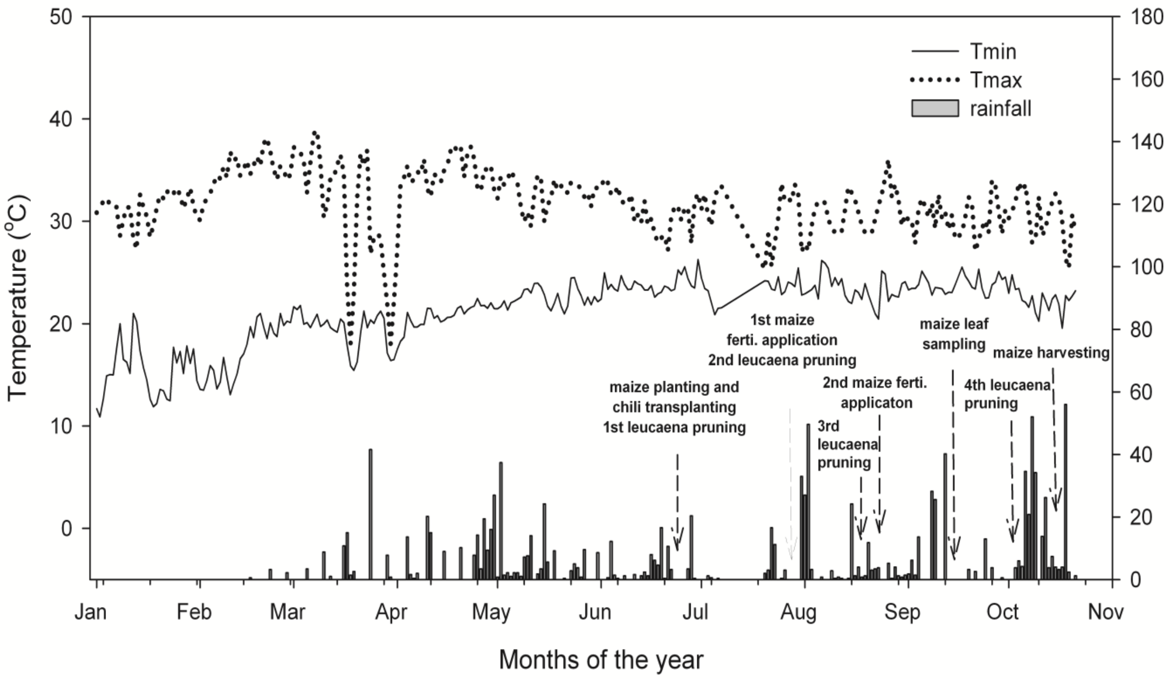

Figure 1: Temperature, rainfall and crop management at experimental site. Data were recorded during 2011 at Queen Sirikit Research Farm, Ratchaburi province, Thailand.

2.3.2 Experimental layout and data collection

The field trial was laid out in a randomized complete block design with six treatments and three replicates. The site has a slope gradient of 20-25%. For this study three treatments were selected: (i) maize monocropping (*Zea mays* L. *cv*. *Pacific 999*), tillage, fertilizer application

(MM/control); (ii) maize intercropped with chilli (*Capsicum annum* L. *cv. Super Hot*), minimum tillage, fertilizer application, Jack bean (*Canavalia ensiformis (*DC) L.) relay cropping and leucaena (*Leucaena leucocephala* (Lam.) de Wit) hedgerow planting (MHF^+); (iii) as MHF^+ but without fertilizer application (MHF^-).

Plots were 13 m long and 4 m wide. Maize was planted on June 26th, 2011 at a spacing of 25 cm within rows and 75 cm between rows. Chilies were intercropped with maize spaced 100 cm apart from each other and also from maize rows. Leucaena hedgerows of 100 cm width were planted at top, middle and lower part of each plot at a distance of 5 m between two hedges (Fig. 2). In MHF^+ and MHF^-, Jack beans were planted as relay crops in-between maize and chili rows on September 15th, 2011 and remained on the plots until the next growing season, providing mulch and green manure to increase soil cover and soil organic matter.

Fertilizer application to maize was 62 kg ha^{-1} of N (urea), split applied in equal doses one and two months after sowing, 11 kg ha^{-1} of P (triple super phosphate) and 36 kg ha^{-1} of K (potassium chloride), while chili received a basal application of N as urea at a rate of 92 kg ha^{-1} at the time of transplanting and 92 kg ha^{-1} N as top dressing one month after transplanting, as recommended for this improved variety. No phosphorous and potassium fertilizer was applied to chili. In MHF^-, no fertilizer was applied to maize and chili.

Maize was harvested row wise in each treatment on October 21st, 2011. In hedge intercrop treatments (MHF^+ and MHF^-) eight plants in each maize row were harvested separately. In maize monocrop treatment (MM/control) seventeen maize rows were harvested in the same way. Each row was kept separately. For this study, maize rows of the control present at similar slope positions as in the hedgerow treatments were evaluated. Samples were dried and row yields were converted into gram per meter square. In hedgerow treatments, no area correction was made to obtain the absolute yields per row. Hence the direct impact of hedges and chilies on adjacent maize rows could be assessed. Leucaena hedges were established in 2009 and pruned four times during the 2011 maize growing period. The first pruning was done just before sowing of maize while the others were carried out at 30, 45 and 105 days after planting (DAP) of maize.

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.

End of September, soil core samples were taken to measure the root length density of maize and leuceana. Therefore, a 2 m long and 1m deep trench on one side of maize monocrop (MM) and both hedgerow treatments (MHF^+, 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 (Fig. 2). 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.

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. We noticed some errors in the rain gauge measurements during mid-September. Rain data after September may have minute errors.

2.3.3 Soil water monitoring

ERT measurements were made in the 3rd replicate (block) from July 25th (28 DAP) to September 15th, 2011 (80 DAP) 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^-. 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 and 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):

$$EC_{b,25} = \frac{EC_b}{1+\alpha(T-25)} \qquad (2)$$

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.

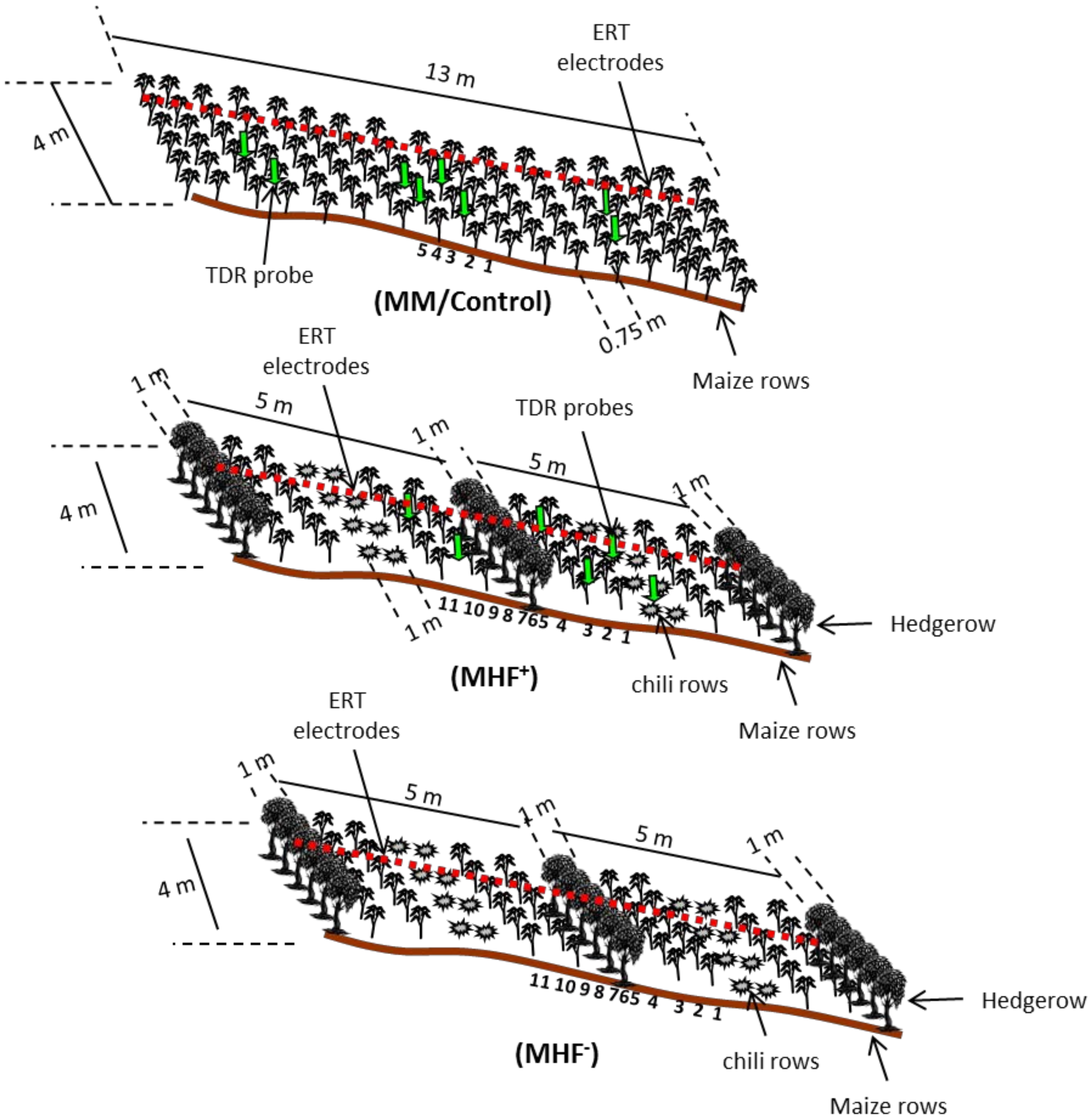

Figure 2: Planting scheme of the selected maize based cropping systems and position of time domain reflectometry (TDR) probes and electrical resistivity tomography (ERT) electrodes within each plot, Queen Sirikit Research Farm, Ratchaburi province, Thailand. Numbers in the middle of each plot indicated position of root core sampling.

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):

$$WC = \left\{ \frac{\left(EC_{b,25} - b\right)}{a} \right\}^{1/n} \quad (3)$$

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. (2013). 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 (Garre et al 2012; Vanderborght et al. 2012). 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:

$$\theta_v = -5.3\times10^{-2} + 2.92\times10^{-2} K_a - 5.5\times10^{-4} k_a{}^2 + 4.3\times10^{-6} k_a{}^3 \quad (4)$$

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 (see also Fig. 2). 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.

2.3.4 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 were collected at around 100 DAP while maize grain samples were taken at harvest. Carbon isotopic ratios of maize leaves and grains were determined per maize row. 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 constant weight was achieved, thereafter ground finely with a ball mill and again oven-dried at 70 °C over night. Finally, well mixed sub samples of these fine maize leaf and grain flour samples were analysed using a Euro Elemental analyser 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 Pee dee belemnite (VPDB) standard (R_{VPDB}):

$$\delta^{13}C_{sample}(‰) = \left\{ \left[R_{sample} / R_{VPDB} \right] - 1 \right\} \times 10^3 \qquad (5)$$

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

2.3.5 Nitrogen concentration and response of maize grains

The nitrogen concentration in maize grains was determined by 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):

$$LnRR_N = In\left(\frac{\text{grain total N concentration with hedges}}{\text{grain total N concentration without hedge (control)}} \right) \qquad (6)$$

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.

2.3.6 Data analysis

SAS Version 9.2 (SAS Institute Inc., USA) was used for statistical analysis. The REG PROCEDURE was used to model the relationships between various dependent and independent or explanatory variables and to check their levels of significance at $\alpha = 0.05$. Analysis of variance using PROC GLM was used to compare the treatments and test significance of factors at $\alpha = 0.05$. Maize row positions from all three replications were used for statistical analysis to compare the means of maize in rows close and distant from the hedge within treatments and also to compare the treatment means.

2.4 Results

2.4.1 Maize above ground biomass development, grain yield and $\delta^{13}C$

The hedge intercrop with fertilizer (MHF^+) treatment produced on average the highest maize above ground biomass (AGB) per row (1251 g m^{-2}) which was statistically similar to the production of the control under monocropping (MM, 1166 g m^{-2}) (Table 1). Maize AGB was significantly lower in the hedge intercrop without fertilizer treatment (MHF^-) than in the same treatment with fertilization (MHF^+). In the hedgerow treatments, maize in rows distant from leuceana hedges produced 46% and 73% higher AGB than maize in rows close to the hedgerow ($p \leq 0.0001$) 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 fertilizer treatment (MHF^-) than in the same treatment with fertilization (MHF^+). In the hedgerow treatments, maize in rows distant from leuceana hedges produced a 41% and 63% higher grain yield than maize in rows close to the hedgerow ($p \leq 0.0001$) in MHF^+ and MHF^-, respectively (Table 1).

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 DAP) 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 1). Maize LAI of all treatments steadily increased during the season, reaching maxima 60 DAP with 2.95 in MM, followed by

Table 1. Maize above ground biomass (AGB), grain yield (GY), plant height, $\delta^{13}C$ in grain and leaf values in maize rows at corresponding positions as affected by maize monocropping (MM), maize hedge intercropping with fertilizer (MHF^+) and without fertilizer (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≤0.001****	*p≤0.01***
	Average row AGB (n=24)	1166 *AB*#	1251 *A*	1077 *B*
		*p≤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≤0.01***	*p≤0.01***
	Average row GY (n=24)	641 *AB*#	701 *A*	602 *B*
		*p≤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≤0.001****	*p≤0.001****
	Average row PH (n=24)	1540 *A*	1374 *B*	1234 *C*
		*p≤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≤0.001****	*p≤0.01***
	Average row $\delta^{13}C$ (n=24)	-10.55 *B*	-10.49 *B*	-9.32 *A*
		*p≤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≤0.01***		

Ns = non significant; *, ** are significant at $p \leq 0.05$ and 0.01, respectively.
#Figures followed by different small letters indicate significant differences within a treatment while capital letters show significant differences among treatments.

MHF^+ with 2.48 and 2.30 in MHF^- (Fig. 3). Thereafter LAI declined in all treatments to around 1.6 ($p \leq 0.05$) at 100 DAP. 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‰, $p \leq 0.0001$) than in maize rows distant to hedge (-10.64‰) in MHF^+ (Tab. 1). 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 DAP while there were no significant differences in leaf $\delta^{13}C$ signals between the rows of each treatment.

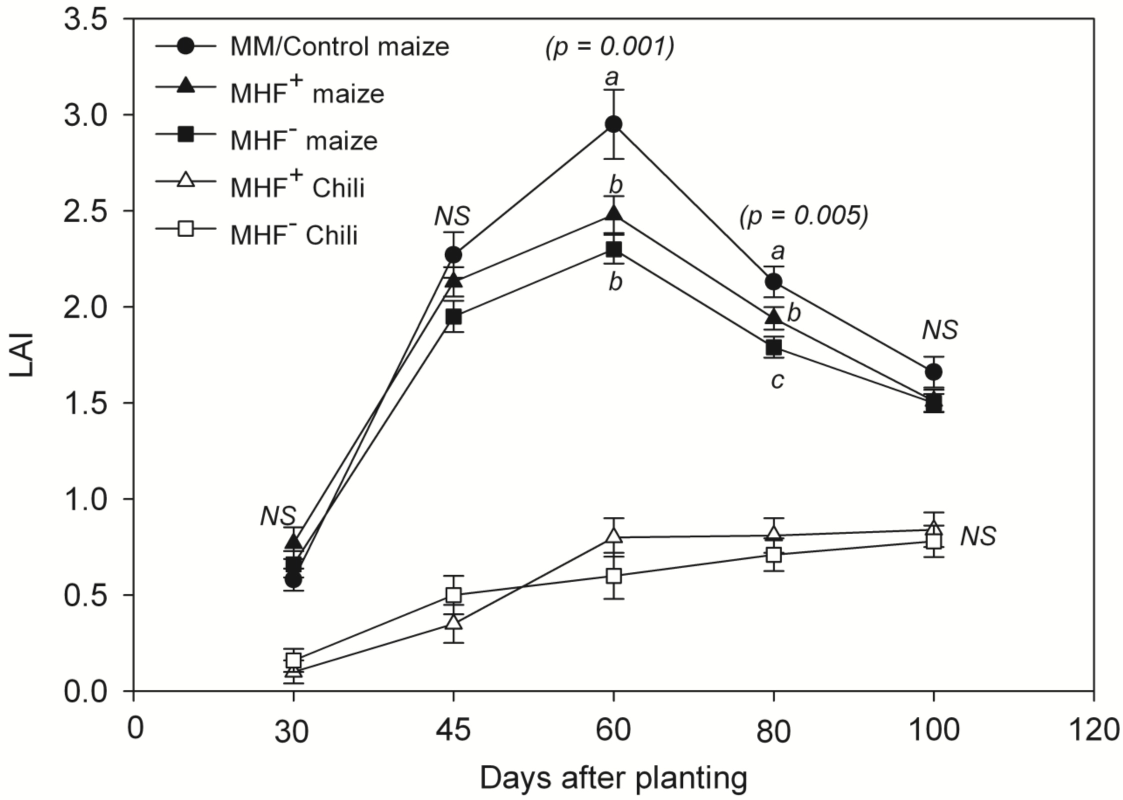

Figure 3: Leaf area index (LAI) of maize and chili as affected by maize monocrop (MM), hedge intercrop with fertilizer (MHF^+) and without fertilizer (MHF^-). Different letters indicate significant while NS shows non-significant differences between the treatments at $p<0.05$. Bars indicate the standard 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.

2.4.2 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 (Fig. 4). 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.

2.4.3 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 (Fig. 5).

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.

2.4.4 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 (Fig. 6). 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

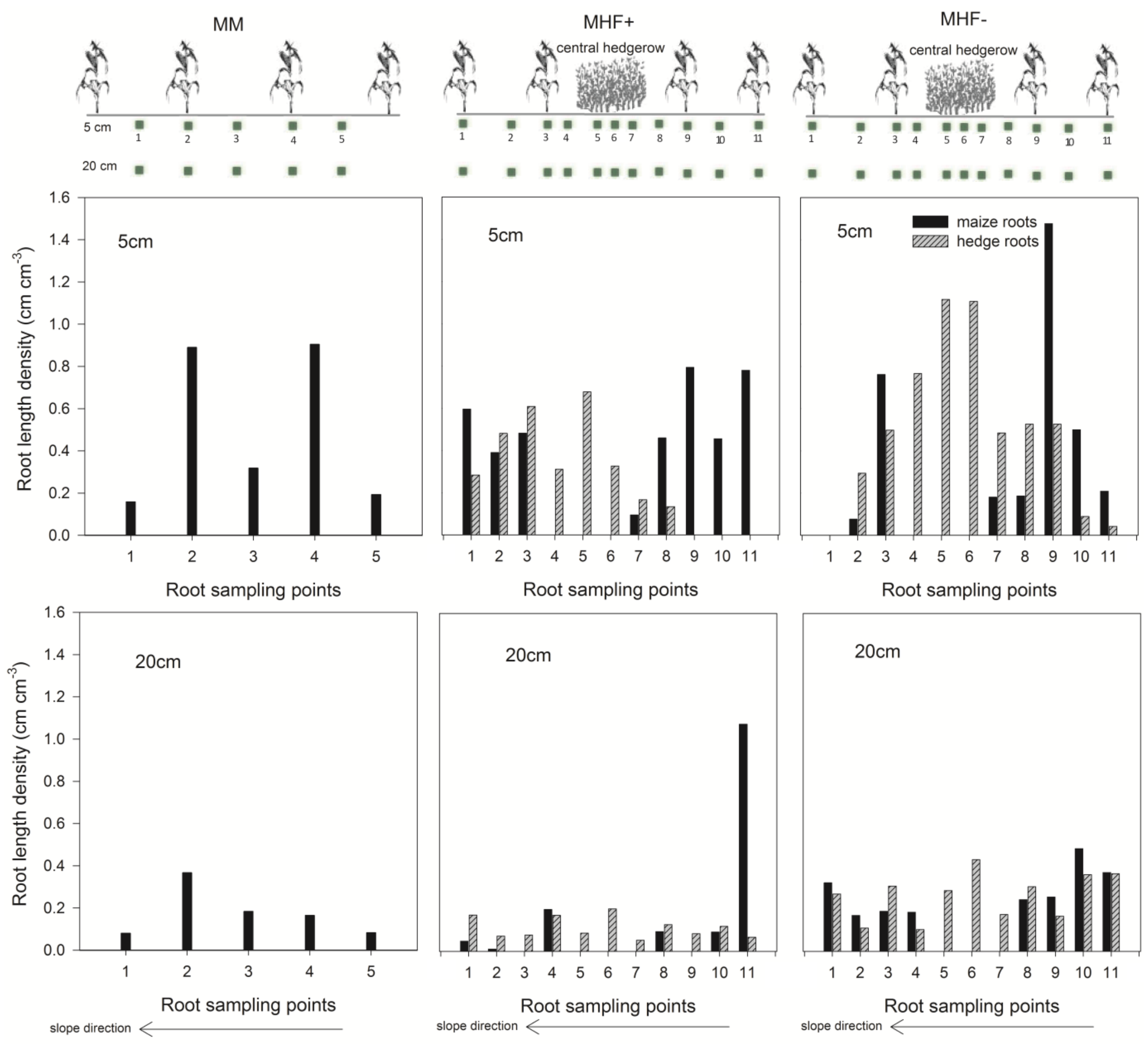

Figure 4: Root length density (cm cm^{-3}) of maize and hedgerow at 5 and 20 cm soil depth in maize monocrop (MM), hedge intercrop with fertilizer (MHF^{+}) and hedge intercrop without fertilizer (MHF^{-}) treatments. Upper portion of the graph is showing the exact root sampling positions at central position within a plot. Data were recorded in September 2011 at Queen Sirikit Research Farm, Ratchaburi province, Thailand.

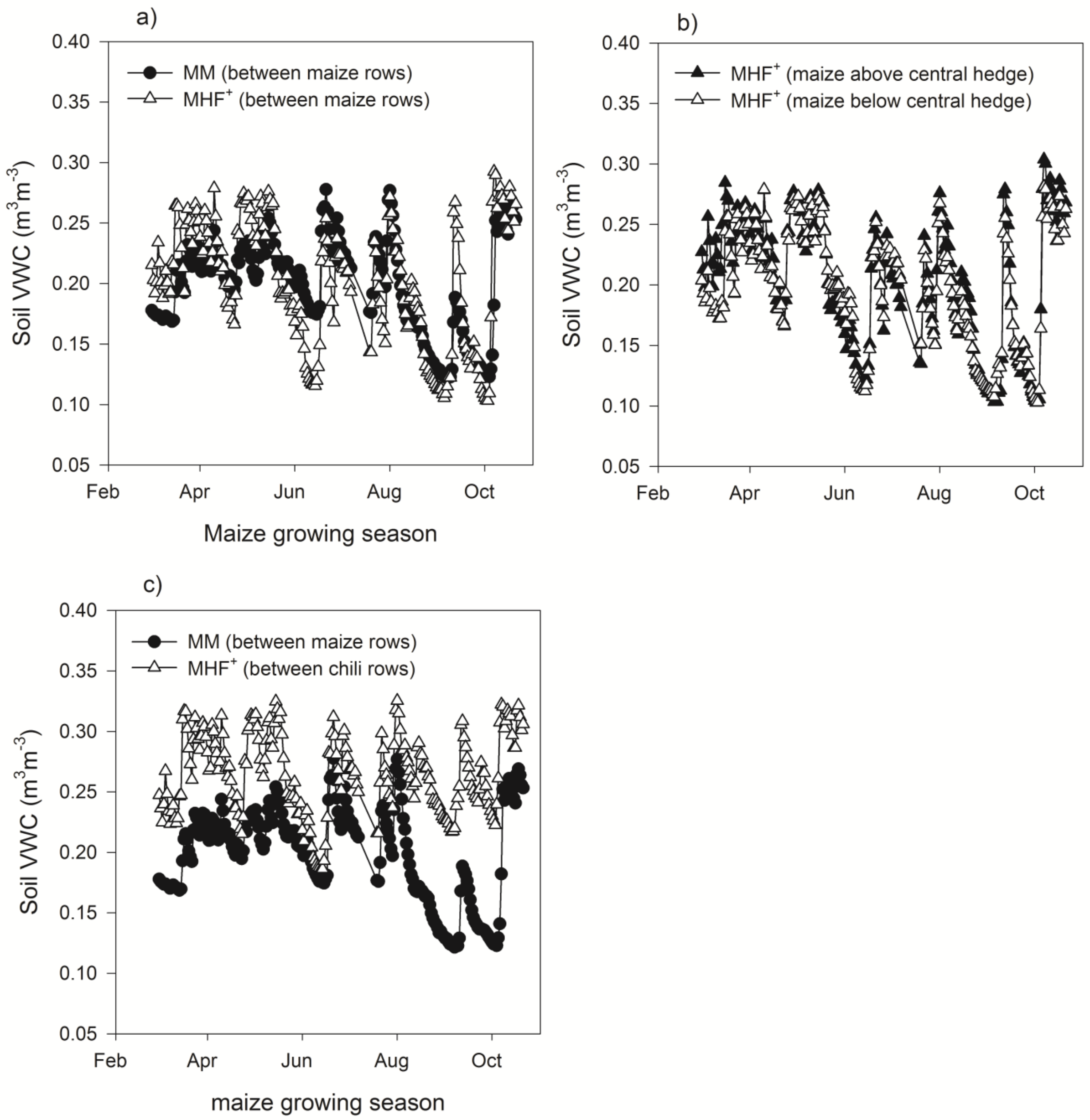

Figure 5: Volumetric water content (m^3m^{-3}) at a soil depth of 0-25 cm measured with TDR probes March to end October, 2011. Data were recorded at Queen Sirikit Research Farm, Ratchaburi province, Thailand.

increased with increase of LAI from July 29th to August 29th, 2011 in all treatments (Fig. 7). 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.

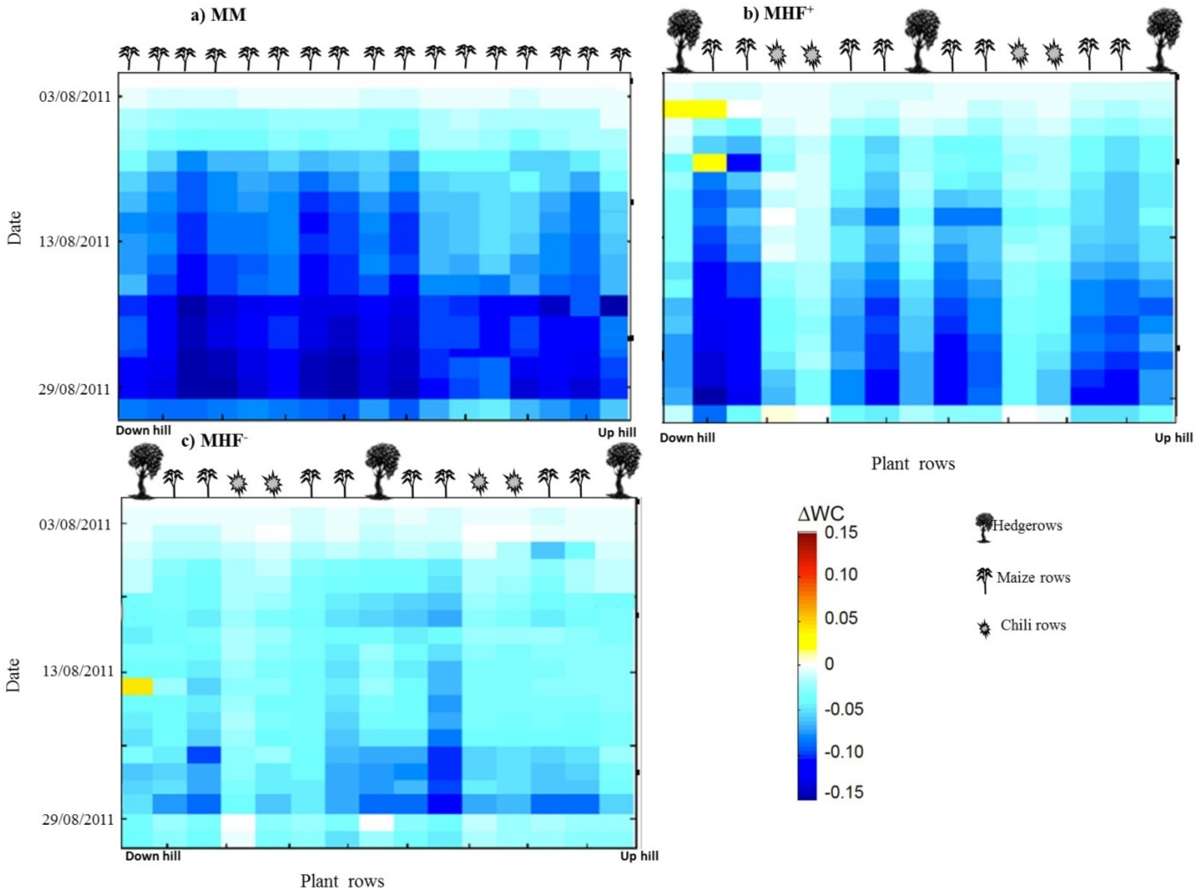

Figure 6: Relative soil moisture depletion (ΔWC) trends of maize based cropping systems along the slope in a soil depth of 0-80 cm based on electrical resistivity tomography (ERT) imaging: a) maize monocrop (MM), b) hedge intercrop with fertilization (MHF^+), c) hedge intercrop without fertilization (MHF^-). Data presented were recorded between August 2nd and 31st, 2011 at Queen Sirikit Research Farm, Ratchaburi province, Thailand (adapted from Garré et al. 2013). ΔWC of August 2nd, 2011 was set as zero soil moisture depletion and initial soil moisture content.

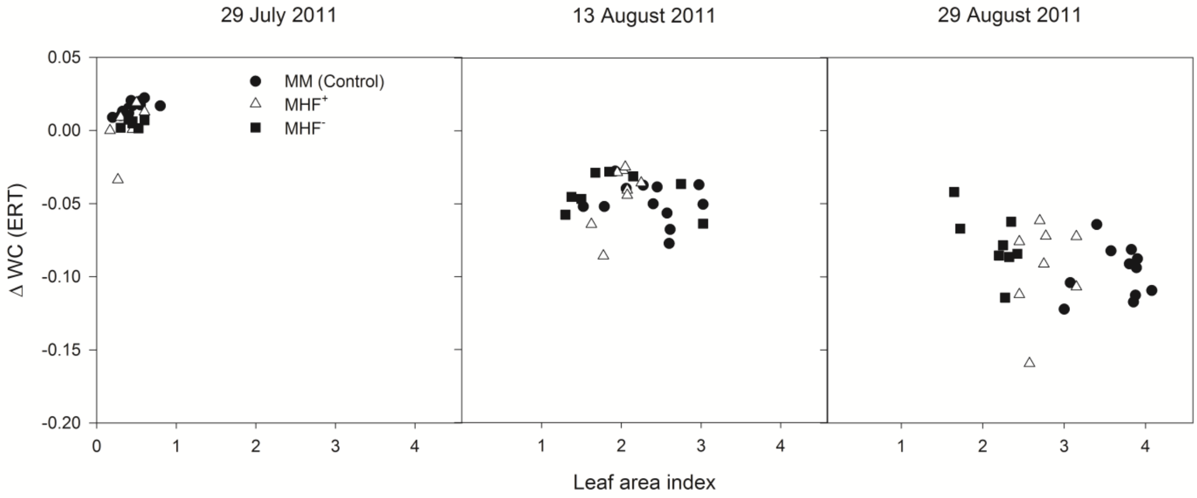

Figure 7: Relationships between actual water contents minus initial water contents(ΔWC (ERT), and LAI of maize rows as affected by monocropping (MM), maize hedge intercropping with fertilizer (MHF^+) and without fertilizer (MHF^-) on 29 July, 13 and 29 August 2011. Data were recorded during the 2011 growing season at Queen Sirikit Research Farm, Ratchaburi province, Thailand.

2.4.5 Nitrogen response ratio in maize grains

A significantly positive correlation was observed in hedge based systems between maize above ground 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 (Fig. 8). In hedge intercrop treatments, maize rows close to the leucaena hedgerow showed lower above ground biomass with lower N concentration while maize in rows distant from leucaena showed higher above ground 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 (Fig. 9). In the hedge-intercrop treatment without fertilization (MHF^-), all maize rows showed negative $LnRR_N$ values except one.

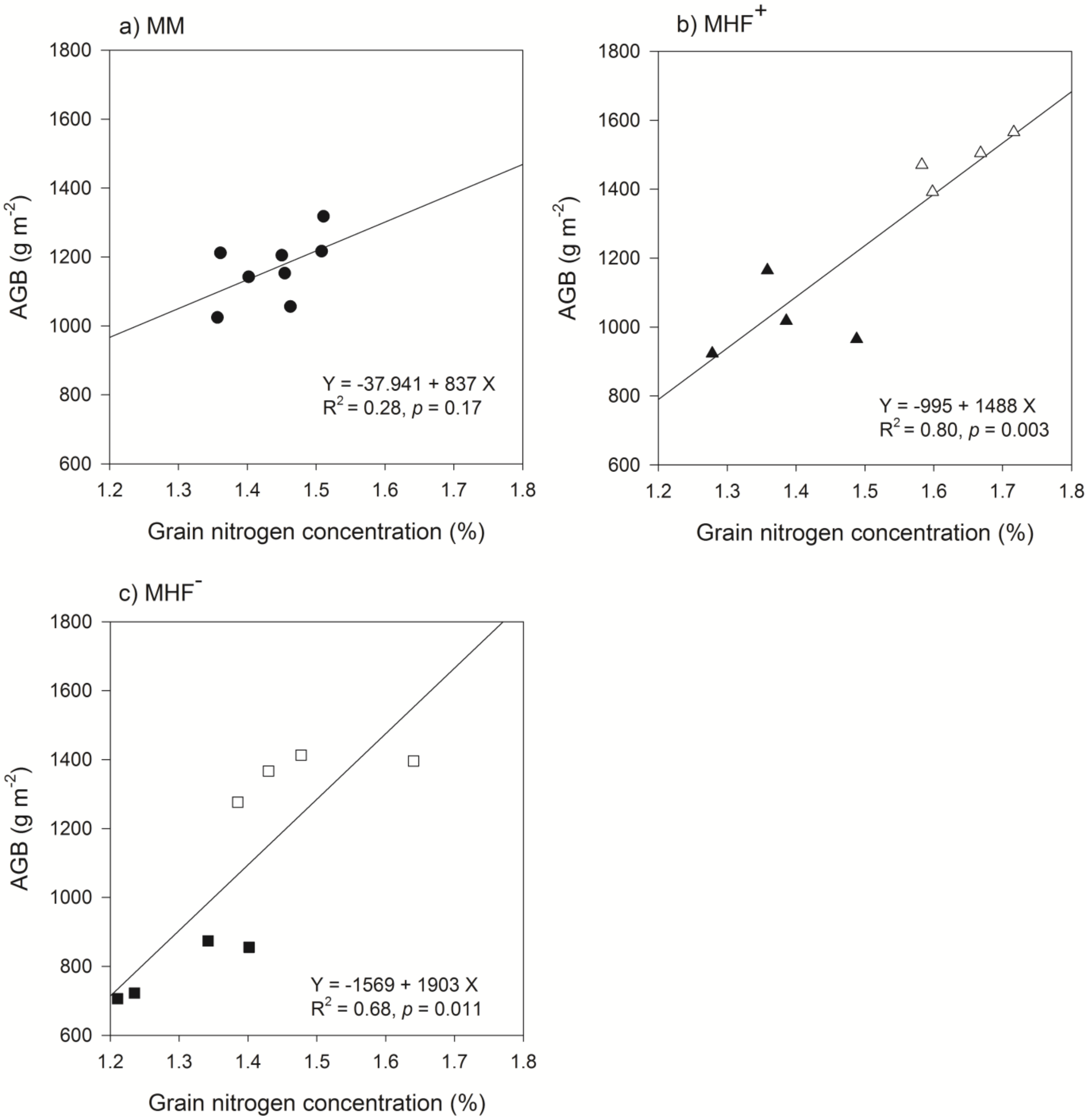

Figure 8: Relationship between maize above ground biomass and total nitrogen concentration (%N) in maize grains planted as a) maize monocrop (MM), b) hedge intercrop with fertilizer (MHF^+) and c) hedge intercrop without fertilizer (MHF^-). Data were recorded during the 2011 growing season at Queen Sirikit 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.

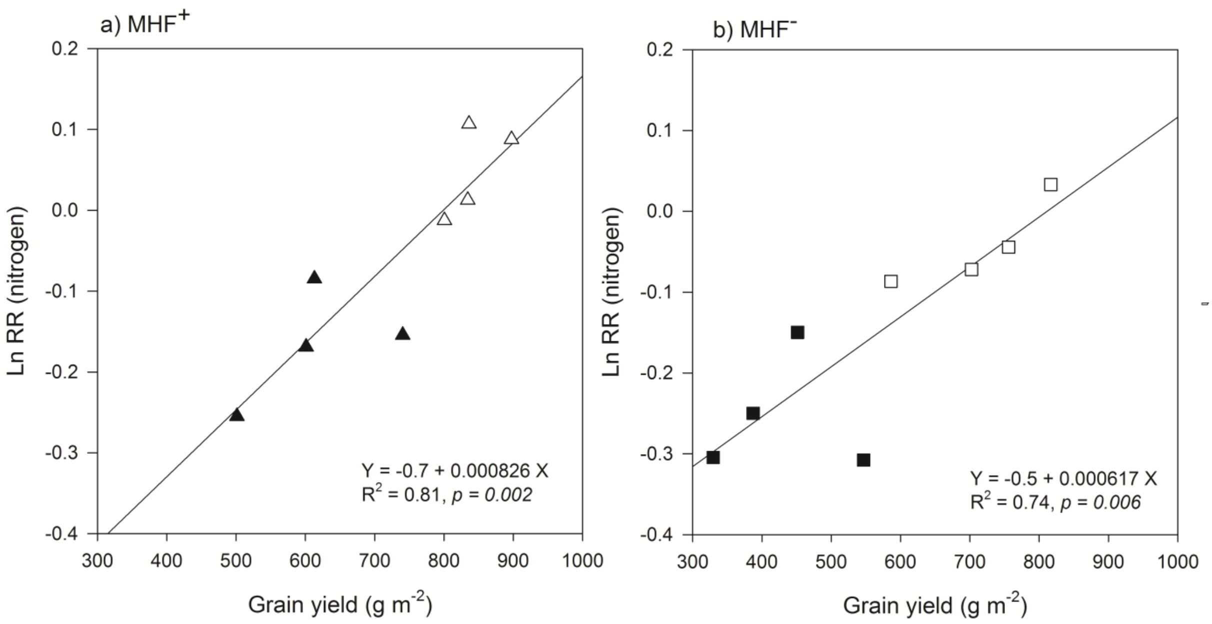

Figure 9: Comparisons of natural log response ratio of grain total nitrogen concentration (LnRRn) and grain yield in various maize rows in a) hedge intercrop with fertilizer (MHF^+) and b) hedge intercrop without fertilizer (MHF^-). Data were recorded during the 2011 growing season at Queen Sirikit Research Farm, Ratchaburi province, Thailand. The filled and unfilled symbols are showing the maize rows present close and distant to hedgerows, respectively.

2.4.6 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 (Fig. 10). 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 (Fig. 11); 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, show ing a significant correlation with each other (r = 0.66 and $p \leq 0.001$; Fig. 12). A similar but not significant trend was observed with $\delta^{13}C$ signals in maize leaves collected at 100 DAP (data not presented).

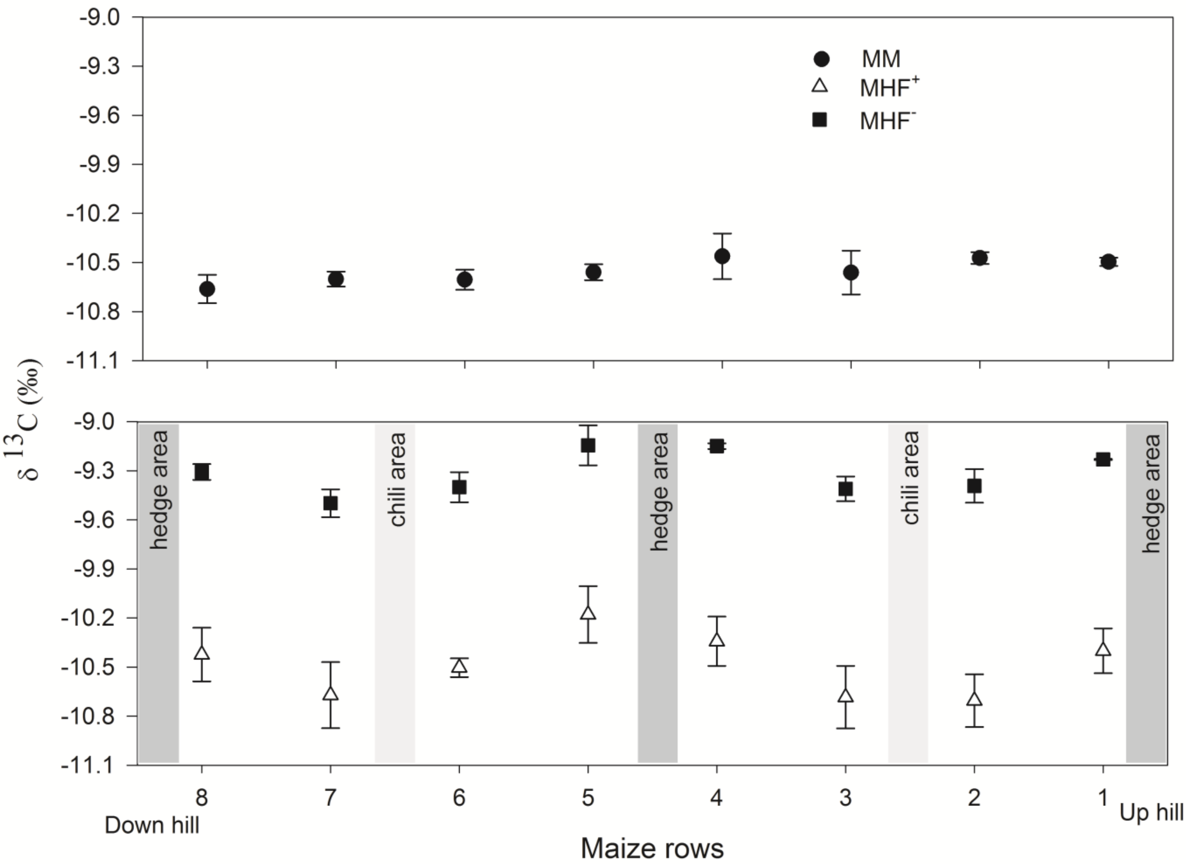

Figure 10: Spatial variability of grain $\delta^{13}C$ signals in various maize rows in maize monocrop (MM) (upper figure), hedge intercrop (lower figure) with fertilizer (MHF^{+}) and hedge intercrop without fertilizer (MHF^{-}). Bars are showing the standard error. Data were recorded during the 2011 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.

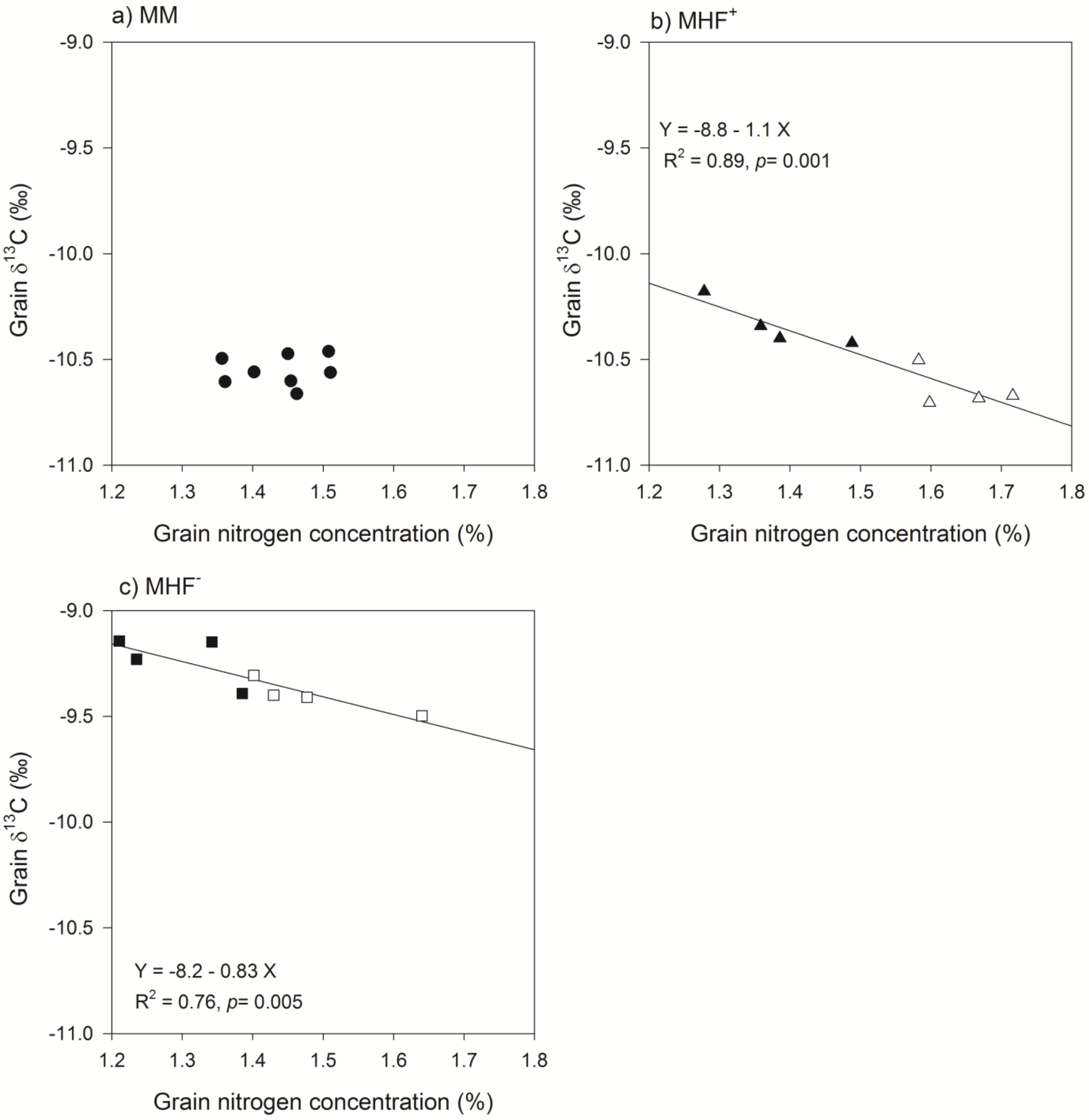

Figure 11: Relationships between $\delta^{13}C$ and total nitrogen concentration (%N) in maize grains planted as a) maize monocrop (MM), b) hedge intercrop with fertilizer (MHF^{+}) and c) hedge intercrop without fertilizer (MHF^{-}). Data were recorded during the 2011 growing season at Queen Sirikit 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.

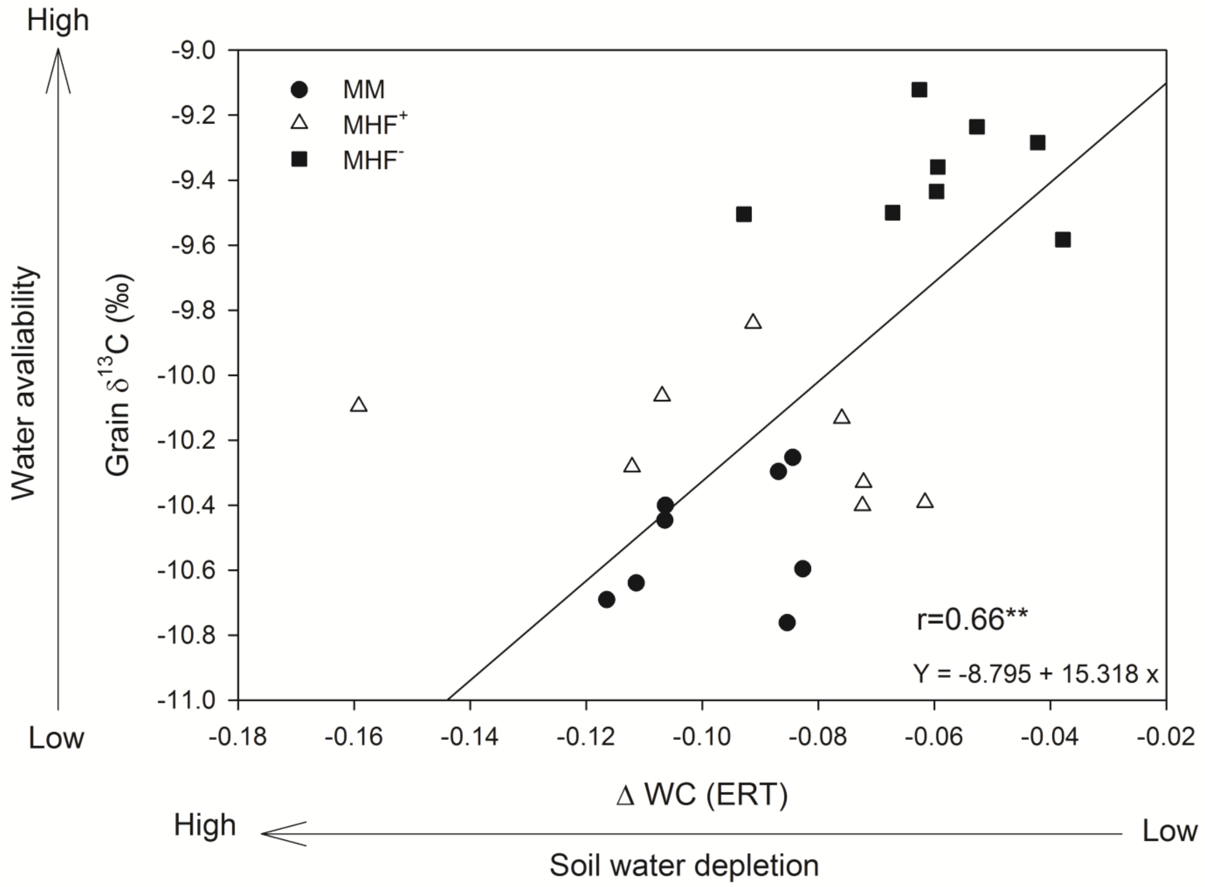

Figure 12: Relationship between grain stable carbon isotope discrimination and ΔWC (ERT) measured on 29th August 2011 (here Δ WC is the difference between actual water contents on 29th August, 2011 and initial water contents which was set zero to calculate soil moisture depletion of a specific date). Data were recorded during the 2011 growing season at Queen Sirikit Research Farm, Ratchaburi province, Thailand.

2.5 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 nutrient 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 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.

2.5.1 Water competition

The results of our study did not confirm our initial hypothesis 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 total numbers 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, soil moisture depletion was larger under maize growing in rows close to the hedge than under maize next to chili (Fig. 6). 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 under 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 (Fig.4). 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 (Tab. 1, Fig. 10), 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. (2001) and Pansak et al. (2007).
In contrast, mean maize grain $\delta^{13}C$ signals were significantly more negative in MM (Tab. 1), pointing to drier soil conditions (Clay et al. 2001; Dercon et al. 2006a; Pansak et al. 2007; Wang et al. 2012) with larger soil moisture depletion (Fig. 6). 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 better moisture conservation by hedgerows slowing down water runoff, additionally facilitating water infiltration (Pansak et al. 2008).

2.5.2 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^+) (Tab.1). 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 above ground 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 DAP did not show yet significant $\delta^{13}C$ effects between rows close/distance to hedge suggests that nutrient limitation increased particularly during later stages or before the development of sampled maize leaves, while 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^+ (Fig. 9). 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 above ground biomass compared to distant maize rows in MHF^+ and MHF^- treatments (Fig. 8).

2.5.3 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 DAP 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 (Fig. 4). 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.

2.6 Conclusions

ERT measurements enabled visualizing spatio-temporal patterns of water depletion in a wide range of cropping systems which cannot be easily obtained by other soil moisture measurements. In combination with the stable isotope discrimination method it 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 as $\delta^{13}C$ signals of these maize rows were less negative. This argument was confirmed by both ERT and TDR soil moisture data and in the unfertilized treatment which showed least negative $\delta^{13}C$ signals, indicating that nutrient deficiency induced less negative $\delta^{13}C$ values. Thus, nutrient competition, especially for nitrogen, was the factor responsible for poor growth and yield performance of maize in rows close to hedgerows in MHF^+ treatment.

ERT imaging was also helpful in understanding the growth and development of plants and particularly in revealing time dependent spatially explicit soil moisture utilization under different management practices under field conditions allowing visualization of water uptake over time. Carbon isotopic discrimination and electrical resistivity tomography imaging proved to be valuable tools in understanding crop behaviour under investigated cropping systems. Moreover, the results revealed that having only ^{13}C values is not sufficient as both water and nutrient deficiency are affecting ^{13}C discrimination in plants. It is thus necessary to have additional treatments or measurements of water availability which aid in separation of water and nutrient stress in mixed systems. Hence, the combination of ^{13}C discrimination and ERT proved to be highly valuable in understanding and distinguishing water competition from nitrogen competition at this complex interface.

Such type of experiments would be useful to fine tune crop management of hedgerow- or grass barrier-based soil conservation systems in mitigating competition by developing specific fertilizer recommendations to overcome the nutrient gap close to tree hedges and grass barriers. This may foster farmers' adoption of hedgerow or barrier based soil conservation measures which are needed for reducing soil erosion, leading to a more sustainable land use in tropical hillside agriculture in the long run. Data of such studies are also demanded 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 1999).

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Chapter 3

Maize performance at crop-hedge interface in tropical hillside agriculture

Chapter 3 Maize performance at crop-hedge interface in tropical hillside agriculture *

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3.1 Abstract

Intercropping and agroforestry systems are important land uses to sustain tropical hillside agriculture. In a field trial with 20-25% slope located in western Thailand, we evaluated the impact of cropping options - monocropping *vs*. intercropping and hedgerow systems; +/- fertilizer application; tillage *vs*. minimum tillage plus legume relay cropping - on maize above ground biomass accumulation (AGB), leaf area index (LAI), grain nitrogen concentration (N_g), canopy interception of photosynthetic active radiation interception (IPAR), light use efficiency (LUE) and land equivalent ratio (LER). Maize AGB production (1365g m^{-2}) was higher in maize-chili intercropping with fertilization than in current farmers' practice of maize monocropping (control). LUE for AGB was 1.44-1.56 g DM MJ^{-1} in fertilized intercropping and hedgerow systems, being 17-27% higher than in the control. With fertilization, LER of maize-chili intercropping (1.03-1.17) and hedgerow intercropping (1.21) was higher than that of the control. Maize N_g of fertilized intercropping systems did not differ significantly as compared to the control but was significantly lower in unfertilized intercropping system with minimum tillage. Intercropping was favorable for exploiting available resources increasing biomass production of maize, whereas hedgerows negatively affected the productivity of maize growing in rows close to them. Higher LUE and LER of hedgerow intercropping with fertilization in contrast to maize monocropping may foster farmers' adoption, as it improves both, land utilization and shelter against erosion. Understanding the spatial variations of LUE and Ng and their impact on crop productivity can be applied for fine-tuning crop management in agroforestry, mitigating resource bottlenecks at the crop-soil-hedge interface.

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3.2 Introduction

Maize (*Zea mays*) has become one of the major crops in Asia. The latest projections by the International Food Policy Research Institute (IFPRI) indicated that by 2020 the demand for maize will overtake the demand for wheat and rice in all developing countries, with Asia accounting for 60% of the global demand for maize (IFPRI 2003); in Thailand, it is cultivated on about 33% of its upland area (Ekasingh et al. 2004). In SE Asia, juvenile growth of maize poses a strong erosion risks (Hilger et al. 2013). Soil erosion is threatening crop production on upland of Thailand having moderate to steep slopes where around 34% of the cultivated land is affected by severe top soil erosion (Pansak et al. 2010). This study was conducted in uplands of Western Thailand facing the soil erosion problem. The government and nongovernment agricultural organization of the area encouraging farmers to use soil conservation practices such as alley cropping, contour hedgerows, grass barriers, establishing of agroforestry systems based on fruit tree planting with minimal disturbance of soil. Intercropping is commonly followed practice of the area.

In future, agriculture have to produce more food from less area of land to meet demands of growing population through efficient use of natural resources with minimal impact on the environment (Hobbs et al. 2008). Light is considered as important natural resource and main input in net primary productivity. The amount of light intercepted by a canopy is mainly determined from its leaf area index (LAI) (Iio et al. 2014). Any change in LAI and intercepted radiation is likely to influence yield performance (Stewart et al. 2003). Early canopy development has a key role to maximize radiation interception. However, radiation interception can be altered not only by row spacing but also by increasing planting density (Tharp and Kells 2001). Many studies pointed to a positive correlation between total dry matter and the amount of radiation intercepted by plants under both monocropping (Edwards et al. 2005; Liu et al. 2012) and intercropping conditions (Chen et al. 2002). The ability to transform the radiant energy absorbed in the form of photosynthetic active radiation into biomass is referred as light use efficiency (LUE). LUE in plant varies with changes in LAI (Campbell et al. 2001), proportion of diffuse radiation in solar radiation (Kanniah et al. 2012), and nitrogen status (Khaliq et al. 2008). Planting patterns directly affect the distribution of radiation within a canopy and the interception of incident light. Some studies pointed out that light use efficiency decreases with increasing planting density while maximum biomass production is not limited by intercepted photosynthetic active radiation (Purcell et al. 2002).

It has been often suggested that plants under intercropping conditions can complement each other and increase their resource use efficiency when two intercropped species do not compete for the same resource niche and, hence, use the resources in a complementary way (Hauggaard-Nielsen et al. 2001). Many studies have been carried out on light interception and light use efficiency of crops under various cropping conditions (Tsubo et al. 2001; Edwards et al. 2005; Liu et al. 2012); however, these results cannot automatically applied to tropical agriculture where agroforestry systems, such as hedgerow cropping, are often proposed to combat erosion (Garrity 2004; Nair et al. 2007; Garrett et al. 2009). Integrating hedgerows into intercropping makes the cropping system even more complex due to various interactions between components of the system. Little information on radiation interception, light use efficiency, land equivalent ratio and harvest index in maize based cropping systems involving more than one species is available for hillside agriculture in tropical regions. We hypothesized that diversification of the cropping system has a positive impact on maize biomass accumulation and light use efficiency along with intercropping while planting patterns as found in hedgerow cropping have a negative impact light use efficiency and biomass accumulation. Larger distances between rows positively affect vertical and lateral PAR capture within canopy. Main objectives this study were to investigate the impact of various cropping system with soil conservation options on maize above ground biomass accumulation (AGB), leaf area index (LAI), grain nitrogen concentration (N_g), canopy interception of photosynthetic active radiation interception (IPAR), light use efficiency (LUE) and land equivalent ratio (LER) on tropical hill-sides of Western Thailand.

3.3 Materials and methods

3.3.1 Study site

This field trial was conducted at Queen Sirikit research farm, Ban Bo Wi village (13°28´ N, 99°15´ E), Suan Phueng District, Ratchaburi province of Thailand. The area has an annual precipitation of about 1200 mm falling mostly from May to October. Mean annual temperature is 28 °C, while the area receives a mean solar radiation about14 MJ m^{-2} d^{-1}. The soil at the study site was classified as a loamy-skeletal, siliceous, isohyperthermic, kanhaplic Haplustult, being prone to surface erosion (Land Development Department, 2011). Most of the area is mountainous with steep to moderate slopes on which maize is commonly grown. Other major crops are cassava (*Manihot esculenta*) and chili (*Capsicum annuum*). The maize growing season starts just after the onset of rains in June and ends mostly end of September to mid of October.

3.3.2 Experimental layout

The study presented here was carried out during 2011, two years after establishment of an erosion trial, so that soil conservation measures had time to develop. The experimental design was a randomized complete block design with three replicates. Plots were 13 m long and 4 m wide with a slope gradient of 20-25%. The following six cropping treatments were investigated (Fig. 1):

(i) Maize (*Zea mays* L. cv. Pacific 999) monocropping, tillage, and fertilization (farmers' practice, control, T1);

(ii) Maize-chili (*Capsicum annuum* L. cv. Super Hot) intercropping, tillage and fertilization (T2);

(iii) Maize-chili intercropping, minimum tillage, fertilization, and Jack bean (*Canavalia ensiformis*) relay cropping (T3);

(iv) Maize-chili intercropping, minimum tillage, fertilization, Jack bean relay cropping, and *Leucaena leucocephala* hedgerows (T4);

(v) As T3 but without fertilization (T5);

(vi) As T4 but without fertilization (T6).

Maize was sown manually on June 29th, 2011. One month old chili seedlings were transplanted on the same day while Jack bean was planted on September 15th, 2011 between all maize and chili rows in the respective treatments. During the dry season, Jack beans remained on the plots and their residues were left as mulch on the soil surface. Tillage was carried out manually by hand-hoeing to a soil depth of around 20 cm. In minimum tillage treatments, all management practices such as planting and weeding were done manually with minimum disturbance of the soil. Nitrogen fertilizer was band-applied to maize as urea in two equal splits, 31 kg N ha^{-1} one month after sowing (MAS) and another 31 kg N ha^{-1} 2 MAS while eleven kg ha^{-1} of P as triple super phosphate and 36 kg ha^{-1} of K as potassium chloride was band applied to maize 1 MAS. Chilies received a basal N dressing as urea at the rate of 92 kg ha^{-1} at transplanting only and 92 kg ha^{-1} N as top dressing one month after transplanting as recommended for this improved chili cultivar in fertilized treatments. T1 have 17 maize rows per plot while each intercropping treatment had eight maize rows and either six (T2, T3, T5) or two (T4, T6) chili rows per plot (Fig. 1). All treatments had 16 maize plants per row. In intercropping treatments, four chili plants were planted in each chili row. In T4 and T6, three hedgerows of 1 m width were planted at the upper, middle, and lower end of each plot. Leucaena hedges were established in 2009. In 2011, these hedges were pruned four times during the maize growing period. The first pruning started just before maize sowing, while the remaining were performed at 30, 60 and 105 DAP of maize. Pruning material was evenly spread within the respective plots and used as mulch. In 2011 around 3.5 and 3.0 kg $m^{-2}$of leucaena residues were applied in T4 and T6, respectively. Maize was planted at an inter-row distance of 0.75 m whereas maize to chili row spacing and chili inter-row distance were 1 m and maize to hedgerow distance 0.25 m.

Experimental measurements, calculations and analysis

3.3.3 Leaf area index and radiation interception

A Sunscan Canopy Analyzer (Delta-T Devices Ltd, UK) was used to monitor LAI and PAR. The system consists of a 1 m long probe with 64 photodiodes equally spaced along the probe length connected to a beam fraction sensor (BFS) III to determine LAI based on above and below canopy PAR readings, zenith angle, an ellipsoidal leaf angle distribution parameter (ELADP), time and location coordinates. For LAI and PAR monitoring, eight measurements per each maize and chili row while four measurements per hedgerow were taken by placing the probe below the canopy parallel to rows and evenly distributed between them to monitor the PAR reaching the soil surface while the PAR reaching the plant canopy was simultaneously monitored by the BFS-III (Fig. 2). LAI and PAR were measured five times during the maize growing period.

Fractions of PAR intercepted (fPAR) by the canopies were derived from following formula:

$$f\text{PAR} = 1 - \frac{I_o\,(MJ\ m^{-2})}{I_t\,(MJ\ m^{-2})} \qquad (1)$$

where I_o is the PAR reaching the soil surface below the canopy monitored with Sunscan probe, I_t is the total PAR hitting the canopy which was measured with beam fraction sensor. These measurements were performed in the same way in all the treatments. The PAR measurements were carried out between 9 a.m. to 12 noon Thai standard time during a day under sufficient sun light conditions to minimize errors.

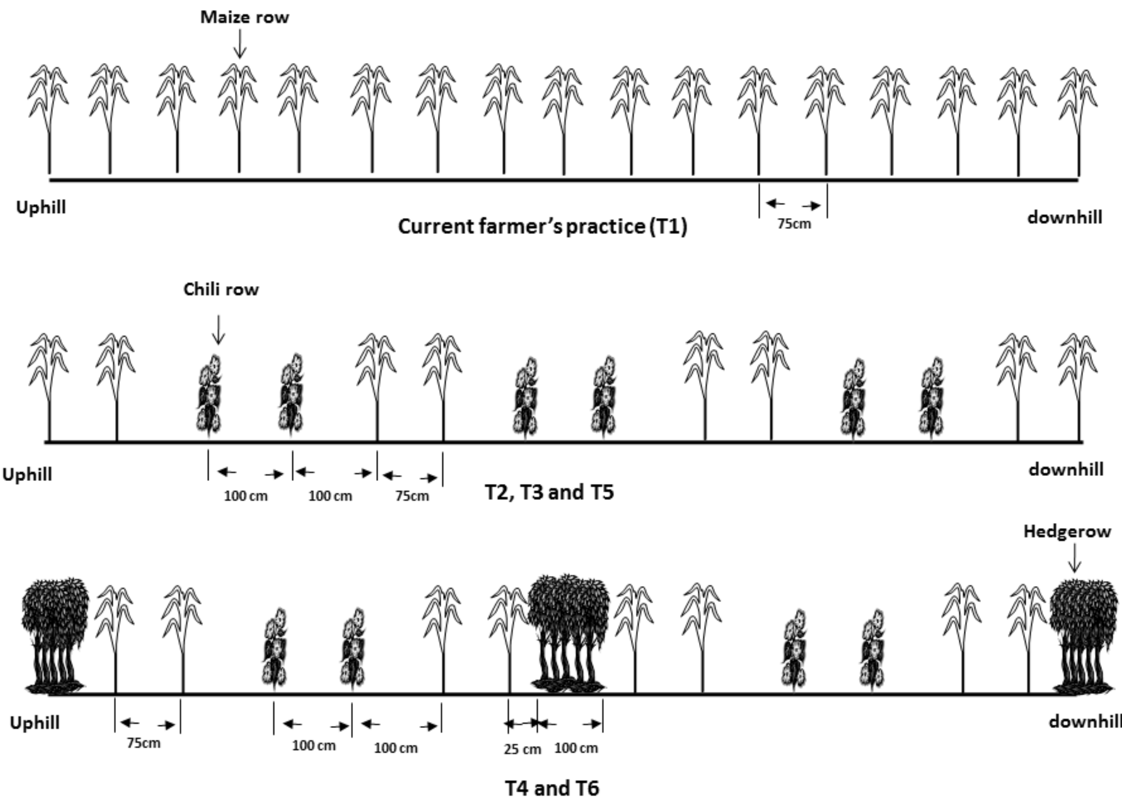

Figure 1: Overview of treatment layout and experimental setup at Queen Sirikit research farm, Ratchaburi Province, Thailand - T1: maize monocropping, tillage, and fertilization (farmers' practice, control); T2: maize-chili intercropping, tillage and fertilization; T3; maize-chili intercropping, minimum tillage, fertilization, and Jack bean relay cropping; T4: maize-chili-leucaena hedgerow intercropping, minimum tillage, fertilization, Jack bean relay cropping; T5: as T3 but without fertilization; T6: as T4 but without fertilization.

The amount of intercepted photosynthetic active radiation (IPAR) was computed as difference between above and below canopy PAR:

$$IPAR\left(MJ\ m^{-2}\right) = total\ \ ACPAR\left(MJ\ m^{-2}\right) - BCPAR\left(MJ\ m^{-2}\right) \qquad (2)$$

where $ACPAR$ is the amount of above canopy photosynthetic active radiations while *BCPAR* is the amount of photosynthetic active radiations below the canopy.

The nitrogen concentrations in maize grains were determined by dry combustion method with Euro Elemental analyzer with Finnigan Delta IRMS (Thermo Fisher Scientific Inc., Germany). For this purpose, well mixed maize leaf and grain samples were oven-dried at 70 °C until constant weight was reached. Thereafter samples were ground finely by using a ball mill and again oven-dried at 70 °C over night. Finally, well mixed sub-samples of grain flour samples were analyzed.

3.3.4 Radiation use efficiency

Light use efficiency (LUE) was calculated as the ratio of the production to the radiant energy intercepted by plants (Gallagher and Biscoe 1978):

$$LUE_{AGB}\,(g\ DM\ MJ^{-1}) = \frac{Above\ ground\ biomass\ yield\,(g\,m^{-2})}{\sum IPAR\,(MJ\,m^{-2})} \tag{3}$$

$$LUE_{GY}\,(g\ DM\ MJ^{-1}) = \frac{Grain\ yield\,(g\,m^{-2})}{\sum IPAR\,(MJ\,m^{-2})} \tag{4}$$

where LUE_{AGB} is the light use efficiency for above ground biomass production, LUE_{GY} is the light use efficiency for grain yield, $\sum IPAR$ is the cumulative PAR intercepted during the season. Above ground biomass and grain yields are expressed as gram dry matter (DM) per square meter.

3.3.5 Maize above ground biomass and grain dry matter computation

Maize was harvested on October 21, 2011. In all treatments, eight maize plants were randomly selected from each row for final harvest. After harvest, well-mixed sub-samples including grain, husk, stover, cob and leaves were taken, oven-dried, weighed to obtain dry weights of all samples, and finally above ground biomass (AGB) yield was calculated. At the same time, the grains from these harvested maize plants were separated from the cobs to calculate total fresh grain weight per row. After measuring the total fresh grain weights of eight maize plants from each row, grain subsamples were taken, weighed, oven-dried and weighed again after drying to get the grain dry matter yield. Row-based grain and above ground biomass sample weights (one row = 1.5 m^2 = 0.75 x 0.25 x 8 plants) were converted into gram per square meter to allow direct comparisons between monocropping, intercropping, and hedgerow cropping. Absolute yield was used to compare the effects of intercropping and conservation methods on row yield production, while area corrected yields were used when calculating land equivalent ratios (LER) of the tested cropping systems.

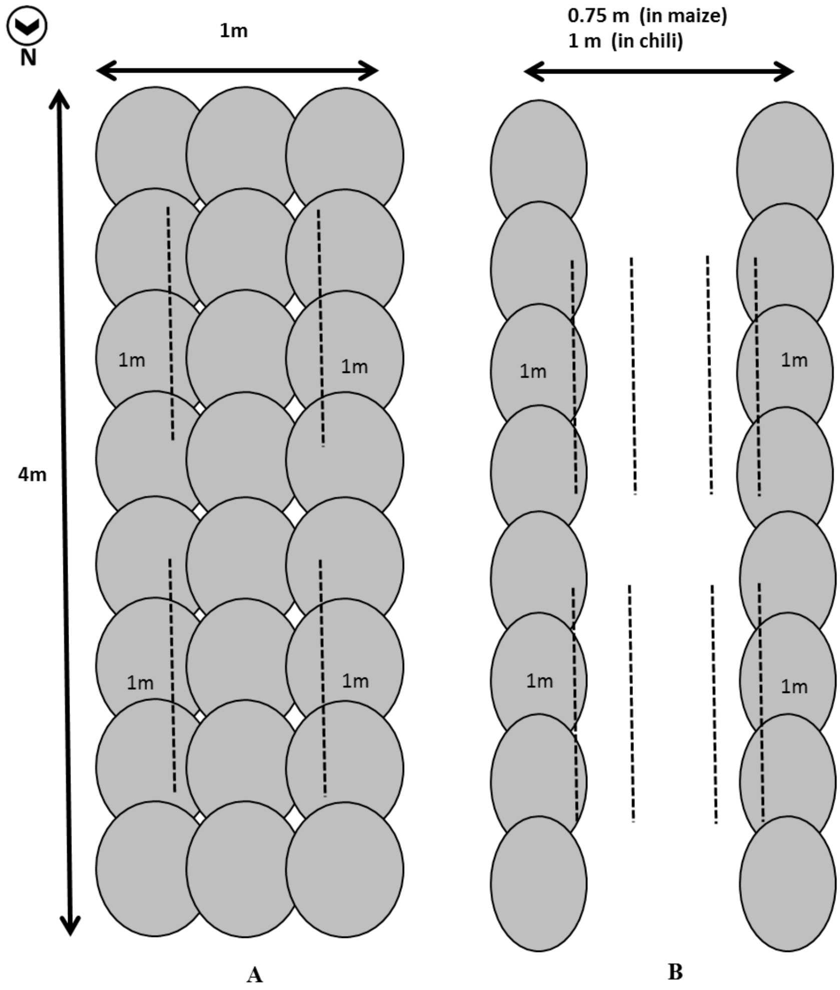

Figure 2: Overview of leaf area index (LAI) and photosynthetic active radiation (PAR) measurements between rows of crops and trees. Gray circles represent crop rows, dotted lines show the eight measurements between maize and chili rows and four measurements below the hedgerow canopy. Measurements were taken parallel to the rows by 1m Delta-T-device Sunscan probe: (A) represents the measurements in each 1m wide hedgerows, (B) indicates measurement position between each maize and chili rows. Data were monitored from July to October, 2011 at Queen Sirikit research farm, Ratchaburi province, Thailand. All positions are showing below canopy measurements.

3.3.6 Productivity evaluation

LER and harvest index (HI) were used for evaluation of cropping systems' productivity. LER is derived from relative land requirements for intercropping versus monocropping (Mead and Willey 1980) which is the sum of relative yields of the component species. LER was calculated as:

$$LER = \frac{MGY_I\,(kg\,ha^{-1})}{MGY_S\,(kg\,ha^{-1})} + \frac{CFY_I\,(kg\,ha^{-1})}{CFY_S\,(kg\,ha^{-1})} \qquad (5)$$

where MGY_I is the maize grain yield production in intercropping condition, MGY_s is the maize grain yield production under sole cropping, CFY_I is chili fruit yield in intercropped conditions and CFY_s is chili fruit yield under sole cropping conditions. For LER calculation, area corrected maize grain yield and chili fresh fruit yield were used because these were the sellable product of maize and chili for the farmers of the area. A chili monocrop treatment was also established at the experimental site for assessing chili yield under sole cropping.

HI is the fraction of economically useful product of a plant in relation to its total productivity. HI was calculated as:

$$HI = \frac{GY\,(g\,m^{-2})}{TAGB\,(g\,m^{-2})} \qquad (6)$$

where *GY* is the grain yield and *TAGB* is the total above ground biomass of maize.

3.3.7 Above ground biomass simulation

Maize AGB was simulated by using simple light capture model which is combination of light use efficiency, fraction of intercepted radiation and incident solar radiation. The simple light capture model used was:

$$B\,(g\,m^{-2}) = LUE_{AGB}\,(g\,DM\,MJ^{-1}) * fPAR * Qs\,(MJ\,m^{-2}) \qquad (7)$$

where B is the biomass yield, LUEAGB is the light use efficiency for maize above ground biomass derived from formula (3), fPAR is the fraction of photosynthetic active radiation, derived by using Equation 1 and Qs is the solar radiation incident on the crop canopy which was measured continuously on the field site with a CS300 Apogee silicon pyranometer (Campbell Scientific Inc., USA) connected to a data logger.

3.3.8 Statistical analysis

The experimental data were analyzed by using the Statistical Analysis System (SAS) version 9 (SAS Institute Inc., USA). Analysis of variance (ANOVA) was used to analyze significant differences among treatments at a significance level of $p \leq 0.05$ for total dry matter, grain dry matter and their respective light use efficiency (LUE), LER and HI. The Tukey's HSD test was used to compare treatment means at $p \leq 0.05$.

3.4 Results

3.4.1 Maize above ground biomass (AGB) and grain yield production

Mean absolute maize AGB (1365 g m^{-2}) was highest in maize-chili intercropping under tillage and fertilization (T2), being significantly ($p \leq 0.0001$) higher than the farmer's practice (T1, control) and both unfertilized intercropping treatments under minimum tillage (T5: without hedgerows; T6: with hedgerows). T2 did not differ significantly when compared to both fertilized intercropping treatments (T3: without hedgerows; T4: with hedgerows). In T2, maize AGB was 18% higher than T1, 32% higher than T5, and 27% higher than T6 (Table 1). In T4, hedgerow intercropping reduced AGB of maize by 9% as compared to T2, without being significantly different. Minimum tillage induced a 10% but non-significant decrease in AGB production (T3 *vs*. T2).

Maize grain yields showed similar patterns as observed in maize AGB production. Highest absolute maize grain yield (743 g m^{-2}) was observed in T2, statistically higher than T1 and both unfertilized treatments (T5 and T6). No significant difference in grain yield was found for T3 and T4. Maize grain yield of T2 was 16% higher than that of T1. In combination with leucaena hedgerows, maize grain yield was statistically higher in intercropping with fertilization (T4) than the same treatment without fertilizer application (T6).

Hedgerow effects on maize above ground biomass production within treatments showed statistical differences ($p \leq 0.0001$) between maize grown close and distant to hedges in T4 and T6. Maize grown in rows grown close to the hedge produced statistically lower biomass than those grown distant to hedgers. Intercropping with chilies showed a statistical increase in maize AGB production in T2 as compared to maize monocropping (T1). Fertilization positively affected AGB production in T3 > T5; T4 > T6; $p \leq 0.001$ (Table 1).

3.4.2 Fraction of intercepted photosynthetic active radiation and leaf area index

All treatments under investigation showed similar trends of increase in $fPAR$ profiles during the active growing period with a decline at maturity (Fig. 3). There was a sharp increase in fraction of radiation interception from 30 to 45 days after planting (DAP) maize and a minor increase sustained up to 60-85 DAP. Maximum interception (0.80) was observed in T1, followed by T4 (0.76), T2 (0.74) and T3 (0.73) at 85 DAP. Thereafter, $fPAR$ in all treatments decreased slightly. Statistically significant variation in interception was observed among the treatments from the first to the final measurement date ten days before harvesting. The increase in $fPAR$ during early vegetative stages was induced by active growth and canopy leaf area development at the start of maize growth. During juvenile growth (30-60 DAP), a

Table 2. Impact of cropping system on mean above ground biomass (AGB), grain yield (GY) light use efficiency for AGB (LUE_{AGB}) and GY (LUE_{GY}) of maize, LER, HI and grain nitrogen concentration (N_g). AGB and GY figures are absolute values based on row-wise assessment.

Treatments	AGB g m^{-2}	GY g m^{-2}	LUE_{AGB} g DM MJ^{-1}	LUE_{GY} g DM MJ^{-1}	LER	HI	Ng (%)
T1	1161 bc	641 bc	1.23 cd	0.68 bc	1.00	0.54	1.45 ab
T2	1365 a	743 a	1.56 a	0.85 a	1.17	0.54	1.56 a
T3	1242 ab	672 abc	1.44 abc	0.78 ab	1.03	0.54	1.51 ab
T4	1250 ab	701 ab	1.50 ab	0.84 a	1.21	0.56	1.51 ab
T5	1033 d	582 c	1.13 d	0.63 c	0.88	0.56	1.31 c
T6	1076 dc	602 c	1.28 bcd	0.71 bc	0.94	0.56	1.39 bc
	P≤0.0001	*P≤0.0001*	*P≤0.0001*	*P≤0.0001*	-	*NS*	*P≤0.001*

Hedge effect	AGB (g m^{-2})	Ng (%)	LUE_{AGB} (g DM MJ^{-1})	AGB (g m^{-2})	Ng (%)	LUE_{AGB} (g DM MJ^{-1})
	T4			T6		
Hedge close maize	1017 B	1.37 B	1.22 B	790 B	1.30 B	0.93 B
Hedge distant maize	1483 A	1.64 A	1.77 A	1362 A	1.48 A	1.62 A
	P≤0.001	*P≤0.001*	*P≤0.001*	*P≤0.001*	*P≤0.001*	*P≤0.001*

Chili effect T1 vs T2	AGB (g m^{-2})	Ng (%)	LUE_{AGB} (g DM MJ^{-1})
T1	1161 b	1.45 b	1.23 b
T2	1365 a	1.63 a	1.56 a
	P≤0.001	*P≤0.001*	*P≤0.001*
Fertilizer effects T3 vs T5			
T3	1242 a	1.51 a	1.44 a
T5	1033 b	1.31 b	1.13 b
	P≤0.001	*P≤0.001*	*P≤0.001*
T4 vs T6			
T4	1250 a	1.51 a	1.50 a
T6	1076 b	1.39 b	1.28 b
	P≤0.001	*P≤0.001*	*P≤0.001*

Figures followed by different small letters indicate significant differences between the treatments while capital letters show significant differences within the treatments.
T1: maize monocropping, tillage, and fertilization (farmers' practice, control); T2: maize-chili intercropping, tillage and fertilization; T3: maize-chili intercropping, minimum tillage, fertilization, and Jack bean relay cropping; T4: maize-chili intercropping, minimum tillage, fertilization, Jack bean relay cropping, and leucaena hedgerows; T5: as T3 but without fertilization; T6: as T4 but without fertilization.

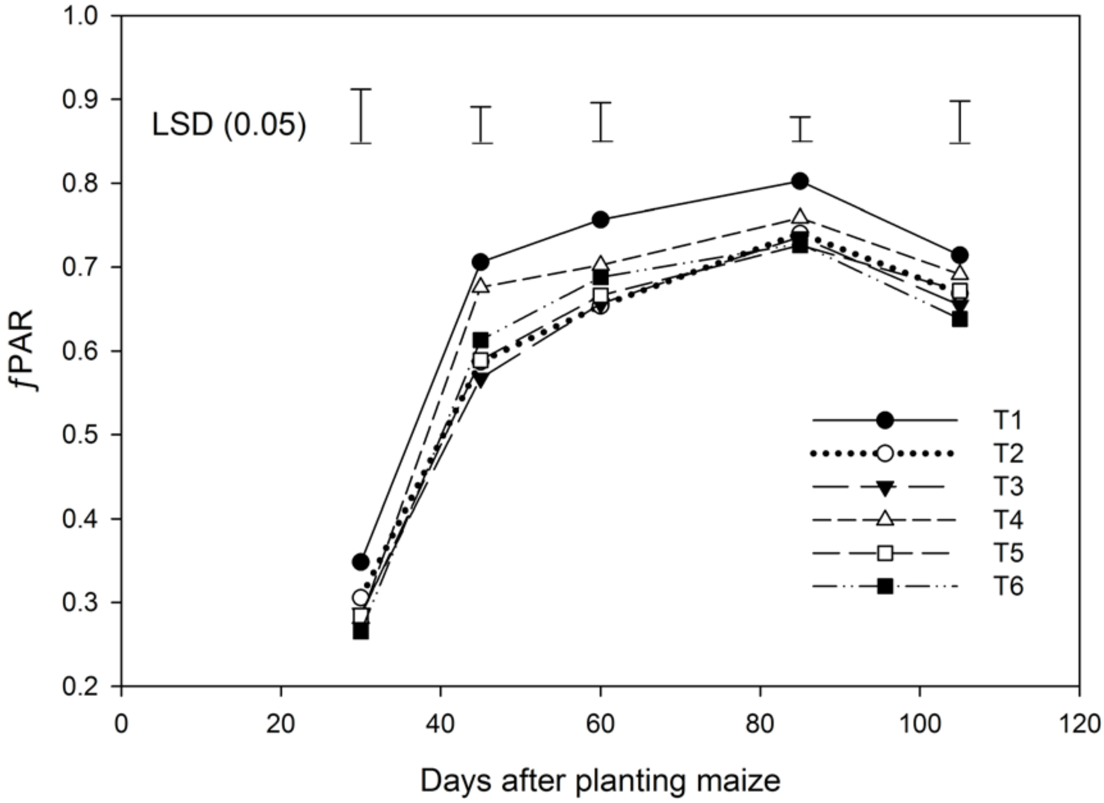

Figure 3: Seasonal changes in fraction of intercepted radiation (*f*PAR) of maize planted under various cropping system treatments T1: maize monocropping, tillage, and fertilization (farmers' practice, control); T2: maize-chili intercropping, tillage and fertilization; T3; maize-chili intercropping, minimum tillage, fertilization, and Jack bean relay cropping; T4: maize-chili-leucaena hedgerow intercropping, minimum tillage, fertilization, Jack bean relay cropping; T5: as T3 but without fertilization; T6: as T4 but without fertilization. Bars show the LSD values. Data were monitored from July to October, 2011 at Queen Sirikit research farm, Ratchaburi province, Thailand.

sharp increase in LAI was observed in all treatments (Fig. 4). A maximum LAI of 2.9 was obtained in T1 followed by T4 with 2.5 at 60 DAP, being significantly higher than the other treatments. Once the LAI attained its maximum, it started declining in all treatments. The increase in LAI at the onset of the growing season was due to a rapid vegetative growth and leaf expansion while the decline at later stages of plant growth occurred due to leaf senescence.

The natural logarithm of transmitted light was significantly and linearly correlated to LAI (R^2 = 0.68-0.77, p≤*0.001*) in all treatments (Fig. 5). The canopy extinction coefficient (k) values ranged from 0.47 to 0.63 among all the treatments but were significantly higher in T5 ($p \leq 0.01$). Intercropped treatments had overall k values (slope of the regression line between natural logarithm of transmitted light and LAI) more or less similar to the maize monocrop/farmer's practice while non-fertilized intercropped treatments had slightly higher k values compared to their corresponding fertilized treatments.

3.4.3 Intercepted PAR and its interaction with above ground biomass

IPAR increased linearly with time in all treatments during maize growing period (Fig. 6). Treatment comparisons showed that IPAR of T1 was significantly ($p \leq 0.0001$) greater than that of T2 from 45 days after planting maize (DAP) onward (Fig. 6a). There was no significant difference in PAR intercepted between T3 and T5 (Fig. 6b), while T6 had a significantly ($p \leq 0.01$) higher IPAR than T4 from 60 to 85 DAP (Fig. 6c). Differences between treatments tended to increase towards later growth stages in T1 *vs*. T2 while in T4 *vs*. T6 differences were higher during the middle of the growing season.

There were significant correlations between above ground biomass (AGB) and cumulative IPAR (∑IPAR) in all the treatments (Fig. 7). The ∑IPAR and maize AGB production relationships were linearly correlated to each other in T1 with R^2=0.88, T2 with R^2=0.80, T3 with R^2=0.74, T4 with R^2=0.93, T5 with R^2=0.78 and T6 with lowest R^2 value of 0.62 with $p \leq 0.001$.

3.4.4 Maize light use efficiency and nitrogen concentration

Mean LUE for AGB and grain yield of all treatments showed significant differences ($p \leq 0.0001$, Table1). T2 had the highest LUE_{AGB} (1.56 g DM MJ^{-1}), being significantly higher than T1 and both treatments without fertilization (T5, T6) but not when compared to T3 (1.44 g DM MJ^{-1}) and T4 (1.50 g DM MJ^{-1}). On an average, LUE_{ABG} of T2 was 27, 38, and 22% higher than that of T1, T5, and T6, respectively. The lowest light use efficiency for AGB production (1.13 g DM MJ^{-1}) was observed in T5, without showing significant differences when compared with T1 and T6. Additionally, LUE for grain yield production showed a similar behavior of radiation use to that of AGB production in all the treatments; i.e. LUE of T2 was 25, 39, and 20% higher as compared to T1, T5, and T6, respectively. Mean grain nitrogen concentration (Ng) also significantly varied among treatments (Table 1). Highest grain nitrogen concentration was observed in T2 (1.56%), statistically higher than in both unfertilized treatments. There were no significant differences in Ng among fertilized treatments (T1, T2, T3 and T4). Maize leaf nitrogen concentration collected during the maize growing period showed similar trends in all treatments without any larger variation (data not presented).

In T4, maize grown in rows close to hedgerows produced 45% lower LUE_{ABG} (1.22 g DM MJ^{-1}) than maize from rows distant to hedgerows. In T6, maize grown in rows close to hedgerows showed 74% decrease in LUE_{ABG} as compared to maize grown in rows distant to hedgerows. In T4, grain nitrogen concentration was also statistically lower in the maize rows planted closed to the hedgerows (1.37 %) than the maize rows planted distant to hedgerows (1.64), $p \leq 0.0001$ (Table 1).

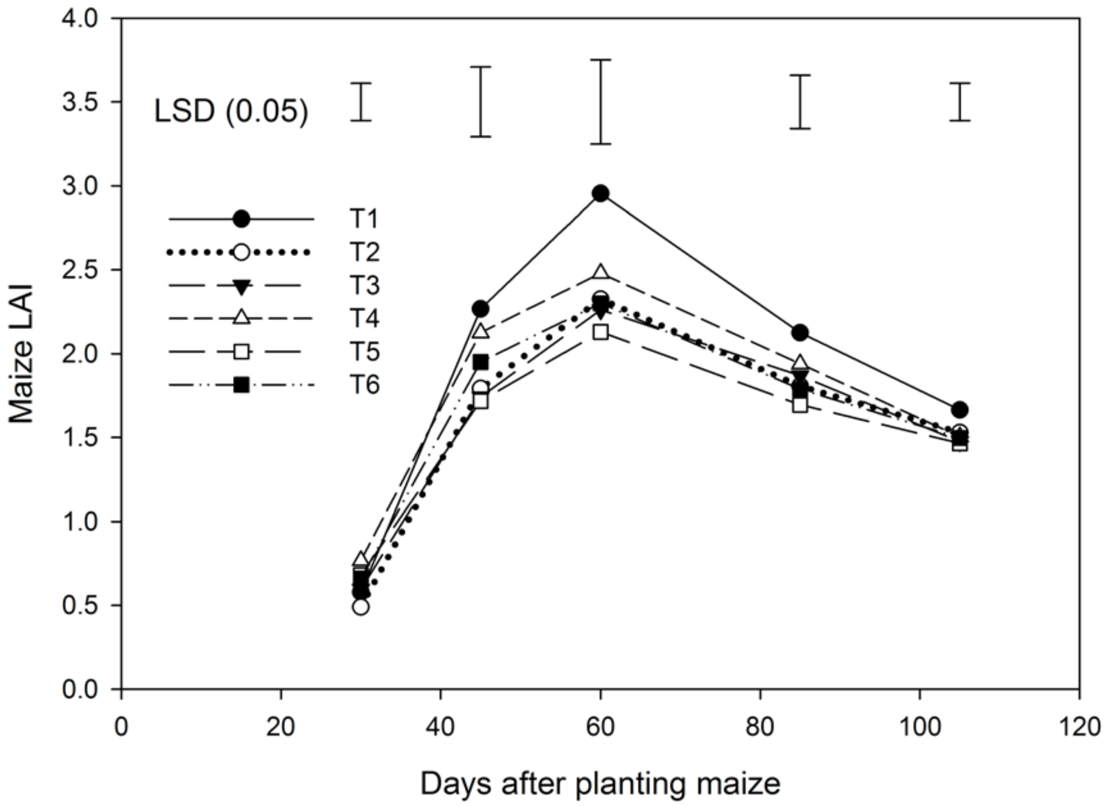

Figure 4: Seasonal changes in maize leaf area index (LAI) of various cropping system treatments T1: maize monocropping, tillage, and fertilization (farmers' practice, control); T2: maize-chili intercropping, tillage and fertilization; T3; maize-chili intercropping, minimum tillage, fertilization, and Jack bean relay cropping; T4: maize-chili-leucaena hedgerow intercropping, minimum tillage, fertilization, Jack bean relay cropping; T5: as T3 but without fertilization; T6: as T4 but without fertilization. Bars show the LSD. Data were monitored from July to October, 2011 at Queen Sirikit research farm, Ratchaburi province, Thailand.

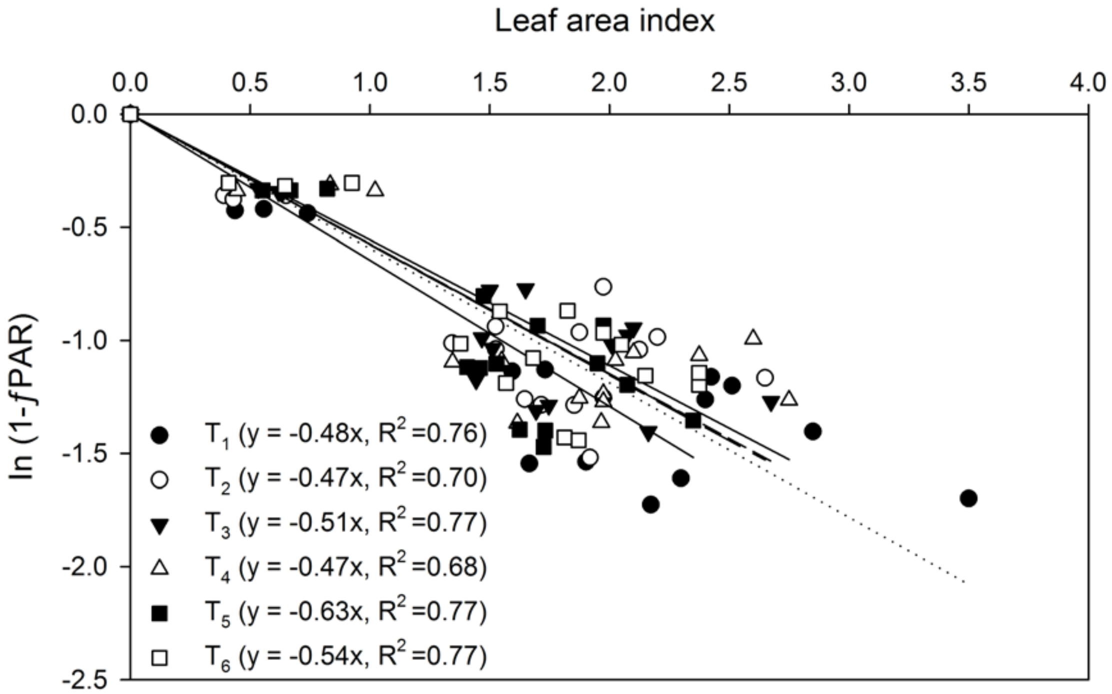

Figure 5: Extinction coefficients (slope) derived from regression of fraction of intercepted radiation and maize leaf area index of various cropping system treatments T1: maize monocropping, tillage, and fertilization (farmers' practice, control); T2: maize-chili intercropping, tillage and fertilization; T3; maize-chili intercropping, minimum tillage, fertilization, and Jack bean relay cropping; T4: maize-chili-leucaena hedgerow intercropping, minimum tillage, fertilization, Jack bean relay cropping; T5: as T3 but without fertilization; T6: as T4 but without fertilization. Data were recorded during 2011 at Queen Sirikit research farm, Ratchaburi province, Thailand.

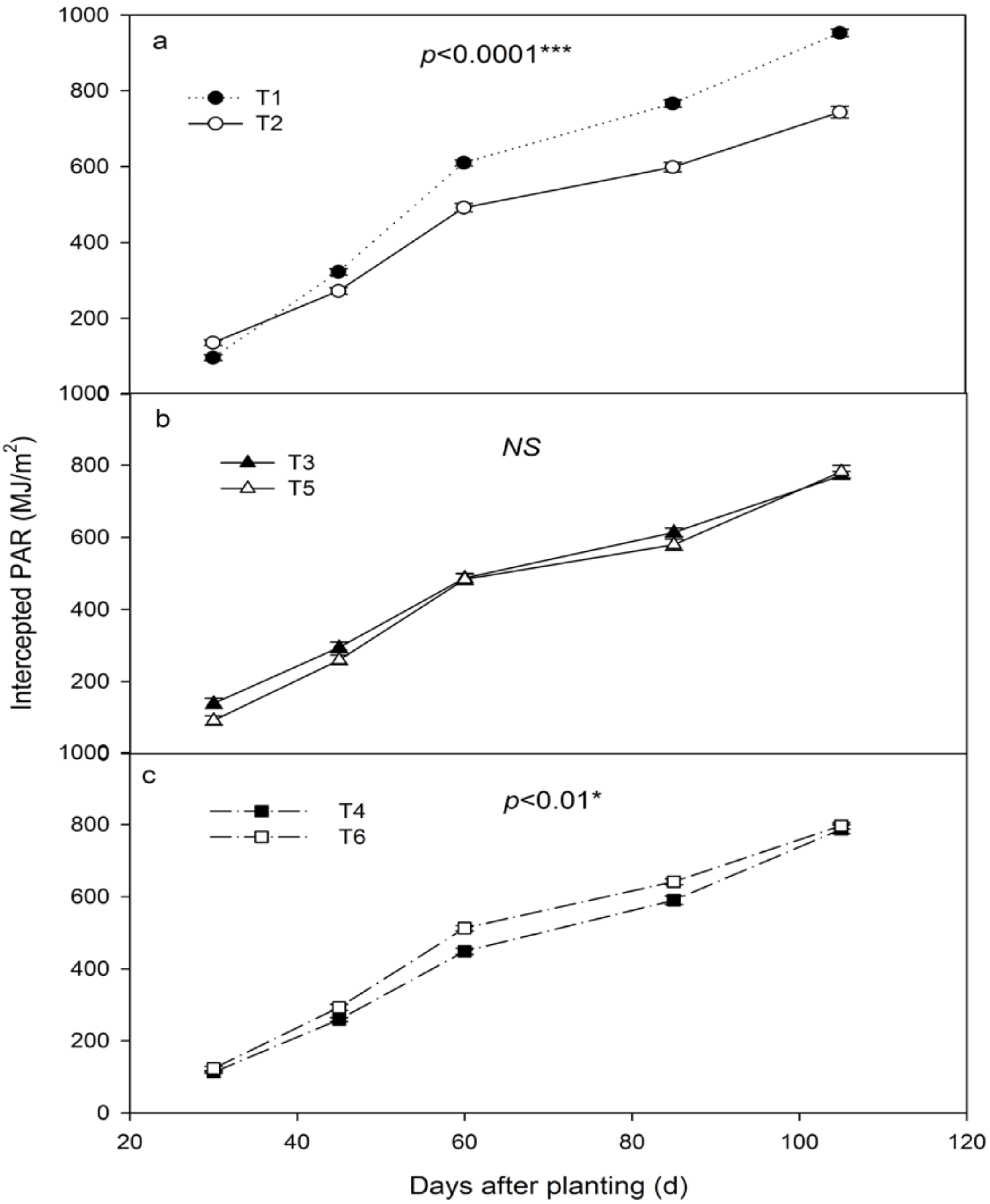

Figure 6: Seasonal changes in intercepted photosynthetic active radiation (MJ m^{-2}) of maize planted under various cropping system treatments T1: maize monocropping, tillage, and fertilization (farmers' practice, control); T2: maize-chili intercropping, tillage and fertilization; T3; maize-chili intercropping, minimum tillage, fertilization, and Jack bean relay cropping; T4: maize-chili-leucaena hedgerow intercropping, minimum tillage, fertilization, Jack bean relay cropping; T5: as T3 but without fertilization; T6: as T4 but without fertilization. Bars represent standard error of mean. Data were recorded during 2011 at Queen Sirikit research farm, Ratchaburi province, Thailand.

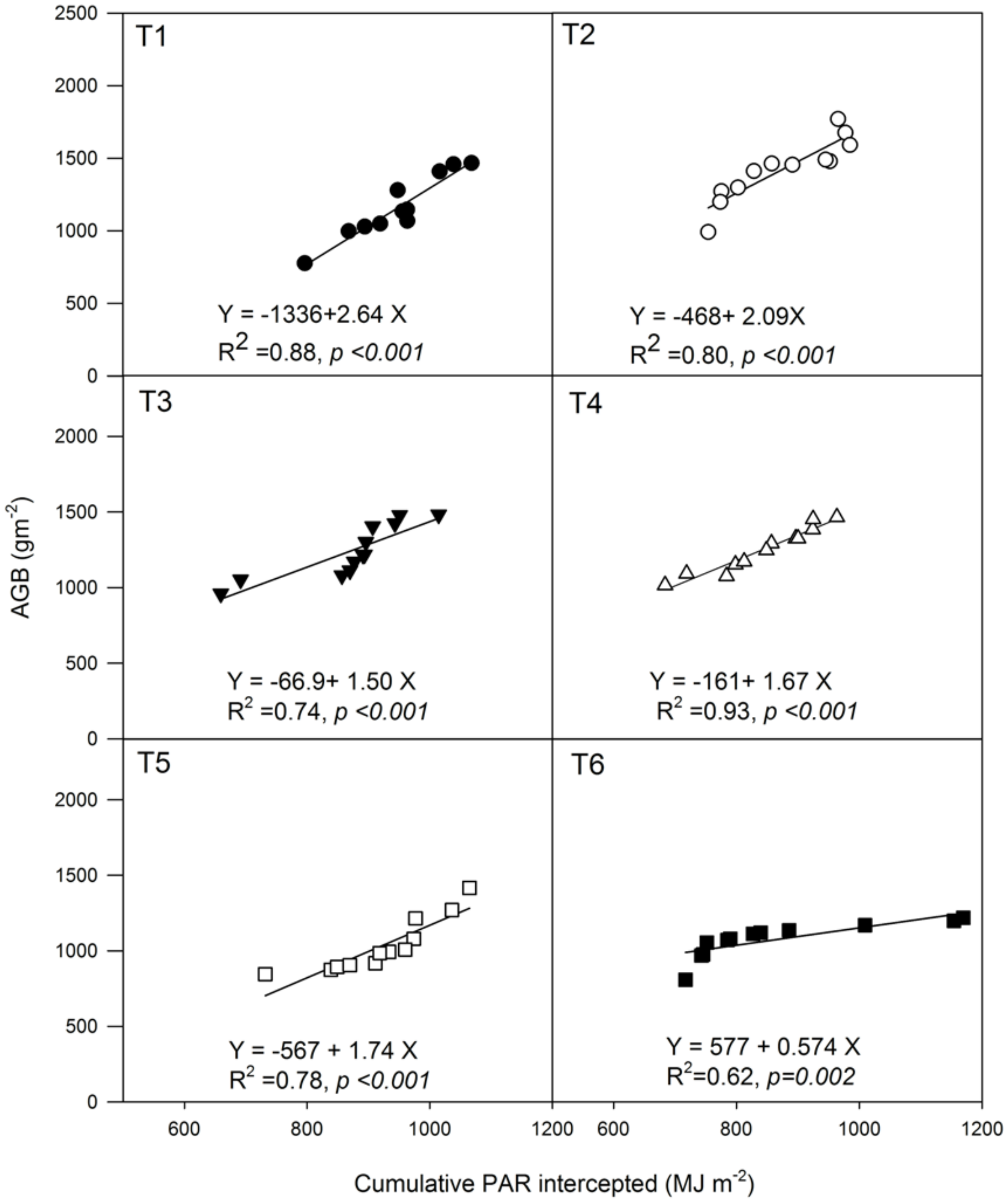

Figure 7: Relationship between cumulative PAR intercepted (MJ m^{-2}) and above ground biomass (AGB) production (g m^{-2}) of maize planted under various cropping system treatments T1: maize monocropping, tillage, and fertilization (farmers' practice, control); T2: maize-chili intercropping, tillage and fertilization; T3; maize-chili intercropping, minimum tillage, fertilization, and Jack bean relay cropping; T4: maize-chili-leucaena hedgerow intercropping, minimum tillage, fertilization, Jack bean relay cropping; T5: as T3 but without fertilization; T6: as T4 but without fertilization.

To investigate the effects of chili on maize LUE and grain nitrogen concentration, a comparison of maize under farmers' practice (T1) with T2 was carried out. T2 showed a positive effect on maize light use efficiency (1.56 g DM MJ^{-1}) as compared to maize monocropping with significantly lower light use efficiency (1.1.23 g DM MJ^{-1}). Similarly, grain nitrogen concentration was statistically higher in T2 as compared to T1. Maize LUE_{ABG} showed a fertilizer effect in maize chili intercrop treatments (T3 *vs*. T5). The fertilized T3 harvested light more efficiently (1.44 g DM MJ^{-1}) than its corresponding unfertilized treatment, T5 (1.13 g DM MJ^{-1}), with a similar cropping pattern, being statistically 27% lower than in T3. In case of grain nitrogen concentration, T3 maize grains showed statistically higher N concentrations (1.51%) in than its unfertilized corresponding treatment (T5) (1.31%). Fertilizer effects on LUE of maize hedgerow intercropping (T4 *vs*.T6) were also clearly visible. Maize mean LUE of T4 was statistically higher (1.50 g DM MJ^{-1}) than T6 (1.28 g DM MJ^{-1}). Fertilization enhanced maize light use efficiency by 18% as compared to its corresponding without fertilization (T4 *vs*. T6). Similarly, maize N_g of T4 under fertilized condition showed statistically higher values (1.51%) than T6 without fertilization (Table 1).

The relationship between LUE_{ABG} and maize N_g was linear and statistically correlated in T3 (R^2= 0.56, p= 0.03), T4 (R^2= 0.81, p= 0.002) and T6 with R^2= 0.73, p= 0.007 (Fig. 8). The trends were linear in T2 (R^2= 0.41, p= 0.07) and T5 (R^2= 0.33, p= 1.3) but the results were not significant. In T1, LUE showed no relationship to that of grain nitrogen concentration. The relationships were strong in T4 and T6, showing higher values with higher N_g in maize growing in the four rows distant to hedgerows. Values, however, were low when maize was planted in rows close to the hedgerows, associated with lower grain N concentrations.

3.4.5 Productivity evaluation and biomass simulation

The LER based on area corrected yields showed for maize intercropping with chili and hedgerows under minimum tillage and fertilizer application (T4) the highest value (1.21), followed by maize-chili intercropping under tillage and fertilization (T2) with a LER value of 1.17 while T3 showed a small LER increase of 1.03 only. Overall, minimum tillage without fertilization reduced the productivity of intercropping systems. Therefore, the lowest LER among all intercropping treatments was found in T5 with 0.88 (15% lower than T3), followed by T6 with an LER of 0.94 (22% lower than T4).

Harvest index, showed no significant differences between the treatments at 0.05% level of significance.

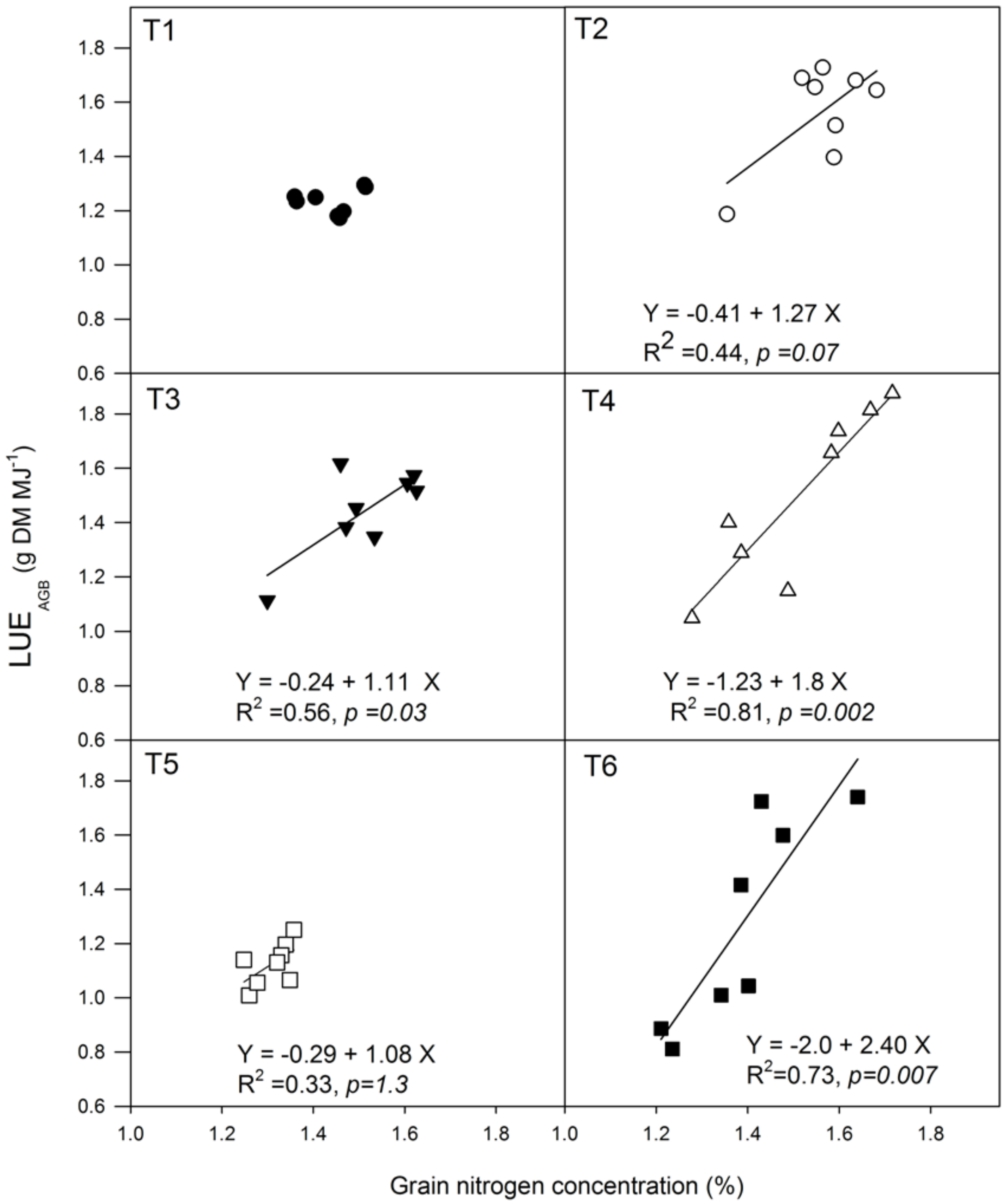

Figure 8: Relationship between maize grain nitrogen concentration (%) and light use efficiency for above ground biomass production (LUE_{AGB}) (g DM MJ^{-1}) of maize planted under various cropping system treatments T1: maize monocropping, tillage, and fertilization (farmers' practice, control); T2: maize-chili intercropping, tillage and fertilization; T3; maize-chili intercropping, minimum tillage, fertilization, and Jack bean relay cropping; T4: maize-chili-leucaena hedgerow intercropping, minimum tillage, fertilization, Jack bean relay cropping; T5: as T3 but without fertilization; T6: as T4 but without fertilization.

Simulation of maize AGB by using a simple light capture model showed promising results and was statistically linearly related to the observed maize AGB production with strong line of fit values in all treatments investigated (Fig. 9). The highest line of fit between observed and simulated AGB was observed in T4 (R^2= 0.82, p<0.001) while the lowest line of fit was observed in T5 (R^2= 0.66, p<0.001). In T4, the simple light capture model simulated the effects of hedgerows on maize grown in rows close to them with lower AGB production. Values were close to the observed values while the model simulated higher AGB production for maize grown in rows distant to hedgerows as observed in the field experiment. The relationship between simulated and observed AGB production of maize grown close or distant to hedgerows without fertilization (T6) was also linear and significant (R^2= 0.66, p<0.001).

3.5 Discussion

3.5.1 Impact of intercropping systems on canopy extinction coefficient, PAR interception and maize AGB

The canopy extinction coefficient (k) is referred to as slope of the regression line between natural logarithm of transmitted light and LAI which usually explains the average projected area of canopy elements onto horizontal surfaces (Campbell and Norman 1989). k values empirically varies from 0.3-1.5; with k >1.0 indicating horizontal leaves positions of while k <1.0 referring to non-horizontal leaf distributions (Jones 2013). Unfertilized intercropped treatments showed higher k values compared to fertilized intercropped treatments, indicating a slight change in leaf orientation which ultimately reduced the capacity of maize canopies under unfertilized conditions to capture light and convert it into biomass (Fig. 5). Maize above ground biomass production was linearly related to PAR intercepted (Fig. 7). Actually, good canopy structure is conducive for higher light capture and enhances crop dry matter production which has a positive correlation with intercepted PAR (Liu et al. 2012). Edwards et al. (2005) also pointed to a positive and linear relationship between AGB production and intercepted PAR in maize, widely confirming our findings.

3.5.2 Impact of intercropping systems on maize light use efficiency and nitrogen concentration

Many studies showed a positive relationship between crop productivity and LUE (e.g. Chen et al. 2002; Li et al. 2006). The findings presented here were in accordance with these studies.

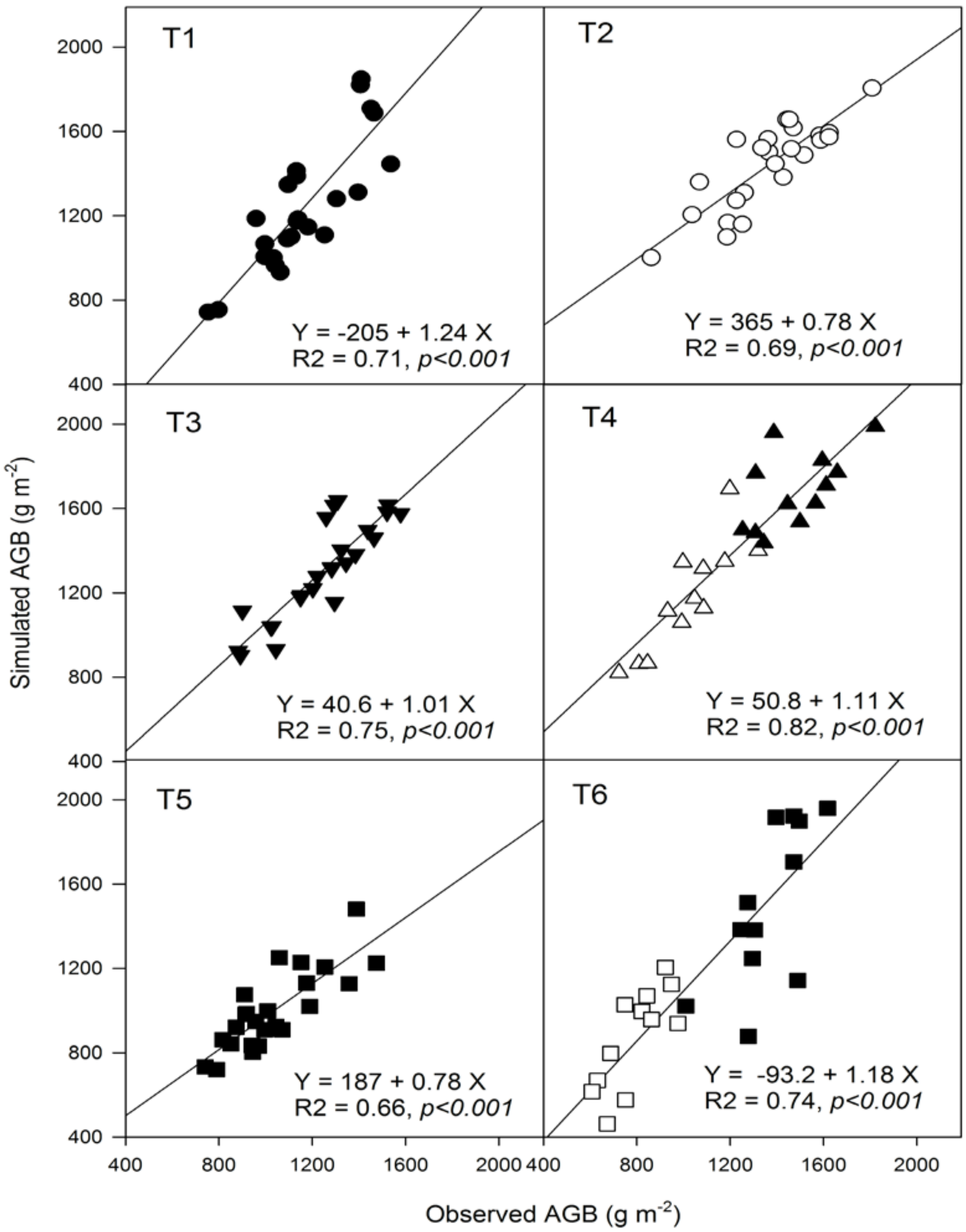

Figure 9: Relationship between observed and simulated above ground biomass (AGB) production (g m^{-2}) of maize planted under various cropping system treatments T1: maize monocropping, tillage, and fertilization (farmers' practice, control); T2: maize-chili intercropping, tillage and fertilization; T3; maize-chili intercropping, minimum tillage, fertilization, and Jack bean relay cropping; T4: maize-chili-leucaena hedgerow intercropping, minimum tillage, fertilization, Jack bean relay cropping; T5: as T3 but without fertilization; T6: as T4 but without fertilization. The filled symbols in T4 and T6 are showing the maize rows planted distant to hedgerows. All three replications data were used to develop the relationship.

However, the main reason for higher yields and LUEs of maize in intercropped treatments (Table 1) was a better vertical and lateral PAR distribution within the maize rows, particularly under tillage and fertilization (T2). In T2, chili rows were present 1 m away from maize rows providing extra space for vertical penetration of PAR down to lower leaves within the maize plants (Fig. 1). In T1 (maize monocropping), maize rows were planted 0.75 m apart from each other; hence less distance between the rows restricted PAR penetration into the crop stand, ultimately reducing the LUE and somehow crop productivity due to intra-specific competition (Table 1). This goes along with findings of Tsubo et al. (2001), who showed that maize-bean intercropping led to a more efficient radiation harvest than sole cropping. Awal et al. (2006) working on sole *vs*. intercropping also suggested that maize-peanut intercropping increased productivity of both intercrops through the efficient use of solar energy. Moreover, chili rows were infested by cercospora leaf spot (*Cercospora capsici*) at around 15-20 days after transplanting which even later created defoliation of chili plants. This was another reason of an increased vertical and lateral PAR capture by the maize leaf canopy in adjacent maize rows. In T3, most of maize rows close to chili rows also showed statistically higher LUE than their corresponding treatment without fertilization (T5). Mean LUE_{AGB} and LUE_{GY} of T3 was statistically higher than T5. Lack of nitrogen induced a poorer crop growth and leaf area development in T5, being the reason for a lower LUE in this treatment than in T3. This is clearly indicated by a significantly lower grain nitrogen concentration of T5 and also from positive and linear relationship between LUE_{AGB} and Ng (Fig. 8). Such findings were also reported by Khaliq et al. (2008) who showed that increasing nitrogen fertilization had positive effects on LUE of maize cropped in diverse environments. Maize in T2 was planted with tillage while the other intercropping treatments (T3, T4, T5, and T6) were established under minimum tillage conditions with Jack bean relay cropping. In T2, mean LUE and maize productivity was higher compared to other intercropped treatments. The slight decrease of maize productivity and light use in T3 and T4 compared to T2 may possibly due to minimum tillage, where soil crusting was observed, as hardness of soils affects root and shoot growth of plant negatively (Passioura 2002). Minimum tillage is encouraged to practice on slopes to reduce soil erosion and was proved beneficial under tropical conditions when practiced with Jack bean which increase soil organic matter (Pansak et al. 2007). Differences in maize AGB, grain yield, LUE and N_g of intercropped treatments with fertilization, however, were not significant.

3.5.3 Impacts of hedgerow cropping on maize production, nitrogen concentration and light use efficiency

Hedgerows negatively affected maize ABG and grain yields at rows close to the hedge, particularly when no fertilizer was applied (Table 1). Many experiments showed a negative impact on maize growth and AGB production when soil conservation measures such as tree hedgerows or grass barriers were applied (e.g. Tuan et al. 2014; Pansak et al. 2008, 2007). Tuan et al. (2014) showed that grass barriers reduced maize AGB production by around 34% in field experiments in NW Vietnam due to nutrient competition and reduction of area for maize cultivation. This is in accordance with AGB reductions of 9-27% presented in this study. Hedgerows or grass barriers reduced the AGB of associated maize due to competition as integration of trees as hedgerows in intercropping system capture parts of resources such as light, water and nutrients that otherwise would be available to crops (De Costa and Surenthran 2005). Maize rows close to leucaena hedgerows achieved smaller plant heights and showed low grain nitrogen concentration despite ample water availability in maize-chili-leucaena hedgerow intercropping pointing to nutrient competition (Hussain et al. 2015). This induced poor crop growth and development which ultimately reduced the ability of these maize rows to convert the captured PAR into above ground biomass production. On the other hand, maize rows planted more distant to hedgerows did not compete for resource with hedges due to longer distances and benefitted from an enhanced radiation penetration in the maize canopy, provided by the chili intercrop. This led to an increase of DM production and LUE of these maize rows by 46-45%, respectively, in T4. Without fertilization (T6), the increase in DM and LUE of maize in distant rows was 72% and 74%, respectively, higher than that of maize growing close to hedges. Miller and Pallardy (2001) showed light as significant factor in reducing yields of maize alley cropped with silver maple (*Acer saccharinum* L.). In this study, however hedgerows were continuously pruned, so shading and light competition between hedges and adjacent growing maize was well controlled. But despite frequent pruning, hedges had still impact on light distribution and transmittance to maize. Small row distances of 25 cm between maize and leucaena may still have decreased LUE of maize as indicated by poor growth due to N competition (Hussain et al. 2015) and poor light transmission. Burner and Brauer (2003) who showed that pine tree row spacing affected the pasture yield and light transmittance; i.e light transmittance was as low as 43% at a spacing of 2.4 m but increasing alley widths up to 4.9 m increased the light transmittance up to 90%.

3.5.4 Production evaluation and biomass simulation

In all intercrop treatments with fertilizer application, the LER was higher than 1.00 (Table. 1), showing a yield advantage of intercropping over sole stands due to a better use of available land and environmental resources for plant growth (Banik et al. 2000). In particular, the LER values of these treatments were 1.03–1.21. This means that 3–21% more land area would be required by a monocropping system to reach the yield of intercropping system, indicating a better LUE of intercrops than monocrops (Midya et al. 2005; Agegnehu et al. 2006). Most of the studies mentioned advantages of mixed stand over the sole stands. Dhima et al. (2007) found LER values 1.05–1.09 in intercropping of common vetch with grain cereals such as wheat, triticale, barley and oat. Bedoussac and Justes (2010) also reported such an advantage for pea–wheat intercropping. On the other hand, without fertilization LER of intercropping treatments were lower than one (T5: 0.88; T6: 0.94), indicating that 6-12 % more land area is required under intercropping to produce the same yield as under monocropping.

The basic idea for simulating maize AGB by using light attributes was to check how closely these light attributes may help in calculating back the biomass production of various cropping systems and management practices. The significant linear relationship between observed and simulated maize AGB with moderate to strong line of fitness values (Fig. 9) give some support for the validity of light use efficiency and fraction of intercepted radiation calculations and their role in biomass production under diversified cropping systems with combination of various species. Moreover, in both maize-chili hedgerow intercropping with and without fertilization (T4 and T6, respectively) the model simulated higher maize AGB in maize rows planted distant to hedgerows as compared to maize rows planted close to hedgerows in a similar way as observed in the field with strong line of fitness values (T4: R^2= 0.82, $p \leq 0.001$, T6: R^2= 0.82, p≤ 0.001).

3.6 Conclusion

The present study indicated that intercropping systems with fertilizer application showed higher maize biomass accumulation, light use efficiency and grain nitrogen concentration. Moreover, land equivalent ratios showed that all fertilized intercropping treatments were found to be more profitable for exploiting the available resource to produce higher yield than the monocropping system. Hedgerows negatively influenced the AGB, Ng and LUE only in maize rows planted close to them but on an average combining hedgerows and maize-chili intercropping with minimum tillage is promising to increase maize productivity as it enhanced 21% LER than maize momocropping and can, thus, be better adopted by farmers for erosion control in tropical hillside agriculture. Information on spatially-variable light use efficiency, plant nitrogen concentration and their impacts on crop productivity can be further helpful in fine-tuning crop management of agroforestry systems to overcome resource competition at the crop-soil-hedge interface. Finally, these results are useful for improving crop models for assessing biomass production and resource competition at the plant-soil-hedge.

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Chapter 4

Modelling resource competition and its mitigation at the crop-soil-hedge interface using WaNuLCAS

Chapter 4 Modelling resource competition and its mitigation at the crop-soil-hedge interface using WaNuLCAS*

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4.1 Abstract

Agroforestry systems have a large potential to increase systems' productivity and provide soil conservation in hilly terrain but comprise complex interactions at the crop-soil-tree interface. Modelling can be an operational approach to unravel the later. We used the spatially-explicit, dynamic Water Nutrient and Light Capture in Agroforestry Systems model to (i) predict maize above ground biomass (AGB) and interactions at the crop-soil-hedge interface, (ii) improve our understanding of trees' impact on crops in alley cropping, and (iii) identify mitigation strategies. A 2-yr-data set from a soil conservation experiment in Western Thailand with maize farmers' practice (monocropping, tillage), maize-chili-hedgerow intercropping (± fertilization; minimum tillage) was used as model input. Model validation showed satisfactory results for maize AGB (R^2=0.76, root mean square error=4.2, coefficient of determination=1.06, model efficiency=0.69). Simulations revealed nitrogen (N) and phosphorus (P), rather than light and water, as main limiting factors at the crop-soil-hedge interface reducing maize AGB in rows close to hedgerows. Growth limitation by P was stronger than that of N while light competition was alleviated by three to four hedgerow prunings already. WaNuLCAS simulations clearly indicated that small targeted additional N and P dressings to maize in rows close to hedges helped overcoming nutrient competition. Such strategic management options can be done by local farmers and hence, foster adaptation of soil conservation systems for sustainable crop production in future.

Keywords: Modelling; competition; maize; alley cropping; N; P

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4.2 Introduction

Maize (*Zea mays*) is a major cash crops of Thailand occupying about 33% of its uplands region (Ekasingh et al. 2004). Its cultivation is mainly done by slash and burn agriculture. Associated with unsuitable land use, this has led to strong soil degradation in these uplands, where around 34% of the agricultural land is affected by severe top soil erosion (Pansak et al. 2010). Therefore, the Thai Land Development Department (LDD) and the International Board for Soil Research and Management (IBSRAM) promote the use of soil conservation measures such as grass barriers, contour hedgerow, systems enriched with fruit trees for income generation, as well as minimum tillage. Crop residue retention and rotations are further important options for sustaining crop production (Mupangwa & Thierfelder 2013).

Several studies reported that soil conservation measures with hedgerows or grass barriers are extremely effective in reducing soil loss and runoff on steep slopes (Pansak et al. 2008; Quinkenstein et al. 2009; Tuan et al. 2014; Hilger et al. 2013). However, these systems are characterized by complex processes and interactions between crops and trees occurring at the soil-atmosphere-interface. Trees planted as hedgerows can negatively affect growth of crops planted next to them due to below-ground competition for nutrients and water (Pansak et al. 2007; Hussain et al. 2015a) or above ground for light (Hauser 1993). The magnitude of competition may vary with type of crop, soil and environmental conditions. Long-term field experiments for testing these effects, however, are time consuming due to the perennial growth pattern of trees and are, therefore, also expensive and laborious.

Dynamic crop modelling can be useful for assessing long-term effects of such complex systems whereby coupling of economic and biophysical models are useful in analysing soil degradation problems and socio-economic constraints (Marohn et al. 2013). Modelling also provides a better understanding of both, processes at the crop-soil-hedge interface and interactions between system components on a long-term basis. Involving models in agricultural research is worth important for testing new technologies, understanding drivers of land use change, decision making and can substitute cost-expensive long-term field trials (Jones et al. 2003; Saseendran et al. 2007; Liu et al. 2011; Mohanty et al. 2012; Chauhan et al. 2013; Lippe et al. 2014).

The spatially-explicit **Wa**ter, **Nu**trient, and **L**ight **C**apture in **A**groforestry **S**ystems model simulates dynamics and processes of crop-soil-hedge interactions on a daily basis at plot and field scales (van Noordwjik & Lusiana 2004). It was successfully applied to simulate effects of soil conservation practices on soil loss and runoff, soil structure, and water infiltration (Pansak et al. 2010), to evaluate the impact of improved fallows on maize yield under various soil and environmental conditions of Kenya (Walker et al. 2007). Martin and van Noordwijk (2009) used WaNuLCAS to assess tree-crop interactions based on site specific data. They simulated maize and tree yields by using intercropping scenarios with various timber tree species and found that trees directly benefit from the inputs such as fertilizer applied to the crops. Bayala et al. (2008) addressed the question how trees and crops influence each other under limitations of the main resources in agroforestry systems by means of WaNuLCAS. They indicated that WaNuLCAS overestimated crop performance but it proved to be an efficient tool for presenting tree-crop interactions for light, water and nutrient capture in an agro-forestry parkland system on a sandy loamy regosols with very low nutrient contents in Burkina Faso.

We hypothesized that WaNuLCAS (i) is able to identify main competition sources at the crop-soil-hedge interface, (ii) copes with a wide range of crop management options well-suited to mitigate competition in contour hedgerow systems, and (iii) can be used for ex-ante analysis of strategies mitigating resource competition. Specific objectives were (i) understanding causes for the lower AGB of maize in rows adjacent to hedgerows, and (ii) identifying management options for an improved and sustainable maize production.

4.3 Materials and methods

4.3.1 Field site description

Input data were collected from field experiments conducted during 2010 and 2011 at Ban Bo Wi village (13°28´ N and 99°15´ E), Ratchaburi province of Thailand. Annual precipitation was 1150 mm in 2010 and 1300 mm in 2011. Mean annual temperature was 28°C in 2010 and 29°C in 2011, while the area receives a mean solar radiation about 14 MJ m^{-2} day^{-1}. The soil varies between an endoleptic Alisol and a hyperskelettic Leptosol (Garré et al. 2013), being prone to surface erosion (Land Development Department, 2011). Most of the area is mountainous with steep to moderate slopes where maize is commonly grown. Other major crops of the region are cassava (*Manihot esculenta*) and chili (*Capsicum annuum*). The maize growing season starts just after the onset of rains in June and ends usually end of September to mid of October.

4.3.2 Experimental setup and data collection

The trial was set up as a randomized complete block design with six treatments and three replicates on a hill with a slope gradient of 20-25%. The treatments were: (T1) maize monocrop, tillage with fertilization (farmer's practice/control); (T2) maize-chili-intercropped with tillage and fertilization; (T3) as T2 but minimum tillage and Jack bean (*Canavalia ensiformis*) relay cropping; (T4) as T3 but with *Leucaena leucocephala* hedgerows; (T5) as T3 but without fertilization; (T6) as T4 but without fertilization. Plot size was 13 m x 4 m. Soil data such as texture, bulk density, pH, soil N and available P, organic C, and cation exchange capacity collected at the field site were used to parameterize WaNuLCAS (Table 1).

Tillage was done by hand-hoeing up to 20 cm soil depth. In treatments with minimum tillage, planting and weeding were done manually with minimum disturbance of the soil. Maize was sown on June 26th, 2010 and June 29th, 2011. In intercropping treatments, one month old chili seedlings were transplanted on the same days. Leucaena hedges were established in 2009. In T1, 17 maize rows were planted (row to row 75 and plant to plant distance 25 cm). Eight maize rows were planted in all intercropping treatments with 75 cm distance between maize rows, 100 cm between chili to chili and chili to maize distance. Three hedgerows of 1 m width were established at the top, middle and bottom of T4 and T6 with a distance of 25 cm between maize and hedgerows. Nitrogen fertilizer (urea) was applied at rate of 62 kg ha^{-1}, split in two equal doses, 30 and 60 days after planting (DAP). P (triple super phosphate) and K (potassium chloride) were applied at rates of 11 and 36 kg ha^{-1} 30 DAP maize, respectively. Chili received a basal application of N (urea) at a rate of 92 kg ha^{-1} at the time of transplanting and 92 kg ha^{-1} N as top dressing one month after transplanting as recommended.

Leucaena hedges were pruned to a height of 50 cm four times during 2010; 7, 30, 60 DAP of maize, and one month after maize harvest. In 2011, hedges were pruned six times; three prunings were done before maize planting, i.e. mid-January, mid-May, and just at maize sowing. The remaining prunings were done at 30, 60 and 105 DAP of maize. All plots were regularly hand weeded. In minimum tillage treatments, Jack beans were planted between all maize rows one month before maize harvest. During the dry season, Jack beans started to die-off and their residues were used to mulch the soil. Maize stalks of all treatments and pruning material of hedgerow treatments were chopped and thereafter evenly spread on top of the soils within the respective plots. Leucaena residues were 2.5 and 2.2 kg m^{-2} in T4 and T6, respectively, for 2010 and 3.5 and 3.0 kg m^{-2} in T4 and T6, respectively, for 2011.

Maize was harvested row wise in each treatment, separated into leaves, stems and cob components, dried and weighed and used further calculation of above ground biomass (AGB). Row yields were converted into kg per meter square to make values comparable with WaNuLCAS output. Grain N and P concentrations of maize was determined per row by dry combustion method coupled with a mass spectrometer and inductively coupled plasma optical emission spectrometry, respectively. A Sunscan Canopy Analyzer (Delta-T Devices Ltd, UK) was used to monitor above and below canopy photosynthetic active radiation (PAR) which later was used to calculate light use efficiency (LUE) as suggested by Gallagher & Biscoe 1978:

$$LUE_{AGB}\,(g\ _{\mathrm{DM\ MJ}^{-1}}) = \frac{Above\ \ ground\ \ biomass\ \ yield\left(g\, m^{-2}\right)}{\sum IPAR\,(MJ\ m^{-2})} \qquad (1)$$

Further details of field measurements and the complete procedure for the LUE calculation are given in Hussain et al. (2015 b).

4.3.3 WaNuLCAS setup and input data

WaNuLCAS represents tree-soil-crop interactions in agroforestry systems in which trees and crops overlap in space and/or time (Iio et al. 2014; Van Noordwijk & Lusiana 1999). The model was developed using STELLA© modeling software (isee systems inc., Lebanon, USA) with a special emphasis on above and below ground interactions.

The modelled system is horizontally represented by four zones and vertically by four soil layers of variable depth.

Input data used for simulation include soil parameters (soil texture, soil organic matter, bulk density, saturated hydraulic conductivity, soil nitrogen and phosphorous contents), crop and tree library (growth parameters such as vegetative period, generative period, LAI), crop and tree management (planting dates, amounts of fertilizer and their application dates, amounts and timing of external application of organic materials if applied, intensity and timing of pruning during a year) and weather data (daily soil temperature, rainfall and evapotranspiration).

From the soil conservation study, three maize cropping systems were selected and divided into four horizontal zones of specific lengths presenting either maize, chili, or leucaena rows and four vertical soil layers of 0-5, 5-15, 15-30 and 30-45 cm (Figure 1). Soil parameters of these layers (Table 1) were entered individually in the pedotransfer functions (PTF) provided by the associated Excel© file. The Hodnett and Tomasella (2002) PTF was used to generate soil hydraulic properties as it represents tropical soil conditions best (Walker et al. 2007). Daily rainfall and soil temperature collected by a self-registering weather station at the experimental site provided input data for the weather module of WaNuLCAS. Crop growth and development is simulated by WaNuLCAS on a daily basis under influence of four main factors, i.e. light, water, nitrogen, and phosphorous. Water and nutrient uptake by plants is driven by the corresponding 'demand' parameter as follows:

Uptake (water, nutrient) = min (demand, potential uptake) (2)

Nutrient demand is calculated from an empirical relationship between nutrient uptake and dry matter production under non-limiting conditions, luxury uptake (assuming that growth will not be reduced until nutrient content is reduced up to 80% of demand), compensation of past uptake deficit and nitrogen fixation. For nutrient deficient situations, target N content is contrasted with current nutrient content and can be met by atmospheric fixation and nutrient additions.

$$CN\_Demand = CN\_Deficit * (1 - 0.5 * Cq\_stage)^2 \quad (3)$$

where *CN_Demand* is the crop nutrient demand (g m^{-2}), *CN_Deficit* is crop nutrient deficit (g m^{-2}), *Cq_stage* is the crop sequence stage.

WaNuLCAS Crop_PosGro parameters show the magnitude of constraining factors (N, P, water, light) for plant growth per zone varying from 0 to 1 whereby the 'zero' indicates no growth and 'one' no stress. Actual nutrient content can be 20% behind a nutrient target before negative effects on dry matter production will start to occur while dry matter production will stop when nutrient content is 40% of nutrient target. Similarly, in case of light capture the term is called as *Light C_RelCap* with 'zero' indicating no light capture while 'one' corresponds with maximum of light capture.

Light capture is calculated as a function of crop leaf area index (LAI) and its relative height in each zone. In crops, only light capture by LAI is considered while light captured by trees is separated in light captured by branches as branch area index (BAI) and leaves as LAI which allows accounting for shading by trees when they are leafless.

Total light capture in each canopy layer is calculated from Beer's Law;

$$TotLightCap_j = 1 - \sum_{k=1}^{j-1} TotLightCap_k - e^{-\sum_i \left(kLLight_i * LAI_i - kBLight_i * BAI_i \right)} \quad (4)$$

where $TotLightCap_j$ is the total light capture (g m^{-2}) by each canopy layer (*j*), *kLLight* is the light extinction coefficient for leaves, *LAI* is the leaf area index, *kBLight* is the light extinction coefficient for branches.

Crop and tree growth and development in WaNuLCAS includes several factors that control plant growth and ultimately above ground biomass production (Figure 2).

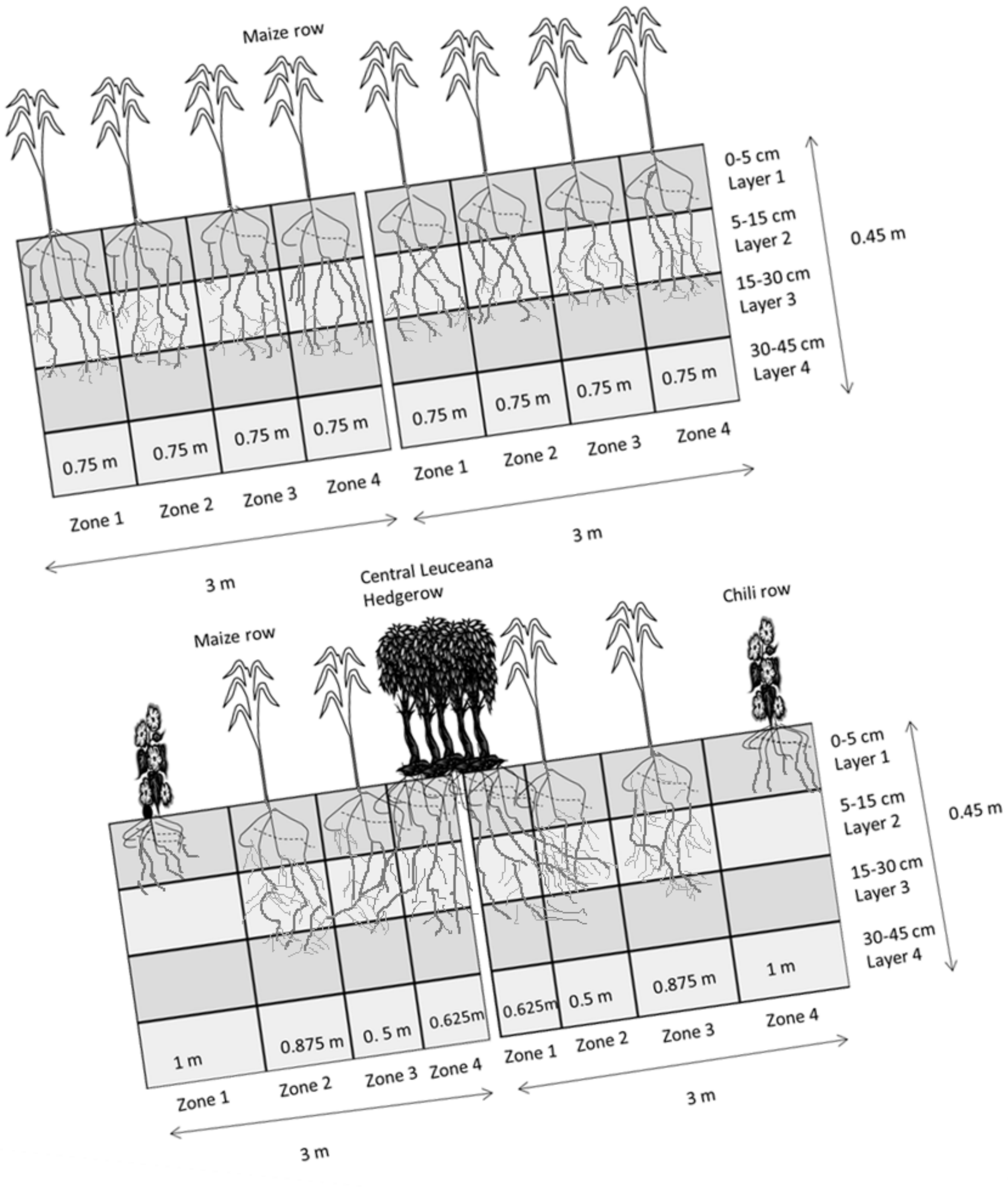

Figure1: Layout of model setup with cropping zones horizontally and soil layers vertically with respective length and depth description based on data from a field experiment at Queen Sirikit research farm, Ratchaburi province, Thailand. In sole cropping, maize was planted in all zones while in intercropping with agroforestry/alley cropping, maize was planted in zone 2 and 3.

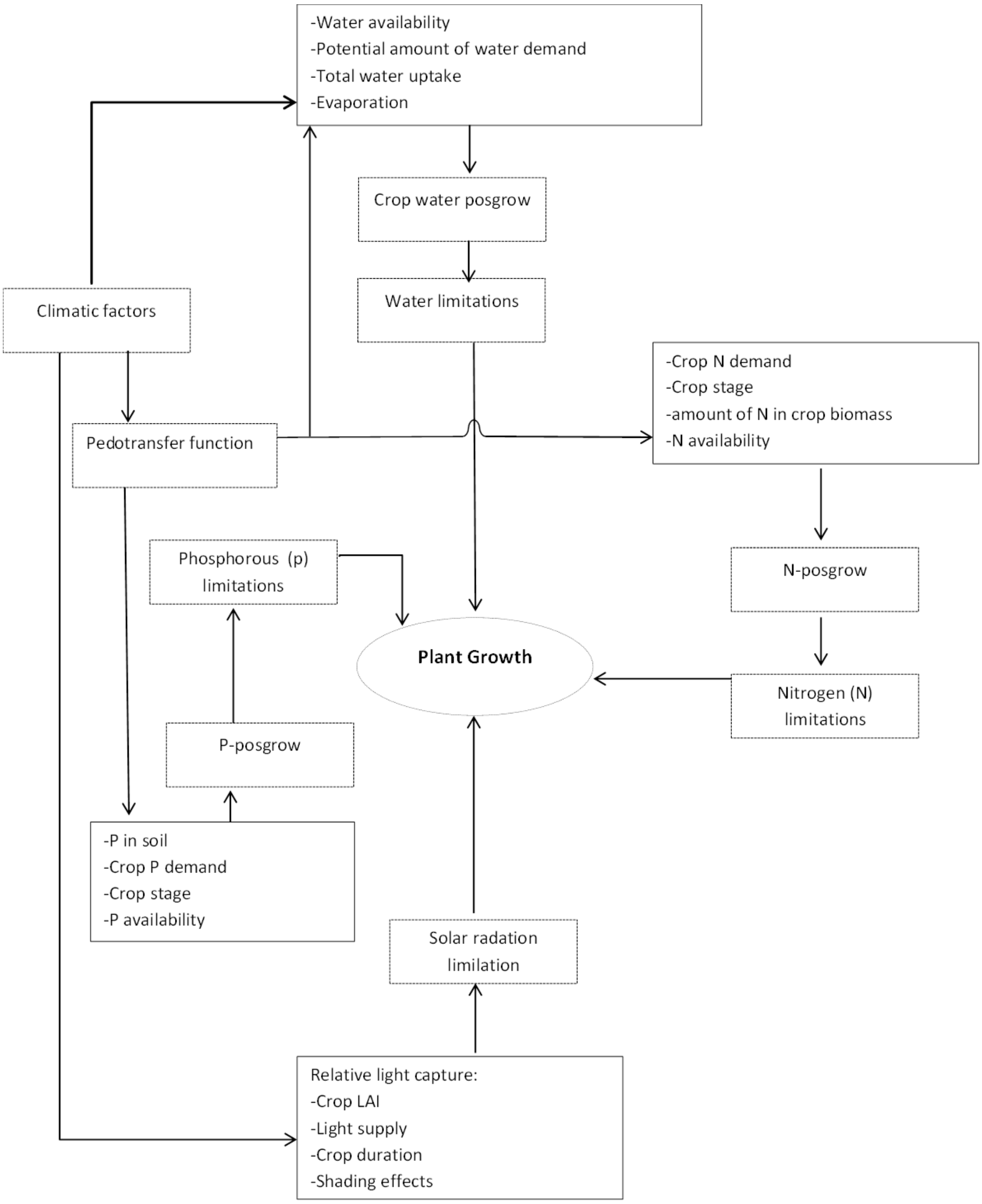

Figure2: Structure of crop growth module in WaNuLCAS and flow chart of involved parameters.

4.3.4 Model calibration and validation

WaNuLCAS was parameterised and calibrated by using a 2-yr-data set with strongly contrasting management and cropping practices, consisting of T1, T4, and T6. The treatments T2, T3, and T5, were used for validation of model. For maize monocropping (control), four horizontal zones, each with a width of 0.75 m, with a single maize row in each zone were set for calibration, being equal to the planting pattern of the field trial (Figure 1). In case of agroforestry systems, two distinct situations were considered, i.e. above and below the hedgerow. For the 'above hedge' situations, hedgerows were placed in zone one while the next two zones were planted with maize and zone four with chili. For 'below hedge' situations, hedges were planted in zone four. During the calibration process various WaNuLCAS parameters were modified and applied (Table 1).

4.3.5 Scenario description

After model calibration and validation, various scenarios were developed to identify causes of above and below ground resource competition in agroforestry systems, evaluating their impact on above ground biomass production of maize, and testing crop management options to mitigate competitive situations. The simulation runtime of each scenario was five years. Three scenarios were developed; scenario 1 *(pruning)*, scenario 2 (*fertilization)*, and scenario 3 (*irrigation)*. Further details are presented in Table 2.

4.3.6 Statistical analysis

For the assessment of model performance the goodness of fit (GOF) procedure suggested by Loague and Green (1991) was used to compare observed and simulated above ground biomass of maize. The mathematical expressions are:

Modeling efficiency (EF);

$$\text{EF} = \left(\sum_{i=1}^{n} \left(Oi - \bar{O} \right)^2 - \sum_{i=1}^{n} \left(Pi - Oi \right)^2 \right) \Big/ \sum_{i=1}^{n} \left(Oi - \bar{O} \right)^2 \qquad (5)$$

Coefficient of determination (CD);

$$\text{CD} = \sum_{i=1}^{n} \left(Oi - \bar{O} \right)^2 \Big/ \sum_{i=1}^{n} \left(Pi - \bar{O} \right)^2 \qquad (6)$$

Root mean square error (RMSE);

$$\text{RMSE} = \left[\sum_{i=1}^{n} \left(Pi - \bar{O} \right)^2 \Big/ n \right]^{0.5} . \frac{100}{\bar{O}} \qquad (7)$$

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

Parameters in WaNuLCAS	Default values	modified values	Description
Cq_GroMax	0.014	0.07	Maximum daily dry matter production rate at full light capture, under local conditions
Cq_Gseed	0.004	0.03	Seed weight (initial C_Carb Hydr Reserves to be used for growth)
Cq_HBiomConv	7	1	Factor for conversion of crop biomass increment (up to crop stage 1) to crop height
Cq_MaxRemob	0.05	0.01	Maximum proportion of stem and leaves remobilized per day to the Carb Hydr Reserves pool, from which it can be used for growth of storage component
Cq_KLight	0.65	0.7	Light extinction coefficient for the crop canopy = efficiency of crop foliage in absorbing light
Cq_RainWStorCap	1	0	Rainfall water stored as thin film at leaf surface
RtCLrvm_1	5	10	Maximum crop root length density in 1st soil layer; corresponds to Rt_ACType=0 and Cq_AType.
RtCLrvm_2	3	8	Maximum crop root length density in 1st soil layer; corresponds to Rt_ACType=0 and Cq_AType.
RtCLrvm_3	0.3	1	Maximum crop root length density in 1st soil layer; corresponds to Rt_ACType=0 and Cq_AType.
Cq_MycMaxInf	0.25	0.1	Fraction of crop roots infected by mycorrhiza for a soil layer where the Rt_MTInfFrac parameter is 1
Cq_RelLUE_stage 0	1.72	0	Crop relative light use efficiency at stage zero
Cq_RelLUE_stage 0.1	1.02	0.2	Crop relative light use efficiency at stage 1

Soil parameter settings based on field data of Queen Sirikit research farm Ratchaburi-Thailand

Treatments	Layers	Sand (%)	Silt (%)	Clay (%)	*OC (%)	*B.D. (g cm^{-3})	pH	*Ksat (cm d^{-1})
T1	0-5 cm	50	34	16	1.26	1.65	6.1	17
	5-15 cm	46	36	16	1.18	1.60	6.0	16
	15-30 cm	54	22	24	0.90	1.77	5.7	7
	30-45 cm	54	22	24	0.90	1.77	5.7	7
T4	0-5 cm	42	40	18	1.34	1.64	5.7	20
	5-15 cm	49	33	18	1.22	1.61	5.7	19
	15-30 cm	52	33	15	0.88	1.76	5.7	8
	30-45 cm	52	33	15	0.88	1.76	5.7	8
T6	0-5 cm	42	40	18	1.22	1.65	5.8	13
	5-15 cm	43	39	18	1.35	1.59	5.9	17
	15-30 cm	50	31	19	1.00	1.77	5.7	8
	30-45 cm	50	31	19	1.00	1.77	5.7	8

*OC= organic carbon, B.D= bulk density, Ksat= saturaded conductivity

Table 2: Description of scenarios used to identify competition, mitigation and sustainability options at the crop-soil-hedge interface

Prefix	Scenarios	Description
Above ground competition		
Scenario 1 (Pruning):		
a	Baseline	As practiced in the two years field experiment
b	No pruning	Hedges were not pruned for five years
c	Continuous pruning	Hedges were pruned every month with 12 prunings in a year
Below ground competition		
Scenario 2 (Fertilization):		
Fertilizer application to all maize rows (i)		
a	Baseline	Standard (62N:11P kg ha^{-1}) as applied in field experiments
b	Double N/ standard P	124N:11P kg ha^{-1}
c	Standard N/ double P	62N:22P kg ha^{-1}
d	Double N/ double P	124N:22P kg ha^{-1}
Fertilizer application only to maize in rows close to hedge (ii)		
a	Baseline	Standard (62N:11P kg ha^{-1}) as applied in field experiments
b	Double N/ standard P	124N:11P kg ha^{-1}
c	Standard N/ double P	62N:22P kg ha^{-1}
d	Double N/ double P	124N:22P kg ha^{-1}
Scenario 3 (Irrigation):		
a	Baseline	Simulation were carried out with field rainfall
b	Irrigation	Irrigation was applied on dry periods during growing season (around 10 mm water per dry day)

Maximum error (ME);

$$\text{ME=Max}\left|Pi - Oi\right|_{i=1}^{n} \tag{8}$$

Coefficient of residual mass (CRM);

$$\text{CRM=}\left(\sum_{i=1}^{n} Oi - \sum_{i=1}^{n} Pi\right) \Big/ \sum_{i=1}^{n} Oi \tag{9}$$

where O_i are the observed values, P_i are the predicted values, n is the number of observations or samples and $\bar{O}$ is the mean of observed values.

For a good performance of model is better to get the values of EF, CD, RMSE, ME and CRM as close as possible to 1, 1, 0, 0, and 0, respectively.

4.4 Results and discussions

4.4.1 WaNuLCAS calibration and validation

After parametrisation and calibration, WaNuLCAS simulated similar amounts of AGB for all maize rows in T1, while in both hedgerow treatments simulated AGB production was higher in maize rows distant to hedge than in rows close to the hedge as observed in the field and showed a significant and linear relationship between observed and simulated maize AGB for T1, T4 and T6 with R^2=0.83, p <0.001 (Figure 3a). RMSE, EF, ME, CRM and CD were satisfactory with values of 6.3, 0.82, 0.2, -0.02 and 1.4, respectively. Model validation with an independent data set consisting of 2, T3 and T5 also revealed a significant and linear relationship between simulated and observed maize AGB with a lower R^2 = 0.76, p <0.001, while RMSE, EF, ME, CRM, and CD values were 4.2, 0.69, 0.24, -0.03 and 1.06, respectively (Figure 3b).

A widely used and accepted procedure for model evaluation is the ‘Goodness of Fit’ or GOF procedure which assesses the ability of a model to simulate observed data within an acceptable range of accuracy and precision (Legates & Davis 1997; Loague & Green 1991; Walker et al. 2007). R^2 values above 0.5 and CD values of 0.5-2 were considered important for a good simulation result, while EF values above zero can be seen as satisfactory for a relationship between observed and simulated results during model calibration and validation (Rykiel Jr 1996). Thus our validation results can be considered satisfactory and suitable for subsequent effective scenario simulations.

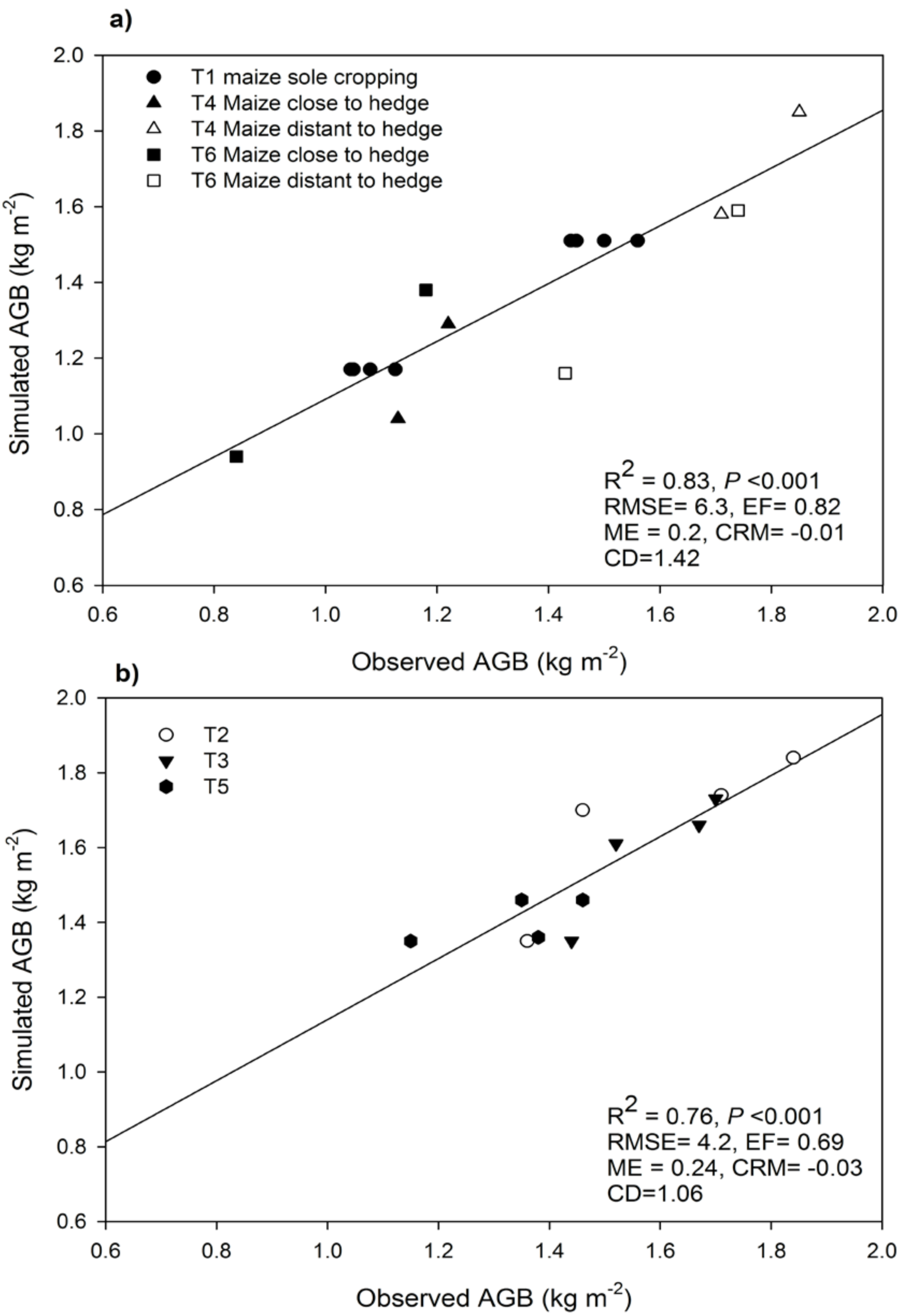

Figure 3: Relationship between simulated and observed maize above ground biomass (AGB) production in sole cropped maize (T1), maize-chili-hedgerow intercropping ± fertilization (T4 and T6, respectively) during (a) calibration; and maize chili intercropping, tillage with fertilization (T2), maize chili intercropping, minimum tillage with fertilization and Jack beans relay cropping (T3), maize chili intercropping, minimum tillage without fertilization and Jack beans relay cropping (T5) during (b) validation of the model.

4.4.2 Resource use and competition

4.4.2.1 Light use efficiency and pruning regimes (Scenario 1)

The *Light C_RelCap* parameter representing the relative simulated light capture in WaNuLCAS revealed that T1 captured light in an effective way along the growing season while light capture of maize in hedgerow treatments (T4, T6) strongly differed between maize planted either close or distant to a hedgerow (Figure 4). Light capture of monocropped maize (T1) and that of maize grown in rows distant to hedge in T4 and T6 showed similar high light capture patterns. On the other side, simulated light capture of maize growing next to a hedge was strongly reduced (T4) although it could be partly improved by addition of fertilizer (T6). Field measured LUE for maize AGB also exposed significant differences between maize rows close to hedges and those distant to them. In hedgerow treatments, maize LUE were generally significantly higher in rows distant to hedgerows when compared to rows close to them while no statistical differences in LUE were found between maize rows of T1 (Table 3). This is in accordance to model simulations.

Several studies show such negative impacts of hedgerows and grass barriers on maize growth and above ground biomass production, especially in maize rows planted adjacent to them (Tuan et al. 2014; Hussain et al. 2015a).

Light is definitely an important factor for yield reduction of maize when planted close to trees due to shading (Everson et al. 2004) but can easily be avoided by tree pruning twice to three times a year (Leihner et al. 1996). In our case, hedges were pruned periodically during field experiments to reduce maize shading. The low simulated relative light capture and the low field measured LUE of maize in rows close to hedges is therefore attributed to other growth factors that hampered maize development in these rows reducing the plants' ability to capture light sufficiently for converting it into biomass as pruning largely reduced competition for light (Hussain et al. 2015b); however hedges still may have slightly reduced the light movement to lower maize leaves due to small distances between hedges and adjacent maize rows. To test potential shading effects we applied different pruning scenarios. The simulated effect of our field based regular hedgerow pruning (Scenario 1) showed that simulated AGB production in maize rows planted close and distant to the hedgerows was similar to the measured data in the first two years(Figure 5a). In contrast, no pruning severely depressed simulated AGB (Figure 5b), while increasing pruning intensity did not substantially alter AGB production as compared to our current pruning regime over a period of 5 years (Figure

5c). Thus simulated results confirmed that in our case light competition was not a major factor in yield reduction of maize grown close to hedges.

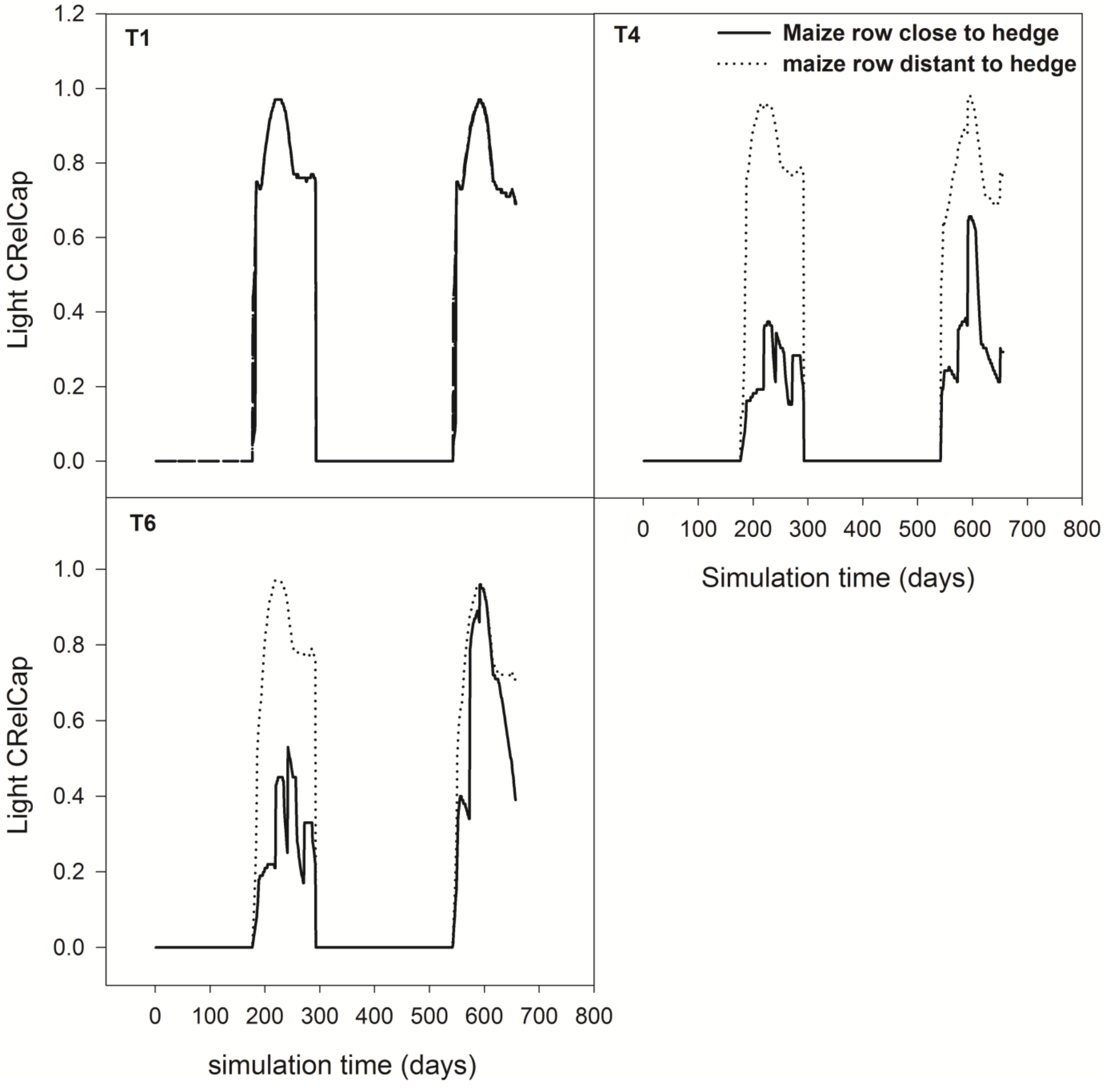

Figure 4: Simulated maize relative light capture (Light CRelCap) in control (T1), maize-chili-hedgerow intercropping ± fertilization (T4 and T6, respectively).

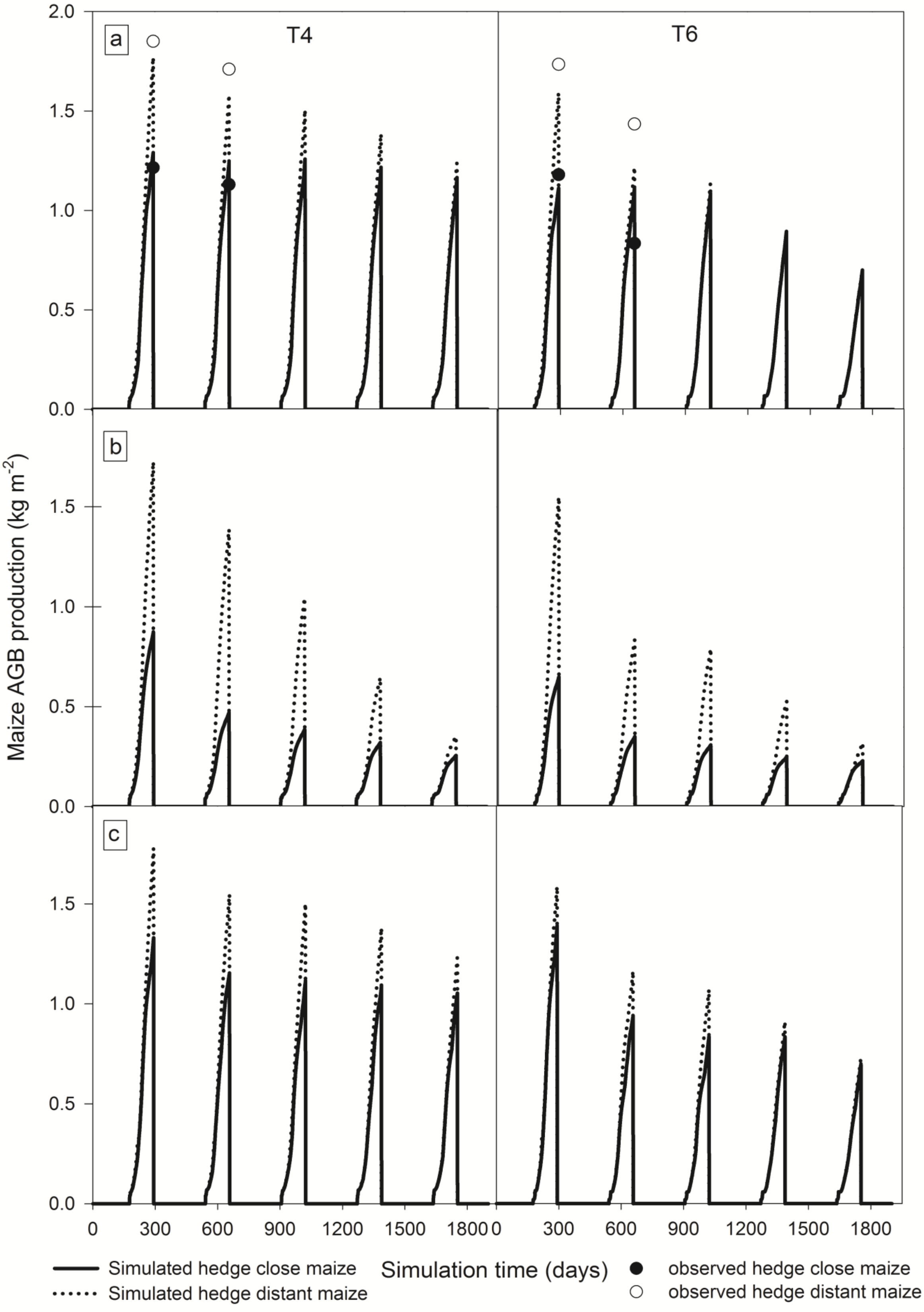

Figure 5: Simulated impacts of pruning management (Scenario 1); a) baseline scenario, b) no pruning, c) continuous pruning on maize AGB (kg m^{-2}) in maize-chili-hedgerow intercropping ± fertilization (T4 and T6, respectively) for continuous five seasons planting.

Table 3: Maize grain N concentration, P contents and light use efficiency for AGB production observed in various treatments during 2010 and 2011

Rows position	T1		T4		T6	
	2010	2011	2010	2011	2010	2011
Grain N concentration (%)						
Maize in rows close to hedge	1.76	1.43	1.63 b	1.37 b	1.52 b	1.30 b
Maize in rows distant to hedge	1.79	1.46	1.77 a	1.64 a	1.69 a	1.48 a
	NS	*NS*	*P<0.01*	*P<0.01*	*P<0.01*	*P<0.001*
Grain P contents (g m^{-2})						
Maize in rows close to hedge	1.45	1.10	1.64 b	1.50 b	1.38 b	1.09 b
Maize in rows distant to hedge	1.46	1.06	2.21 a	2.49 a	1.87 a	2.27 a
	NS	*NS*	*P<0.01*	*P<0.01*	*P<0.01*	*P<0.01*
Light use efficiency (g DM MJ^{-1})						
Maize in rows close to hedge	1.95	1.22	1.60 b	1.22 b	1.12 b	0.93 b
Maize in rows distant to hedge	1.98	1.24	2.24 a	1.77 a	2.12 a	1.62 a
	NS	*NS*	*P<0.001*	*P<0.01*	*P<0.01*	*P<0.001*

NS = not significant

Different small letters indicate significant differences within treatments

T1: maize monocropping, tillage, and fertilization (farmers' practice, control); T4: maize-chili-hedge intercropping; T6: as T4 but without fertilization.

4.4.2.2 Nitrogen and phosphorous competition (Scenario 2)

In maize monocrop simulated N uptake was similar in all rows (Figure 6) which was in accordance to observed values of maize grain nitrogen concentrations with no statistical differences between rows (Table 3). In T4, maize in rows close to hedgerows showed lower simulated N uptake as compared to distant rows which was endorsed by observed grain nitrogen concentration with statistically lower N concentration in maize grown adjacent to hedgerows as compared to those grown in distance to the hedge (Table 3). In T6, with no fertilizer addition simulated N uptake was low due to reduced N availability as compared to fertilized treatments (Figure 6) which is well represented by low grain nitrogen concentrations found under field conditions (Table 3). Maize rows planted close to hedgerows produced low AGB with lower total N concentrations in grains, indicating low N availability in these rows due to competition for nutrients. Simulated N uptake was higher in the first year of simulation as compared to the second one, probably pointing to a reduced N availability over time. This is supported by a field measured reduction of grain nitrogen concentration from 2010 to 2011 found in all treatments which reduced maize production over time. Several studies mentioned that in presence of hedges crops often compete for nutrients rather than for water in humid and sub-humid conditions (e.g. Pansak et al. 2007; Dercon et al. 2006). The competition was especially evident in the 5-15 cm soil layer which was also indicated from leuceana roots intercepting with maize roots under maize rows close to them at 0-20 cm depth (Hussain et al. 2015a).

In the tropics, soils are often considered low in plant available P which is a strong limitation to crop productivity in these regions. In hedgerow treatments, simulated P uptake pattern of maize rows differed compared to the control where no hedges were established (Figure 7). P uptake in T4 and T6 were influenced by row position and soil depth, being particularly higher in rows distant to the hedge at a soil depth of 15-30 cm. Overall, maize grown in rows close to hedgerows showed a low simulated P uptake as compared to maize form rows distant to the hedge which was in accordance to observed low P concentrations in maize grains from rows growing close to hedgerows than those of maize growing distant to hedges (Table 3).

P_PosGro values also indicated P limitations (Figure 7) particularly during early maize growth in contrast to N where limitations occurred towards the end of the maize growth cycle. Results of simulated tree (hedgerow) N and P uptake showed that trees took up nutrient not only from the area where the hedgerows were planted but also from maize growing area (Figure 8). The simulated uptakes reached a maximum at the soil depth 5-15 cm. In T4, simulated hedgerow N and P uptake from the maize row area showed small peaks of uptake at the time of fertilizer dressings to maize at 0-5 cm soil depth. Hence, hedges competed for nutrients with maize growing in rows close to them which reduced AGB production of maize. Low P availability in these maize rows may have adversely affected root development during juvenile maize growth while N is more likely to be available in the top soil by residue and soil organic matter decomposition and atmospheric depositions. Root length density measurements of maize and hedgerows also showed that hedge and maize roots overlapped within both hedge treatments (Hussain et al. 2015a) and is, hence, likely to confirm nutrient competition.

4.4.2.3 Water competition (Scenario 3)

Model simulations revealed that soil water content remained above the critical level of competition in all treatments (data not presented). Consistently, model simulations also did not indicate any changes in maize AGB production under both irrigation scenarios (Table 2), revealing that rainfall was sufficient for maize production at the field site and that water was not a limiting factor for maize AGB production during the rainy season. The simulation results were in accordance to a parallel study at same site by Hussain et al. (2015a) who combined ^{13}C stable isotope discrimination and electrical resistivity tomography for evaluating competition at the crop-soil-hedge interface and pointed out that there was no water limitation between maize and hedgerows.

4.4.3 Impact of time on simulated maize above ground biomass production

To evaluate the performance of soil conservation measures over time, WaNuLCAS was set to run for five years with same management as used in the field experiment (Figure 9). WaNuLCAS simulations suggested that above ground biomass of T1 maize would steadily decrease by around 48% over a five years simulation period. In T4, the decline in simulated maize AGB over a period of 5 year was lower than in T1 and T6 due to soil improving effects of soil conservation measures (Figure 9). These conservation measures decreased soil loss, provided higher organic inputs by leucaena prunings and Jack bean harvest residues, and additional N by biological N fixation (28 kg ha-1 y-1 N added to soil in prunings) under fertilized conditions (Wongleecharoen et al. 2015). Field yield data and simulations revealed that these effects had a positive effect on maize grown distant to the hedges where row yields were larger than corresponding yields of maize monocropping. Pansak et al. (2010) showed positive effects of hedgerow intercropping, minimum tillage and Jack bean relay cropping on soil structure which increased infiltration and reduced runoff substantially under similar conditions but they also indicated yield reductions due to reduced maize area in hedge based systems (Pansak et al. 2008). Our simulation results further revealed that fertilization was essential to reduce maize yield decline in hedge based system. Tuan et al. (2014) emphasized therefore that such measures will only be accepted by farmers if competition is limited and if they are economically attractive.

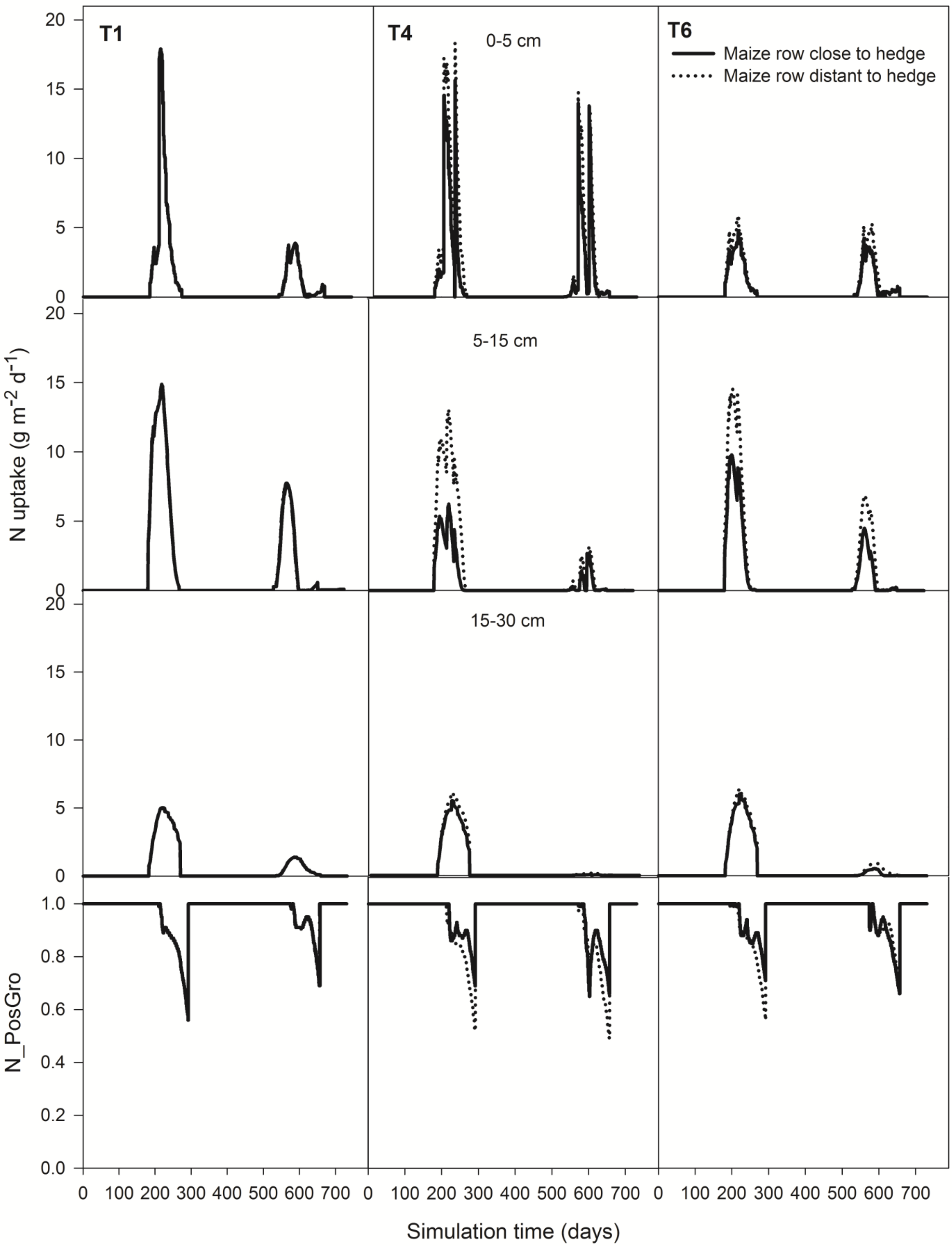

Figure 6: Simulated maize N uptake (g m^{-2} day^{-1}) at three soil depths and N_PosGro (1= no N limitation) in control (T1), maize-chili-hedgerow intercropping ± fertilization (T4 and T6, respectively).

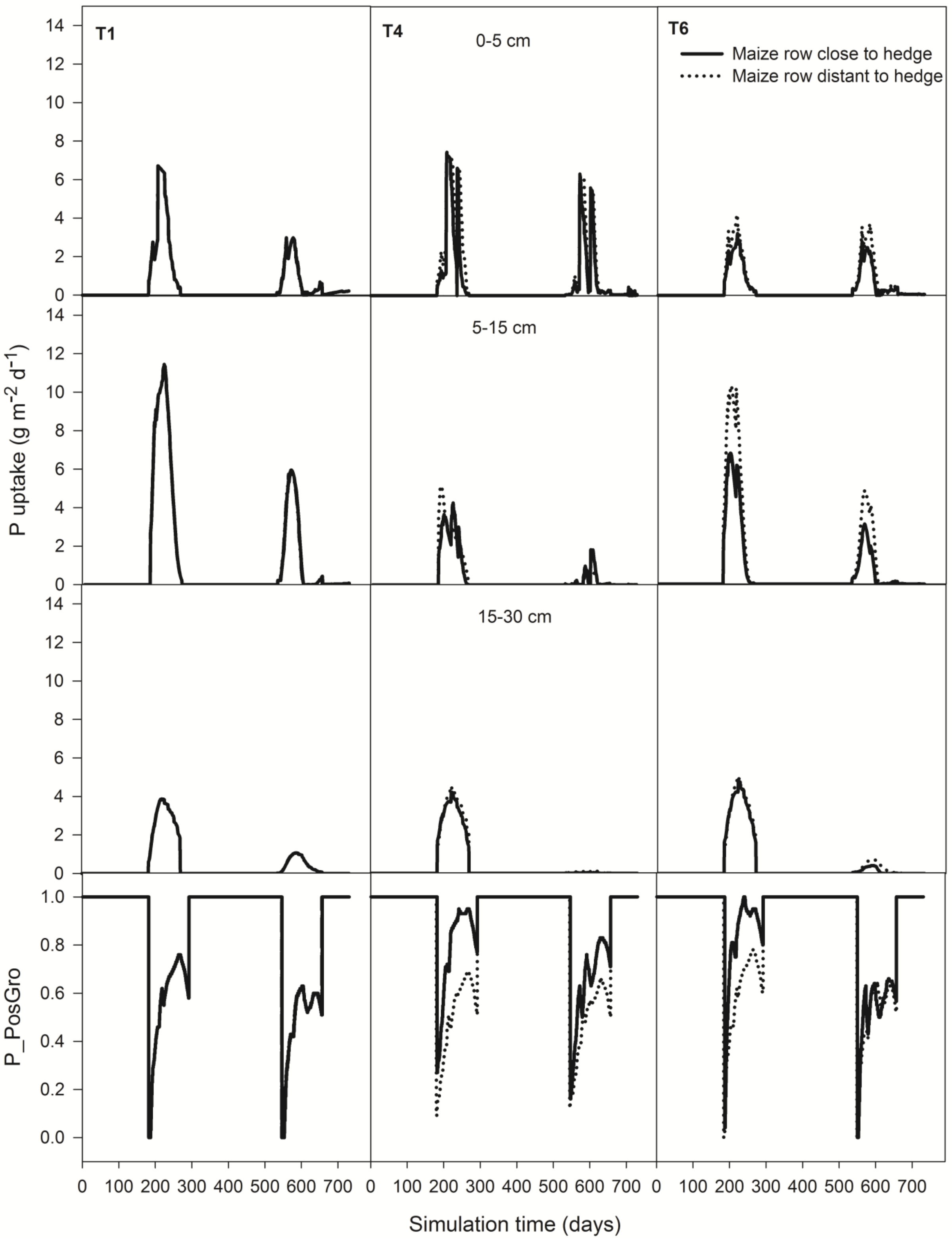

Figure 7: Simulated maize P uptake (g m^{-2} day^{-1}) at three soil depths and P_PosGro (1= no P limitation) in control (T1), maize-chili-hedgerow cropping ± fertilization (T4 and T6, respectively).

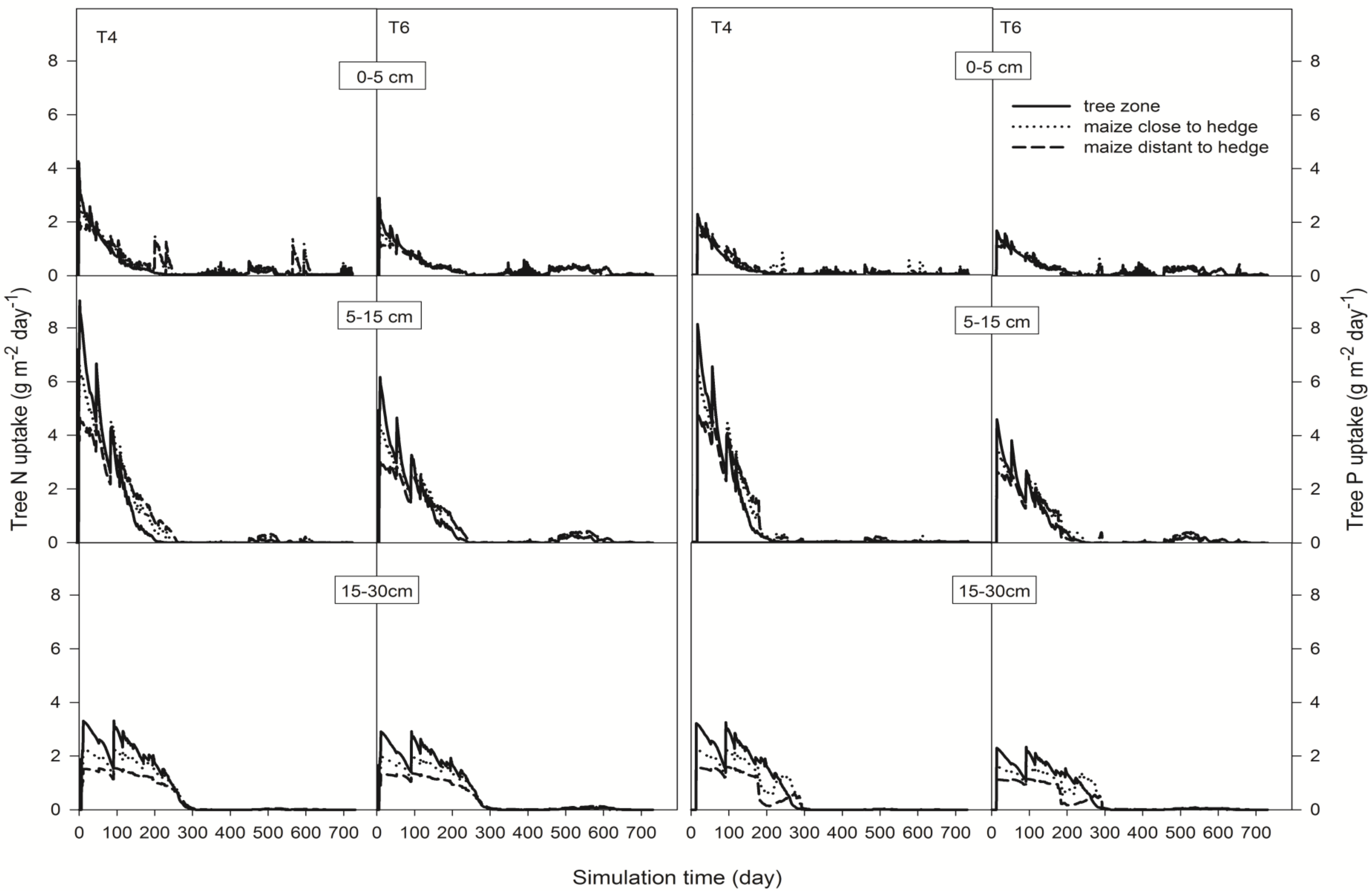

Figure 8: Simulated tree (hedgerow) N and P uptake (g m^{-2} day^{-1}) at three soil depths in maize-chili-hedgerow intercropping ± fertilization (T4 and T6, respectively) during two years planting.

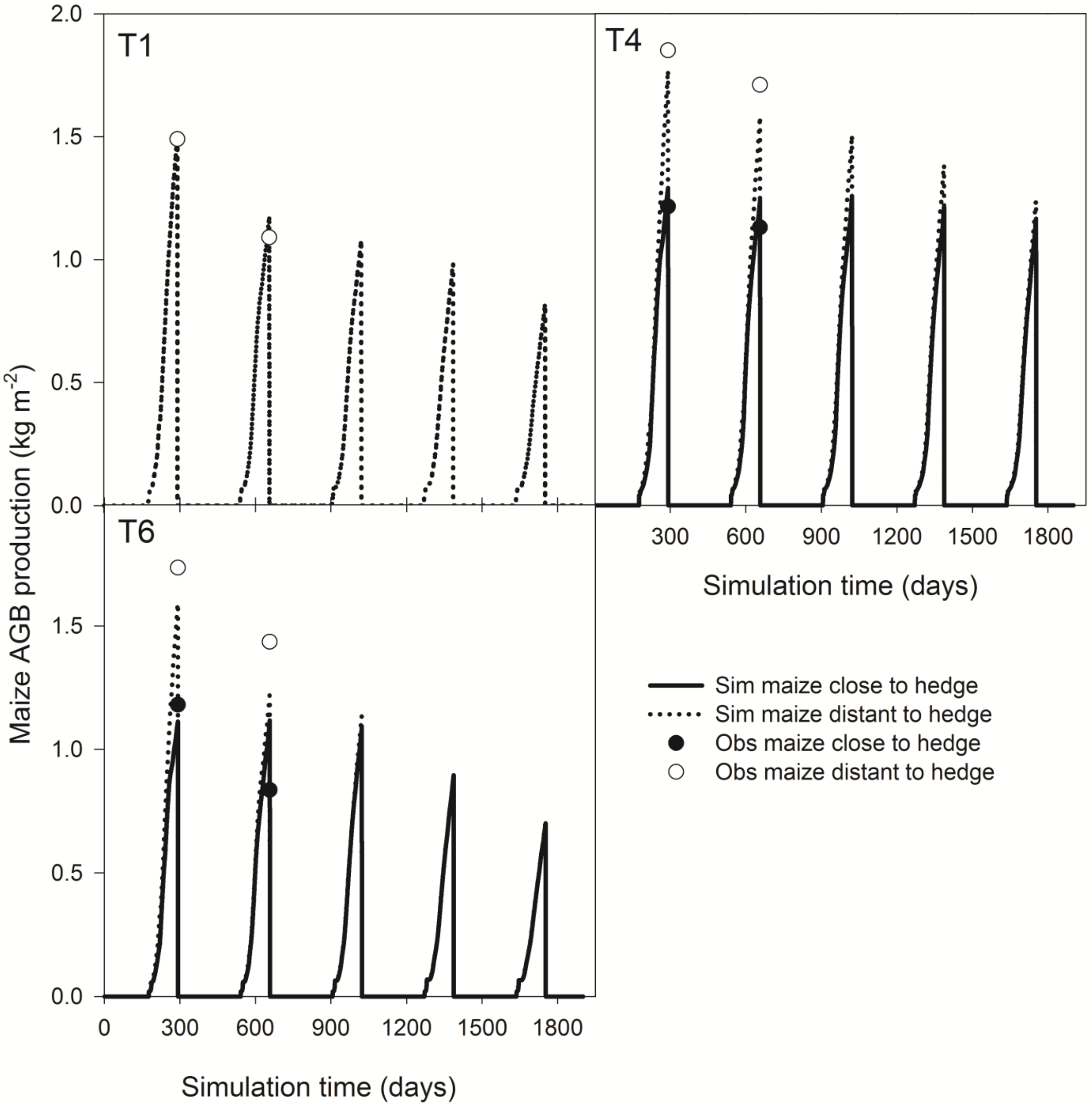

Figure 9: Simulated impacts of cropping systems on maize AGB, kg m^{-2} in control (T1), maize-chili-hedgerow intercropping ± fertilization (T4 and T6, respectively) for continuous five seasons planting.

4.4.4 Mitigation strategies for nutrient competition at the crop-soil-hedge interface

In order to mitigate nutrient competition effects in hedge based systems we simulated the impact of four fertilizer regimes on maize AGB. For the hedgerow treatment two options of additional fertilizer applications were considered, (i) enhanced fertilizer application in all maize rows and (ii) only in maize rows close to the hedgerows. For maize monocropping doubling the standard (farmers practice) amount of N fertilizer could reduce the decrease in biomass production over time (Figure 10a+b). Doubling the P fertilizer rate and keeping the standard N already maintained the productivity of maize AGB over the entire simulation period (Figure 10c).

In T4, the baseline scenario showed a continuous maize AGB decline in rows distant to the hedge (Figure 10a; T4i, ii). Double only N but with standard P fertilization had no impact on maize AGB (Figure 10b; T4i, ii) whereas standard N in combination with double P application maintained biomass production in maize rows distant to the hedge along with a moderate impact on maize in rows close to hedges over the entire simulation period (Figure 10c; T4i, ii). Application of double N/double P amounts showed improvements in AGB from 2nd year of simulation and an earlier start of the positive effect on maize rows close to the hedge but a decrease in the last simulation year (Figure 10d; T4i). Changing the fertilization just in maize rows close to the hedge gave best results in case of double N/double P scenarios, which not only increased maize AGB over time but also helped overcoming the lack of N and P between maize and hedges in their vicinity (Figure 10 d; T4ii). Targeted increase of fertilizer application at the crop-soil-hedge interface not only increased maize AGB in rows adjacent to hedgerows but also sustained productivity. Thus, our simulation clearly demonstrated that nutrient competition in hedge based systems can be overcomes with a targeted site specific increase of fertilization.

4.5 Conclusions

Modelling agroforestry systems need a balance between processes and patterns and between temporal and spatial aspects but most of the crop growth models are more detailed in processes and control one dimensional variation but do not take in account the spatial patterns of agroforestry systems. Our results reveal that WaNuLCAS not only maintains these balances but also is spatial explicitly allowing to explore resource competition at the crop-soil-tree interface. Model results showed a good agreement between simulated and observed

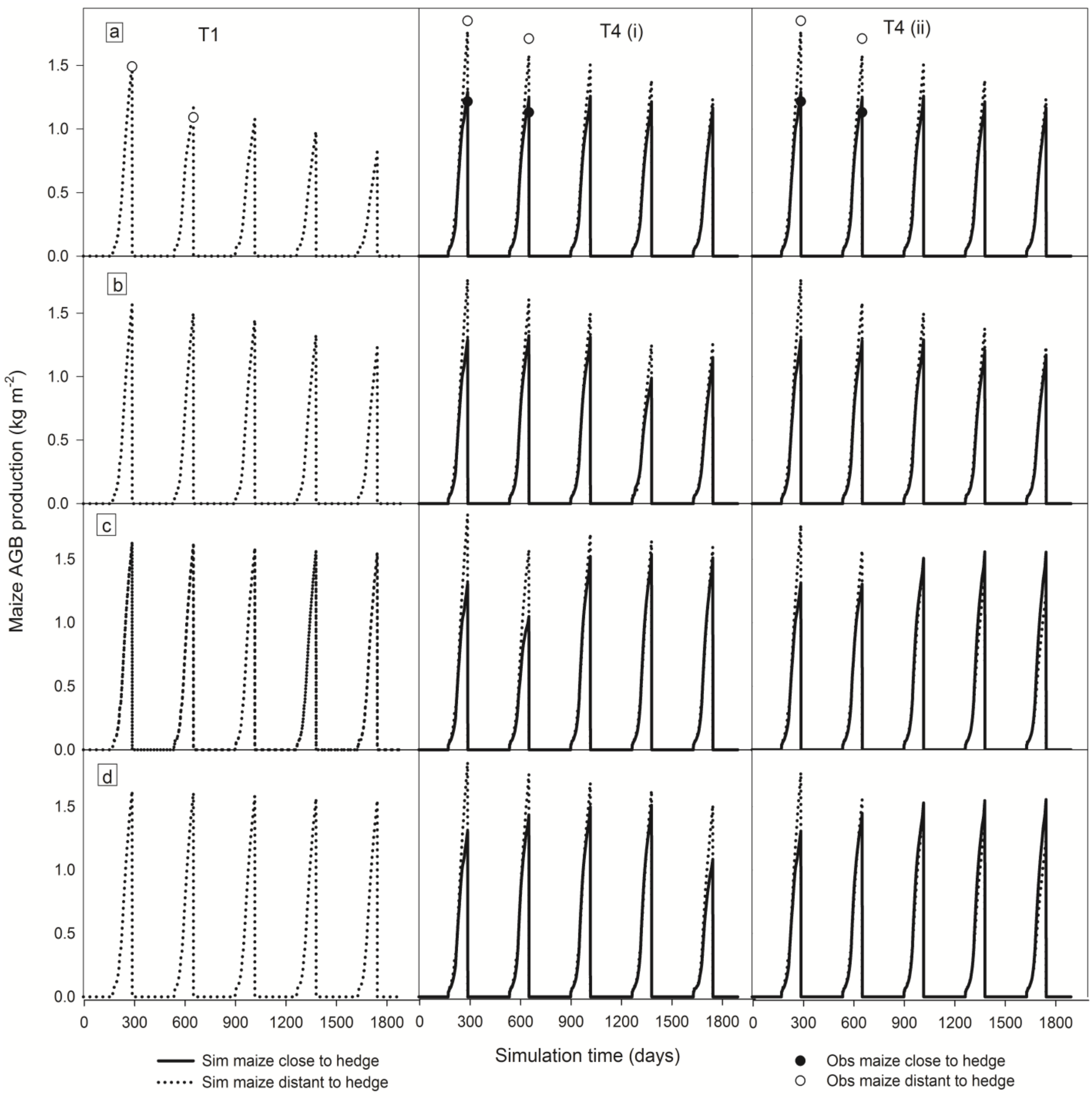

Figure 10: Simulated impacts of fertilizer management (Scenario 2) with various amounts of N and P combinations; a) baseline scenario (62N:11P kg ha^{-1}), b) 124N:11P kg ha^{-1}, c) 62N:22P kg ha^{-1}, d) 124N:22P kg ha^{-1} on maize AGB, kg m^{-2} production in control (T1), maize-chili-hedge intercropping with fertilization (T4) with change of fertilizer application in maize (i) and with change of fertilizer application only to maize in rows close to hedgerows (ii) for continuous five seasons planting.

maize AGB during calibration and validation. Furthermore, WaNuLCAS's spatial explicit layout allowed us to identify causes of resource competition at the crop-soil-tree interface as well as to explore mitigation options for improving maize productivity in agroforestry based soil conservation approaches. This study revealed that N and particularly P availability were the most prominent limiting growth factors between managed hedges and maize growing in rows close to them. WaNuLCAS also showed that three to four hedgerow prunings activities per year with increased application of N and P fertilizer to maize rows planted close to the hedges are key options for a successful application of an agroforestry system on tropical hillsides and with sustainable maize production. Such small additional fertilizer dressings are doable for local farmers under Thai conditions and may, hence, foster adaptation of soil conservation systems for sustainable crop production in future.

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Chapter 5

General Discussion

Chapter 5 General Discussion

5.1 Resources use competition in soil conservation systems

Among soil conservation measures, contour hedgerow and grass barrier systems are considered highly effective for erosion control in mountainous tropical regions (Pansak et al., 2008). These systems are often based on the concept of inter planting leguminous trees or fodder grasses with food crops. These systems are effective in reducing soil and nutrient losses on sloping terrain (Baudry et al., 2000; Morgan, 2009). Kongkaew (2000) observed a reduction in soil loss of 2 Mg ha^{-1} per year after establishing *Leucaena leucocephala* hedges or ruzi grass (*Brachiaria ruziziensis Germain et Evrard*) barriers in maize based cropping systems in Thailand. On the other hand, many studies showed negative impacts of hedgerows and grass barriers on annual crops (Kinama et al., 2007; Tuan et al., 2014). Hedges often compete with crops for light as above ground resource, if not pruned regularly; while below ground competition for nutrients and water occurs with crops planted close to them. In this study, hedges were pruned regularly at 0.5 m height during maize growing season to minimize above ground competition.

5.1.1 Is water competition the driving factor for maize yield reduction in hedgerow systems?

The results from the field experiment carried out at Queen Sirikit research farm, Ratchaburi province of Thailand showed that maize rows planted close to hedgerows produced 46 and 73% less above ground biomass compared to maize rows planted distant to hedgerows with and without fertilization, respectively, indicating negative impacts of hedgerows on production of maize planted close to them. Many studies mentioned such negative impacts of hedgerows on production of crops when planted together (Govindarajan et al., 1996; Odhiambo et al., 2001; Kinama et al., 2007; Pansak et al., 2007; Tuan et al., 2014). Govindarajan et al. (1996) and Pansak et al. (2007) observed that leucaena hedgerows reduced maize yield 39-49%, while Tuan et al. (2014) pointed out that inclusion of grass barriers reduced maize above ground biomass production by around 34% in highlands of Southeast Asia. Odhiambo et al. (2001) also observed 40-50% maize yield reduction by using hedgerows with crops and concluded that this yield depression was highest in crop rows planted close to trees. This observed negative impact on yield of maize rows planted close to hedgerows poses questions about the factors responsible for this effect. These factors could be due to below ground (e.g. water competition, nutrient competition, or both) and/or above ground (e.g. light competition) processes. The results of current study did not confirm initial hypothesis that competition for water between species was a driving force for a poor yield performance of the annual crop as moisture patterns of both, electrical resistivity tomography (ERT) water depletion patterns and time domain reflectometry (TDR), showed lower soil moisture depletion and higher water availability in the hedgerows intercrop treatment as compared to maize monocropping. Additionally, in the maize-chili-hedgerow intercropping treatment with fertilizer application, maize growing close to the chili rows had to a lower water depletion compared to maize monocrop at a similar position along the slope. This was possibly due to a better moisture condition in this treatment with fertilization and presence of chili. The wider row spacing and the poor growth of chilies may have induced less water depletion, favoring maize growth. Water depletion was higher in maize rows close to hedgerows compared to maize rows planted distant to them. The higher water depletion in these rows was due to uptake of water by maize and leucaena as leucaena roots extended towards maize grown area and intercepted maize roots. However water availability below maize was still above the threshold level of competition as this depletion of moisture was lower than under maize monocropping. The rather heterogeneous soil moisture depletion found in hedgerow treatments regardless fertilization corresponded very well with their rooting pattern. This induced heterogeneity in soil water depletion was shown by the ERT images. Pansak et al. (2007) also indicated the existence of such a spatial impact of hedges on water and nutrient uptake but were not able to show its spatial resolution in the course of time. Furthermore, maize rows planted close to hedgerows had higher grain $\delta^{13}C$ being an indication of higher water availability (Clay et al., 2001; Pansak et al., 2007). However, $\delta^{13}C$ signals are sensitive to both water and nutrients (Clay et al., 2005), and it is, therefore, not immediately clear if higher $\delta^{13}C$ values mean higher water availability. To answer this question we studied $\delta^{13}C$ signals of maize in unfertilized hedgerows intercrop treatments where lack of fertilizer application was the only difference between both hedgerow intercropping treatments. The results showed that $\delta^{13}C$ signals of unfertilized maize were statistically higher (less negative values) as compared to those of maize grown under hedgerow intercropping with fertilization and maize monocropping (results presented in Chapter 2). Additionally, ΔWC (ERT) of the unfertilized hedgerow intercropping treatment also showed lowest soil moisture depletion which is also a sign of higher soil moisture in the soil profile. These observations support the theory that higher $\delta^{13}C$ signals indicated higher water availability. Therefore, we concluded that water was not a major limiting factor which reduced maize growth and biomass production in rows planted close to hedgerows under fertilized conditions.

WaNuLCAS has utilities to analyze stress situation for plant growth and to identify factors limiting plant growth, such as water, nitrogen, phosphorus and light, during cropping period. Simulations using WaNuLCAS showed that water remained above the level of competition in maize rows planted close and distant to hedgerows during both growing seasons. These results clearly indicated that water was not limiting between maize and hedgerow which supported the above mentioned conclusion as well

5.1.2 Nitrogen stress and carbon isotopic discrimination in soil conservation systems

Measurements of the carbon isotopic discrimination in C_4 plants have shown a variable response to soil water availability and plant N levels (Clay et al., 2001; Dercon et al., 2006; Ghannoum, 2009). $\delta^{13}C$ signals decrease (more negative values) with increasing water stress while $\delta^{13}C$ signals increase (less negative values) with decreasing nitrogen availability (Dercon et al., 2006) because N stress reduces the photosynthetic capacity of plants. N effects on $\delta^{13}C$ can be separated from water effects with inclusion of some selected treatments in the experiments (Clay et al., 2005). For that purpose, a unfertilized hedgerow intercroping treatment was included in the experimental setup. The results indicated that $\delta^{13}C$ signals in the maize rows planted close to hedgerows were much higher (less negative) than maize rows planted distant to hedgerows in fertilized hedge intercrop treatment. To test the effect of nutrients on $\delta^{13}C$ signals, we again examined the hedgerows intercropping treatment without fertilizer application. Results showed that $\delta^{13}C$ signals were statistically higher than in the fertilized hedgerows intercrop treatment and maize monocrop. These comparisons suggested that a reduced fertilization inducing higher $\delta^{13}C$ signals and favoured the statement that competition for nutrients led towards an increase in grain $\delta^{13}C$ signals. ERT soil moisture depletion patterns showed lower water depletion under unfertilized conditions as nutrients limitation actually hindered plant water uptake. The maize rows planted close to hedgerows also had higher grain $\delta^{13}C$ than the maize rows grown distant to the hedge, showing similar $\delta^{13}C$ behaviour as observed under unfertilized conditions. This indicated that lack of nutrients limited maize growth when growing in rows close to the hedge. Moreover, maize rows close to hedgerows produced less above ground biomass with lower total N concentrations in grains, also indicating low N availability in these rows. *Leucaena leucocephala* is a biological nitrogen fixing species; labeled ^{15}N was used to monitor percent N derived from fixation by leucaena hedges. Unfertilized hedge intercrop treatment was used as natural abundance. The results showed that 25-30 kg N per year was fixed by leucaena and added to soil pool (Wongleecharoen et al., 2015). N competition between leucaena hedges and adjacent maize row in unfertilized treatment would be more severe but was possibly reduced due to leucaena biological nitrogen fixation (BNF) as compared to fertilized treatment. Natural log response ratio of nitrogen ($LnRR_N$) further indicated a negative impact of hedgerows on maize in rows planted close to them by competing for nitrogen. Hence, insufficient nutrient availability, especially nitrogen, was most likely the reason of higher $\delta^{13}C$ signals in maize rows planted close to hedgerows with lower above ground biomass production (Vanlauwe et al., 2001). Pansak et al. (2007) proposed a framework to distinguish between nutrient and water competition based on a relationship between ^{13}C isotopic discrimination and soil NO^{3-}–N availability for maize and mentioned that both factors were inversely proportional to each other. Hence, these findings also point to nutrient competition between maize and hedgerows in this experiment. In the unfertilized hedgerow intercropping treatment, maize leaf area index development was lower due to limited N availability as also reported by other studies (Muchow, 1988; McCullough et al., 1994). Grain nitrogen concentrations were quite low in maize rows planted close to hedgerows with lower above ground biomass compared to distant maize rows in both fertilized and unfertilized hedgerows intercrop treatments. Grain nitrogen concentration depends on the crop growth (Lemaire and Gastal, 2009) and its source and sink relationship. Large amounts of nitrogen are stored in vegetative parts just before grain filling stage (Barbottin et al., 2005; Schiltz et al., 2005) which acts as source and any change in the source sink relationship will ultimately affect the grain nitrogen concentration (Lhuillier-Soundélé et al., 1999).

WaNuLCAS is able to show the fate of nitrogen (N) and phosphorus (P) fates during growing period of crops. Model simulations also indicated N limitations between hedgerows and maize growing in rows close to the hedge regardless fertilization. The magnitude of N limiting maize growth was not severe. WaNuLCAS indicated that maize growth was limited by P as well. N uptake (g m^{-2} day^{-1}) was similar in all maize rows of sole cropping while maize N uptake was higher in rows planted distant to hedges as compared to maize of rows close to them. These simulated N uptake trends were in accordance to grain N concentration from the field experiments. The low relative N uptake by maize in rows close to hedgerows was at least partly due to soil N uptake by the hedge in the course of time which finally reduced simulated biomass production in these hedge-close maize rows. These simulations were also in accordance to the findings on maize grain $\delta^{13}C$ discriminations signals of this study which pointed to nutrient limitations between maize and hedgerows.

5.1.3 Light use efficiency in intercropping systems with and without soil conservation systems

Crop growth may either be limited by lack of light, water and nutrients or by competition for them above and below ground resources with other plants (Friday and Fownes, 2001). Trees often limit crop growth due to competition for light in agroforestry systems (Sanchez, 1995). Quantification of competition and separation of above ground competition for light and below ground competition for nutrients or water is difficult under field conditions (Friday and Fownes, 2001) but is important for providing insight into options to improve crop performance of soil conservation systems based on contour hedgerow or grass barrier systems. Monteith (1977) defined light use efficiency as the ratio of dry matter produced per unit of radiant energy used in its production. Many studies showed a positive relationship between crop yield and light use efficiency (LUE) (Chen et al., 2002; Li et al., 2006). The two years experimental findings of this field study were in accordance with the results of those above mentioned studies. The hedgerows were pruned to a height of 0.5 m to minimize light competition between hedges and adjacent maize rows. However, the results showed that maize rows planted close to hedgerows had a lower LUE as compared to maize rows distant to them. The main reason for the low LUE of maize rows planted close to hedgerows was not only light competition between hedgerows and maize rows but also poor growth and development of maize rows adjacent to hedges (Chapter 3). Maize rows planted close to leucaena hedgerows developed poorly due to nutrient competition. This argument was also supported by the results of low above ground biomass production and lower plant heights of these maize rows planted close to hedges. This poor growth and development not only reduced the ability of these maize rows to capture the available PAR but also its conversion into above ground biomass production. Khaliq et al. (2008), reported that increasing nitrogen rate had positive effects on light use efficiency in diverse environments. Maize rows planted distant to hedgerows had an increase in LUE of about 45% under fertilized conditions and 74 % without fertilization compared to maize rows planted close to hedgerows. Similarly, model results showed that maize planted close to leucaena hedgerows showed lower and uneven relative light capture during both growing seasons Pruning of hedgerows reduces shading and light competition on crop rows planted close to the hedge. However, hedgerows still might have had an impact on light distribution and transmittance on close planted crop rows due to the small distance of 25 cm between hedge and adjacent maize row, which indirectly would have reduced their light use efficiencies and was, next to nutrient deficiency, one of the reasons of low efficiencies in maize rows planted close to hedgerows.

On the other hand, a higher crop yield with a higher radiation use efficiency in intercropping treatments without hedgerows was not only because of the high amount of PAR captured by the canopy but was also due to a better vertical and lateral PAR distribution within the crop stand. In the maize-chili intercropping along with tillage and fertilization treatment (T2), maize rows showed highest LUE with higher crop production compared to maize monocropping due to better vertical distribution of PAR. In this case chili rows were present 1 m apart from the maize rows which provided an extra space for vertical distribution of PAR even down to lower leaves of maize plants; while in the maize monocropping treatment (T1), maize rows were planted 0.75 m apart from each other restricting vertical PAR distribution to lower plant parts and reducing the LUE and crop yield. Tsubo et al. (2001) figured out that planting maize and beans as intercropping had more efficient radiation harvest than respective sole cropping. During cropping season chili rows were infected with cercospora leaf spot (*Cercospora capsici*) at around 15-20 days after transplanting which later created defoliation. This was another reason of increasing the surface area for vertical and lateral light distribution around adjacent maize rows. PAR interception increases with plants growth and development along the season but slightly decreases before crop harvest due to senescence (Natarajan and Willey, 1985; Lunagaria and Shekh, 2006; Liu et al., 2012). The increase in fraction of intercepted PAR ($fPAR$) in all treatments from 30 to 45 DAP (Chap. 3; Fig. 3) was possibly due to a strong increase in growth of maize plants which was indicated by rapid LAI development during that time span. Leaf orientation and distribution in the canopy is an important influential factor in PAR capture. The regression line is considered as canopy extinction coefficient (k) and represents the average projected area of canopy elements onto horizontal surfaces (Campbell and Norman, 1989). The extinction coefficient empirically varies from 0.3-1.5; greater than 1.0 indicates horizontal leaves positions while less than 1.0 refers to non-horizontal leaf distributions (Jones, 2013). The unfertilized intercropped treatments had slightly higher k values compared to fertilized treatments, indicating a small change in leaf distribution which also affected their LUEs.

The chili cultivar 'super-hot' was used in the field experiments. This cultivar has a spreading nature and is recommended to maintain around 1 meter distance between rows and plants which was followed in this field experiment. Before starting field trial, an interaction between maize and chili was assumed as well. Midmore et al. (1995) indicated reduction in chili fruit set in maize chili intercropping as compared to sole cropping due to competition for light and space for canopy expansion with associated maize while there were no significant maize yield reductions. On the other hand, Junqiang et al. (2010) indicated that maize chili intercropping increased hot pepper light utilization which may decrease light availability to maize plants but in this study it was not possible to see any such type of interaction between maize and chili due to chili disease infestation and hence poor growth.

5.2 Assessment of sustainability of maize based cropping systems and mitigation options for reducing competition between maize and hedgerows

Most of the cultivations in Western Thailand on uplands is carried out on freshly cleared forests and it was observed that the fertility of land reduces over time due to many factors such as high losses of fertile soil, low fertilizer inputs, intensive use of land and land mismanagement. The field experimental results also showed a yield decrease in all treatments from 2010 to 2011, and these were in accordance with model simulations. WaNuLCAS was used to run for five year continuous cropping seasons with the same practices as were used in the field experiments during 2010 and 2011 (Chap. 4; Fig. 8). Simulations over a period of five years showed that maize above ground biomass decreased by 48% in maize monocropping (T1). For maize-chili hedgerow intercropping with fertilization (T4) WaNuLCAS predicted a 10 to 29% AGB decrease in maize planted close and distant to the hedgerow, respectively, while for the same row positions a 37 to 56% decrease was simulated in the same treatment without fertilization (T6). Maize above ground biomass decrease was lower in - hedgerow intercropping with fertilization as compared to sole cropped maize. *Leucaena leucocephala* is a biological nitrogen fixing (BNF) species and the study of Wongleecharoen et al. (2015) showed that 28 kg N ha^{-1} year^{-1} were fixed by leucaena (1.6 Mg ha^{-1} pruning materials) and added to soil pool These observations based on 5 years continuous simulations can be seen as hints for a better production sustainability of maize in hedgerow intercropping with fertilization as compared to maize sole cropping. BNF and leucaena pruning residue addition in soil N pool was reason which resisted crop failure in maize hedge intercrop without fertilization conditions. The yearly decrease in maize above ground biomass production was basically due to a continuous decrease in soil available resources (2010: 1.97% soil organic matter, 10.6 mg kg^{-1} extractable P *vs.* 2011: 1.76 % soil organic matter, 9.5 mg kg^{-1} extractable P at 0-45 cm soil depth).To test this fertilizer scenarios were simulated for treatments (T1 and T4) with various fertilizer regimes i.e. 62N:11P (standard as used in field experiments), 120N:11P, 62N:22P and 120N:22P, over a period of five years. Simulation runs showed that increasing the amount of fertilizer application sustained yield along the simulation time in both investigated fertilized treatments (Chapter 4). This supported the above experimental and isotopic results which also showed nutrient limitations over time.

However, increasing the amount of fertilizer application to all maize rows will increase the input cost which may also reduce the interest of farmers to adopt such systems.

To evaluate options to overcome the major limiting nutrient deficiency and also reduce input cost at the crop-soil-hedge/tree interface, fertilizer application was only increased at maize rows planted close to hedgerows, while keeping the standard amount of fertilizer in maize rows distant to the hedgerows. WaNuLCAS simulations suggested that above ground biomass production in maize rows planted close to hedgerows increased as compared to maize rows distant to hedges over a period of five years simulation period and improved the crop performance under soil conservation practice based on contour hedgerow cropping. The results also showed that model response to P increase was greater than the impact of increasing N, indicating P limitations at crop-soil-hedge interface along with N limitations which is also proved by grain P content.

5.3 Potential recommendations

From these findings the following recommendations can be concluded:

- Maize performance is better when planted in intercropping conditions with fertilization than in sole cropping. Intercropping fosters use of available resources and reduces risk of crop failure. Inclusion of hedgerows in intercropping with minimum tillage and fertilization not only conserve soil but also increase production efficiency by increases land utilization as compared to sole cropping.

- Carbon isotopic discrimination technique can successfully separate nitrogen and water limitations with inclusion of some special treatments in field studies. ERT soil moisture depletions make it possible to measure spatio-temporal distribution of water along the slope and gave an idea of water uptake by each row of crop and hedge. A combination of both techniques proved to be efficient in understanding nutrient and water studies in mixed cropping systems.

- WaNuLCAS modeling is well suited to fine tune maize based cropping systems with soil conservation options as studied in NW Thailand. Fertilizer management in the rows planted close to hedgerows not only reduces the competition between the components of the system but also increase productivity of these plants. Increased nitrogen and phosphorous fertilizer additions just in the rows close to hedgerows can overcome maize yield reduction in these rows.

5.4 Conclusions and outlook

The study covered several aspects of upland agriculture in western Thailand such as type of cropping systems being practiced, potential impacts and adoptions of conservation systems, evaluation of resource use efficiency and resource use competition between components of conservation systems. It also evaluated the scope of stable carbon isotope discrimination, electrical resistivity tomography, time domain reflectometry and modelling approaches for evaluation of above and below ground competition and options for conservation systems improvement. Stable carbon isotope discrimination, electrical resistivity tomography and time domain reflectometry results from the experiment showed that the reduction in maize production in rows planted close to hedgerows was not due to water limitation. All the techniques showed that water remained above threshold level of competition and pointed that soil moisture was high in the maize chili leucaena hedgerows intercropping with fertilizer application conservation system compared to other investigated systems. The observed increase in $\delta^{13}C$ signals (less negative values) was due to nutrients limitation which was clearly supported by $\delta^{13}C$ signals in grains of maize planted under unfertilized conditions. Similarly, high $\delta^{13}C$ signals in maize rows planted close to hedgerows under fertilized conditions were observed, which indicated nutrient limitations between maize and hedgerows and reduced production in hedgerows adjacent maize rows. Additionally, grain nitrogen concentration was statistically lower in maize rows planted close to hedgerows also supported nitrogen limitation between maize and leucaena hedges.

Electrical resistivity tomography imaging was also helpful in understanding the growth and development of plants and particularly to revealing time dependent spatially explicit soil moisture utilization under different management practices in field conditions and allows visualization of water uptake over time. Carbon isotopic discrimination and electrical resistivity tomography imaging proved to be valuable tools in understanding crop behaviour in various cropping systems under field conditions. Combining both methods proved to be more valuable in understanding and distinguishing water competition from nitrogen competition in complex interface of plant soil and hedgerows. WaNuLCAS model simulations also showed that water was not a limiting factor between maize and hedgerows planted close to each other and also figured out nutrient limitation in plant soil hedge interface which reduced maize above ground biomass production in maize rows planted close to hedgerows.

The main findings of above ground resource use efficiencies in six investigated maize cropping with and without soil conservation systems showed that planting patterns affected the canopy characteristics and photosynthetic active radiation (PAR) distribution within crop canopy. Maize intercropped with chili, tillage with fertilizer application intercepted more PAR than maize sole cropping and other intercrop treatments. The reason for high PAR interception was due to long row spacing between maize and chili and poor chili development enhanced lateral and vertical distribution of PAR which increased the ability of maize plants to convert radiant energy into biomass efficiently with highest above ground biomass and grain yield production. In maize intercropped with chili, minimum tillage, Leucaena hedgerows with and without fertilizer (T4 and T6 resp.), and poor development of maize plants close to leuceana hedgerows due to nutrient competition reduced light use efficiency for above ground biomass production in these hedges close maize rows. On the other hand, maize rows distant to hedgerows got more surface area for lateral and vertical capturing of PAR. The productivity evaluation also showed that inclusion of hedgerows in tropical hill side agriculture is promising in enhancing crop production and thus can be adopted by farmers with yield advantage and erosion control. WaNuLCAS simulations showed promising results of maize above ground biomass production under various cropping systems with and without tress and fertilizer application. Modelling outputs provided multiple options not only to figure out resource competition at plant soil hedge interface but also showed several mitigation options. Model results showed that negative impacts of hedgerows on crops can be reduced by managing and increasing fertilizer application in hedge adjacent maize rows for successful application of agroforestry systems on long-term basis not only for soil conservation but also for sustainable crop production in tropical uplands.

Results of carbon isotopic discrimination and ERT imaging trends supported each other but the correlation between them was low. Several issues affected the correlation between both methods. Therefore, the following issues should be considered during such type of experiments: $\delta^{13}C$ samples should be collected from the same maize plants having the ERT electrode. $\delta^{13}C$ samples should also be collected simultaneously to ERT soil moisture depletion.

Field experiments with soil conservation studies preferentially should be conducted for longer periods to figure out effects of conservations practices on production efficiency. This would also be useful for modelling approaches to further fine tune the conservations systems. Thereafter, modelling predictions should also be tested for one or two seasons for solid dissemination of these fine-tuned management practices to the farming community for long term sustainable agriculture.

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Summary

Thailand's western uplands are facing severe soil loss and runoff problems due to intensive cultivation of cash crops for high food, feed, fiber, and fuel demand by an increasing population. Thus the Land Development Department and the International Board for Soil Research and Management in Thailand are promoting the use of soil conservation measures such as contour hedgerows, grass barriers and agroforestry systems based on fruit trees and annual crops. Although such measures have been shown to be effective in controlling soil erosion, farmers often are reluctant to adopt such practices as inclusion of trees reduces the cropped area and yields competition for available resources with crops. Hence, a better understanding of the underlying processes at the crop-soil-hedge interface is needed to design soil conservation systems that are more attractive for farmers. It was hypothesized that soil conservation systems with hedgerows and intercropping will induce spatial patterns of resource use which can be linked to competition while planting patterns affect canopy characteristics and light distributions. This study focused on the following objectives; (i) to improve understanding of competition at the crop soil hedge interface by combining stable isotope discrimination, electrical resistivity tomography and time domain reflectometry, (ii) to identify the effects of intercropping and hedgerows on maize biomass accumulation, nitrogen concentration and light use efficiency, (iii) to evaluate the competition between maize hedges at crop-soil-hedge interface, (iv) to explore possible mitigating options to cope with competition between hedge and maize by using a modelling approach.

A field trial was laid out in randomized complete block design with three replicates at Queen Sirikit research farm, Ban Bo Wi village (13°28´ N and 99°15´ E), Suan Phueng District, Ratchaburi province in western Thailand with 20-25% slope magnitude. The experiment was established in 2009 while the research presented here was carried out during the 2010 and 2011 maize growing seasons. Six cropping treatments with following management practices were investigated: (T1, control) maize [*Zea mays* L.) monocrop, tillage, with fertilizer application (farmer's practice; (T2) maize intercropped with chili (*Capsicum annuum* L. *cv. Super Hot*), tillage and fertilizer application; (T3) maize intercropped with chili, minimum tillage, fertilizer application, and Jack bean (*Canavalia ensiformis* (DC) L.) relay cropping; (T4) maize intercropped with chili, minimum tillage, fertilizer application, Jack bean relay cropped, and leucaena (*Leucaena leucocephala* (Lam.) de Wit) hedgerows; (T5) and (T6) as (T3) and (T4), respectively, but both without fertilizer application. Tillage was carried out manually by hoe to around 0-20 cm depth. Plots were 13 x 4 m. Fertilizer was applied to maize at a rate of 62, 22, 36 kg ha^{-1} of N, P, and K, respectively. Urea (N) application to

maize was done in two splits as 31 kg ha^{-1} of N one month after sowing maize and another split of 31 kg ha^{-1} of N two months after sowing maize Chili received 92 kg N ha^{-1} at the time of transplanting and 92 kg ha^{-1} N as top dressing one month after transplanting.

The impact of competition at the crop-soil-hedge interface was studied in 2011, two years after establishment of soil conservation measures, to exclude the establishment period of leucaena with a potentially weak impact on maize. At this time, highest above ground biomass (AGB) production of maize of 1364 g m^{-2} was witnessed in T2 being statistically different from all other treatments, except T4 and T3; while lowest above ground biomass production of 1034 g m^{-2} was observed in T5. In hedgerow treatments, maize rows planted distant to hedges produced 46% and 73% higher AGB than maize growing in rows close to the hedgerow ($p \leq 0.0001$) in T4 and T6, respectively. Similar effects were observed for plant height, grain nitrogen concentration and grain yield. Mean grain $\delta^{13}C$ was significantly higher in T6 (-9.32‰) than in T4 (-10.49‰) and T1 (-10.55‰). Generally, higher $\delta^{13}C$ signals mean higher water availability; however the higher $\delta^{13}C$ signals in unfertilized T6 treatment imply that lack of nutrients may have led to increased $\delta^{13}C$ values. Similarly in T4, $\delta^{13}C$ signals were significantly higher in maize grains originating form rows planted close to hedges (-10.33‰, $p \leq 0.0001$) than samples obtained from maize rows distant to hedges (-10.64‰). These results point out that competition at the crop-soil-hedge interface was driven by nutrient rather than water limitation. The electrical resistivity tomography (ERT) imaging further supported this finding showing that maize monocrop showed higher soil moisture depletion patterns than hedge intercrop with fertilizer (T4) treatment, while hedge intercrop without fertilization (T6) depleted soil moisture least.

Light use efficiency (LUE) for maize above ground biomass production was statistically higher LUE_{AGB} (1.56 g DM MJ^{-1}) in maize and chilli intercrop (T2) than in maize sole cropping LUE_{AGB} (1.23 g DM MJ^{-1}). In T4 and T6 maize rows planted close to hedgerows had lower LUE_{AGB} than rows distant to hedgerows. The land equivalent ratio showed that inclusion of hedgerows with fertilizer application in the intercropping treatment enhanced land utilization by 21%.

The Water, Nutrient and Light Capture in Agroforestry (WaNuLCAS) model simulated AGB with R^2= 0.83, RMSE=6.3, EF=0.82 and CD=1.4 during calibration while model validation also showed promising results with R^2= 0. 76, $P<0.001$, RMSE=4.6 and EF=0.69. Simulations also pointed to major nutrient limitation between maize rows planted close to hedgerows. Simulations showed that negative impacts of hedgerows on crops can be reduced by managing fertilizer application in hedge adjacent maize rows leading to a successful application of agroforestry systems on a long-term basis not only for soil conservation but also for sustainable crop production in tropical uplands.

The study figured out the scope of stable isotopic discrimination, ERT, light use efficiency and modelling approaches for evaluating resource use competition at crop-soil-hedge interface on hillside agriculture. The combination of isotopic discrimination and ERT measurements provided useful information for identification of cause-impact relationships. Spatial LUE patterns provided insights for canopy light harvest under various soil conservation options. Furthermore, light use data was also helpful in validation of WaNuLCAS model which did not only provide multiple options to figure out resource use competition at crop-soil-hedge interface but also allowed to test mitigation options for sustainable crop production in tropical uplands. Model scenarios showed that negative impacts of hedgerows on crops growing close to hedges can be reduced by applying minute additional doses of fertilizer only to the crop rows planted close to hedgerows, leading to a sustainable crop production along with soil conservation. Productivity evaluation of investigated cropping systems showed that inclusion of hedgerows and intercropping in tropical hillside agriculture is promising in enhancing crop production and thus can be adopted by farmers with yield advantage.

Zusammenfassung

Auf Grund des intensiven Anbaus von Marktfrüchten für hochwertige Lebensmittel, Futtermittel, Fasern und des Kraftstoffbedarfs für eine wachsende Bevölkerung, steht Thailands westliches Hochland vor schwerem Bodenabtrag und Problemen mit Oberflächenabfluss.

Das Landesentwicklungsministerium und der Internationale Rat für Bodenforschung und Management in Thailand fördert daher die Verwendung von Bodenschutzmaßnahmen wie Konturhecken, Grasbarrieren und Agroforstsystemen auf Basis von Obstbäumen und einjährigen Kulturen. Da die Einbeziehung von Bäumen die Anbauflächen verkleinert und es zur Konkurrenz um die verfügbaren Ressourcen mit den Feldfrüchten kommt, sind Landwirte oft zögerlichbei der Anwendung solcher Praktiken, obwohl sich diese Maßnahmen als effektiv bei der Kontrolle von Bodenerosion erwiesen haben.

Um Bodenschutzsysteme für Landwirte attraktiver zu gestalten, ist daher ein besseres Verständnis der zugrunde liegenden Prozesse an der Schnittstelle von Feldfrucht, Boden und Hecke erforderlich. In dieser Studie wurde die Hypothese aufgestellt, dass Bodenschutzsysteme mit Hecken und Mischkulturen räumliche Muster der Ressourcennutzung induzieren, welche mit Konkurrenz in Zusammenhang gebracht werden können, wohingegen die Pflanzmuster Bodenbedeckungseigenschaften und Lichtverteilung beeinflussen.

Diese Studie konzentrierte sich auf die folgenden Ziele; (i) Verbesserung des Verständnisses des Konkurrenz an der Schnittstelle von Feldfrucht, Boden und Hecke durch die Kombination der ^{13}C Isotopendiskriminierungsmethode, elektrische Widerstandstomographie und Zeitdomänenreflektometrie, (ii) die Auswirkungen von Mischkulturen und Hecken auf die Biomasseakkumulation von Mais, Stickstoff-Konzentration und Lichtnutzungseffizienz zu untersuchen, (iii) die Konkurrenz zwischen Maishecken und der Schnittstelle von Feldfrucht, Boden und Hecke zu bewerten, (iv) mit Hilfe eines Modellierungsansatz mögliche vorbeugende Maßnahmen untersuchen, um die Konkurrenz zwischen Hecke und Mais zu bewältigen.

Ein Feldversuch wurde in randomisierter vollständiger Blockanlage, mit drei Wiederholungen, auf der Queen Sirikit Forschungsfarm, in Ban Bo Wi (13 ° 28 'N und 99 ° 15' E), im Distrikt Suan Phueng, Provinz Ratchaburi in West – Thailand, bei einer Neigung von 20- 25%, angelegt.

Das Experiment wurde im Jahr 2009 gestartet. Jedoch wurde die Forschungsarbeit die hier vorgestellt wird, während der Maisanbauperiode der Jahre 2010 und 2011 durchgeführt.

Sechs Anbauverfahren mit folgenden Managementpraktiken wurden untersucht: (T1, Kontrolle) Mais [*Zea mays* L.] Monokultur, Bodenbearbeitung, mit Düngeapplizierung (Anbaumethode der Bauern; (T2) Mais mit Chili als Mischkultur (*Capsicum annuum* L. cv Super Hot.), Bodenbearbeitung und Düngung; (T3) Mais mit Chili, Minimalbodenbearbeitung, Düngung, und Jackbohne (*Canavalia ensiformis* (DC) L.) im Überlappungsanbau; (T4) Mais mit Chili als Mischkultur, Minimalbodenbearbeitung, Düngung, Überlappungsanbau und Leucaenahecken (*Leucaena leucocephala* (Lam) de Wit.); (T5) und (T6) als (T3) und (T4), jeweils, aber beide ohne Düngung.

Bodenbearbeitung wurde manuell durch Hacke auf rund 0-20 cm Tiefe durchgeführt. Die Parzellen waren 13 x 4 m groß. Bei Mais wurde Dünger in einer Menge von 62 kg ha^{-1} N, 22 kg ha^{-1} P und 36 kg ha^{-1} K appliziert. Harnstoff (N) wurde bei Mais in zwei Schritten appliziert, mit 31 kg ha^{-1} N einen Monat nach der Aussaat von Mais und mit 31 kg ha^{-1} N zwei Monate nach Aussaat von Mais. Chili erhielt 92 kg N ha^{-1} zum Zeitpunkt der Umpflanzung und 92 kg ha^{-1} N als Kopfdüngung einen Monat nach der Umflanzung.

Um den Entwicklungszeitraum von Leucaena mit einer potenziell schwachen Auswirkungen auf Mais auszuschließen zu können, wurden die Auswirkungen der Konkurrenz an der Schnittstelle von Feldfrucht, Boden und Hecke im Jahr 2011 untersucht, zwei Jahre nach Etablierung der Bodenschutzmaßnahmen.

Zu diesem Zeitpunkt wurde die größte oberirdische Biomasseproduktion (AGB) von Mais 1364 g m^{-2} bei T2 beobachtet. Diese war statistisch verschieden von allen anderen Behandlungen, außer T4 und T3; während die niedrigste oberirdischen Biomasseproduktion von 1034 g m^{-2} bei T5 beobachtet wurde. In den Heckebehandlungen produzierten die Maisreihen, welche entfernt zu den Hecken gepflanzt wurden, 46% und 73% mehr AGB als Mais welcher in Reihen in T4 bzw. T6 dicht an den Hecken wuchs ($p \leq 0.0001$). Ähnliche Effekte wurde für Pflanzenhöhe, Kornstickstoffkonzentration und Kornertrag beobachtet. Durchschnittliche $\delta^{13}C$ Werte für Körner waren signifikant höher bei T6 (-9,32 ‰) als bei T4 (10.49 ‰) und T1 (-10,55 ‰).

Generell bedeuten höhere $\delta^{13}C$ Signale höhere Verfügbarkeit von Wasser; aber die höheren $\delta^{13}C$ Signale in unbefruchteten T6-Behandlung bedeuten, dass Nährstoffmangel zu erhöhten $\delta^{13}C$ Werte geführt haben kann. Ähnlich wie in T4, waren die $\delta^{13}C$ Signale deutlich höher in Maiskörnern welche von Reihen in der Nähe von Hecken stammen (-10,33 ‰, $p \leq 0.0001$) als Proben von Maisreihen die entfernt von Hecken stammen (-10,64 ‰). Diese Ergebnisse weisen darauf hin, dass die Konkurrenz an der Schnittstelle von Feldfrucht, Boden und Hecke von Nährstoff statt von Wassermangel angetrieben wurde. Die elektrische

Widerstandstomographie (ERT)-Bildgebung unterstützt diesen Befund weiter und zeigt, dass Maismonokultur eine größere Verringerung der Bodenfeuchtemuster zeigt als als Hecken mit Mischfruchtanbau und Düngebehandlung (T4), während Hecken mit Mischfruchtanbau ohne Düngebehandlung (T6) die Bodenfeuchte am wenigsten verringerte.

Lichtnutzungseffizienz (LUE) für die oberirdische Biomasseproduktion von Mais war statistisch höher LUE_{AGB} (1,56 g DM MJ^{-1}) in Mais und Chili Mischfruchtanbau (T2) als bei Mais als einziger Feldfrucht LUE_{AGB} (1,23 g DM MJ^{-1}). In T4 und T6 zeigten Maisreihen, die in der Nähe von Hecken gepflanzt wurden, niedrigere LUE_{AGB} als Reihen die entfernt von Hecken waren.

Das Landäquivalentverhältnis zeigte, dass die Integrierung von Hecken mit Düngerbehandlung in der Behandlung mit Michfruchtanbau die Landnutzung um 21% verbesserten.

Das Water, Nutrient and Light Capture in Agroforestry (WaNuLCAS) Model simulierte AGB mit R^2 = 0,83, *RMSE* = 6,3, *EF* = 0,82 und *CD* = 1,4 während der Kalibrierung, während die Modellvalidierung auch vielversprechende Ergebnisse mit R^2 = 0. 76, p <0,001 , *RMSE* = 4,6 und *EF* = 0,69 zeigte. Simulationen wiesen auch auf eine wichtige Nährstoffbegrenzung, zwischen Maisreihen in die in der Nähe von Hecken gepflanzt wurden, hin. Simulationen zeigten, dass negative Auswirkungen der Hecken auf Pflanzen durch die Reglung der Düngebehandlung in an Hecken angrenzenden Maisreihen verringert werden können, was zu zu einer erfolgreichen Anwendung von Agroforstsystemen auf einer langfristigen Basis nicht nur für die Erhaltung der Böden, sondern auch für eine nachhaltige Pflanzenproduktion in tropischen Hochländern führen kann.

Die Studie hat den Rahmen ermittelt, mit dem die Bewertung der Konkurrenz beim Ressourcenverbrauch mit der ^{13}C Isotopendiskriminierungsmethode, ERT, Lichtnutzungseffizienz und Modellierungsansätze an der Schnittstelle von Feldfrucht, Boden und Hecke im Ackerbau von Hanglagen ermittelt werden kann.

Die Kombination von ^{13}C Isotopendiskriminierung und ERT-Messungen lieferte nützliche Informationen für die Identifizierung von Ursache-Wirkung-Beziehungen.

Räumliche LUE Muster ermöglichten Einblicke für Strahlungsabsorption des Bestandes unter verschiedenen Bodenschutzoptionen. Darüber hinaus waren die Lichtnutzungsdaten auch bei der Validierung des WaNuLCAS Modells hilfreich, das nicht nur mehrere Optionen bietet, um die Ressourcennutzungkonkurrenz an der Schnittstelle von Feldfrucht, Boden und Hecke zu bestimmen, sondern auch um Massnahmen zur nachhaltigen Pflanzenproduktion in tropischen Hochland zu testen.

Modellszenarien zeigten, dass die negative Auswirkungen von Hecken auf in der Nähe wachsenden Pflanzen durch kleine zusäzliche Düngedosen, die nur auf die, der Hecke nahestehenden Reihen angewendet werden, vermindert werden können, was zu einer nachhaltigen Pflanzenproduktion und verbessertem Bodenschutz führt. Untersuchungen zur Produktivität der untersuchten Anbausystemen zeigte, dass die Einbeziehung von Hecken und Mischkulturen im Ackerbau von tropischen Hanglagen eine Verbesserung der Pflanzenproduktion verspricht und somit von Landwirten mit Ertragsvorteil übernommen werden kann.