Trade-off analysis of integrating legumes in East-African maize cropping systems

A meta-analysis on maize - common bean and maize - pigeon pea intercrops

MSc thesis Plant Production Systems

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August 2018

WAGENINGEN UNIVERSITY & RESEARCH

CGIAR

RESEARCH PROGRAM ON Climate Change, Agriculture and Food Security

CCAFS

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Course code: PPS-80436

Date: June 2018

Examiner: Prof. Dr. Ir. Martin Van Ittersum

Disclaimer: This thesis report is part of an education program and hence might still contain (minor) inaccuracies and errors.

Correct citation: A.P.P. Ravensbergen, 2018, A trade-off analysis of integrating legumes in East-African maize cropping systems: a meta-analysis on maize common bean and maize pigeon pea intercrops in Kenya and Tanzania, MSc Thesis Wageningen University.

Contact office.pp@wur.nl for access to data, models and scripts used for the analysis.

This work was implemented as part of the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), which is carried out with support from CGIAR Fund Donors and through bilateral funding agreements

Abstract

Because of population growth and dietary changes cereal demand is expected to triple in East-Africa in 2050 relative to the 2010 production level. Simultaneously, climate is changing as a result of increased greenhouse gas emissions. Both issues can be addressed through ecological intensification, i.e. increasing outputs while reducing inputs. Intercropping maize with legumes seems to be a viable option to ecologically intensify maize monocropping systems. A trade-off analysis has been performed to evaluate maize common bean intercropping systems in Kenya and maize pigeon pea intercropping systems in Tanzania in terms of crop productivity, financial return and N_2O emissions. Intercropping resulted in a land equivalent ratio (LER) of 1.46 for maize common bean intercrops in Kenya and a LER of 1.57 in maize pigeon pea intercrops in Tanzania, meaning that the intercrops were more productive. In Kenya this resulted in a better financial return for the intercrops. In Tanzania however, maize monocrops had the highest financial return. Differences in profitability were mainly attributed to differences in prices. A trade-off occurred for yield scaled N_2O emissions as these were for both countries higher in intercrops than maize monocrops when legume residues were returned to the soil, but this difference was reversed when fertilizers were added to the cropping systems at high rates. Overall, it can be concluded that maize legume intercropping can be beneficial compared to the monocrops, if good markets for both maize and legume produce are in place. Recommendations for further research are especially in the domain of including long-term in-situ data on N_2O emissions and LER in a long-term analysis.

Contents

Acknowledgement

This thesis has been written as part of my MSc degree in Plant Sciences. For the completion of this thesis I would like to thank many people. First and most important of all I would like my supervisors Renske, Marloes and Esther who always supported me during the thesis writing at different stages of the report. Secondly, I am very grateful to Frederick Baijukya, Paul Woomer, Endalkachew Woldemeskel, Wytze Marinus, Samuel Njoroge and Joseph Oloo who provided me with input data for the economic analyses in this thesis. Although it was not used as part of the research outputs in this thesis, I also want to thank Joseph Oloo for teaching me in farmer's fields in Western Kenya about maize legume intercropping systems in Western Kenya. I want to thank Eva Thuijsman, who taught me the basics of the R programming language and Marleen Hermelink, who provided me with very useful R scripts for the analysis. Lastly, I want to thank all my colleague students who gave feedback on my work during thesis rings.

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1 Introduction

The current population in Africa is estimated to double by 2050 (United Nations, 2017). The increase in food demand is expected to be even higher. As a result, the demand for cereals in 2050 will probably be more than three times the 2010 demand for East-Africa (van Ittersum *et al.*, 2016). A challenge lies ahead to provide the countries' populations with enough food as current rates of increasing food production are two to three times lower than needed to maintain productivity (Breman & Debrah, 2003).

Not only the food demand is growing in Africa, also climate is changing. Smallholder farmers in Africa are vulnerable to changes in climate, because they lack capital and technology to adapt to climate change (Morton, 2007). Over the past 60 years droughts have become more prevalent in East-Africa (Dai, 2012), but farmers sometimes have limited access to improved varieties that are able to cope with these droughts (Shiferaw *et al.*, 2011). Increasing variability in climate can thus disrupt smallholder farmers across sub-Saharan Africa (Funk *et al.*, 2008 & Pauw *et al.*, 2011).

Climate change is a result of the increased amount of greenhouse gasses (GHG) in the atmosphere. Agriculture is a large contributor to the emissions of GHG's. Directly, agriculture contributes 14 % to the global emissions of greenhouse gas (GHG). Indirectly, agriculture contributes another 17 % to the emissions of GHG through the expansion of agricultural land (Barker *et al.*, 2007). In Africa, 42 % of the N_2O emissions arise from agriculture and emissions may be doubled in 2050 compared to the levels of 2000 (Hickman *et al.*, 2017). Because of the high contributions of land expansion to GHG emissions, and because of the impact of land expansion on biodiversity and ecosystems (Foley *et al.*, 2005 & Fitzherbert *et al.*, 2008), increasing food production on current agricultural land, rather than via expanding agricultural area, is seen as a more viable option (Cassman, 1999 & Cassman *et al.*, 2003).

There is still a large potential to increase crop production in sub-Saharan Africa, including East-Africa, as actual yields in SSA are only 15-27 % of the water-limited potential yield (van Ittersum *et al.*, 2016), which is the maximum achievable yield limited by water supply (van Ittersum *et al.*, 2013). This gap between actual and water-limited yield potential is also referred to as the yield gap. In order to close the yield gap, fertilizer use should be increased, as nutrient limitation is the main reason for low productivity (Breman & Debrah, 2003; Rusinamhodzi *et al.*, 2011 & Sanchez, 2015). Inefficient intensification of nutrient inputs can potentially lead to higher GHG emissions (Schils *et al.*, 2006). To minimize the effect on climate change, production in East-African small-holder systems should therefore intensify in such a way that productivity is increased, but simultaneously the GHG emission intensity, i.e. GHG emissions per unit yield (Bellarby *et al.*, 2014), is minimized (Struik & Kuyper, 2017).

Such intensification is called ecological intensification, i.e. "a means of increasing agricultural outputs while reducing the use and the need for external inputs, capitalising on ecological processes that support and regulate primary productivity in agroecosystems" (Tittonell & Giller, 2013, p76). In the context of African smallholders ecological intensification is a necessity (Rusinamhodzi, 2013), but has not often been addressed (Tittonell & Giller, 2013). It is essential to anticipate and avoid potential negative impacts of intensification for the environment (van Ittersum *et al.*, 2016).

A promising way to intensify crop production in East-African smallholder farmers' fields is through integrating grain legumes in maize based cropping systems, either via a rotation or via intercropping (Vanlauwe *et al.*, 2014). Grain legumes can increase soil fertility by bringing nitrogen to the system through biological nitrogen fixation (Drinkwater *et al.*, 1998). As a result of higher soil fertility, productivity might increase (Ojiem *et al.*, 2014) and thereby also household income can be improved (Rusinamhodzi, 2013). Grain legumes can also improve the N efficiency (Drinkwater *et al.*, 1998 & Droppelmann *et al.*, 2017) and reduce the N surpluses (Droppelmann *et al.*, 2017) because of increased complementarity between maize and grain legumes. Additional benefits of integrating legumes arise as well, such as a diversified and more nutritious diet (Droppelmann *et al.*, 2017) and an increased weed suppression (Franke *et al.*, 2006).

In order to assess the suitability of integrating grain legumes in maize production systems it was necessary to address the socio-economic and bio-physical conditions of the smallholders environment (Ojiem *et al.*, 2006), together with the crop productivity and GHG emissions. On the level of smallholder farmers, cash income is a primary production objective (Rusinamhodzi, 2013). On the national and global level, reducing the GHG emissions is an important objective. Increasing crop productivity is an objective on all three levels. Because of these different objectives at different levels, a multi-level trade-off assessment of the viability of integrating legumes in maize cropping systems in East-Africa was performed to assess how crop productivity, financial return and GHG emissions relate to each other.

In this study three hypotheses were considered. First of all, it was hypothesised that integrating legumes would increase the crop productivity of a maize legume cropping system compared to a maize monocropping system, which would improve the economic return to a farmer. Secondly, it was hypothesised that the integration of legumes would decrease the greenhouse gas emissions per tonne yield as resources are used more efficiently. Lastly, it was expected a trade-off between crop productivity and GHG emissions would occur when fertilizers are added to the cropping systems.

2 Methodology

This chapter elaborates on the methods used in this study. First, this chapter explains the selection of the maize grain legume cropping systems that form the scope of this study. Then, it is elaborated how a database was made with suitable data for the analysis of crop productivity and which methods were used to analyse the data on crop productivity. Following, it is explained how data was collected and analysed on the financial return of maize grain legume cropping systems. In the last part of this chapter the methodology used for analysing greenhouse gas emissions is explained.

2.1 Cropping system selection

2.1.1 Literature search

The objective of this research was to do a trade-off analysis on crop productivity, financial return and GHG emission intensity for maize-grain legume mixed cropping systems in East-Africa. However, as low data availability was expected to be a potential issue for this research, no decision was made beforehand which country, which cropping system and which grain legume would shape the scope of this trade-off analysis. Literature search therefore initially focussed on three East-African countries included in the Crop Nutrient Gap project (Tanzania, Kenya and Ethiopia) (Global Yield Gap Atlas, 2018), on several grain legumes species and on both intercropping and rotational cropping systems. Based on the available literature, a selection was made for which cropping system, for which grain legume species and for which country a trade-off analysis would be performed.

Scopus was used to systematically look for publications using the search terms '(maize OR corn) AND (legume OR bean OR "pigeon pea" OR pigeonpea OR cowpea OR groundnut OR peanut OR soybean) AND (Kenya OR Tanzania Or Ethiopia)' for the title, abstract and keywords. All 390 publications that were found were assessed on their relevance for this trade-off analysis according to the title and abstract. Additionally the OFRA dataset (OFRA, 2017) was checked for any relevant sources of data.

During this stage of literature search it became apparent that most data was available for maize common bean intercropping systems in Kenya and Ethiopia and maize pigeon pea intercropping systems in Tanzania. To extend the literature search with non-peer reviewed data, the search terms 'maize common bean intercrop (Kenya OR Ethiopia)' and 'maize pigeonpea intercrop Tanzania' were used in Google Scholar. These search terms resulted in 11700 and 2510 hits respectively. Due to the large amount of publications that came out, only the first 200, sorted by relevance, were checked for their suitability.

From all the retrieved publications, published data were assessed for their suitability related to this research according to seven criteria (Table 1). Next to the posed criteria, ideally only studies would be selected that included both treatments with and without N and or P additions. This would enable an assessment of both the effect of adding fertilizers as well as adding grain legumes to a maize cropping system. This criterion was however not included as it would render too few publications. For the same reason no criteria were posed on planting density, plant variety or inclusion of monocrop grain legume treatments in the experiment.

Table 1. Overview of selection criteria used to select relevant papers for inclusion in this study.

Selection criteria	
1)	The experiment was performed in Ethiopia, Kenya or Tanzania
2)	The experiment was a rotation or intercrop of maize with a grain legume species
3)	A monocrop maize treatment with the same fertilizer rate was included in the experiment as a reference treatment
4)	Planting arrangement of either the maize or grain legume in the intercrop was not more than two rows of the same species wide.
5)	Common bean varieties used in the experiments were bush beans
6)	Results were published for separate fertilizer application rates[1]
7)	Experiments did not include any additions of farmyard manure

[1] Senkoro *et al.* (2017) averaged yields of treatments with 0 & 15 kg P ha^{-1} applied. Data from this publication was still included as it was stated that the yields of the different P treatments did not show any different responses to P application. It was assumed no P was applied.

Using the posed criteria, 34 publications were considered as potentially suitable for this trade-off analysis. Checking the references of these publications and using the ‘referenced by’ option in Scopus and Google Scholar brought the total to 42 suitable publications (Table 2).

Table 2. List of suitable papers found based on the posed selection criteria, sorted per legume species, cropping system and country. 'Total' means total quantity of publications. '0N', '0P' and '0N & 0P' indicate the quantity of publications that included a treatment for the legume-maize intercrop without additional N, P or N & P respectively. '+N & +P' indicates the quantity of publications that included a treatment for the legume-maize intercrop with addition of N and P

Legume species	**Cropping system**	**Country**	**Number of publications that include following N and P treatments**					**Publications**
			Total	0N	0P	0N & 0P	+N & +P	
Common bean	Intercrop	Ethiopia	10	1	1	1	9	Debele, 1997; Tamado *et al.*, 2007; Belay *et al.*, 2008; Workayehu & Wortmann, 2011; Worku, 2013; Hirpa, 2014; Lulie *et al.*, 2016; Alemayehu *et al.*, 2017; Liben *et al.*, 2017 & Rediet *et al.*, 2017
		Kenya	8	5	3	3	4	Fisher, 1979; Mochoge, 1993; Kimani *et al.*, 1998; Maingi *et al.*, 2001; Odhiambo & Ariga, 2001; Muraya *et al.*, 2006; Mucheru-Muna *et al.*, 2011 & Karuma *et al.*, 2016
	Rotation	Kenya	1	0	0	0	1	Ojiem *et al.*, 2014
Cowpea	Intercrop	Ethiopia	2	1	1	1	1	Karel et al., 1982 & Alemseged et al., 1996
		Kenya	3	2	1	1	2	Saidi *et al.*, 2007; Miriti *et al.*, 2011 & Mucheru-Muna *et al.*, 2011
		Tanzania	1	1	1	1	1	Jensen *et al.*, 2003
	Rotation	Kenya	1	1	0	0	1	Miriti et al., 2011
Groundnut	Intercrop	Kenya	1	1	1	1	0	Mucheru-Muna *et al.*, 2011
	Rotation	Kenya	1	0	0	0	1	Ojiem *et al.*, 2014
Pigeon pea	Intercrop	Ethiopia	1	0	0	0	1	Merkeb, 2016
		Kenya	3	3	2	2	0	Rao & Mathuva, 2000; Niang et al., 2002; Wanderi et al., 2011 & Kwena et al., 2017
		Tanzania	4	3	3	3	3	Myaka *et al.*, 2006; Kimaro *et al.*, 2009; Rusinamhodzi *et al.*, 2017 & Senkoro *et al.*, 2017
	Rotation	Kenya	1	1	1	1	0	Niang et al., 2002
Soybean	Rotation	Kenya	4	3	1	1	3	Anyanzwa *et al.*, 2008; Kihara *et al.*, 2009; De Groote *et al.*, 2010 & Ojiem *et al.*, 2014
	Intercrop	Kenya	1	1	1	1	1	Nekesa et al., 2011

2.1.2 Study selection

The final list of available publications that contain suitable data for an analysis on grain legume maize cropping systems in East-Africa was then narrowed down to specific cropping systems for certain areas. For maize common bean intercropping in Ethiopia only one experiment without N fertilizer application was available (Table 2). This would exclude the possibility to do an analysis of the effect of legume intercropping without fertilizer application. In case of pigeon pea maize intercropping systems in Kenya, the design of the cropping cycle and intercropping pattern were different between publications, which would complicate the analysis. Because of these constraints for common bean maize cropping systems in Ethiopia and pigeon pea maize cropping systems in Kenya, it was decided to do two trade-off analyses: on maize common bean intercropping systems in Kenya (1) and maize pigeon pea intercropping systems in Tanzania (2). For these cropping systems sufficient data was available and no constraints were present on the design of the cropping systems. The intercropping systems followed an additive design, where maize and pigeon pea plant density were equivalent for monocrops and intercrops. Common bean plant densities were half the amount in intercrops compared to monocrops.

Tables 3 & 4 give a short overview of the design of the different experiments included in the trade-off analysis in this thesis. Four studies included multiple fertilizer rates. Some studies also included additional treatments, next to comparing monocropping and intercropping systems (e.g. different tillage practices or different crop varieties). A few studies from Kenya only presented season averaged data. Studies on maize common bean intercropping in Kenya cover the central and western part of the country (Fig. 1). Studies on maize pigeon pea intercropping in Tanzania were done in the central and northern part of the country.

Time frame of the study

The analysis in this thesis were performed over a time span one cropping season. The number of seasons analysed in the publications used for the meta-analysis were too low (< 5 years) and too variable (Table 3 & 4) to be able to do an analysis over multiple seasons. In Tanzania there was one cropping season per year. In Kenya there were two cropping seasons per year, one during the long rains and one during the short rains. Because data of Kenya was in some publications aggregated for multiple seasons no distinction was made in the analysis or results between the long and short rain seasons.

Table 3. Meta-data of maize common bean intercropping systems in Kenya. Indicated for each publication are year of the experiment, number of seasons, N application rate, P application rate, possible additional treatments, inclusion of a legume monocrop in the experiment, field type of the experiment, number of replicates used in the experiment and any additional information for the different publications selected for the meta-analysis.

Publication	Year of experiment	Number of seasons	N applied (kg ha^{-1})	P applied (kg ha^{-1})	Additional treatments	Legume monocrop included	Field type of experiment	Number of replicates	Additional information
Fisher, 1979	1976-1977	2	0	32	Plant density (season 1), sowing dates (season 2)	Yes	Experimental field	2	
Mochoge, 1993	1986-1991	10, average	0 / 25 / 50 / 75	0 / 25 / 50 / 75	None	No	Experimental field	Not specified	Five study sites
Kimani et al., 1998	1990-1992	3	0	0	None	Yes	Experimental field	Not specified	Bean seeds were inoculated
Maingi et al., 2001	1997	2, average	0 / 10	9	Inoculated & non-inoculated seeds	Yes	Experimental field	4	
Odhiambo & Ariga, 2001	1999	2	58	28	1 row and 2 row intercrop spacing	Yes	On farm	2	Heavy striga infection in fields; four study sites
Muraya et al., 2006	2003	2, average	73	30.5	4 different maize varieties	Yes	Experimental field	3	
Mucheru-Muna *et al.*, 2011	2004-2006	4	0	0 / 60	Conventional / MBILI intercrop	No	On farm	3	Two study sites
Karuma et al., 2016	2012-2013	4	120	25.7	6 different tillage treatments	Yes	Experimental field	4	Bean seeds were inoculated

Table 4. Meta-data of maize pigeon pea intercropping systems in Tanzania. Indicated for each publication are year of the experiment, number of seasons, N application rate, P application rate, possible additional treatments, inclusion of a legume monocrop in the experiment, field type of the experiment, number of replicates used in the experiment and any additional information for the different publications selected for the meta-analysis.

Publication	Year of experiment	Number of seasons	N rates (kg ha^{-1})	P rates (kg ha^{-1})	Additional treatments	Legume monocrop included	Type of experiment	Number of replicates	Comments
Myaka et al., 2006	2002-2004	3	0*	0*	None	No	On farm	20	Two study sites
Kimaro *et al.*, 2009	2004-2005	2	0 / 40 / 80	0 / 20 / 40	None	Yes	On farm	3	
Rusinamhodzi *et al.*, 2017	2012-2015	4	98	46	Tillage & conservation agriculture, ratooning	Yes	Experimental field	3	
Senkoro et al., 2017	2014-2016	2	0 / 30 / 60 / 90	0 / 15	None	No	Experimental field & on farm	3	Three study sites

* Fertilizer rate was not mentioned. It was only stated that the area was similar in low fertilizer input. It is assumed that this is equal to no additional N and P fertilizer input

Figure 1. Map of locations of the included experiments within Kenya and Tanzania. Tags refer to the first author of the corresponding publication. In case an author is depicted multiple times the study was performed at multiple locations. (Odhiambo & Ariga, 2001) did the experiment at four locations in Western Kenya. Only one location could be located. This location is shown on the map.

2.2 Crop productivity

2.2.1 Data collection

Once it was decided a trade-off analysis would be performed on maize common bean and maize pigeon pea intercropping systems in Kenya and Tanzania, a database was created with relevant data for a meta-analysis on crop productivity. Of all publications, data were included of at least maize grain yield of monocropping and intercropping systems, year of measurements, legume grain yield of intercropping systems, N and P fertilizer rate, year of experiment, maize and legume plant density, study area and potential other treatments. If information was presented on maize and legume biomass yield, N concentrations of grain and aerial biomass, the study area and soil characteristics, this information was included in the database as well. After finalizing the database it turned out not enough data was available on these characteristics mentioned in the previous sentence to include them in the final analysis.

2.2.2 Data preparation

Correcting moisture content

Prior to the data analysis, data on crop grain yield needed to be prepared in order to allow for fair comparisons between studies of different publications in the trade-off analysis. Maize and legume grain yield data were corrected to 15.5 % and 13 % moisture content respectively. In case fresh yield and no moisture content was reported, it was not possible to do corrections. Moisture content was then assumed to be at 15.5 % for maize and 13 % for legumes.

Aggregating and separating data

Yield data was averaged for additional treatments. These treatments consisted of different soil tillage methods, different crop varieties, different spatial arrangements of the intercropping systems and different sowing dates. Data was used as separate observations for different experimental sites, different N and P fertilizer treatments and different cropping seasons. Only for Mochoge (1993), Maingi *et al.* (2001) & Muraya *et al.* (2006) average data of multiple seasons was used as data was already averaged in the publications. The publications were still included, due the limited amount of data available from other publications.

Checking outliers

Part of the preparation was also checking of outliers in the dataset, through making boxplots of different subsets of the dataset. Odhiambo & Ariga (2001) showed outliers in the yield data. As it was reported that the plots in this study were affected by heavy striga infestation, the study was considered as an outlier and therefore not included in the final meta-analysis.

Categorizing data

To assess the effect of fertilizer application rates, treatments were divided in different fertilizer classes. Different classes, rather than continuous variables were used, because it allowed for easier comparisons of the results, especially in the case of non-linear responses. Classes were divided in a similar way as was done by Franke *et al.* (2017). For Kenya three classes were made, with zero N application (1), less or equal than 50 kg N ha^{-1} applied (2) and more than 50 kg of N ha^{-1} applied (3). For Tanzania classes differed between 0 kg N ha^{-1} application (1), less or equal than 60 kg N ha^{-1} applied (2) and more than 60 kg N ha^{-1} applied (3). Classes were not divided in the same way for both countries to prevent that the amount of data available for one class would be too small. Also P fertilizer rate was divided into three classes, which were the same for Kenya and Tanzania. The lowest fertilizer class had no addition of P fertilizer (1). Fields in the middle class received more than 0 kg of P ha^{-1} and equal or less than 30 kg of P ha^{-1} (2). In fields in the highest class more than 30 kg of P ha^{-1} was added to the field (3).

2.2.3 Data analysis

During the analysis, first maize grain yield in intercrops and monocrops were compared. Following, legume grain yields were analysed. As the intercrop was an additive design, yield was not corrected for planting density in the intercrop. Presented yields are thus yields as directly measured in one hectare.

Estimating maize grain yield

Mixed effects models were used to estimate average maize grain yields. The reason these models were used is that they take into account the size effect of publications on the average by calculating a weighted averaged. Additionally, mixed effects models allow to take variation between publications and locations into account through the inclusion of random variables. Studies were inversely weighted for the number of replicates in the study. Publication and experimental site were included as random variables. Average maize grain yield was estimated with cropping system, N class, P class and season as explanatory variables. Where differences in yield between seasons is analysed as a difference between the first and a subsequent season. For Tanzania, this is the first or a following year. For Kenya, this is the first or second cropping season, but can either be the long rain or short rain seasons. Different combinations and interactions of the explanatory variables were included to create the best fitting model. Estimating maize grain yield included all maize grain yield data of intercropping and monocropping systems, but was done separately for Tanzania and Kenya as the maize was intercropped with two different legume species.

Estimating legume grain yield

Mixed effects models were also used to estimate average legume grain yields. Two data subsets were used for the calculations, because not all studies included both legume grain yield of an intercrop and of a legume monocrop. One subset was made which included only studies with legume grain yield data of both intercrops and monocrops. This subset was used to estimate the difference in legume grain yield between intercrops and monocrops. For Kenya this included Fisher (1979), Kimani *et al.* (1998), Mucheru-Muna *et al.* (2011) & Karuma *et al.* (2016). For Tanzania this included Kimaro *et al.* (2009) & Rusinamhodzi *et al.* (2017). Because this first subset was small, it was extended with additional data from other countries to check the validity of the results (Appendix C). For the analysis on common bean data from Ethiopia was added (Tamado *et al.*, 2007; Belay *et al.*, 2008; Workayehu & Wortmann, 2011 & Hirpa, 2014). For the analysis on pigeon pea, additional data from Kenya was used (Kwena *et al.*, 2017). For further analyses in this thesis only data on common bean in Kenya and pigeon pea in Tanzania was used.

A second subset was made with only legume grain yield data of the intercrops to estimate average legume grain yields in intercrops more accurately. This subset included all publications that were collected (Tables 3 & 4). This subset was also used to separately estimate the effect of N & P application rate on legume intercrop yield. Explanatory variables were not used to estimate the difference between legume monocrop and intercrop yield, as not enough data was available to make reasonable estimates.

All mixed effects model analyses were done with the lme function of the lmer package in R version 3.4.2. ANOVA was used to assess whether an explanatory variable had a significant effect on yield predicted by the model. Tukey's HSD was used as a post-hoc test to assess significant differences between classes within a significant explanatory variable.

Estimating crop productivity of the intercrop

Next to the separate analyses on maize and legume grain yield, an analysis was done to assess the overall productivity of maize and legumes combined. For both Kenya and Tanzania one Land equivalent ratio (LER) value was calculated with estimated average yields, combining the average partial LER of maize and the average partial LER of legumes (eq. 1). LER could not be calculated for each individual location, because not enough data on monocrop legume grain yield was available.

$$LER = {}^{Y_{im}}/_{Y_{mm}} + {}^{Y_{il}}/_{Y_{ml}} \qquad \textit{eq. 1}$$

Where Y_{im} is yield of maize in an intercrop, Y_{il} is the yield of the grain legume in an intercrop and Y_{mm} and Y_{ml} are the yield in a monocrop of maize and the grain legume in respectively.

Additionally, intercrop legume grain yield was estimated as a function of intercrop monocrop maize grain yield to be able to calculate total crop yield in an intercrop. Intercrop maize grain yield was plotted against intercrop legume grain yield. Regression lines between intercrop maize grain yield and intercrop legume grain yield were estimated using the lme function. Also minimum and maximum boundaries of intercrop legume grain yield relative to intercrop maize grain yield were estimated using stochastic frontier analysis. Boundaries were drawn by plotting regression lines plus and minus the confidence intervals. The analysis was done using the sfa function from the frontier package in R version 3.4.2.

2.3 Financial return

The estimated yields from the crop productivity meta-analysis were used as an input for the calculation of the average financial return to farmers. Additional data was collected for calculations as well. For the analysis of the financial return, and further on in this thesis, seven combinations of cropping systems and fertilizer rates were used (Table 5). Three cropping systems and three fertilizer rates were taken into account. Cropping systems considered were a maize monocrop, maize legume intercrop and legume monocrop. A combination of a legume monocrop with fertilizer application was not considered. Fertilizers were applied in a low, medium and high rate. It was assumed that for low, medium and high application rates respectively 0, 40 & 80 kg N ha^{-1} and 0, 20 & 40 kg P ha^{-1} were applied to the fields.

Table 5. Fertilizer cropping system combinations. Type of cropping system and N and P fertilizer rate (kg ha^{-1}) are shown.

Combination	Cropping system	N fertilizer rate (kg ha^{-1})	P fertilizer rate (kg ha^{-1})
1	Maize monocrop	0	0
2	Maize monocrop	40	20
3	Maize monocrop	80	40
4	Maize legume intercrop	0	0
5	Maize legume intercrop	40	20
6	Maize legume intercrop	80	40
7	Legume monocrop	0	0

2.3.1 Data collection

Data on farm gate prices and required quantities of all inputs and outputs were needed in order to perform an economic analysis on the intercropping systems. Inputs included fertilizers, seeds and labour. Outputs included maize and legume grain yields. Data on farm gate prices and seed and labour requirements were collected through N2Africa and IPNI country agronomists (Appendix A). All collected data (Table 6) were corrected to the same units for Kenya and Tanzania. Prices were changed to USD, using the average exchange rate for 2016 as provided by the World Bank. In Kenya the exchange rate was 101 Ksh for a dollar. The exchange rate in Tanzania was 2177.1 Tsh for a dollar. Labour requirements were converted to man-days ha^{-1} or man-days t^{-1}, where a man-day consisted of 8 hours. Based on data from the country agronomists it was assumed that for sowing maize, 25 kg ha^{-1} and 16 kg ha^{-1} of maize seeds were needed in Kenya and Tanzania respectively. In Kenya 45 kg common bean seeds ha^{-1} were required for monocrops and 22.5 kg ha^{-1} for intercrops. In Tanzania 14 kg pigeon pea seeds ha^{-1} were required for both intercrops and monocrops.

Estimated maize yields from the meta-analysis on crop productivity and fertilizer levels of the seven fertilizer cropping system combinations were used as a starting point for the calculation of the financial return. Estimated average legume monocrop yields were also used for the analysis of the financial return. Legume intercrop yields were estimated with the established relations between maize intercrop yield and legume intercrop yield as this was the only way to account for variable legume intercrop yields at different fertilizer levels. In addition, the economic analysis was performed with the individual data points from the publications used in the crop productivity meta-analysis. This was done in order to compare the financial return of each individual location with the average maize grain yield estimated in the meta-analysis on crop productivity. In addition, data from individual locations was used to investigate the variation in responses for different locations.

Table 6. Labour requirements and farm gate prices for Kenya and Tanzania. Data is separated for maize monocrops (SMC), intercrops (int) and legume monocrops (SLC) in case values were different between the three cropping systems.

	Kenya			Tanzania		
Labour requirements	SMC	int	SLC	SMC	int	SLC
Land preparation (man-day ha^{-1})	15	15	15	23	23	23
Sowing (man-day ha^{-1})	8	14	6	4.5	9	4.5
Fertilizer application (man-day ha^{-1})	4	4	0	4	4	0
Weeding (man-day ha^{-1})	20	24	20	6.5	9.5	6.5
Harvesting (man-day t^{-1})	3	3-5	5	2.5	2.5-4.5	4.5
Treshing (man-day t^{-1})	5	5-8	8	3	3-4.5	4.5

Farm gate prices	**Kenya**	**Tanzania**
Maize seeds (USD kg^{-1})	0.99	0.44
Common bean seeds (USD kg^{-1})	2.23	-
Pigeon pea seeds (USD kg^{-1})	-	0.80
Maize grains (USD kg^{-1})	0.35	0.19
Common bean grains (USD kg^{-1})	0.99	-
Pigeon pea grains (USD kg^{-1})	-	0.18
N (USD kg^{-1})[1]	1.38	0.99
P (USD kg^{-1})[1]	2.33	2.65
Labour (USD man-day^{-1})	3.96	4.90

[1] It is assumed DAP and CAN are used as fertilizers

2.3.2 Data analysis

Three indicators were used for the analysis of the financial return. Net revenue (\$ ha^{-1}) was calculated as the net difference between gross revenue minus the total costs (*eq. 2*).

$$net\ revenue = gross\ revenue - total\ costs \qquad eq.\ 2$$

Where gross revenue is the income from sold grain products and total costs are the costs for labour, seeds and fertilizers.

The benefit cost ratio (BCR) (-) was calculated as gross revenue divided by the total costs (*eq. 3*). A value of two is often used as a criteria for viable cropping systems in countries with a high interest rate (Bielders & Gérard, 2015 & Ronner *et al.*, 2016). In this thesis BCR was related to this threshold as well.

$$BCR = \frac{gross\ revenue}{total\ costs} \qquad eq.\ 3$$

Return to labour (in USD man-day^{-1}) was calculated as the gross revenue minus the total input costs divided by the required labour (*eq. 4*). Return to labour gives an indication of the opportunity costs of labour.

$$return\ to\ labour = \frac{gross\ revenue - input\ costs}{labour} \qquad eq.\ 4$$

Where input costs are the costs for fertilizers and seeds only and labour is the total amount of man-days required for cultivation.

The three indicators were calculated for all seven fertilizer cropping systems combinations with the estimated yield data from the crop productivity meta-analysis. Additionally, calculated net revenue, BCR & return to labour for each individual location were compared to estimated average net revenue, BCR & return to labour. Mixed effects models were used on the individual location data to test for significant differences in the three economic parameters between intercrops and maize monocrops. The lmer package in R was used to only estimate average differences between cropping systems. Additional explanatory variables were not taken into account in the mixed effects models.

2.3.3 Sensitivity analysis

Data of prices can vary substantially between years, within years and between areas. A sensitivity analysis was done to assess the influence of changing prices on financial return to a farmer. The country agronomists that provided input data reported price ranges of 100 % for some inputs and outputs. Based on these differences, the sensitivity analysis was performed by changing prices with plus and minus 50 %, which is in line with other studies (Franke *et al.*, 2010 & Ronner *et al.*, 2016). Prices that were changed were input prices, labour price, price of legume grains and the price of the maize grains. The sensitivity analysis was done for all three economic indicators; net revenue, benefit cost ratio and return to labour.

2.4 N_2O emissions

For the calculations on GHG emissions only N_2O emissions were taken into account. Similar to the analysis of the financial return, estimated yields from the crop productivity meta-analysis formed the basis for the calculations of the N_2O emissions. For these calculations, the seven fertilizer cropping system combinations (Table 5) were used as well. Additionally, data was collected on nitrogen concentrations of plant tissues and on harvest indices of different crops. N_2O emissions were calculated using the IPCC guidelines. Moreover, a net N-balance was made to assess the potential pool of N that could be emitted as N_2O.

2.4.1 Crop residues

Application of crop residues to the soil can also contribute to N_2O emissions. Likewise, removal of crop residues can reduce N_2O emissions. In this thesis different situations were assumed. For the maize monocrop it was assumed that all maize residues were taken from the soil and no crop residues were returned to the soil. For the legume monocrop it was assumed that all crop residues were applied to the soil. For the intercrops two situations were assumed. The first situation considered that all crop residues were removed from the field. In the other situation it was assumed that maize residues were removed from the field and that legume residues remained in the field. This assumption that legume residues were returned to the field was only used to calculate N_2O emissions. Yield was considered to be the same for cropping systems with and without residue application to the soil. Also compensation of emissions through potential C sequestration in the soil as a result of residue application was not taken into account.

2.4.2 Data collection

The IPCC presents guidelines to calculate N_2O emissions in agricultural fields (De Klein *et al.*, 2006). However, these guidelines are not specified to Africa. Therefore, in order to use more location specific data, the literature was initially searched for availability of data on N_2O emissions for maize monocropping systems and maize grain legume intercropping systems. The initial literature search for creating a database with yield data was used as a starting point. Additionally, Scopus was systematically searched with the search query '(maize OR "pigeon pea" OR pigeonpea OR "common bean" OR bean OR legume) AND (N_2O OR "nitrous oxide" OR "greenhouse gas") AND (Ethiopia OR Kenya OR Tanzania OR Africa)'. This query yielded some relevant papers. However, data was not sufficient to do a meta-analysis that reflects N_2O emissions of maize monocropping and maize grain legume intercropping systems in East-Africa. Thus, it was decided to stick to the IPCC guidelines. Moreover, a N balance analysis was done to assess the pool of N that potentially can be emitted as N_2O.

Calculating N_2O emissions with the IPCC guidelines required information on nitrogen inputs and emission factors. For maize legume intercropping systems, with addition of inorganic N fertilizers, the only potential N inputs were crop residues and fertilizers applied to the field. As N fertilizer inputs, the rates of the seven fertilizer cropping system combinations (Table 5) were used to calculate average N_2O emissions. Extra input data needed for calculations were taken from existing literature (Table 7).

Calculating a N balance required data of all inputs and outputs. Atmospheric N deposition, legume nitrogen fixation, N fertilizers and legume crop residues were considered as inputs. Maize and legume grains and shoot biomass were considered as outputs. Necessary data of crop parameters for calculations were taken from peer reviewed literature (Table 7). Atmospheric deposition was assumed to be 11.5 kg N ha^{-1} (Dentener *et al.*, 2006).

Table 7. Harvest index (-), N content of grains (in %), N content of aerial biomass (in %) and N fixed by legume (% of total N) for maize, common bean and pigeon pea.

Crops	Harvest index (-)	N content grains (%)	N content aerial biomass (%)	N fixed by legume (% of total N)
Maize[1]	0.34	1.25	0.39	-
Common bean[2]	0.42	3.30	1.94	49
Pigeon pea[3]	0.40	3.38	1.24	43

[1] Myaka *et al.* (2006), Wanderi *et al.* (2011) & Matusso *et al.* (2014)
[2] Dawo *et al.* (2007), Ojiem *et al.* (2007) & Cernay *et al.* (2016)
[3] Rao & Mathuva (2000), Myaka *et al.* (2006), Ncube *et al.* (2007), Wanderi *et al.* (2011), Cernay *et al.* (2016) & Senkoro *et al.* (2017)

2.4.3 Data analysis

N_2O emissions

N_2O emissions were calculated with the equation provided by the IPCC (*eq. 5*).

$$N_2O - N = \left(N_{fert} + N_{residue}\right) * EF \qquad eq.\ 5$$

Where $N_2O\text{-}N$ is the amount of N emitted in the form of N_2O, N_{fert} is the amount of N input from fertilizers, $N_{residue}$ is the amount of N input from crop residues (*eq. 6*) and EF is the emission factor, set by the IPCC to be 1% of applied N. $N_{residue}$ was only taken into account for the situation where legume residues were applied

$N_{residue}$ was calculated as the grain yield times the inverse of the harvest index (i.e. ratio between grain and total biomass) minus the grain yield times the N concentration of the biomass tissue (*eq. 6*).

$$N_{residue} = ((yield_{grain} * \left(\frac{1}{HI}\right)) - yield_{grain}) * Ncon_{biomass} \qquad eq.\ 6$$

Where $yield_{grain}$ is the grain yield of the crop, HI is the harvest index of the crop based on dry matter content and $Ncon_{biomass}$ is the aerial biomass of the crop.

Greenhouse gas emissions of production of fertilizers were not taken into account in the analysis. However, N fertilizer application rates were considered to be the same for intercrops and monocrops and would thus not affect the results.

Net N balance

The net N balance was calculated by subtracting all flows out of the system from all flows into the system (eq. 7-9). In the N balance it was assumed both biomass and grain yields were taken from the field as harvest.

$$net\ N\ balance = N_{IN} - N_{OUT} \qquad eq.\ 7$$

Where N_{IN} is the total input in the cropping system and N_{OUT} is the total output of the cropping system

$$N_{IN} = N_{fert} + N_{residue} + N_{fixed} + N_{atm} \qquad eq.\ 8$$

Where N_{fixed} is nitrogen fixed via biological nitrogen fixation, assuming a percentage of aboveground N is fixed (Table 7) and N_{atm} is the atmospheric deposition of N. $N_{residue}$ was only considered as input in cropping systems where crop residues were returned to the soil.

$$N_{OUT} = N_{residue} + N_{grain} \qquad eq.\ 9$$

Where N_{grain} is the amount of nitrogen in the grains of the crop. For $N_{residue}$ it was assumed that crop residues were always part of the output of that specific season. If crop residues were returned to the field it was considered as input for the next season (eq. 8).

In the final analysis, N_2O emission and net N balance values were expressed as absolute values and as yield scaled values. As the intercropping system consists of different crops, yield scaled values were based on N content of the grain products (table 7). Yield scaled values of N_2O emissions and the N balance were also calculated for each individual location. Similar to the economic analysis, differences between the overall averages of intercrops and maize monocrops were tested for significance with the mixed effects models. Additional explanatory variables were not taken into account.

2.5 Trade-off

After the analysis on each separate indicator, a trade-off analysis was performed on all indicators combined. First of all, this was done by creating spider web plots to give an overall visual overview of the three trade-off indicators. For crop productivity, LER could not be used in the spider web plots, because only on average value was calculated. Therefore maize and legume grain yield were included in the plots. For the financial return, net revenue, BCR and return to labour were added to the plots. For the N_2O emissions only the IPCC yield scaled values were used in the comparison. The spider web plots were created by rescaling the estimated values relative to the maximum value found in previous analyses. Only yields scaled N_2O emissions were inversely weighted, meaning that a higher rescaled value indicates lower yield scaled N_2O emissions. Other parameters were normally weighted, meaning that a higher rescaled valued also indicates a higher original value.

Additionally, the three trade-off parameters calculated with the individual data were plotted against each other. Yield scaled N_2O emissions were plotted against net revenue as an indication of N_2O emissions against financial return. Yield scaled N_2O emissions and financial return could not be plotted against LER, as LER was not calculated for each individual location. Therefore, figures used in earlier analyses, where yield scaled N_2O emissions, net revenue, BCR and return to labour of both intercrops and maize monocrops were plotted against monocrop maize yield, were used as a proxy for the trade-offs and / or synergies.

3 Results

This chapter shows the results of the data analysis on crop yield (section 3.1), financial return (section 3.2), GHG emissions (section 3.3) and the trade-offs (section 3.4). In the section on crop yield, first maize grain yields are compared between monocrops and intercrops (section 3.1.1). Then, legume grain yields are compared between a monocrop and intercrop (section 3.1.2). Lastly, the intercrop legume grain yield is compared against the intercrop maize grain yield (section 3.1.3). In the section on the financial return (section 3.2.1) first, net revenue, benefit cost ratio and return to labour are calculated. Thereafter, a sensitivity analysis is done on these three economic parameters (section 3.2.2). Section 3.3 shows results of total GHG emissions and yield scaled GHG emissions. In the final section a comparison is made between yield, financial return and GHG emissions to evaluate the trade-offs and synergies that occurred.

3.1 Crop productivity

3.1.1 Maize grain yield

Across 12 study sites in Kenya and 7 in Tanzania, average monocrop maize grain yields were estimated at 3.7 and 3.5 t ha^{-1} for Kenya and Tanzania respectively (Fig. 2). Intercropping with legumes reduced the maize grain yields compared to the maize monocrops. Maize grain yield of the intercrops were 0.24 t ha^{-1} lower for Kenya and 0.47 t ha^{-1} lower for Tanzania. However, this was only significant for Kenya ($p = 0.028$).

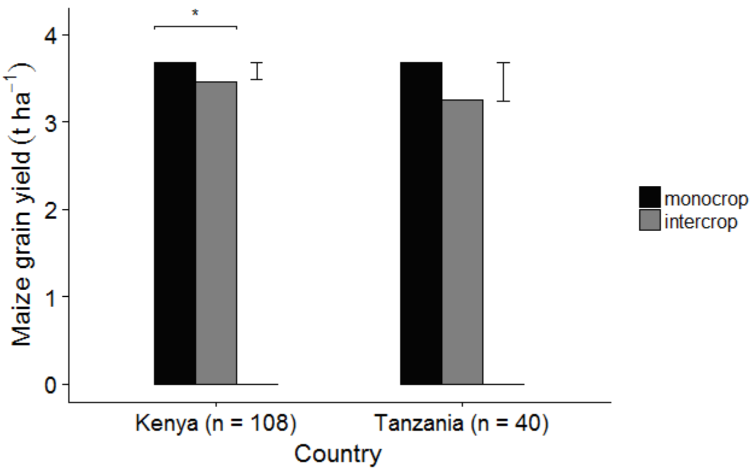

Figure 2. Maize grain yield (in t ha^{-1}) of monocropping and intercropping systems in Kenya and Tanzania, estimated by the mixed effects model. The error bars indicate the LSD (least significant difference). The number of observations per country are included between the brackets. * indicates a significant difference between monocrop and intercrop maize grain yield at $p < 0.05$.

Whereas the average maize grain yield differences between monocrops and intercrops were only small (-3.3 % for Kenya and -7.3 % for Tanzania) (Fig. 3), a farmer might also be interested in the minimum and maximum yield difference between monocrops and intercrops to be able to gain insight in maximum losses or gains. These minimum and maximum yield differences were much larger than the average relative yield difference. For both Kenya and Tanzania maize grain yield of intercrops were up to 60 % lower or higher compared to a monocrop (Fig. 3). However, In Kenya this range was smaller at higher maize monocrop yield levels than at lower yield levels. For Tanzania, such a pattern was not visible. Absolute differences of maize grain yields in intercrops and monocrops are shown in Appendix B.

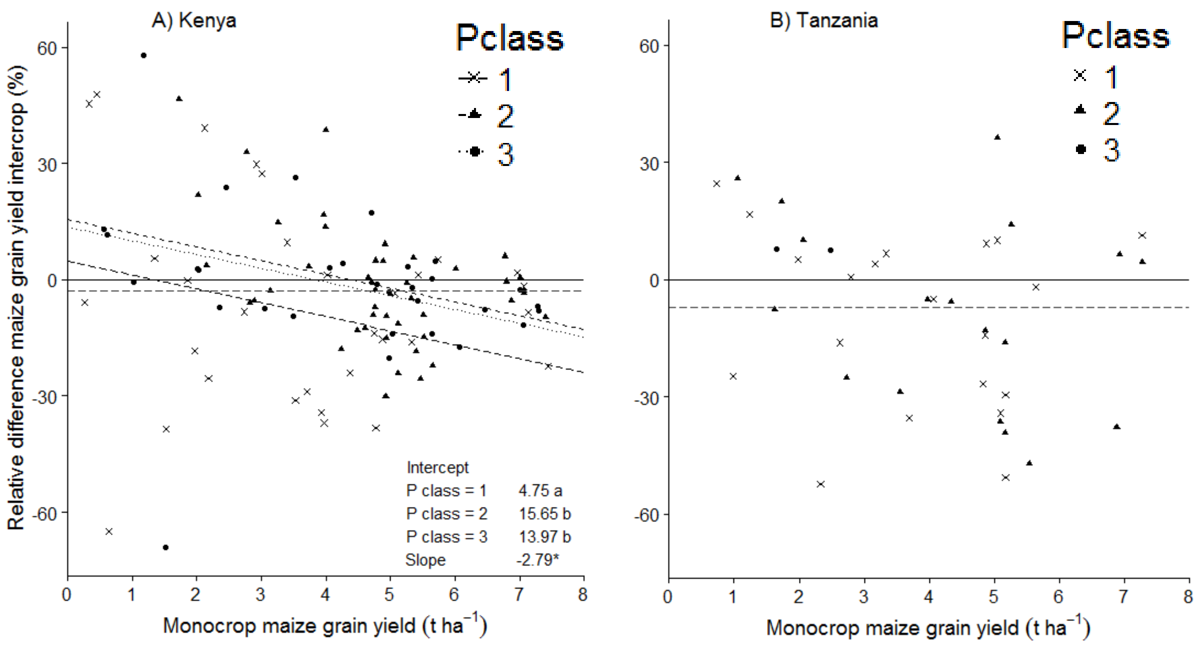

Figure 3. Relative difference of the maize grain yield of an intercrop compared to maize monocrop yield for Kenya (A) and Tanzania (B). A negative value indicates a higher maize grain yield of the monocrop. Different symbols and trendlines are used to indicate different P fertilizer rates. The dashed, short-dashed and dotted lines represent Pclass 1, 2 & 3 respectively. The horizontal dashed line shows the average relative difference of the maize grain yields. A star behind the slope and different letters behind the intercepts indicate a significant value at *$p < 0.05$*.

The results from the mixed effects models showed that in Kenya the relative maize grain yield in an intercrop compared to a maize monocrop was significantly lower at increasing monocrop maize grain yield levels (ANOVA, $p = 0.048$) (Fig. 3). This means that the intercrops compared to the maize monocrops performed relatively better if maize yields in the maize monocrop were lower. Not only monocrop maize grain yield was relevant, also applying P resulted in a better performing maize in an intercrop relative to a maize monocrop than when no P was applied (ANOVA, $p = 0.014$). A relation between N application rate and maize grain yield difference was not found for Kenya. In Tanzania no significant relations were found between the difference in maize grain yield and any of the explanatory variables.

No significant interactions were found between cropping system and either N application rate, P application rate or season for both Kenya and Tanzania, when absolute maize yield levels were estimated (Table 8). This means that the difference in maize grain yield between intercrops and monocrops was the same for different fertilizer application rates and for the different seasons in the cropping cycle. This is contradictory to the effect of P on relative maize grain yield differences, which was found when mixed effects models were used to estimate relative maize yield differences (Fig. 3).

A significant effect of N application rate on absolute maize grain yield was found, when mixed effects models were used to estimate absolute maize grain yield levels. For Kenya all three different N classes were significantly different from each other. For Tanzania class 2 and 3 were significantly different from class 1, but not between each other. On average, maize grain yield was not found to be different in Tanzania between intercrops and maize monocrops (Fig. 2). However, when N fertilizer application level was included as explanatory factor as well, maize grain yield was significantly lower in an intercrop than in a monocrop (Table 8).

Table 8. Estimated maize grain yield of monocrops with standard errors, estimated yield difference of an intercrop compared to a monocrop, standard error of the yield difference, p values of factors, estimated yield difference and interactions, estimated using a mixed effects model including publication and experimental site as random effects. Different letters behind the estimated maize grain yield of monocrop indicate a significant differences between classes. Vertical lines indicate classes to which estimated yield difference applies. P-values < 0.05 indicate a significant effect of the factor, estimated yield difference or interaction and are shown in bold.

Factor	*n*	Estimated maize grain yield of monocrop (t ha^{-1})		Estimated yield difference (t ha^{-1})	SE of yield difference	*p-value*
A) Kenya						
N application class						***0.000***
1) 0 kg N ha^{-1}	42	3.39 ± 0.53	a	-0.24	0.09	***0.008***
2) > 0 =< 50 kg N ha^{-1}	41	3.80 ± 0.53	b			
3) > 50 kg N ha^{-1}	25	4.19 ± 0.53	c			
*N application class * cropping system*						*0.239*
P application class						***0.000***
1) 0 kg P ha^{-1}	31	3.37 ± 0.57	a	-0.24	0.09	***0.011***
2) > 0 & ≤ 30 kg P ha^{-1}	46	3.70 ± 0.57	b			
3) > 30 kg P ha^{-1}	31	3.88 ± 0.57	b			
*P application class * cropping system*						*0.326*
*N application class * P application class*						*0.926*
First or following season						***0.030***
first season	7	2.71 + 0.53	a	-0.08	0.23	*0.753*
2nd or subsequent seasons	18	2.14 + 0.53	b			
*Season * cropping system*						*0.650*

B) Tanzania

N application class						***0.000***
1) 0 kg N ha^{-1}	14	2.81 ± 0.61	a	-0.48	0.23	***0.045***
2) > 0 =< 60 kg N ha^{-1}	14	4.30 ± 0.62	b			
3) > 60 kg N ha^{-1}	12	4.19 ± 0.63	b			
*N application class * cropping system*						*0.788*
P application class						0.215
1) 0 kg P ha^{-1}	16	3.03 ± 0.69	a	-0.43	0.25	*0.856*
2) > 0 & ≤ 30 kg P ha^{-1}	18	3.79 ± 0.70	a			
3) > 30 kg P ha^{-1}	6	4.12 ± 0.92	a			
*P application class * cropping system*						*0.913*
*P application class * N application class*						*NA*[1]
First or following season						*0.472*
first season	18	3.55 ± 0.65	a	-0.43	0.26	*0.101*
2nd or subsequent seasons	22	3.36 ± 0.64	a			
*Season * cropping system*						*0.688*

[1] for the interaction between P and N not enough data was available to calculate a p-value for Tanzania

In Kenya, absolute maize grain yields were also significantly different for different P fertilizer levels, but only between zero P application and application of P. Applying more than 30 kg of P did not result in a significantly higher yield. In Tanzania, P fertilizer rate did not have an effect on maize grain yield.

Additionally, it was tested whether there was a significant difference in maize grain yield between the first season in a cropping sequence or a subsequent season. For Tanzania, such an effect was not significant (Table 8). For Kenya, a significant effect was found. However, maize grain yield was lower in subsequent seasons than in the first season. This is contradictory to what would be expected, that maize grain yields will increase after a longer period with legume intercropping.

3.1.2 Legume grain yield

Using all data, the average common bean grain yield of the intercropping systems in Kenya was 0.5 t ha^{-1}. Intercrop pigeon pea yield in Tanzania was 0.9 t ha^{-1}. N & P fertilizer rates did not significantly affect intercrop common bean or pigeon pea yield. Common bean and pigeon pea intercrop yield were estimated at 0.8 and 0.5 t ha^{-1}, when only data from the subset with studies that include legume intercrop and monocrop yields was used. With this same subset common bean monocrop yield was estimated at 1.4 t ha^{-1}, which was significantly different from the common bean intercrop yield. For Tanzania, the yield difference of 0.2 t ha^{-1} between the monocrop and intercrop pigeon pea grain was not significant. Average common bean yield was slightly different when data from Ethiopia was included (Appendix C). Including data on pigeon pea yield from Kenya had a bigger effect on average pigeon pea yield (Appendix C).

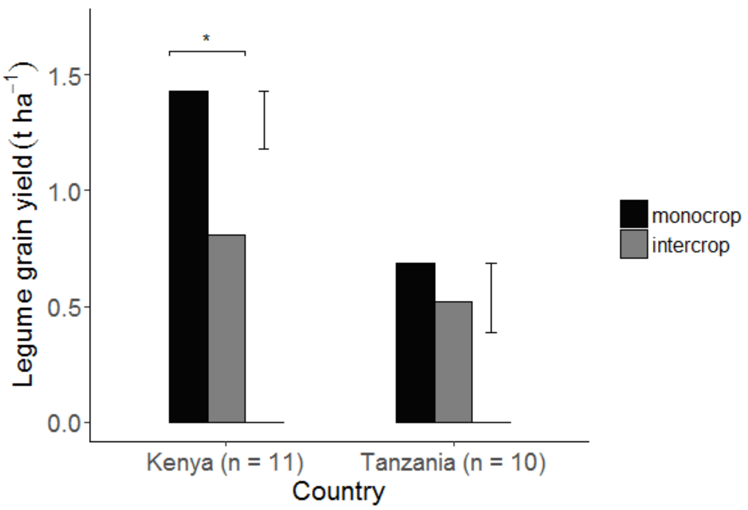

Figure 4. Legume grain yield (in t ha^{-1}) of monocropping and intercropping systems in Kenya and Tanzania, estimated by the mixed effects model. The error bars indicate the LSD. The number of observations per country are included between the brackets. * indicates a significant difference between monocrop and intercrop maize grain yield at *$p < 0.05$*.

The average relative yield differences of intercrops compared to monocrops were -43 % for common bean in Kenya and -20% for pigeon pea in Tanzania (Figure 5). Ranges in differences between legume grain yields of intercrops and monocrops were much larger than for the average difference. In Kenya, the minimum and maximum yield difference was between 0 and -80 %. In Tanzania, the minimum and maximum yield difference was between 0 and -40 %. These ranges were even larger when yield data of common bean and pigeon pea from different countries was included (Appendix C). Absolute yield differences can be found in Appendix B.

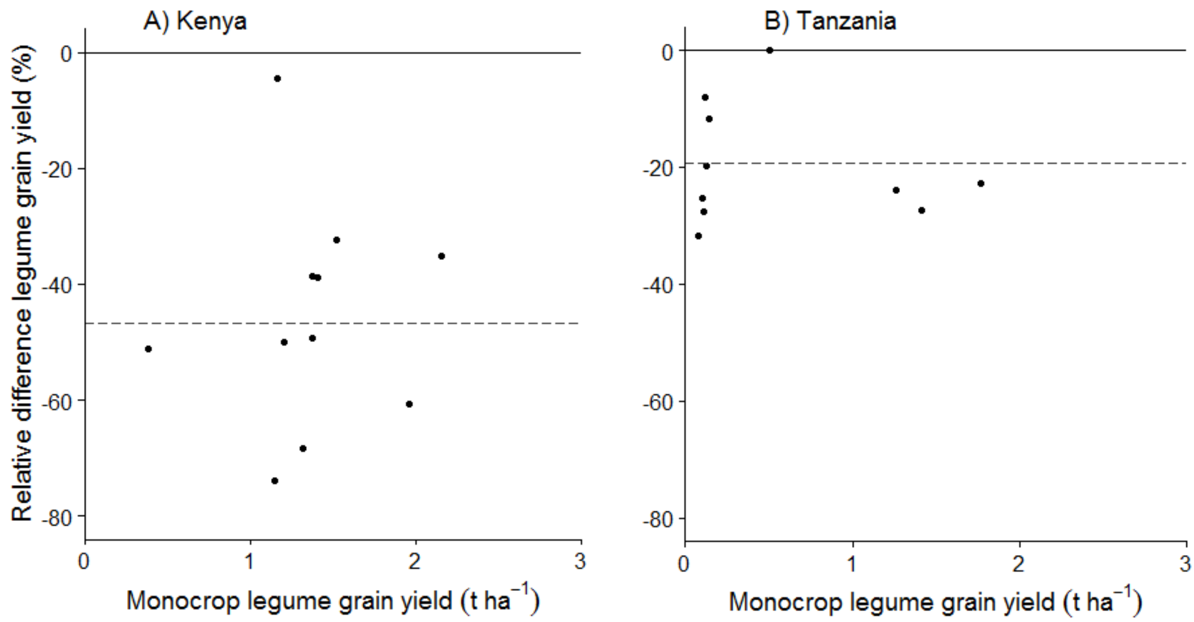

Figure 5. Relative difference of the legume grain yields of an intercrop compared to a monocrop for common bean maize intercropping systems in Kenya (A) and pigeon pea maize intercropping systems in Tanzania (B). A negative value indicates a higher legume grain yield for the monocrop. The dashed line represents the average relative difference of the legume grain yields.

3.1.3 Ratio maize and legume grain yield

In Tanzania pigeon pea intercrop yield significantly increased with an increasing maize intercrop yield. In Kenya maize common bean intercrop yield did not show a linear relation with maize intercrop yield. A regression line was still estimated as it was used for further analysis in this thesis. In both Kenya and Tanzania, fertilizer rates had no significant effect on the relation between intercrop legume and maize grain yield. The boundary lines (Fig. 6) show that for a certain maize grain yield level in an intercrop a minimum and maximum legume grain yield existed. The range of the minimum and maximum intercrop legume grain yields, i.e. the distance between the two boundaries, remained similar as intercrop maize grain yield increased for both Kenya and Tanzania. Overall, the productivity of the intercrops was higher than of the respective monocrops. The LERs were 1.46 and 1.57 for Kenya and Tanzania respectively (for maize n = 108 and n = 40, for legumes n = 11 and n = 10 for Kenya and Tanzania respectively).

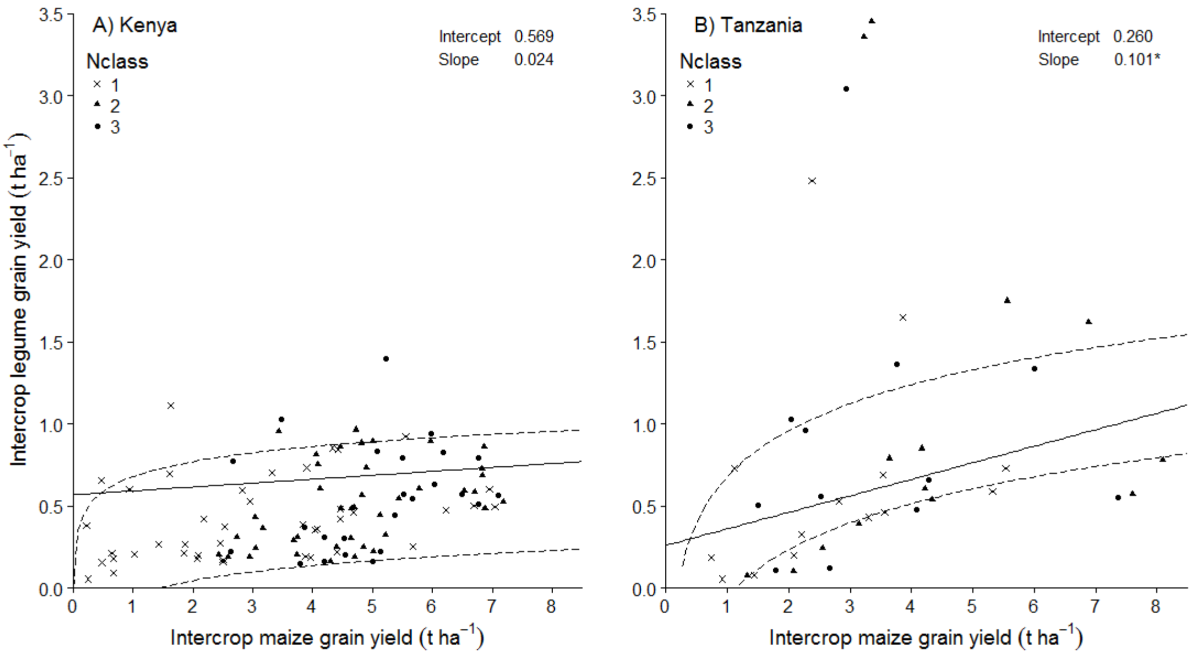

Figure 6. Intercrop legume grain yield against intercrop maize grain yield (in t ha^{-1}) for the maize legume intercropping system for Kenya (A) and Tanzania (B). Different symbols indicate different N fertilizer classes. The dashed lines indicate borders of minimum and maximum intercrop legume grain yield for a certain intercrop maize grain yield, estimated with stochastic frontier analysis. The solid line indicates a linear trendline. Intercept and slope of the trendline are given in the figure. A star behind the intercept and slope indicates a significant value at *$p < 0.05$*.

3.2 Financial return

3.2.1 Net revenue, benefit cost ratio and return to labour

In Kenya net revenue was higher for intercrops than for both monocrops (Fig. 7), comparing with the same fertilizer application rate. Also BCR (benefit cost ratio) and return to labour were higher for intercrops than monocrops, suggesting that intercropping is more favourable at all financial aspects. Taking fertilizer rates into account, the conclusion gets more complex. Net revenue was higher when more fertilizers were added. However, BCR was lower in case more fertilizers were added to the field. Return to labour was then again higher with increasing fertilizer application rates. Legume monocrops performed more or less equal to maize monocrops without fertilizer application.

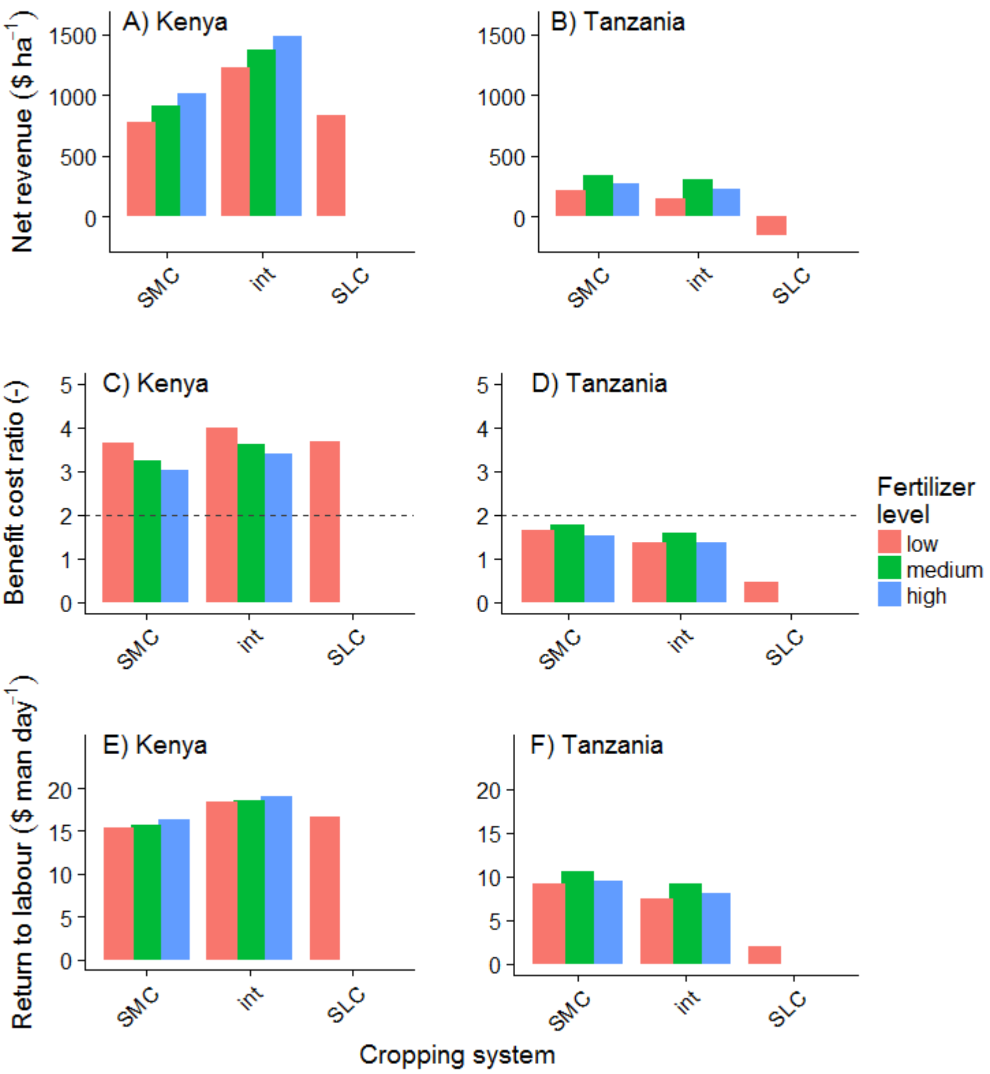

Figure 7. Net revenue ($ ha^{-1}) (A, B), benefit cost ratio (-) (C, D), and return to labour ($ man-day^{-1}) (E, F) for the monocrop maize (SMC), intercrop (int) and the monocrop legume (SLC) at three different fertilizer rates for Kenya (A, C, E) and Tanzania (B, D, F) calculated with yield estimates from the crop productivity meta-analysis.

In Tanzania intercrops were less profitable than maize monocrops, although differences were small (Fig. 7). BCR and return to labour were lower for intercrops than for monocrops as well, indicating that for all three economic parameters maize monocrops were more profitable than intercrops. The same conclusion can be drawn when maize monocrops are compared to legume monocrops. In terms of fertilizer use, the medium fertilizer level makes farming more profitable than the low fertilizer level. In contrast to Kenya, the highest fertilizer level is less profitable than the medium fertilizer level.

A comparison between maize monocrops and intercrops was also made with the individual yield data from papers used in the meta-analysis of crop productivity (Fig. 8). The results were comparable, but still important differences were found. In Kenya, average net revenue and return to labour were higher in intercrops than maize monocrops (ANOVA, $p < 0.001$ for both parameters). In Tanzania BCR and return to labour were higher in monocrops than maize intercrops (ANOVA, $p = 0.033$ and $p = 0.020$ for BCR and return to labour respectively). Return to labour in Kenya and net revenue in Tanzania were not significantly different between the cropping systems. Although on average intercrops seem to be more profitable in Kenya and less profitable in Tanzania, this did not apply to all farms. In Kenya, it was observed that at some locations an intercrop was less profitable than a maize monocrop. In Tanzania this was the other way around. Additionally, for both countries differences between the profitability of maize monocrops and intercrops were at some locations much smaller or larger than the average difference. Minimum and maximum values were at the individual locations also much larger than for the averages (Fig. 7 & 8).

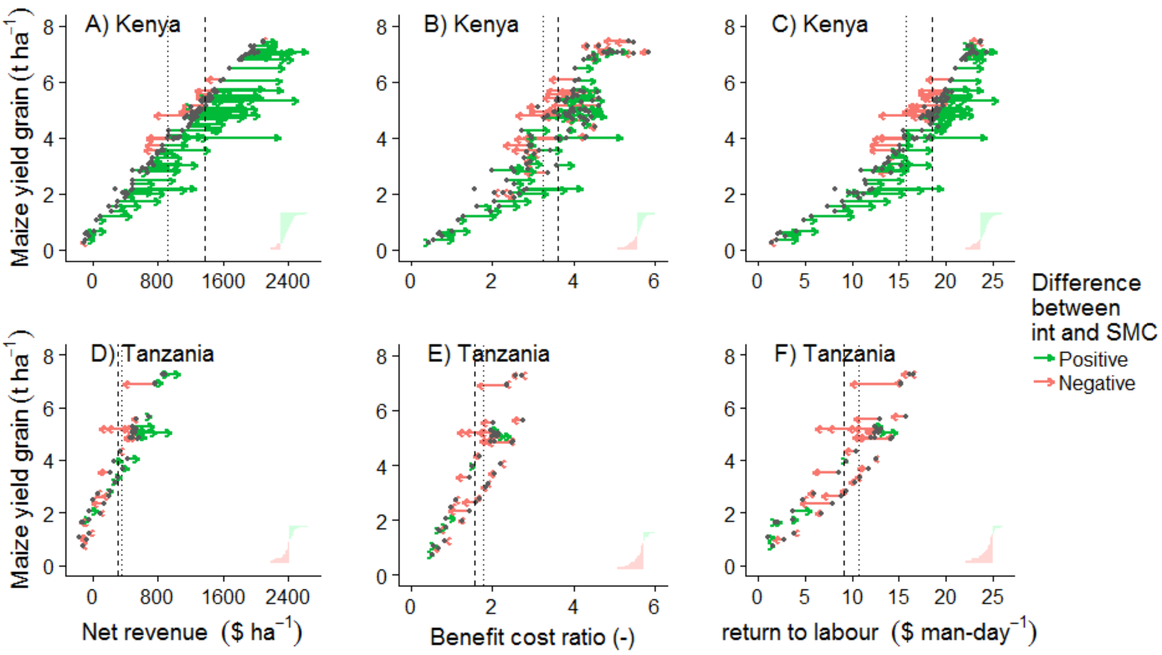

Figure 8. Net revenue ($ ha^{-1}) (A, D), benefit cost ratio (-) (B, E), and return to labour ($ man-day^{-1}) (C, F) for the intercrop compared to the maize monocrop against monocrop maize grain yield (in t ha^{-1}) for Kenya (A, B, C) and Tanzania (D, E, F) calculated with individual data of papers used in meta-analysis of crop productivity. Dots indicate values for maize monocropping system. The arrow shows the difference with the intercropping systems. A green arrow means the intercrop performed better than the monocrop. A red arrow means the intercrop performed worse than the monocrop. Dotted vertical lines indicate average calculated values for the monocrop with medium fertilizer rate. Dashed vertical lines indicate average calculated values for the intercrop with medium fertilizer rate. Small subplots present sorted negative and positive differences between the three economic indicators.

3.2.2 Sensitivity Analysis

The main goal of the sensitivity analysis was to analyse whether lower or higher input & output prices affected the order of profitability of the different fertilizer cropping systems combinations. Hence, whether for example at a low legume price a maize monocrop is most profitable and at a high legume price an intercrop is most profitable. Changing the input prices showed that for net revenue this is not clearly the case (Fig. 9). Only when the maize price is strongly reduced in Kenya the legume monocrop becomes slightly more profitable than the intercrop. In Tanzania a strong increase in the legume price, brought the net revenue of an intercrop equal to the net revenue of a maize monocrop, but it did not become higher. The sensitivity analysis on BCR and return to labour showed a similar pattern as for net revenue (Fig. 10 & 11). Only when maize prices were reduced or legume prices increased in Kenya, the legume monocropping systems clearly had a higher BCR and return to labour than the other cropping systems. Furthermore, in Kenya a strong increase in maize price or reduction in legume price resulted in a more or less equal BCR and return to labour for an intercrop and maize monocrop. In Tanzania however, a strong reduction in maize price or strong increase in legume price resulted of a similar BCR and return to labour for an intercrop and maize monocrop.

From the sensitivity analysis it was also observed that the profitability of farming is highly dependent on input and output prices. Especially maize price had a high influence in the financial return. In Kenya maximum net revenue varies between 750 and 2200 \$ ha^{-1} (Fig. 9). In Tanzania net revenue varies between losing money and gaining 750 \$ ha^{-1}. Large differences in BCR and return to labour as a result of changing prices were observed as well (Fig. 10 & 11). A change in maize price had the strongest affect, as well as a change in labour for the BCR.

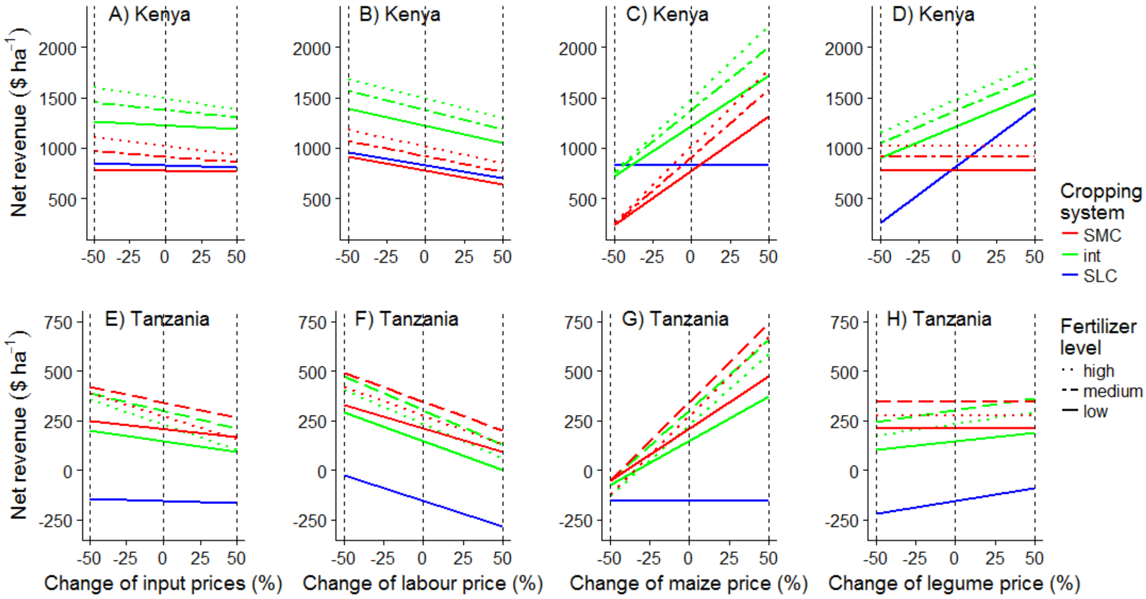

Figure 9. Net revenue (\$ ha^{-1}) against a relative change in input price for Kenya (A, B, C, D) and Tanzania (E, F, G, H). Input prices (A, E), labour price (B, F), maize price (C, G) and legume price (D, H) are changed. Different coloured lines indicate different cropping systems. Different striped lines indicate different fertilizer levels.

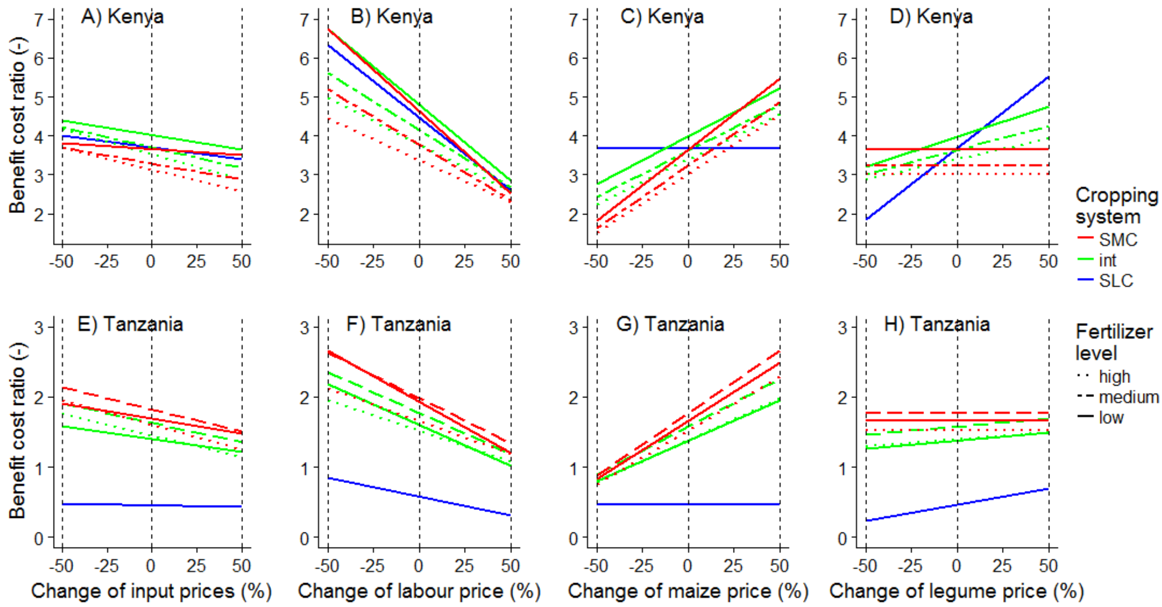

Figure 10. Benefit cost ratio (-) against a relative change in input price for Kenya (A, B, C, D) and Tanzania (E, F, G, H). Input prices (A, E), labour price (B, F), maize price (C, G) and legume price (D, H) are changed. Different coloured lines indicate different cropping systems. Different striped lines indicate different fertilizer levels.

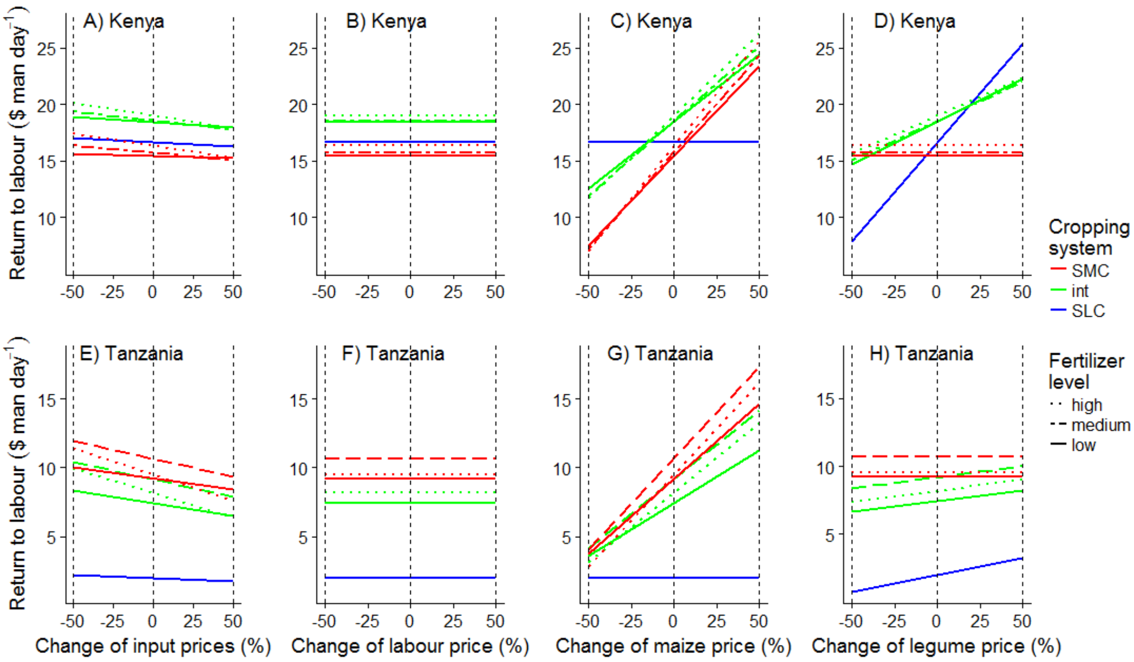

Figure 11. Return to labour ($ man day^{-1}) against a relative change in input price for Kenya (A, B, C, D) and Tanzania (E, F, G, H). Input prices (A, E), labour price (B, F), maize price (C, G) and legume price (D, H) are changed. Different coloured lines indicate different cropping systems. Different striped lines indicate different fertilizer levels.

3.3 N_2O emissions

Based on calculations according the IPCC principles, N_2O emissions were on a per hectare basis equal for Kenya and Tanzania for the maize monocrop and intercrop without residue application (Fig. 12). N_2O emissions were higher in the intercrop than in the monocrop in both Kenya and Tanzania, when legume residues in the intercrop were returned to the soil. For Kenya this increase was larger than for Tanzania. However, using the IPCC guidelines, additions of fertilizers to the fields remained the main contributors of greenhouse gas emissions. On a per hectare basis the monocrop legume crops emitted more N_2O emissions than the intercrop or maize monocrop in the case no fertilizers were applied to the soil.

The N balance showed that for maize monocrops and intercrops the N balance was negative in both Kenya and Tanzania. Also, both in Kenya and Tanzania the N balance was less negative for intercropping systems than for maize monocropping systems, if legume residues were returned to the field. If legume residues were not applied to the field the N balance was more negative in the intercrop than in the maize monocrop. Application of fertilizers resulted in a smaller deficit, except in Tanzania for the medium fertilizer level. Legume monocrops had a positive balance, but only added a low amount of N to the field.

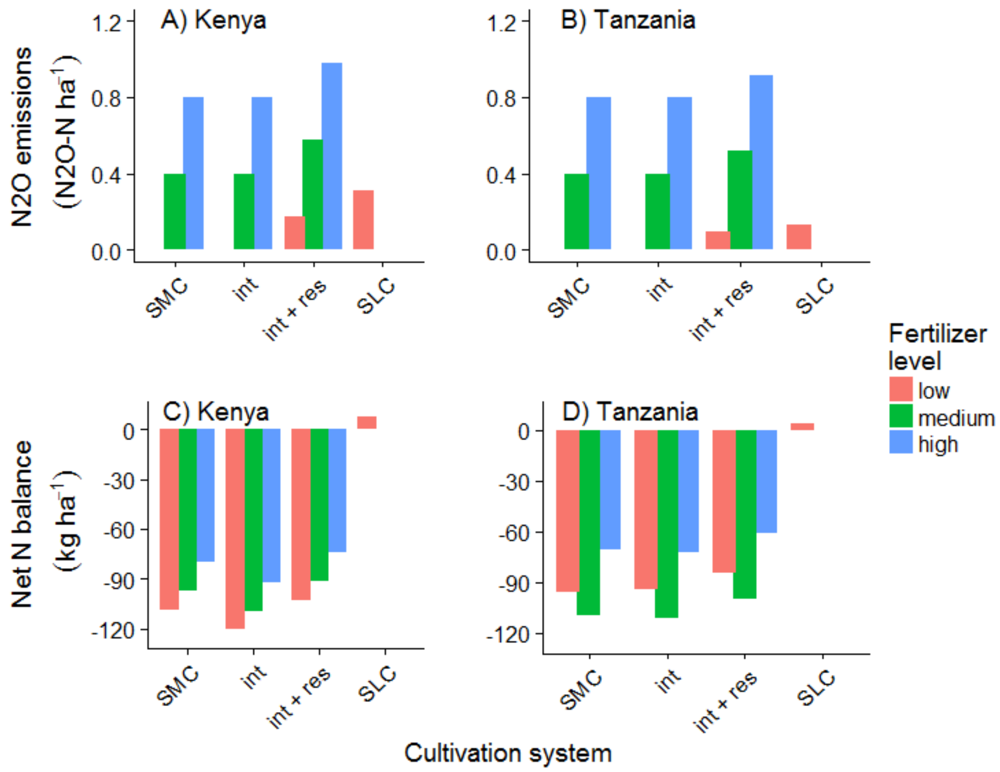

Figure 12. N_2O emissions (N_2O-N ha^{-1}) (A, B) and net N balance (kg ha^{-1}) (C, D) for the monocrop maize (SMC), intercrop without residues applied (int), intercrop with residues applied (int + res) and the monocrop legume (SLC) at three different fertilizer rates for Kenya (A, C) and Tanzania (B, D) calculated with average yield estimates from the crop productivity meta-analysis.

At the low and medium fertilizer application rates, yield scaled N_2O emissions were higher or equal in the intercrop compared to the maize monocrop, if residues were included in the intercrop (Fig. 13). However, at the highest fertilizer application rate the yield scaled N_2O emissions of the intercrop with residues emitted less N_2O than a maize monocrop. If no residues were returned to the field in an intercrop emissions were lower than in a maize monocrop for all fertilizer levels. Legume monocrops emitted most N_2O, when measured on a yield scaled basis and compared for the same fertilizer rate.

For both Kenya and Tanzania the yield scaled N balance was most negative in the maize monocrop and highest in the legume monocrop (Fig. 13). Intercropping resulted in a less negative N balance compared to a maize monocrop. This effect was stronger when residues were added to the field. Also on a yield scaled basis, N fertilizer application resulted in a smaller deficit.

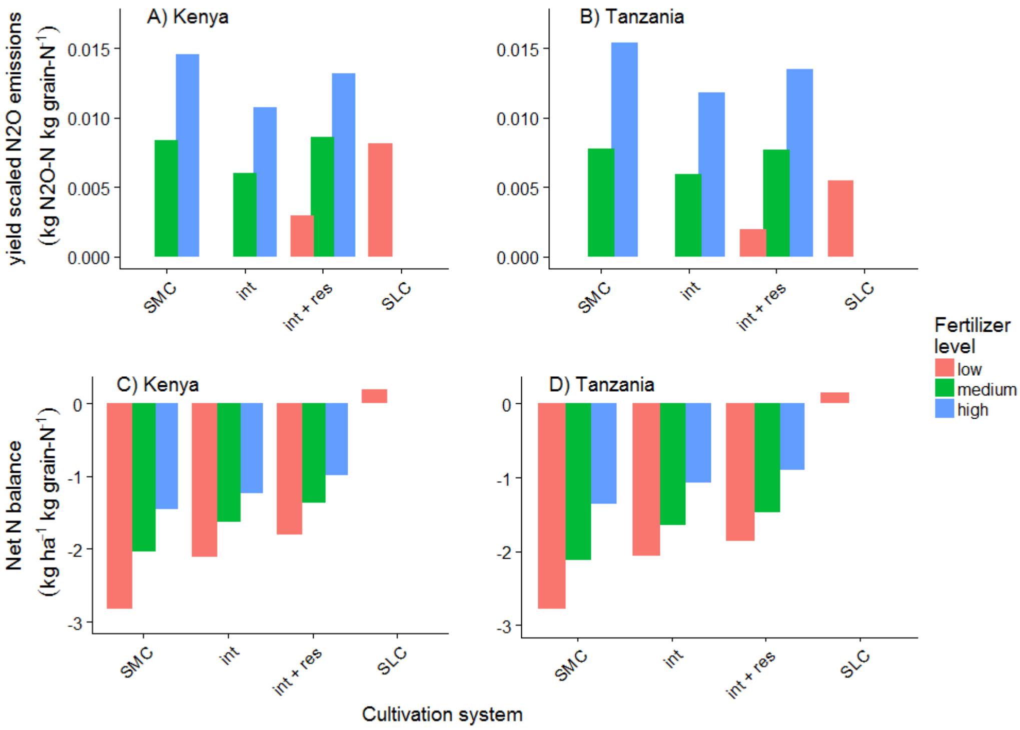

Figure 13. Yield scaled N_2O emissions (N_2O-N ha^{-1} kg grain-N^{-1}) (A, B) and yield scaled net N balance (kg ha^{-1} kg grain-N^{-1}) (C, D) for the monocrop maize (SMC), intercrop without residues applied (int), intercrop with residues applied (int + res) and the monocrop legume (SLC) at three different fertilizer rates for Kenya (A, C) and Tanzania (B, D) calculated with yield estimates from the crop productivity meta-analysis.

Similar as for the economic analysis, absolute N_2O emissions and differences in N_2O emissions between cropping systems were much more variable for the individual locations than described with the average estimated N_2O emissions. When analysed at location level with individual data points, intercrops in Kenya emitted at most locations more than maize monocrops when legume residues were added to the field (Fig. 14). The average yield scaled N_2O emissions were however not significantly different between the intercrop and maize monocrop. In Tanzania, in half of the locations emissions were higher in intercrops than maize monocrops. In the other half of the locations emissions were lower in intercrops. Also for Tanzania no significant differences were found between yield scaled N_2O emissions in intercrops compared to monocrops. The N balance was in almost all fields less negative in intercrops with residues applied than maize monocrops. This was significant and similar as was found in the analysis with the seven fertilizer cropping systems combinations (ANOVA, $p < 0.001$ for Kenya and $p < 0.001$ for Tanzania). The analysis of N_2O emissions and N balance with individual data was also done for intercropping systems without residue application (Appendix D).

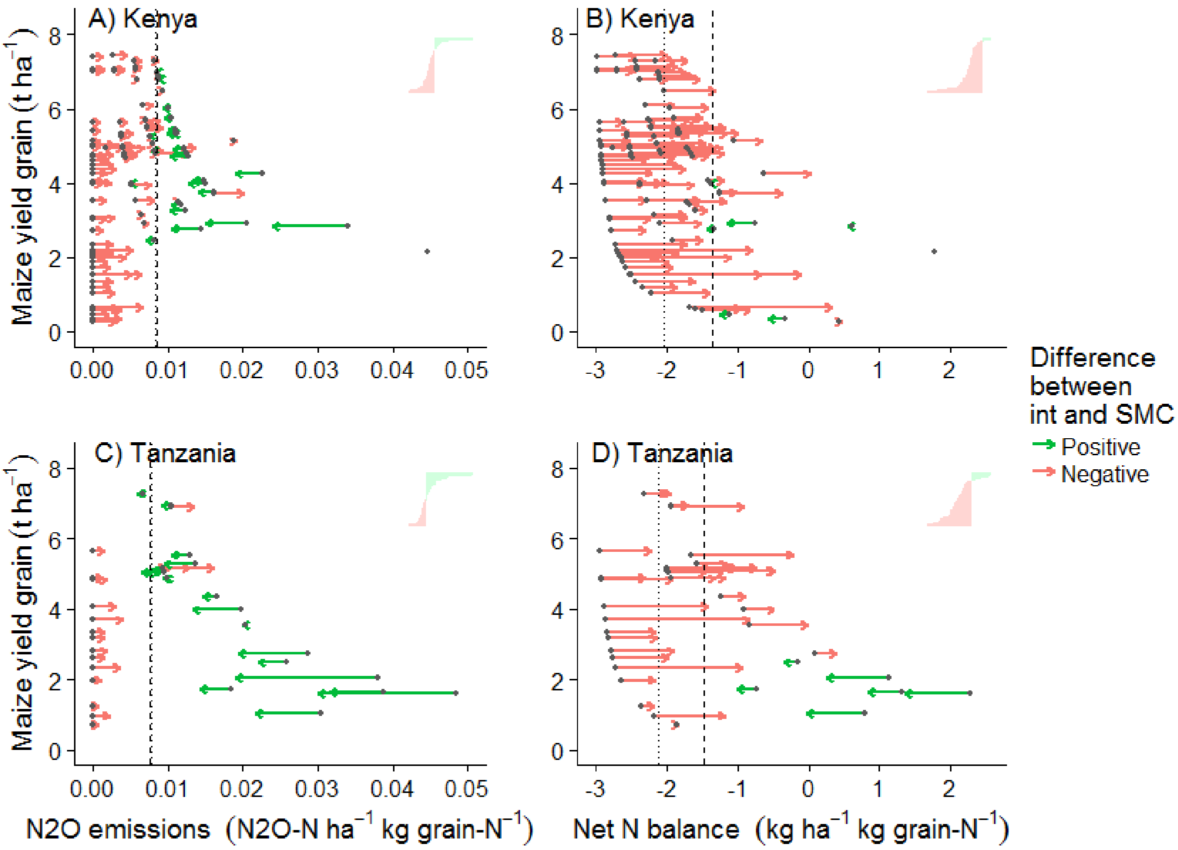

Figure 14. Yield scaled N_2O emissions (N_2O-N ha^{-1} kg grain-N^{-1}) (A, C) and yield scaled net N balance (kg ha^{-1} kg grain-N^{-1}) (B, D) for different cropping systems and fertilizer levels for Kenya (A, B) and Tanzania (C, D) compared to monocrop maize grain yield (in t ha^{-1}). Values are calculated with individual yield data from selected publications. Dots indicate values for maize monocropping system. The arrow shows the difference with the intercropping systems wit residue application. A green arrow means the intercrop performed better than the monocrop. A red arrow means the intercrop performed worse than the monocrop. Dotted lines indicate average calculated values for the monocrop with medium fertilizer rate. Dashed lines indicate average calculated values for the intercrop with medium fertilizer rate. Small subplots present sorted negative and positive differences between the three economic indicators.

3.4 Trade-off

Overall, in Kenya the intercropping system performed best on all values and in Tanzania the maize monocropping system performed best on all values (Fig. 15). In Kenya, a synergy occurred between crop productivity and financial return (Fig. 15). At all fertilizer levels the intercrop performed better than the monocrops. A trade-off occurred with yield scaled N_2O emissions. At low fertilizer rates the intercrop performed worse on N_2O emissions than the monocrop. A trade-off also occurred when low fertilizer input systems were compared to high fertilizer input systems. Crop productivity and financial return were increased, but also the N_2O emissions were increased.

In Tanzania a clear trade-off occurred with fertilizer application rate as well (Fig. 15). Yield increased after fertilizer application, but also N_2O emissions increased after fertilizer application. Between intercropping and monocropping systems also a trade-off occurred in Tanzania. Intercropping had a higher overall crop productivity, but performed worse on all three economic parameters.

Analysis of the individual locations showed similar conclusion as for the seven fertilizer cropping system combinations. In most fields in Tanzania and Kenya a trade-off occurred between net revenue and yield scaled N_2O emissions (Fig. 16). However, interestingly most often in maize monocrop fields with high yield scaled N_2O emissions, intercropping both reduced yield scaled N_2O emissions and increased net revenue. The trade-offs between crop productivity and yield scaled N_2O emissions and financial return were only partly assessed. With the information available, no trade-off nor synergy occurred in both Kenya and Tanzania between the cropping system and yield scaled N_2O emissions (Fig. 14), as on average yield scaled N_2O emissions were equal for intercrops and maize monocrops. For the financial return both synergies and trade-offs occurred. In Kenya there was a synergy between financial return and crop productivity, whereas in Tanzania there was a trade-off (Fig. 8).

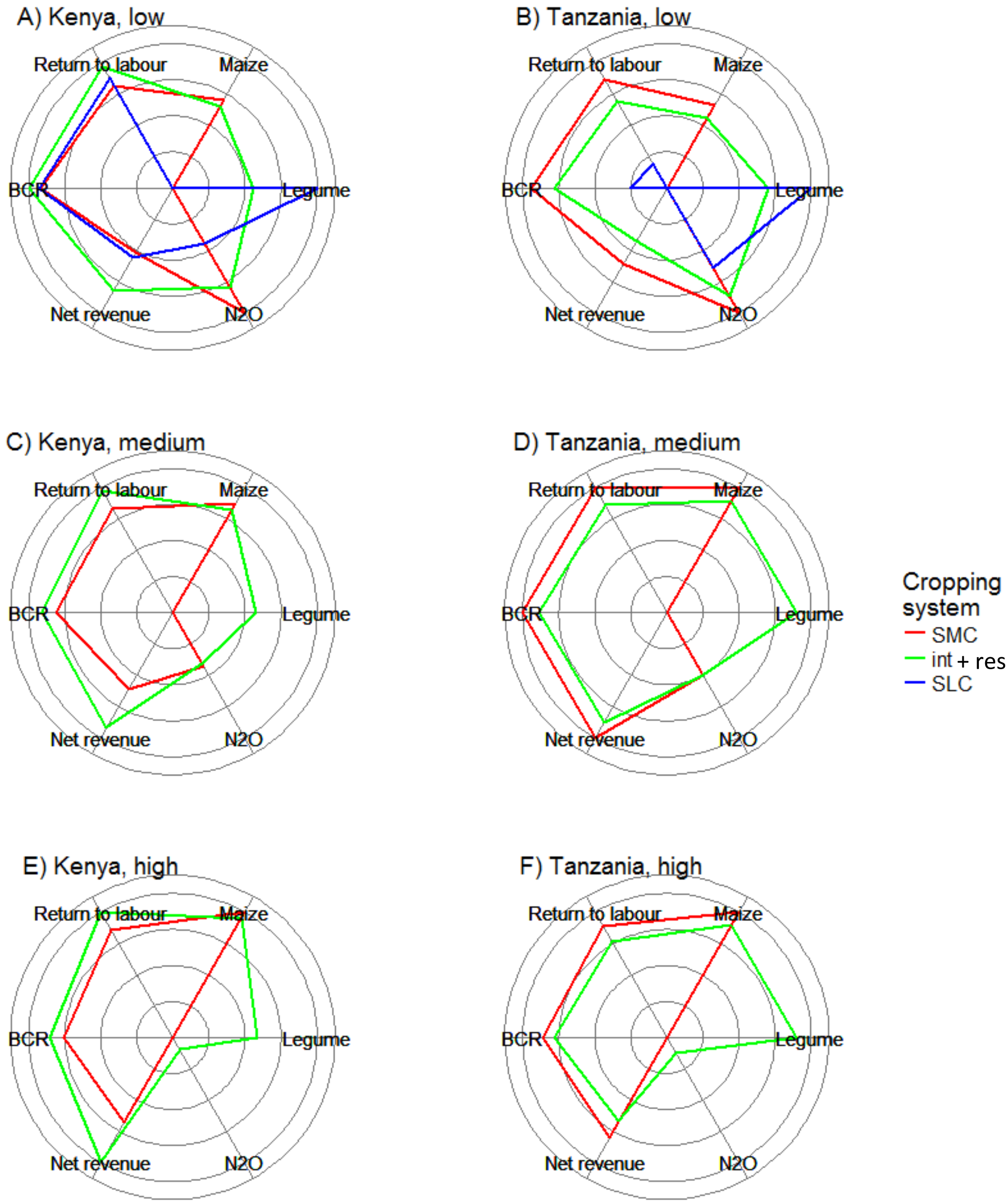

Figure 15. Spider plots combining the different trade-of parameters. Values are scaled values. Maize is the maize grain yield, legume is the legume grain yield, N_2O is the reversely scaled yield scaled N_2O emissions, net revenue is the net revenue, BCR is the benefit to cost ratio and return to labour is the return to labour. Data is shown for Kenya (A, C, E) and Tanzania (B, D, F), for low fertilizer rates (A, B), medium fertilizer rates (C ,D) and high fertilizer rates (E, F) for maize monocrops (SMC), intercrops with residue application (int + res) and legume monocrops (SLC). Plots on medium and high fertilizer levels did not include SLC as only legume monocrop without fertilizer application were considered in this thesis.

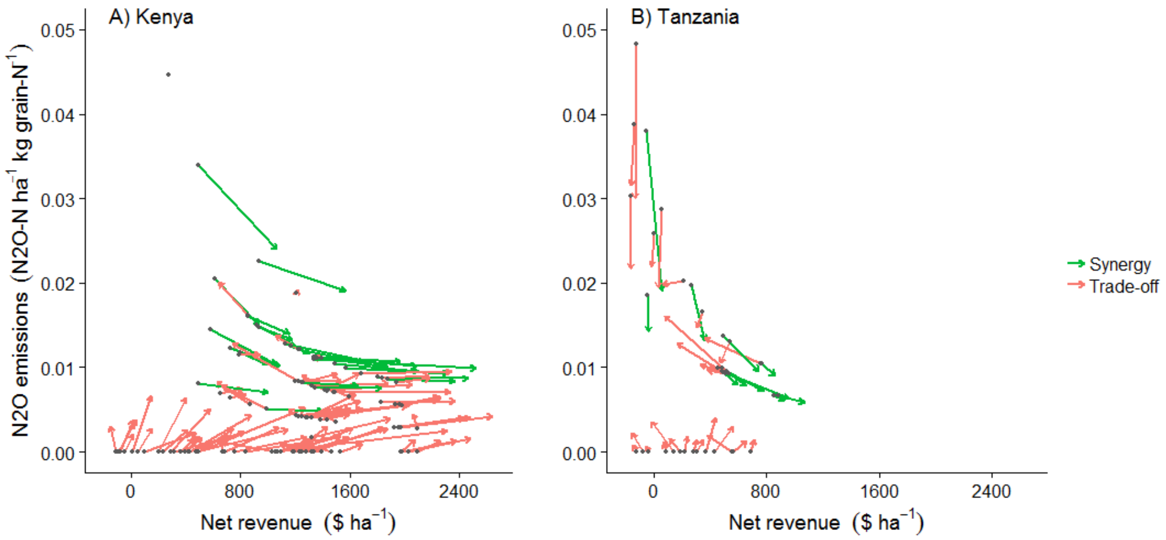

Figure 16. Yield scaled N_2O emissions (N_2O-N ha^{-1} kg grain-N^{-1}) against net revenue (\$ ha^{-1}). Dots indicate values for maize monocropping system. The arrow head shows values for intercropping systems with residue application. Green arrows indicate a synergy and red arrows indicate a trade-off between yield scaled N_2O emissions and net revenue.

4 Discussion

In this chapter the implications of the results and methodologies used to come to these results are discussed. First, it is discussed how integrating legumes in maize cropping systems can improve crop productivity. Following, it is evaluated which implications integrating legumes in maize cropping systems has for the economic return to a farmer. Thereafter, it is discussed how integrating legumes in maize cropping systems can affect the N_2O emissions in smallholders' fields. Lastly, the findings on the trade-offs that occur between the three parameters and the relevance of these findings in space and time are discussed.

4.1 Crop productivity

4.1.1 Causes of variable crop productivity

From the results, the hypothesis can be confirmed that, on average, intercropping maize with common bean or pigeon pea increases overall crop productivity. The LER of around 1.5 for both Kenya and Tanzania (section 1.1.3) indicates that on the same area an intercrop is 1.5 times more productive than their respective monocrops. However, further analysis of collected data has also revealed that productivity can be very variable amongst cropping systems, cropping seasons and studies (Fig. 3 & Table 8). There are different aspects that played a role in the causes of crop productivity variability and the implications of the variability.

First of all, yield variability is caused by differences in soil fertility levels both within fields and between fields (Vanlauwe *et al.*, 2006 & Ebanyat *et al.*, 2009). Different spatial temporal patterns in crop yield are observed as a result of differences in soil fertility in sub-Saharan Africa (Zingore *et al.*, 2007; Ojiem *et al.*, 2014 & Njoroge *et al.*, 2017). Potential causes of differences in soil fertility levels are different soil physical characteristics and different current and historical management practices (Zingore *et al.*, 2007). Soil organic matter is for example one of the soil physical characteristics which can strongly affect yield and yield responses to fertilizer applications (Tittonell & Giller, 2013 & Kurwakumire *et al.*, 2015). Management choices can for example be influenced by the distance of a field relative to the homestead, where infields are found to be more fertile than outfields (Zingore *et al.*, 2007 & Ojiem *et al.*, 2014). Different initial soil fertility levels can lead to different yields (Ojiem *et al.*, 2014), to different responses to fertilizer applications (Njoroge *et al.*, 2017) and to different effects of integrating legumes in maize cropping systems (Zingore *et al.*, 2007). In most studies used in this research, nothing or little was known about initial soil fertility conditions, hence the effect of soil fertility on crop productivity has not been analysed in this thesis. However, it is not more than likely that differences in soil fertility levels were a major cause of variability in both maize and legume grain yield in Kenya and Tanzania and could therefore have blurred correlations between yield and explanatory variables.

Different soil fertility levels are also likely to have affected the productivity of an intercrop relative to its' monocrops. It has been shown by others that the LER of maize legume intercropping systems decreases with N application (Ofori & Stern, 1986 & Kermah *et al.*, 2017). This could not be confirmed in this study as an analysis on LER for each individual study was not possible. Neither the analysis of the effects of N application levels on maize grain yields confirmed a relative change in yield between intercrops and monocrops as a result of different N application rates (Table 8). However, this research showed that P can play a role in the maize grain yield differences (Fig. 3 A). Additionally, it was shown that in Kenya intercrop maize yield was significantly lower at higher maize monocrop yield levels (Fig. 3 A and Appendix B). Higher maize monocrop yield levels are likely to be related with better soil fertility conditions (Jensen *et al.*, 2003). This means that the partial LER for maize decreased with better soil fertility conditions. Simultaneously common bean yield was only slightly, although not significantly, increased at higher intercrop maize grain yield levels (Fig. 6), which results in a similar or slightly higher partial LER for common bean. Overall, this would suggest that the LER is lower at a higher monocrop maize grain yield. Therefore it is likely that in this research the LER decreased with increasing N status as well, but more site specific data on LER of intercropping is needed to confirm this. For Tanzania a similar pattern seemed to occur. Statistically this was not verified (Fig. 3 B).

Another major cause of variable crop yields are differences in water availability (Sileshi *et al.*, 2010). In this study, water availability is relevant at three spatial and temporal scales. First of all, water availability was different between study sites. Long term average precipitation in Kenya ranged for instance in one publication from 520 mm in one experimental site to 900 mm in another experimental site (Mochoge, 1993). Precipitation varies between cropping seasons as well. In Tanzania this is mainly important from year to year. In Kenya precipitation is not only variable between years, but also between short rains and long rains seasons (Mucheru-Muna *et al.*, 2011). The effect of variability in precipitation on yield has not been analysed in this study. Not only a limited amount of data was available to do so, also precipitation data that was available had been measured in different ways across studies. Therefore, too few data was available to do an analysis on precipitation from which reliable conclusions can be drawn. However, also for water availability it is not more than likely that it was a major cause of yield variability in this study.

As with soil fertility, precipitation and therefore soil moisture content does not only have an effect on absolute yields, they could also affect relative yields of maize and legume grains in an intercrop

(Natarajan & Willey, 1986). In Mozambique pigeon pea yield was for example relatively higher compared to maize in a drier season than in a wetter seasons (Rusinamhodzi, 2013). This effect of water availability on intercrop yield ratio is something that was not taken into account in this study. However, variability in the ratio of intercrop maize and legume yield was clearly present in this study (Fig. 6). It can be highly relevant for the farmer to increase the knowledge on maize legume yield differences in intercrops, as it can be part of a strategy to cope with drought stress (Brouwer *et al.*, 1993 & Shiferaw *et al.*, 2014).

4.1.2 The role of legumes in the productivity of an intercrop

Before this study was done, it was expected that legume intercropping with a maize crop would improve maize yield the following year relative to continuous maize cultivation, which was found to be the case for legume maize rotations (Rao & Mathuva, 2000 & Cheruiyot *et al.*, 2001). However, a higher maize grain yield in a following season compared to the maize grain yield of the first season was not found (Table 8). Different explanations can be given why this might have been the case. First of all, in an intercrop legume biomass is lower as a result of competition for resources with the maize and lower planting densities in the case of common bean in Kenya. Therefore, also the benefits of biological nitrogen fixation are lower, compared to including legumes in a crop rotation (Franke *et al.*, 2017). Secondly, in an intercrop non-rotational benefits of integrating legumes, e.g. pest suppression, such as occur in monocrops, are less (Franke *et al.*, 2017). On the other hand, seasonal variability of yields or retardation of the benefits might have obscured seasonal differences. Variability of yields could have been higher than the difference between seasons. Also, the benefits of integrating legumes in a maize cropping system might come after multiple seasons (Kihara *et al.*, 2011 & Paul *et al.*, 2013). In both cases there could still have been an effect, but this effect could simply not be detected based on the data included in this study.

Also relevant for the role of legumes in an intercrop is the performance of legumes in the intercrop. P is one of the nutrients which is important for a good performance of the legume. P is important to support good growth of and nitrogen fixation by the grain legume (Kennedy & Cocking, 1997). Furthermore, a residual effects of P in legume crops can improve maize grain yield in a next season (Kihara *et al.*, 2009). In this study P did not have an effect on legume yield (Fig. 5). However, P application did affect maize yield in Kenya (Table 8). Additionally, relative intercrop maize yield compared to the maize monocrop was higher when P was added (Fig. 3). It cannot be excluded this is due to a better performance of the legume, but it might form part of the explanation.

A trade-off analysis was performed on maize legume intercropping systems as legumes contribute nitrogen to the maize in intercropping systems, mainly in the following season. Nevertheless, in terms of nitrogen fixation, grain legumes might not be the best suitable option for intercropping in maize cropping systems, as not all legumes fix nitrogen and contribute to soil fertility (Vanlauwe & Giller, 2006). Grain legumes are rather bred to produce high grain yields than to have high N fixation capacities or large biomass production. Especially common bean can be a poor N fixing legume (Giller, 1990). In terms of N addition to the field it might be relevant to consider adding different legumes to the field (Franke *et al.*, 2008). Still, this research has shown that the grain legumes have potential to reduce the negative N balance found in the fields (Fig. 12), assuming a default N fixation value, especially when analysed at a yield-scaled basis (Fig. 13).

A full evaluation of the role of legumes in intercropping systems should be done on the long-term. In this study the effect of maize legume intercropping on the long term could not be evaluated as only short-term (< 5 seasons) or average data was available (Table 3 & 4). However, from the N balance it could be hypothesized that the integration of legumes is even more beneficial on the long term. The N balance was less negative for intercropping systems with residues than for maize monocropping systems (Fig. 12), which is in line with other studies (Giller *et al.*, 1997 & Ojiem *et al.*, 2007). On a yield scaled basis the relative lower deficit of intercrops compared to maize monocrops was even larger. This lower N deficit implies that production levels will be better maintained and that thus over multiple years LER would be even higher than is estimated now. More data would be needed to confirm this hypothesis.

4.1.3 Implications of data quantity and quality for the analysis on crop productivity

The limited amount of available data is in general something to take into account in the interpretation of the results in this study. For example no difference was found between intercrop and monocrop maize grain yield in Tanzania (Fig. 2). However, when N application class was considered in the model as well, a difference was found between monocrop and intercrop maize grain yield (Table 8). Also, this study showed that in Tanzania maize grain yield was reduced when applying more than 60 kg of N (Table 8). This is unexpected as a yield limiting effect of N application is only expected to occur after application rates that 200 kg of N (Chen *et al.*, 2015). Therefore it is more likely that an increase in maize grain yield after applying more than 60 kg of N is absent because a small dataset is used. Lastly, in appendix C, a clear example is given how the data availability might have changed the outcome of these results. Adding data from maize pigeon pea intercropping systems in Kenya resulted in a significantly different pigeon pea grain yield between monocrops and intercrops, whereas excluding data from Kenya did not show a significant difference (Fig. 4).

Although care has to be taken with drawing conclusions on the results with small sized datasets, the research is still valuable as from the current analysis (such as in appendix C) it appears that it is mostly the absolute numbers that change when more data is added, not per se the relative numbers. In the case of pigeon pea, yield levels were different with the inclusion of additional data. However, pigeon pea yield was still higher for monocrops than for intercrops (Fig. 4 & Appendix C). This result was not changed by adding data.

Apart from the data availability of yield data, the available yield data should be handled with care as the yield levels do not necessarily reflect the yield levels found in farmers' fields. Maize grain yield in Kenya and Tanzania in this study were on average estimated around 3.5 t ha^{-1} Fig. 2. This number is coherent with the average yield in some parts of Kenya, such as Kitale (Global Yield Gap Atlas, 2018). However, in Kisumu and Tanzania maize grain yields are only 1.4 and 1 t ha^{-1} respectively (Global Yield Gap Atlas, 2018), which is much lower than the average estimated maize grain yield. One reason is the better management practices in research fields (Rao & Mathuva, 2000). Another reason could be the low fertilizer application rates in these regions, with average levels of 13 kg ha^{-1} (Minot & Benson, 2009). However, also in this study average maize grain yield of fields without fertilizer inputs was still above 3 t ha^{-1}. Yields of pigeon pea in this study were close to the actual yield in Tanzania (Global Yield Gap Atlas, 2018). For common bean yield levels of this study could not be compared with yield levels in the global yield gap atlas as there is no data available on common bean cultivation in Kenya.

4.2 Financial return

This study has shown that it is not as straightforward as hypothesized that a higher yield will always lead to a better economic return. In Kenya, intercropping resulted in a higher net revenue, BCR and return to labour (Fig. 7). In Tanzania, net revenue, BCR and return to labour were lower for intercropping than for monocropping systems, while for both regions crop productivity increased with intercropping.

4.2.1 Effect of price variability

The main reason for differences in profitability is the differences in prices that farmers receive for their produce, which can be due to price fluctuations over years and seasons and across locations (Alene *et al.*, 2008). First of all this is reflected in the difference in profitability of farming between Kenyan and Tanzanian farmers (Fig. 7 & 8). The maize price was almost three times as high in Kenya as in Tanzania (Table 6). Common bean price was even 5 times higher than the pigeon pea price. Summing up, this resulted in a higher profitability in Kenya.

Current prices did not only explain different average net revenues between Kenya and Tanzania. Price differences also provide an explanation why intercropping compared to maize monocrops is less profitable in Tanzania than in Kenya. In Tanzania a farmer gets the same price for a kg of pigeon pea as for a kg of maize. The loss in revenue from maize yield and the increase in labour costs in the intercrop could not be compensated by the additional gain in pigeon pea yield. In Kenya, common beans were worth three times more than maize. This is enough to compensate the loss in revenue from maize and the increase in labour costs when maize is intercropped.

The effect of price differences and changes on profitability was also reflected in the sensitivity analysis (Fig. 9-11). The difference in net revenue between the lowest and highest price was for example 1500 \$ ha^{-1} in Kenya and 750 \$ ha^{-1} in Tanzania. The price fluctuations can be very important to take into account, when assessing the suitability of cropping systems. In Tanzania, BCR was higher than the threshold level of 2 (Ronner *et al.*, 2016), when maize prize was increased. Meaning that farmers would be more willing to invest. In Kenya, investing gets less attractive with a strong reduction of the maize price as the BCR drops below 2.

4.2.2 Effect spatial variability on financial return

Not only does profitability of farming depend on the input and output prices. This research has shown that it can be very location specific, mainly as result of different yield responses (Fig. 8). In Kenya the net revenue was as low as -200 \$ ha^{-1} and as high as 2500 \$ ha^{-1}. Profitability can also be very crop specific. Mucheru-Muna *et al.* (2010) showed that profitability was much higher in maize groundnut intercropping systems than in maize common bean intercropping systems. Information provided by the country agronomist from Tanzania supports this applies for Tanzania as well, as pigeon pea was the least valuable legume crop.

The strong temporal and spatial effects on financial return found in this thesis support that strong markets are essential to ensure a good income for farmers and support farmers to invest in intercropping systems (Poulton *et al.*, 2006 & Frelat *et al.*, 2016). This is needed to maintain productivity and income in the long-term as earlier results in this thesis showed that it is likely yields will decline as a result of negative N balances.

4.3 N_2O emissions

Using the simple assumptions from the IPCC guidelines to calculate N_2O emissions, this study has shown that a trade-off potentially occurs between crop productivity and N_2O emissions. If legume crop residues were added to the field and relatively low levels of N fertilizers were applied, yield scaled N_2O emissions were higher in intercrops than in monocrops (Fig. 13). Higher N application levels on the other hand resulted in a mitigation of N_2O emissions when the intercrops were compared to the maize monocrops (Fig. 13). However, many uncertainties arise when calculating N_2O emissions.

4.3.1 Uncertainties around calculating N_2O emissions

N_2O emissions in agriculture are very complex and variable (Jensen *et al.*, 2011). N_2O emissions vary with different N application rates, crop types, fertilizer types, soil moisture contents, soil textures, soil pH and soil organic matter contents (Stehfest & Bouwman, 2006; Adviento-Borbe *et al.*, 2007; Pimentel *et al.*, 2015; Albanito *et al.*, 2017). Most of these variabilities could not be taken into account in this thesis for the calculations on N_2O emissions. This thesis showed however that management strategies have a big influence on the variability of N_2O emissions. Yield scaled N_2O emissions at the individual locations were calculated to range from 0 to 0.05 kg N_2O-N grain-N^{-1}, which is much larger than the limit of 0.015 kg N_2O-N kg grain-N^{-1} calculated with average yield estimates (Fig. 13 & 14). Lower yield scaled N_2O emissions were mainly attributed to high yields, showing that in order to reduce N_2O emissions ecological intensification is very important. Meaning it is thus important to aim at the highest possible output with minimum inputs.

N_2O emission rates calculated with the IPCC guidelines depend mainly on the value of the emission factor that is used in the calculations. IPCC provides an emission factor of 1 % for applied N in any form. This means that of every 100 kg of N that is applied, 1 kg of N will be emitted in the form of N_2O. However, there is not yet consensus whether this is the right value to use in calculations. Hickman *et al.* (2017) suggests emission factors should be much lower for Africa, which is based on an emission factor of 0.07 % - 0.11 % that has been found earlier (Hickman *et al.*, 2015). Changing the emission factor for East-Africa can be supported when emission rates of East-African countries (Millar *et al.*, 2004; Baggs *et al.*, 2006; Hickman *et al.*, 2014; Kimaro *et al.*, 2015 & Rosenstock *et al.*, 2016) are compared with emission from other regions where higher rates of N are applied (e.g. Cui *et al.* (2013), Huang *et al.* (2014) & Shen *et al.* (2018)). Relative to the amount of N applied, N_2O emissions appear to be much higher in these other regions than in East-Africa. Contradictory to Hickman *et al.* (2015), Albanito *et al.* (2017) suggests in a meta-analysis on N_2O emissions in tropical agriculture an emission factor of 1.4 % for Kenya. This suggests that the emission factor should be even higher for Kenya than the standard value of the IPCC. However, mean N application rates were around 200 kg N ha^{-1} in Albanito *et al.* (2017). This was much higher than analysed application levels in this thesis or levels used by Hickman *et al.* (2015). A threshold of increasing N_2O emissions is around 200 kg N ha^{-1}, above which emissions will double (Van Groenigen *et al.*, 2010). Using an emission factor of 1.4 % would thus likely be an overestimation of N_2O emissions in the fields used in this study, where lower amounts of N fertilizers were applied. Adding to the uncertainty of using one emission factor in this study is that N_2O emissions are found to be higher (Stehfest & Bouwman,

2006) and lower (Tang *et al.*, 2017) in legumes than in cereals. Hence, a distinction in emissions factors should maybe be added for the different crops as well.

Because of the uncertainty of estimating N_2O emissions based on N inputs and because N_2O emissions are more related to the N surplus (Van Groenigen *et al.*, 2010), it has been suggested to calculate N_2O emissions based on N surplus rather than based on N Inputs. From the analyses on N surplus in this thesis, it might be expected that no N is emitted at all, as the partial N balance is already negative without taking into account all losses pathways (Fig. 12 & 13). This is not realistic as background emissions occur (Van Groenigen *et al.*, 2010). However, N_2O emissions are found to be rather low in East-Africa (Millar *et al.*, 2004; Baggs *et al.*, 2006; Jonathan E. Hickman *et al.*, 2014; Anthony A. Kimaro *et al.*, 2015 & Rosenstock *et al.*, 2016), which is in line with the negative N balance found.

Uncertain is also how emissions in intercrops are related to monocrops. There is evidence that on a hectare basis an intercrop emits less N_2O emissions than a maize monocrop (Tang et al., 2017), which might be a result of increased nutrient use efficiency in a legume maize intercrop compared to a maize monocrop (Droppelmann *et al.*, 2017). However, the effect of interactions between crops is not taken into account or described in the IPCC guidelines. For sure, the comparison of N based yield scaled N_2O emissions in intercrops is biased as different crops have different N conversion efficiencies (Crutzen *et al.*, 2016). The total N in maize is much higher than the N in legumes. Therefore, when emissions are yield scaled based on N yield, emissions will automatically be lower for a maize crop than for a legume crop.

4.3.2 The role of legumes on N_2O emissions

In this thesis it was found that incorporating legume residues is the main reason why intercrops emit more N_2O than monocrops (Fig. 12 & 13). Application of legume residues might indeed increase N_2O emissions as is supported by Chikowo *et al.* (2004), Millar *et al.* (2004); Rochette & Janzen (2005) & Jensen *et al.* (2011). However, this especially applies to green manure legumes. The residues of grain legumes that remain after cultivation is not expected to be a major source of N_2O emissions (Jensen *et al.*, 2011). It is rather the C/N ratio which is important in terms of N_2O emissions (Millar *et al.*, 2004; Frimpong *et al.*, 2011 & Pimentel *et al.*, 2015). Emissions of intercrops where grain legume biomass is returned to the field might thus be lower than is estimated in this research, especially if maize residues – with a high C/N ratio – are added to the field as well.

As legumes increased crop productivity in the intercrop (section 3.1.3), less land is needed to produce the same output. Emissions as a result of deforestation (Bellarby *et al.*, 2014) and of additional crop cultivation are thus prevented with intercropping. This was not accounted for in this study. Increase of organic matter as a result of residue application might also decrease net greenhouse gas emissions in intercropping systems (Anyanzwa *et al.*, 2008). However, no significant evidence was found that cropping systems with legumes will increase the soil organic matter content (Franke *et al.*, 2017). This might be due to the limited duration of studies that were included in the meta-analysis. Also the analysis by Franke *et al.* (2017) was done on legume cereal rotations rather than legume cereal intercrops.

4.4 Trade-off

As far as is known, this is the first study on a trade-off analysis in maize legume intercropping systems in East-Africa combining crop productivity, financial return and N_2O emissions as indicators. This study has shown that it can depend on the context whether synergies or trade-offs occur (Fig. 15). There is considerable variability in synergies and trade-offs between countries, locations and management strategies (Fig. 15 & 16). This variability made it challenging to draw concise conclusions on the trade-offs and synergies that occur. However, as this study provides a first identification and quantification of the trade-offs, it is highly relevant to gain insights in the trade-offs and assess major knowledge gaps.

On the goals on national and global level, intercropping showed great potential as intercropping could reduce the N_2O emissions per kg of yield produced (Fig. 13). However, this depended on the application of residues and fertilizers to the field. Simultaneously, uncertainties around N_2O emissions are still large as N_2O emissions is a process affected by many factors. To be able to draw more accurate conclusions on N_2O emissions in intercrops, in situ research is needed where intercrops are compared to monocrops, as this information is not available in the literature yet.

Decreasing N_2O emissions via intercropping would only be possible if the financial return for a farmer is higher in intercrops than in monocrops. This research has been important as it confirmed that financial return can be improved through intercropping (Fig. 7). But even more importantly, this research has shown that intercropping does not improve financial return in all areas (Fig. 8). The main factor affecting financial return was the price of the produce. This research supports that creating good markets is highly relevant for farmers to invest in their fields and thereby also maintain productivity. Also this research showed that promotion of fertilizer use is thereby relevant to simultaneously address a reduction in yield scaled N_2O emissions and an even higher increase in crop productivity (Fig. 7).

It is also important to realise that in this interdisciplinary research other parameters were not taken into account. For intercropping for example, more labour and inputs were needed than in a monocrop (Table 6) (Rusinamhodzi, 2013). For Kenyan farmers this resulted in a higher financial return (Fig. 7). It is however known that labour and capital availability might be a constraint for farmers to invest in their fields (Frelat *et al.*, 2016). Therefore it is highly relevant to take the local and social contexts into account when interpreting the results. Adoption rates of intercropping were 66 % in Tanzania and 72 % in Kenya (Shiferaw *et al.*, 2014). Hence, for these countries it is an indication intercropping is considered by farmers as a profitable options. Nevertheless, for extrapolating this research to other areas or countries, not only the three assessed trade-off parameters should be taken into account, also the local context will be highly relevant to taken into consideration.

Uncertainties on the trade-offs remain for the future. By 2050, cereal demand in Kenya will rise more than the country will be able to produce itself (van Ittersum *et al.*, 2016). This is the case when yield levels reach 80 % of the water limited yield. In order to close the yield gap nitrogen inputs should be increased (Lobell *et al.*, 2009). Fertilizer rates assessed in this study were rather low (0 – 120 kg N, Table 3 & 4). As increasing nitrogen input levels is unavoidable to increase productivity levels that meet the food demand in Africa, it will be relevant for future research to assess the trade-offs between crop productivity, financial return and N_2O emissions at higher input levels as well.

5 Conclusion

The trade-off analysis that was performed in this study showed that both trade-offs and synergies occur between crop productivity, financial return to farmers and N_2O emissions. However, it depended on the regional context how the trade-offs and synergies looked like. In both Kenya and Tanzania maize yield was respectively only 3.3 and 7.3 % lower in an intercrop compared to a maize monocrop. Common bean and pigeon pea yield were respectively 43 and 20 % less in an intercrop compared to the legume monocrops. Overall crop productivity was thus increased in the intercrops in both Kenya and Tanzania with an LER of 1.46 and 1.47. Additionally, this research showed that crop productivity was increased with fertilizer application and that crop productivity of and intercrop was even higher compared to a maize monocrop when P was applied. In Kenya a higher crop productivity led to a better financial return, where net revenue, benefit cost ratio and return to labour were higher for maize legume intercropping systems than maize monocropping systems. On the other hand, in Tanzania a trade-off occurred between crop productivity and financial return. Crop productivity was increased in an intercrop, but the financial return was decreased. One of the reasons was the low price of the pigeon peas. A sensitivity analysis showed that good and stable prices are important to create a solid financial return. Therefore, good market systems should be created in order to encourage farmers to invest in their fields and favourable cropping systems. Lastly, a trade-off occurred between crop productivity and yield scaled N_2O emissions when maize monocrops were compared to intercrops with legume residues applied to the soil, in both Kenya and Tanzania. Emissions were higher in the intercrops than the maize monocrops. However, this trade-off can be minimized or reversed into a synergy with the right management of legume residues and N fertilizer application. It shows that ecological intensification through maize legume intercropping can be an important strategy to minimize greenhouse gas emissions. Important is to realize that this study took place over the scope of one cropping season. It is thus relevant to perform the research on a longer time scale including more specific data on LER and N_2O emissions of maize legume intercrops for a full evaluation of the trade-offs and synergies that occur between crop productivity, financial return and N_2O emissions.

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7 Appendices

7.1 Appendix A – N2Africa and IPNI country agronomists

Data on labour requirements, input prices and output prices were obtained from various agronomists that are active in the area (Table 9). These country agronomist are employed by the IPNI (International Plant and Nutrition Institute) and N2Africa (International project led by Plant Production System chair group from Wageningen UR, funded by the Bill and Melinda Gates foundations).

Table 9. Country agronomists that provided data on labour requirements and input and output prices. Indicated are the country they provided data for and the institution or organisation where they are employed.

Country agronomist	Country	Employer
Endalkachew Woldemeskel	Ethiopia	N2Africa
Paul Woomer	Tanzania	N2Africa
Frederick Baijukya	Tanzania	N2Africa
Wytze Marinus	Kenya	N2Africa
Samuel Njoroge	Kenya	IPNI
Joseph Oloo	Kenya	IPNI

7.2 Appendix B – absolute maize and legume yield differences

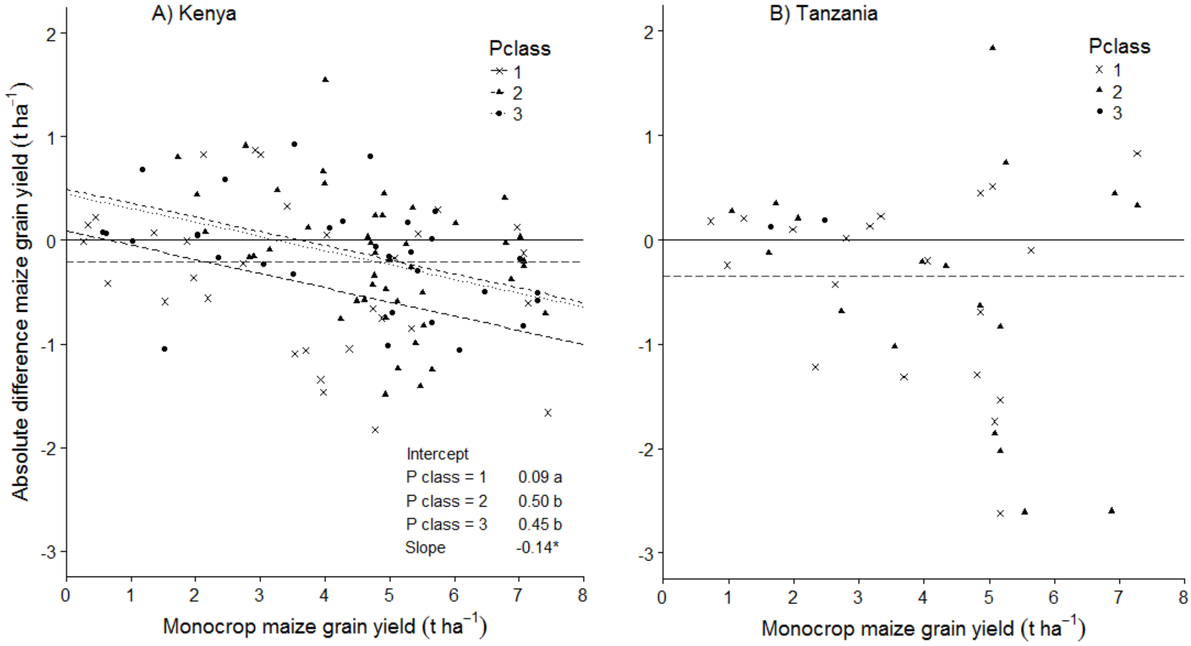

Figure 17. Absolute difference of the maize grain yield of an intercrop compared to maize monocrop yield for Kenya (A) and Tanzania (B). A negative value indicates a higher maize grain yield of the monocrop. Different symbols and trendlines are used to indicate different P fertilizer rates. The dashed, short-dashed and dotted lines represent Pclass 1, 2 & 3 respectively. The horizontal dashed line shows the average absolute difference of the maize grain yields. A star behind the slope and different letters behind the intercepts indicate a significant value at *$p < 0.05$*.

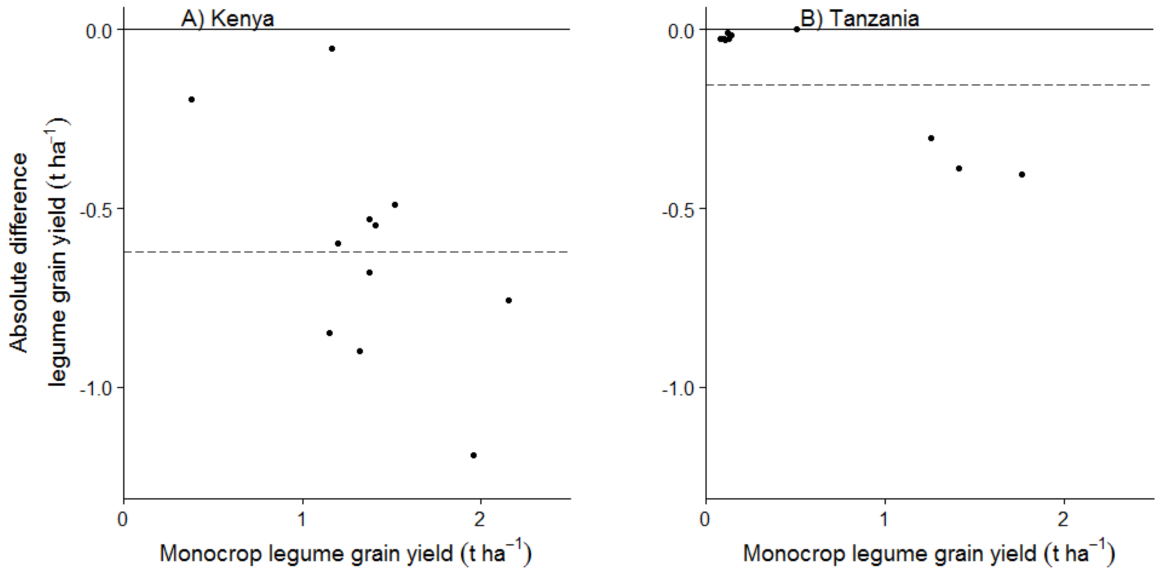

Figure 18. Absolute difference of the legume grain yield (t ha^{-1}) of an intercrop compared to monocrop legume grain yield for Kenya (A) and Tanzania (B). A negative value indicates a higher maize grain yield for the monocrop. Different symbols are used to indicate different N fertilizer rates. The dashed line shows the average relative difference of the maize grain yields.

7.3 Appendix C – legume grain yield calculated with additional data

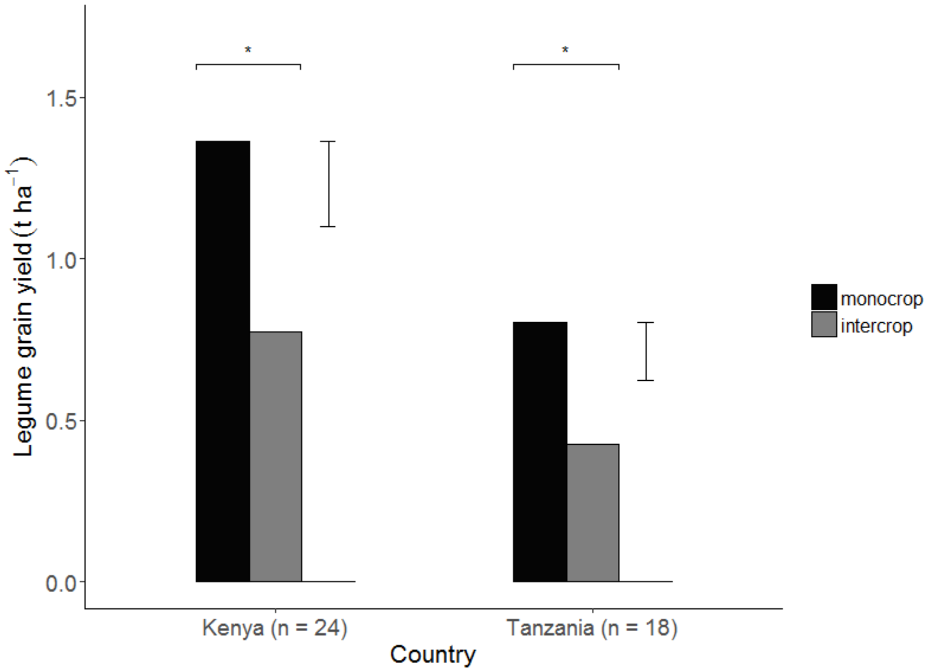

Figure 19. Legume grain yield (in t ha^{-1}) of monocropping and intercropping systems in Kenya and Tanzania, estimated by the mixed effects model. Additional data from Ethiopia on common bean is used and from Kenya on pigeon pea. The error bars indicate the LSD. The number of observations per country are included between the brackets. * indicates a significant difference between monocrop and intercrop maize grain yield at *$p < 0.05$*.

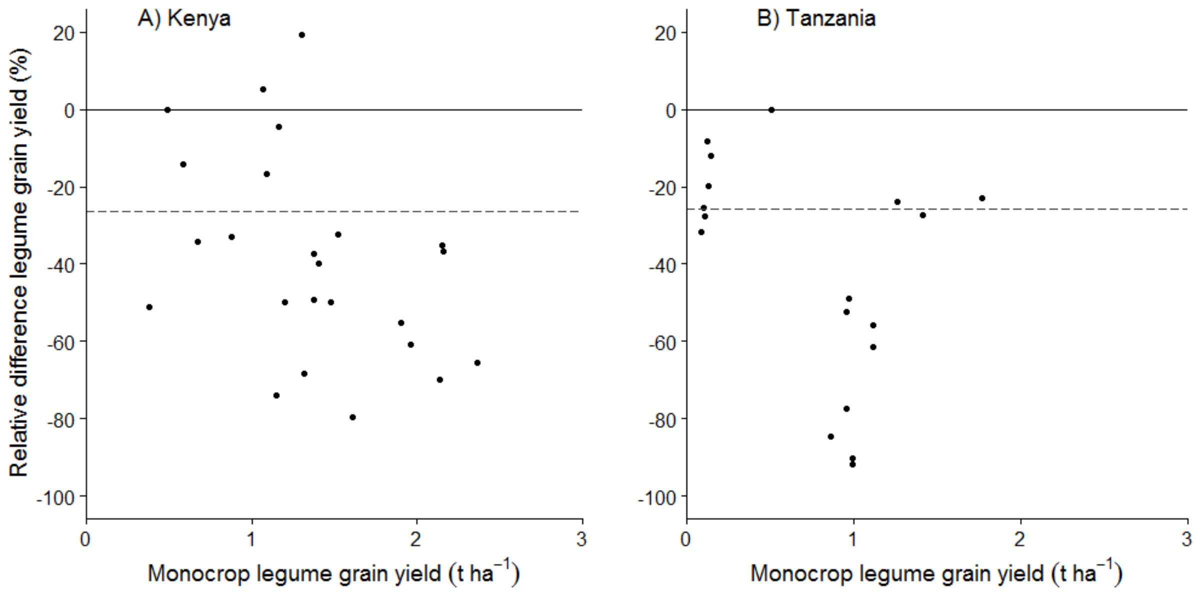

Figure 20. Relative difference of the legume grain yields of an intercrop compared to a monocrop for common bean maize intercropping systems in Kenya (A) and pigeon pea maize intercropping systems in Tanzania (B). Additional data from Ethiopia on common bean is used and from Kenya on pigeon pea. A negative value indicates a higher legume grain yield for the monocrop. The dashed line represents the average relative difference of the legume grain yields.

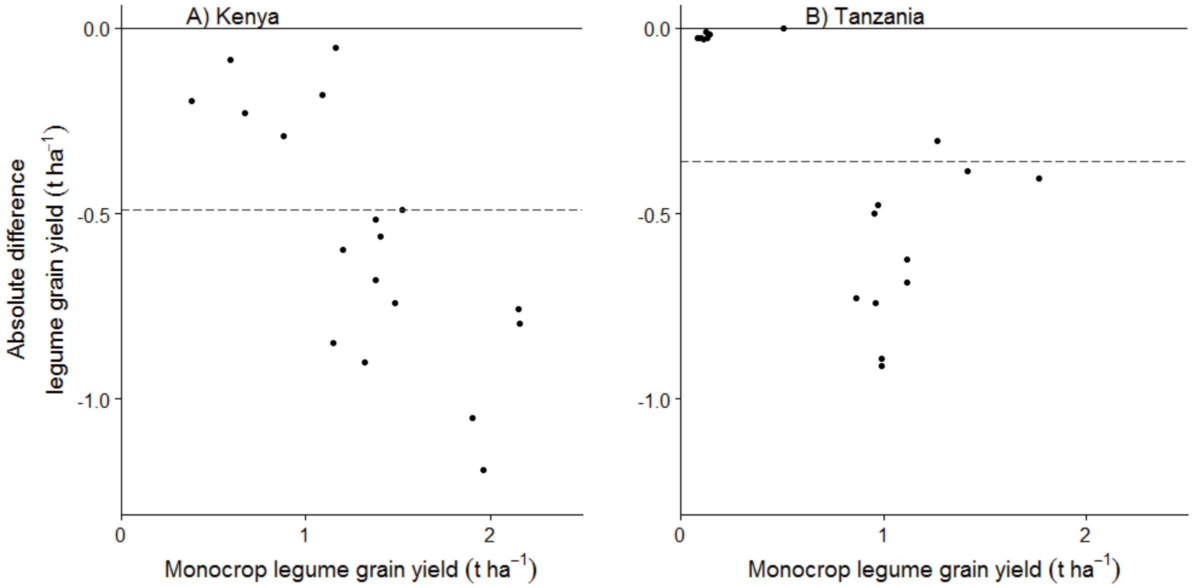

Figure 21. Absolute difference of the legume grain yield (t ha^{-1}) of an intercrop compared to monocrop yield for Kenya (A) and Tanzania (B). A negative value indicates a higher maize grain yield for the monocrop. Additional data from Ethiopia on common bean is used and from Kenya on pigeon pea. Different symbols are used to indicate different N fertilizer rates. The dashed line shows the average relative difference of the maize grain yields.

7.4 Appendix D – N_2O emissions without legume residue application

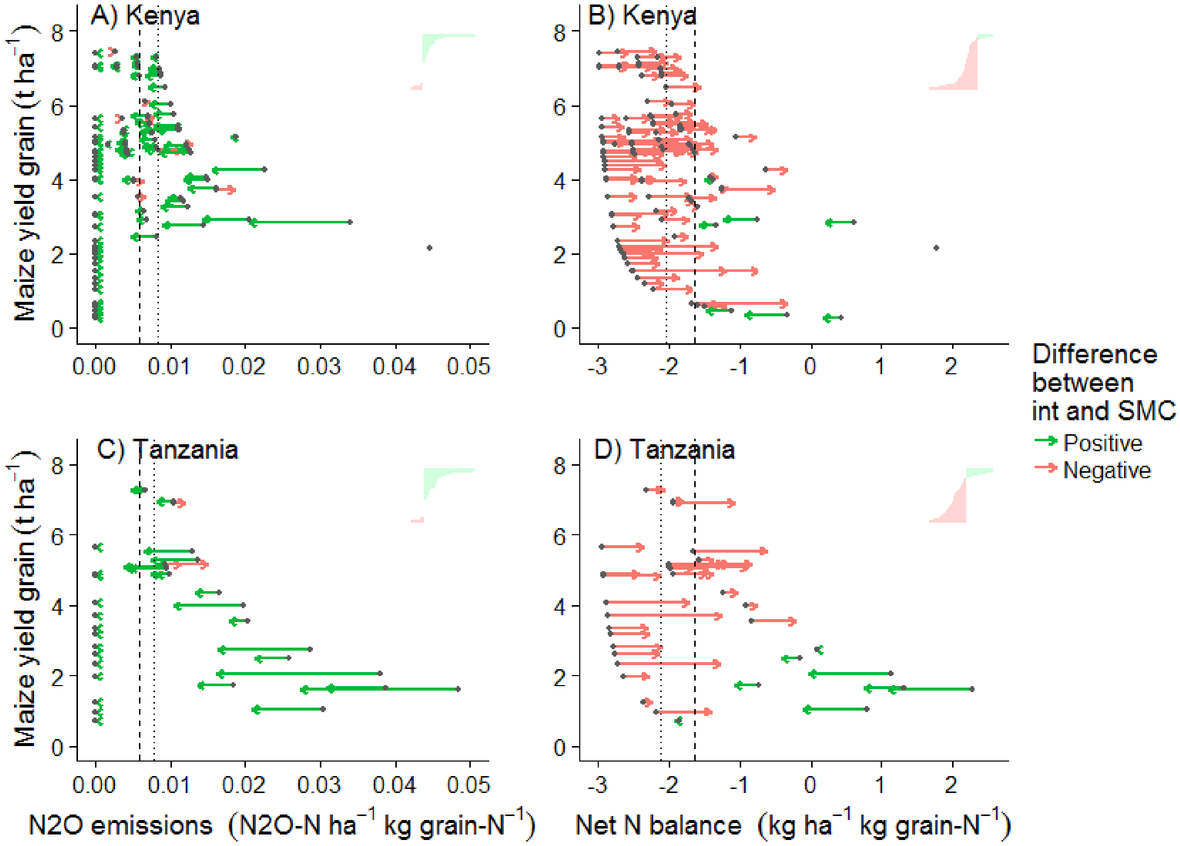

Figure 22. Yield scaled N2O emissions (N_2O-N ha^{-1} kg grain-N^{-1}) (A, C) and yield scaled net N balance (kg ha^{-1} kg grain-N^{-1}) (B, D) for different cropping systems and fertilizer levels for Kenya (A, B) and Tanzania (C, D). Addition of legume residues is not taken into account in the calculations. Values are calculated with observed yield in experiments. Dots indicate values for maize monocropping system. The arrow shows the difference with the intercropping systems. A green arrow means the intercrop performed better than the monocrop. A red arrow means the intercrop performed worse than the monocrop. Dotted lines indicate average model calculated values for the monocrop with medium fertilizer rate. Dashed lines indicate average model calculated values for the intercrop with medium fertilizer rate. Small subplots present sorted negative and positive differences between the three economic indicators.

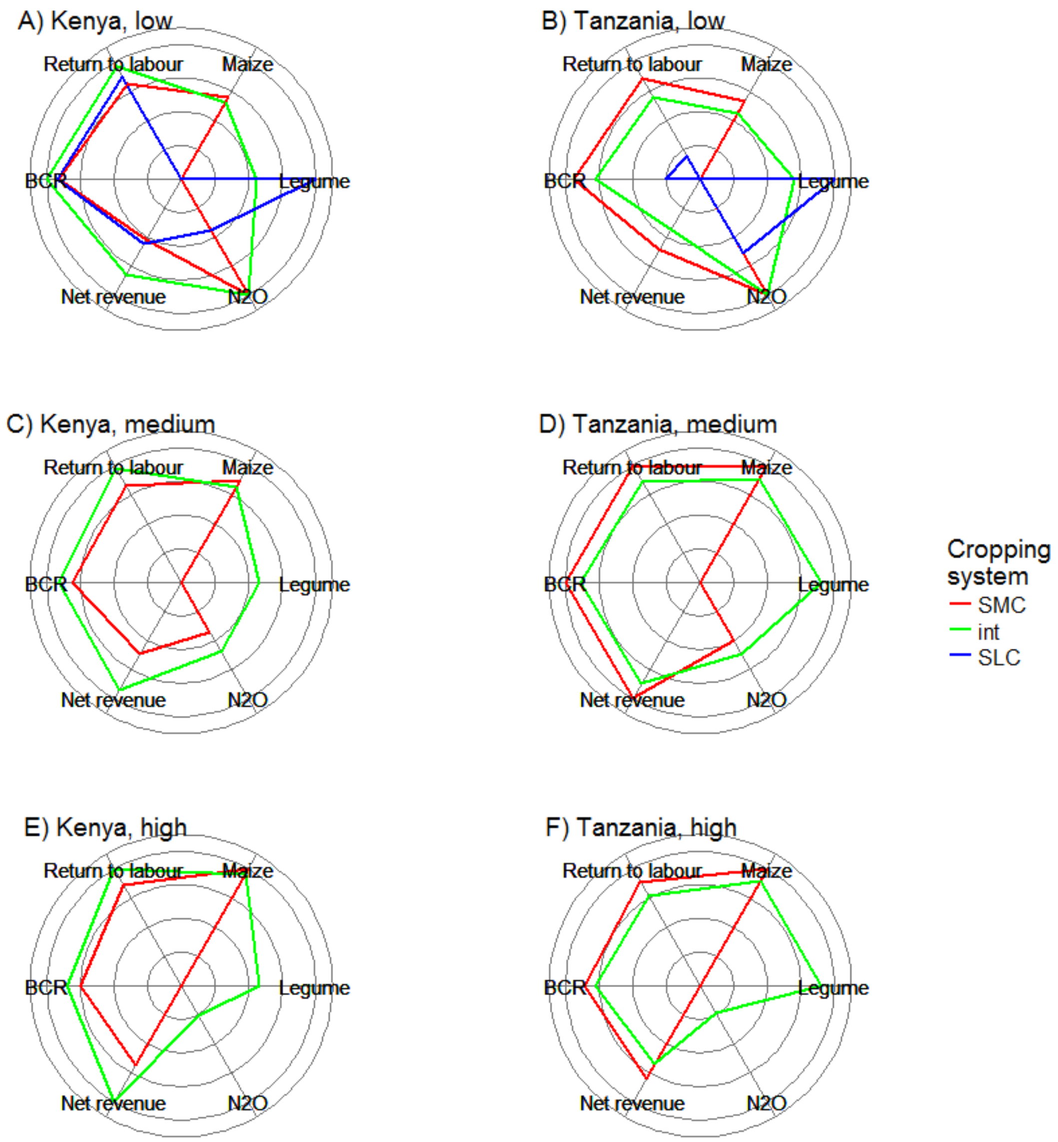

Figure 233. Spider plots combining the different trade-of parameters. Values are scaled values. Maize is the maize grain yield, legume is the legume grain yield, N_2O is the reversely scaled yield scaled N_2O emissions, net revenue is the net revenue, BCR is the benefit to cost ratio and return to labour is the return to labour. Data is shown for Kenya (A, C, E) and Tanzania (B, D, F), for low fertilizer rates (A, B), medium fertilizer rates (C ,D) and high fertilizer rates (E, F) for maize monocrops (SMC), intercrops without residue application (int) and legume monocrops (SLC).

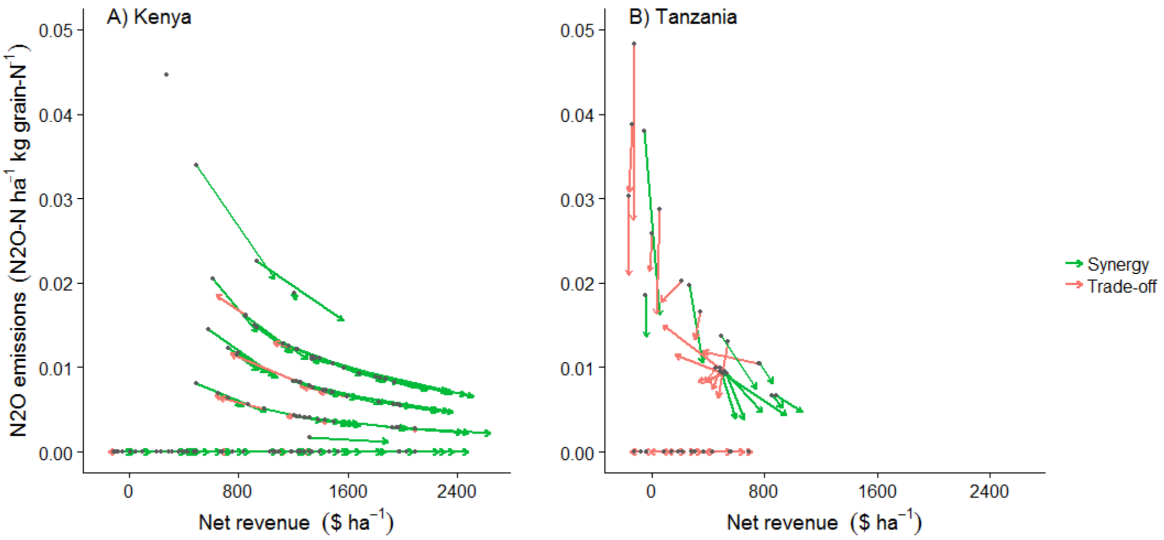

Figure 244. Yield scaled N_2O emissions (N_2O-N ha^{-1} kg grain-N^{-1}) against net revenue (\$ ha^{-1}). Dots indicate values for maize monocropping system. The arrow head shows values for intercropping systems without residue application. Green arrows indicate a synergy and red arrows indicate a trade-off between yield scaled N_2O emissions and net revenue.