MEKELLE UNIVERSITY

Evaluating the productivity and economic benefits of cereal-legume intercropping with and without supplementary irrigation in the semi-arid highlands of Tigray, Ethiopia

By

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DECLARATION

I, **ETANY SOLOMON** hereby present for consideration by the **Dryland Crops and Horticultural Science** Department within the College of Dryland Agriculture and Natural Resources at Mekelle University, my dissertation in partial fulfillment of the requirement for the degree of Masters in **Evaluating the Productivity and Economic Benefits of Cereal-Legume Intercropping with and without Supplementary Irrigation in the Semi-Arid Highlands of Tigray, Ethiopia**. I sincerely declare that this thesis is the product of my own efforts. No other person has published a similar study which I might have copied, and at no stage will this be published without my consent and that of the **Dryland Crops and Horticultural Science** department.

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THE PRODUCTIVITY AND ECONOMIC BENEFITS OF CEREAL-LEGUME INTERCROPPING WITH AND WITHOUT SUPPLEMENTARY IRRIGATION IN THE SEMI-ARID HIGHLANDS OF TIGRAY, ETHIOPIA

ABSTRACT

Farmers in the northern dryland areas of Ethiopia practice a cereal based rainfed crop-livestock mixed farming and are predominantly rainfed. However, low soil fertility and limited water availability are the major hampering factors to crop production thus poverty and food shortage is evident to the ever increasing population. Comprehensive integration of n-fixing leguminous species with cereals supported with supplementary irrigation could greatly improve soil fertility, moisture availability and increase livestock feed-base, resulting in increased production and productivity. In line with this, a study was conducted at Mekelle University main campus, located in the northern highlands of Ethiopia to evaluate the economic and agronomic performance of cereal-legume intercropping under rainfed conditions and with supplementary irrigation, during the 2015/16 rainfall season. Wheat (Triticum aestivum L.) was intercropped with lentil (Lens culinaris Medik) and dekoko (psium aestivum var. abyssinicum) in a solitary ratio and supplemented with irrigation. The experiment was laid in a split-plot design with three replications under traditional management practices. Each of the crops were grown in single-stand for comparison. The results from analysis of variance indicated that intercropping increased significantly the grain yield of wheat up to 30.5% under rainfed conditions in wheat-lentil mixture and a noticeable yield increase was also noted in wheat-dekoko intercropping, nevertheless, supplementary irrigation increased the yields by up to 100%. Yield reduction in legumes was compensated by higher cumulative yield per unit area. This was reflected in the higher LER (1.83 and 2.38) and LEC (0.82 and 1.34) registered for wheat-lentil intercropping under rainfed and supplementary irrigation respectively. Monetary equivalent index (MAI) for wheat-lentil were7,937.2 ETB and 20,642 ETB for rainfed and supplementary irrigation respectively. It was concluded that intercropping provided more advantage to sole cropping, both in terms of total yield per unit area and profitability. However, wheat-lentil combination is recommended for the area since it showed minimum interspecific competition, higher yield as well as economic viability. Wheat-dekoko was overall more profitable both under rainfed and supplementary irrigation.

Keywords: dryland, cereal-legume, intercropping, rainfed, supplementary irrigation, dekoko.

DEDICATION

To my lovely parents Mr. and Mrs. Tom Ogwang

BIOGRAPHY OF THE AUTHOR

The author of this paper was born on May 01, 1990 in Barr sub-county, Lira district, Uganda. He then started his academic journey from St. Phillips C.O.U nursery school in 1995 after which he joined Adekokwok Primary School for his primary level. After successfully completing his primary level and being awarded with Primary Leaving Examination (PLE) in 2003, he later joined Adwari Secondary School in 2004 for his secondary (Ordinary Level) which he finished with a Uganda Certificate of Education (UCE) in 2007.

He later joined Kiira College Butiki, Jinja-Uganda for his Advanced Level in between 2008 and 2009 where he did the subject combination Biology, Chemistry, Mathematics and Agriculture (BCM/A) and was awarded Uganda Advanced Certificate of Education (UACE) upon successful completion.

This led him being awarded a government scholarship to pursue a degree of Bachelor of Agriculture in Gulu University from 2010 to 2013 where he graduated with Bachelors (Honors) of Agriculture (General Agriculture).

He later was temporarily appointed as a Research Assistant for a project (CATALIST Uganda) under the University immediately after graduation, until he earned a scholarship from Regional Universities Forum for Capacity Development in Agriculture (RUFORUM) in October 2014 to pursue his Postgraduate Studies in Masters of Dryland Agronomy from Mekelle University, Ethiopia, which he successfully finished and was awarded his masters in 2016.

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May God reward you abundantly!

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LIST OF ACRONYMS

FAOSTAT	Food and Agriculture Organization Statistics
GDP	Gross Domestic Product
ISFM	Integrated Soil Fertility Management
CSA	Central Statistics Authority
SI	Supplementary Irrigation
N_2	Nitrogen
N_2O	Nitrous oxide
BNF	Biological Nitrogen Fixation
WUE	Water use efficiency
APSIM	Agricultural Production Systems Simulator
APSRU	Agricultural Production Systems Research Unit
ET_0	Reference Evapotranspiration
ET_{crop}	Crop Evapotranspiration
K_c	Crop coefficient
P_{eff}	Effective rainfall
REP	Replication
Cm	Centimeter
Kg	Kilogram
Ha	Hectare
LER	Land Equivalent Ratio
MAI	Monetary Advantage Index
ANOVA	Analysis of variance
LSD	Least Significant Difference
USDA	United States Department of Agriculture
SCE	Soil Conservation Service

IFPRI	International Food Policy Research Institute
FAO	Food and Agriculture Organization
CEC	Cation exchange capacity
TARI	Tigray Agricultural Research Institute
DAP	Diamonium phosphate
I_n	Net irrigation
cm	Centimeters
DAS	Days after sowing
LEC	Land equivalent coefficient
K	Crowding coefficient
PC	Productivity coefficient
CV	Coefficient of variation
SEm	Standard Error of means
TGW	Thousand grain weight
HI	Harvest index
SW	Sole wheat
SL	Sole lentil
SD	Sole dekoko
WL	Wheat-lentil
WD	Wheat-dekoko
ETBr	Ethiopian birr

CHAPTER 1: INTRODUCTION AND BACKGROUND

1.1 Introduction

Drylands, generally referred to as semi-arid and arid ecosystems cover about 40% of the world's total land surface and more than two thirds of Africa and nearly the whole of Middle East lie here (Haren *et al.,* 2010). A greater populations living in these regions largely depend on agriculture. However, rainfall uncertainty remains a serious challenge confronting smallholder farmers in drylands (Ndamani and Watanabe, 2015). According to Owesis *et al.* (1999), dryland areas normally receive very little rainfall amounts (100 mm to 600 mm annually) agriculture being one of the major users. Owing to the above, drylands areas are known for low agricultural productivity which is based on opportunistic farming-after exceptional rains or as floods recede as well as small scale mixed farming on uplands, plains and along the river banks.

In addition, the biological and productive potential of dryland soils is low due to the widespread land degradation which is a result of natural or man-made factors or a combination of the two (Haren *et al.,* 2010). Despite possessing a vast indigenous knowledge about the sound land use practices in the dry land areas, farmers are losing out in terms of yield reduction due to the impacts of climate change. Therefore there is a pressing need for appropriate change of technology to boost production in these low rainfall areas which are undergoing continuous population growth.

The common farmers' practice of sole cropping cannot meet the varied needs of the small scale farmers (Ogutu *et al.,* 2012). It is therefore important for farmers to adopt improved and sustainable technologies in order to guarantee improvements in food productivity and thereby food security (Landers, 2007), In addition, for early adoption of the technologies by the poor-resource farmers, these practices should be self-sustaining, low-input and energy efficient (Neufeldt *et al.,* 2011). Intercropping is known to provide more yield per given land area and provide for a more efficient use of the available resources. Secondly, if legumes are included in the system, soil fertility is improved through Biological nitrogen fixation and increased soil biomass. The results of various studies conducted on cereal-legume intercrop have shown that higher benefits (in terms of yield and monetary value) are obtained from intercropping than from sole cropping (Lemlem, 2013; Hassan *et al.,* 2013).

In Sub-Saharan Africa, rainfed agriculture is the main approach to food production (Doto *et al.,* 2015). However it has very low potentials for increasing food production posing challenges to meeting the increasing food demands of the constantly growing African population in the face of climate variability. For example, due to the high variability in rainfall coupled with poor agronomic practices the yields of cereals remains as low as 1 t ha^{-1} or less for small-holder farmers in the region (e.g., FAOSTAT, 2003; Rosengrant *et al.,* 2002). As opposed, 3-5 times higher yield has been obtained under experimental conditions and commercial farms (Rosengrant *et al.,* 2002). Small-holder rainfed farming largely realize low crop yields mainly due to water shortages during crop growth stages (Makurira *et al.,* 2010). According to World Bank (2003), the risk of rainfall shortage during crop growth can reduce yields up to 90%. However, yields can significantly be increased with the introduction of suitable farming practices, even with little and highly variable rainfall. Various studies that have been done to determine the effects of intercropping under irrigation on crop yields have yielded positive results. For instance, a research conducted in Nigeria showed that intercropping cereals with nitrogen fixing leguminous crops under irrigation can substantially increase yields of about 2 t ha^{-1} in maize as well as for the component crops (Hassan *et al.,* 2014).

Ethiopia is one of the highly populated dryland countries in the Sub-Saharan Africa (Awlachew *et al*., 2006);and the main lifeblood of its economy is agriculture, earning about 45% and 85% to the GDP and the national export earnings respectively. The dry lands occupy about 70 percent of the total landmass and 45 percent of the arable land in Ethiopia (Awlachew, 2005).This means agriculture is central to food security and economic growth in the country. Mixed crop-livestock farming system is the main small-holder practice Ethiopia (Mpairwe *et al.*, 2003; Hassan *et al.*, 2014). The major crops grown are maize, sorghum, wheat, barley, teff, sorghum, and chick pea (Araya and Stroosnijder, 2011); Livestock like goats, sheep, cattle and poultry are also kept. However, like most of the countries in the Sub-Saharan Africa, agriculture in the country is largely rainfed, depending on the highly erratic rainfall, coupled with the widespread land degradation and agricultural output remains low enough to feed the increasing population resulting in food insecurity and vulnerability to climate change (Hagos *et al.*, 2006).

Land degradation is another challenge of agriculture in the area, mainly intensified by overpopulation in the highlands, over cultivation, soil erosion, and unstable crop and livestock production methods (Girma, 2001; Araya *et al.*, 2010). In addition, soil erosion and limited use of organic and inorganic fertilizers has resulted in severe decline in soil quality leading to lower productivity (Lakew *et al.*, 2000; Ahmed *et al.* 2003, Menale, 2011)

In the northern highlands of Tigray, the rainy season is characterized a highly variable rainfall distribution which has resulted in crop failure for the past three decades (Yared *et al.*, 2012). According to Ermias *et al.* (2005), about 85 % of the population of Tigray earns a living through subsistent agriculture, extensively cultivating small units of land and livestock rearing. The same author further argued that the agriculture sector is predominantly rainfed with low productivity and rainfall is insufficient during the growing season. This erratic rainfall, characterized by late on-set and early cessation of rains has been causing crop failure over the past three decades in Tigray (Tezera *et al*., 2012). Soil moisture in the region is insufficient due to periodic draught, light soils, regular tillage, and high runoff rates from sloping lands during occasionally excess rainfall (Mati, 2006).

Therefore to successfully manage these challenges needs the adoption of farming technologies that enhance water retention capacities of soils and resource recyling (Kassie *et al.*,n.d). Such practices comprise the use of integrated soil fertility management (ISFM), which have intercropping cereals with legumes as one of its main components (Mucheru-Muna *et al.*, 2010; Matusso *et al.*, 2014). Intercropping is seen as an attractive strategy for increasing productivity through the efficient use of resources in the environment (Seran and Brintha, 2010).

1.2 Problem statement

The smallholder farmers in Ethiopia have for years depended on mixed crop-livestock subsistence farming as a means of survival. Livestock provide these farmers meat and milk, draught power for crop cultivation and transport, and also can be sources of organic fertilizers (Bekele *et al.*, 2013), as well as an important asset that could be converted to monetary means during bad times to avert risks. However, due to the dependence of the farmers on cow dung as a major energy source of energy for households and improper livestock management among others, their ecological roles in recycling nutrients has been hampered.

In addition, the crop residues are always carried away from the farms for feeding livestock, leaving the fields vulnerable to erosion hence low productivity. Araya et al., (2010), argues that farmers in Tigray region harvest the straw of crops in order to feed their animals leaving no residues as soil cover. Farmers in the area also practice free communal grazing of animals on the stubble residue after harvest. These practices have led to the long term decline in soil organic matter content which consequently increased soil erosion, resulting in low crop production over the years, and as a result, food insecurity is witnessed in many households in the region.

Therefore, the depletion of organic matter driven by competing use of crop residues and animal manure as fuel sources instead of enriching the soil is one of the challenges to agricultural productivity. This is because soil organic matter is the central to achieving long-term increased biomass production for improved soil fertility, increased food production, livestock feeds and ensuring food security at household level.

This problem of reduced soil fertility does not only limit the supply of nutrients but also affects other soil physical qualities, causing multiple problems to agricultural growth and generally resulting in food insecurity. Therefore in integrated crop-livestock systems, there is need to incorporate forage legumes with food crops to lessen the chemical fertilizer use and improve crop-livestock productivity and sustainability (McIntire et al. 1992; Humphreys 1994; Giller 2001; Peters and Lascano 2003; Kassie, 2011).

Even when the rainfall is favorable, the yield in Tigray region is low compared to the average yield at national level. This is because of the low soil moisture availability which also results from the decline in soil quality, making the crops to suffer from moisture stress, resulting to crop failure. And in most cases crops are subjected to terminal soil moisture stress especially during reproductive and maturity phases leading to poor yields

It is hypothesized that comprehensive integrations of leguminous (nitrogen fixing) livestock feeds as intercrop with cereals supported with supplementary irrigation could greatly improve the soil fertility, moisture availability and in-turn increase livestock feed availability which will increase productivity in households and strengthen the food security in the region. A few studies conducted in the study area on intercropping also gave positive results in terms of yields, (e.g. Kassie *et al.* 2011). Supplementary irrigation (SI) is reported to increase yield by over 50%, in various researches, including in the studies by Bello (2008), Caliandro and Boari (n.d), and Allam *et al.*(2007)

However, most research studies on cereal-legume integration in the region have focused much on its impacts on yield and yield components and less attention is paid to the economic benefits, and impacts of supplementary irrigation. More so, information on the long-term effects of the integration of cereals with legumes, with water management practices, considering a mixed crop-livestock system is still scant; the feasibility of integration of livestock production in relation to water and nutrient management under subsistence farming system taking into account the present and the future interactions and long-term benefits to food security has not been documented, and this justifies the need for this research. .

1.3 Objectives

1.3.1 General objective

To evaluate the economic returns and effects of cereal-legume intercropping and supplementary irrigation on yield and soil quality in the semi arid highlands of Tigray, Ethiopia.

1.3.2 Specific objectives

i. To evaluate the effect of cereal-legume intercropping on yield and yield components of bread wheat and component legumes, and soil fertility.
ii. To assess the effect of supplementary irrigation on yield and yield components of wheat and component legumes.
iii. To determine the economic returns of cereal-legume intercropping under rainfed and supplementary irrigation.

1.3.3 Research Hypothesis

i. Cereal-legume Intercropping under supplementary irrigation significantly affects crop yields and soil quality
ii. Cereal-legume Intercropping with and without supplementary irrigation has significant effects on farmers' net income
iii. Cereal-legume Intercropping, with supplementary irrigation can significantly affect the future soil fertility and crop yields

CHAPTER 2: LITERATURE REVIEW

2.1. Small Grain Production: Opportunities and Challenges

Wheat (*Triticum spp.),* one of the small cereals is one of the highly produced cereal grains in the world. It is ranked only third globally after maize (*Zea mays L*.); 875 million tons and rice (Oryza sativa L); 718 million tons, with a total production of above 674 million tons on over 216 million ha, with an average yield of 3.1 t ha^{-1} (FAO, 2013). The growth of wheat production in Sub Saharan Africa (SSA) has also appreciated in recent years with consequent increase in consumption (Jayne et al., 2010; Shiferaw et al., n.d).

Ethiopia has experienced a significant growth the production and yield of small cereals since 2010 (Gray, 2014). However, Ethiopia's small grain production is complex with a large variation in the types of crops produced across different regions and agroecosystems of the country. The major small grains grown in the country include; teff (3.8 million tons), wheat (3.3 million tons) and barley (1.7 million tons); all of which are predominantly grown under rainfed conditions. The northern and central regions have registered the highest production of these grains as according to Gray (2014). For this study, the main focus will be on wheat, being one of the most important cereal in the diets and the economy of the country.

Ethiopia is second in wheat production in SSA after South Africa and it accounts for over half of total wheat area in the SSA. According to FAOSTAT 2010, by the year 2010, the country was producing 3 million metric tons (Bergh et al., 2012). The highest production of wheat in the country is realized in the central, southeastern and northeastern parts of the country and production is mainly dominated by smallholder farmers (Gray, 2014). Bread wheat (*Triticum aestivum L.*)and durum wheat (*Triticum durum L.)* are the major species of wheat grown in the country . Bread wheat accounts for more than half of the total wheat area, and is mainly grown in the highland and semi-highland areas of Oromia, Tigray, and Hamara regions (Bergh et al., 2012). Durum wheat however covers about 40% of wheat area in the country.

Wheat in Ethiopia is normally planted in the summer, prior to the *meher* (main) season rains in June to September, and harvested in October - November (CSA., 2012; Bergh et al., 2012). Oromia and Hamara regions are the leading producers of wheat, accounting for 88% of domestic wheat production in the country. Wheat production however is dominated by smallholders with an average landholding less than a hectare, which is also allocated to the production of other cereals like teff and rice (Bergh et al., 2012).

Wheat production in the country experienced a significant increase from 2005 to 2010 - largely due to improved yields (MAFAP, 2013). The yields of wheat increased from an average of 1.68 t ha^{-1} in 2004/2005 to 1.8 t ha^{-1} in 2011. The slower increase in area harvested with wheat compared to the rate of production also reflects an increase in yields (Bergh et al., 2012). Furthermore, improving price incentives, expanded extension services and favorable weather conditions have also contributed to an increase in wheat production over the years according to MAFAP (2013).

However, despite the increased yields over time, wheat yields in Ethiopia have consistently lagged behind the average yields for the SSA region, for instance in 2011/2012, the regional average was 2.2 t ha^{-1}, as compared to Ethiopia's 1.8 t ha^{-1} (Bergh et al., 2012). USDA FAS (2012) estimated that wheat yields in Ethiopia were 60 - 94% of the average yields in the region over the past ten years. Bad weather, input prices, amount of fertilizer use, the quality of seed varieties have been mentioned as the contributing factors to yield gaps. For instance, the timing and length of the *meher* rains have a huge impact on yields.

According to Weddington et al. (2010), limited access to inputs and biotic constraints like rust disease and weeds account for yield gaps to a larger extent than management practices; which holds true for Ethiopia. Nitrogen deficiency and soil fertility depletion, among other constraints have also been reported to cause yield losses amounting to 0.146 and 0.106 t ha^{-1} respectively according to this author. Most of all, land degradation as a result of intensive crop production, over grazing and population growth has also greatly impacted on the yield of wheat in the country (Kato et al., 2011).

Conventional tillage, a common practice in wheat production also increases the rate of organic matter loss from the soil besides predisposing the soil to erosion by running water and wind. As a result of these constraints and more, Ethiopia still faces a growing wheat supply deficit and is still importing wheat.

Nevertheless, soil scientists suggest that more efforts should be put to invent and adopt to environmentally and economically sustainable systems for small grain producers. In addition, it is worthwhile to restore degraded soils by means of integrated ecological practices in crop production and management of soil resources. Intercropping grain legumes with small grains has been suggested as one of the strategies to meet these goals.

2.1.1 Soil degradation in Ethiopia: An emerging challenge in production of small grains

In simple terms, soil degradation refers to the decline in soil fertility, including the deterioration of physical, chemical and biological qualities of the soil (Enters 1998; Yusuf et al., 2005). These can be a result of several factors, such as; soil erosion, compaction, surface sealing and crusting, water logging, nutrient depletion and loss of organic matter. The continuing degradation and decline in land productivity in the country have persistently hampered the successful production of small grains.

Soil degradation is one of the foremost causes of low and declining agricultural productivity, food insecurity and poverty among rural farmers in Ethiopia (IFPRI 2005). A report by Jagger and Pender (2003) indicates that 2 million hectares of land in Ethiopia has suffered from severe land degradation. This has resulted in a yield reduction of 1-2% in the country (Hurni, 1993; Woubet et al., 2014). The high rate of population growth and exploitative way of subsistence farming with little or low addition of soil amendments has also resulted in the growing state of soil degradation (Gebreyesus and Kirubel 2009; Temesgen et al., 2014). Mulugeta (2004) on the other hand argued that soil degradation in Ethiopia is caused by biophysical factors which are socioeconomic and political; such as subsistence agriculture, poverty and illiteracy.

However, according to IFPRI (2005), soil erosion has been the leading cause nutrient and organic matter loss due to poor farming technologies at the steep slopes of the highlands. For example, the central region alone loses between 200 - 300 t ha^{-1} of top soil annually due to rill and sheet erosion, accounting for 2.5 cm in depth of soil being lost yearly per hectare in only one region of the country (Abegaz, 1995; Tegegne, 2014). In Hamara region, studies have shown that soil loss due to erosion vary at the rates of 0.04 to 212 t ha^{-1} yearly (Lakew et al., 2000). This problem is more pronounced in areas where small cereals like teff and wheat are produced since they require finely tilled seedbed (Tegegne, 2014). As a result, every year the country loses billions of birr in soil, nutrients, water and biodiversity due to erosion (Paulos 2001; Temesgen et al., 2014).

In efforts to alleviate soil degradation, many technologies have been suggested; which ensure sustainable restoration of the degraded soils in an environmentally friendly and economically viable way. This will see the production of cereals go on am increase and livelihood of the smallholder farmers improved through improved income and food security. Therefore, cereal-legume intercropping, reduced tillage systems and generally practices that maximize soil coverage and reduce runoff have been suggested for the restoration of degraded soils in the country (Coxhead and Ygard 2008)

2.2.0 Intercropping as an alternative to conventional small grain production

Intercropping has been defined in many ways by different authors; generally it is as a multiple cropping system that combines the planting of two or more crops species simultaneously in the same field during a growing season. These crops can be planted at the same time or at different times as long as it is within the same field and growing season. (Ofori and Stern, 1987; Mazaheri*et al*., 2006; Mousavi and Eskandari, 2011).

It has the capacity to fulfill several ecological goals like increasing agro diversity and biological diversity, promoting species interaction and enhancing the natural nutrient regulation (Hauggaard-Nielsen et al., 2007). Other additional remunerations like erosion reduction, weed suppression, moisture retention, increasing soil fertility through nutrient cycling, and biological nitrogen fixation makes intercropping an important practice to improve agricultural productivity by increasing yields. The combination of different species in cropping systems may accrue a range of benefits that are shown in different space and time scales. This can range from short-term increase in yield and quality of crops, to a longer-term benefits such as the development of a sustainable agroecosystem and other ecological and societal benefits ((Malezieux et al., 2009, Lina et al., 2010)

It therefore requires that all traits and features of the production system be exploited in the design of intercropping system in order to exploit diversity and enhance the crop function (Newton et al., 2009). According to Inal et al. (2009), an efficient combination of intercrops is one that produces a greater total crop yield on a given piece of land and efficiently utilizes the resources than each of the component crops would. Usually, this consists of different crop species or families, with one acting as the major crop of primary importance (like food) and the other providing another benefit like N_2 fixation (Chapagain, 2014).

Peas (Lina et al., 2010) and beans (Chapagain, 2014) are valuable groups of leguminous species undergoing assessment as intercrops in small grain cropping systems. Wheat and barley have also in most cases been intercropped with lentil (*Lens culinaris* L.) and red clover, (*Trifolium pratense* L.) (Chapagain, 2014). When the leguminous and non-leguminous species are combined (e.g. wheat and pea), numerous benefits can be obtained over their monoculture, for example improved soil fertility through biological nitrogen fixation, weeds and pest control, and more so a higher total yield per area. According to USDA (1980), this combination better suits organic farming principles since it eliminates the use of agrochemicals and inorganic fertilizers from the farming systems. In line with this, the integration of small grains with legumes can be a great means to avert the effects of land degradation and end enhance sustainable increase of production and also enhance economic and environmental sustainability.

2.3.0 Production of pulses in Ethiopia

While Ethiopia experience severe levels of food insecurity, aggravated by population growth, land degradation and frequent draughts, pulse crops are important alternative sources of protein, income and food security. The most common pulses grown in Ethiopia include horse bean (*Vicia faba* var. *minor*), field pea (*Pisum sativum*), haricot bean (*Phaseolus vulgari*), chickpea (*Cicerarietinum*) and lentils (*Lens Culinaris Medikus*) (Dereje and Eshetu, n.d.). Pulses are the second most important components of Ethiopia's diet endowed with primary proteins and an important dietary supplement to the cereal based diets of the country.

The acreage under pulse production increased from 12% to 12.4% in the periods between 1995-2009, and the annual production was averagely 1.5 million tons representing 8.5% of total yearly production. Within the last ten years, the area cultivated with pulses has increased at the rate of 6.6% per year, higher than that of cereals (4.6%) according to Alemayehu et al., (2011).

2.3.1 Lentil production and its importance in smallholder farming systems in Ethiopia

Lentil (***Lens Culinaris Medikus) is said to be among the oldest annual food crops ever grown as an important dietary source as*** einkorn, emmer, barley and pea (Dhuppar et al.,2012; Abraham, 2015). It belongs to the genus *Lens* of the *Viceae* tribe in the family *Legumnosae* (*Fabaceae*), commonly known as the legume family (Fikiru et al., 2007). The scientific name *Lens culinaris* in 1787 was given to the plant by Medikus, a German botanist and physician (Hanelt, P., 2001). There are two varietal types of cultivated lentil, *Lens culinaris*spp. *Culinaris;* the small seeded (*microsperma*) and large seeded (*macrosperma*) (Sharma et al., 1995). It is believed to have originated from the Near East and Egypt, Central and Southern Europe, the

Mediterranean basin, Ethiopia, Afghanistan, India, Pakistan, China and spread later to Latin America (Cubero 1981, Duke 1981; Alihan and Munqez, 2012).

Ethiopia is one of the important lentil-producing countries in the world besides India, Canada, Turkey, Bangladesh, Iran, China, Nepal and Syria (Ahlawat, 2012). According to FAO (2010), lentil covers a total area of 4.6 million hectares globally, producing 4.2 million tons of grains and producing an average of 1.095 t ha^{-1}. It has contributed significantly in the food, feed and farming systems of West Asia, North and East Africa where both the red and green lentils are produced in varied proportions (Akibode and Maredia, 2011). Besides playing a vital role in human and animal nutrition, lentil also maintains and improves soil fertility (Sarker and Kumar, 2011; Abraham, 2015). This is because its cultivation enriches the soil with organic carbon, organic matter and nitrogen, which are important for the sustainable cereal-based production systems (Sarker and Kumar, 2011).

In Ethiopia, lentil is one of the pulses grown in heavy black soils of the highlands , mainly in rotation with teff, wheat and barley (Jarso et al., 2009). According to Korbu (2009), lentil serves an important part of the farming system and diet of the small holder farmers of the country. It is a popular ingredient of everyday's diet in most households. The pulse is consumed as stew, boiled or roasted, and in some cases mixed with other pulses or cereals and the different ways of consumption makes it a good source of balanced diet and is highly consumed locally in the country. It also produces highly nutritious straw used by farmers for fattening their livestock (Brennan et al., 2011).

The production of lentil in Ethiopia is dominated by small-scale farmers who do so on small and fragmented plots, mainly for subsistence (Jarso et al., 2009). However, the total area under pulses has increased in the past one decade by 6% and that under lentil production has appreciated in the last ten years by an average of 11% which indicates the importance of the crop (Abraham, 2015). The crop also experienced a production growth rate of 19.03%, relative to 11% for general pulses in the last ten years. The average yield for lentil in Ethiopia is 1.23 t ha^{-1} and according to CSA (2013), Ethiopia produced 151,499.93 tons of lentil in the 2012/2013 growing seasons and this was greater than the 2011/2012 production (128, 008.8 tons) by 18.35%.

This yield still remains lower than the potential yield and is mainly as a result of low yielding and disease susceptible cultivars which have affected both the yield and quality of Ethiopian Lentil (30,66). Therefore with proper breeding and research, and good agronomic practices, the full potentials of this very important pulse can be utilized and the yield boosted. This will also utilize the crop's importance in human and animal nutrition, and soil fertility improvement.

2.3.2 The production of field pea (*Pisum sativum L.*) in Ethiopia and its importance in smallholder households

Although its origin is still controversial, Ethiopia is believed to be the centre of diversity for field pea (*Pisum sativum L.*) since the wild and primitive forms are found in the highlands of the country, that is; south Tigray and north Wello areas (Yirga and Tsegay, 2013). The cultivated form of *pisum* in Ethiopia is dominated by *p.sativum*, although *p.sativum* species abyssinicum (*p.abyssinicum*) is a unique species developed and cultivated in Ethiopia, according to Yirga and Tsegay (2013). Ethiopia is known to be one of the vavilovian centers of diversity for quite a lot of grain legume crops, for example lupine, field pea and wild ancestors of cowpea.

Globally, field pea (*Pisum sativum L.*) has a production area of 7,238,123 ha, being the fourth annual legume after soybean (*Glycine max* (L.) Merr), faba bean (*Phaseolus vulgaris* L.) and ground nut (*Arachis hypogea* L (FAOSTAT, 2011; Yirga et al., 2013). In Ethiopia, it ranks fourth both in terms of area coverage and total production after faba bean, haricot bean and chick pea (Yirga et al., 2013). According to (CSA, 2011), *p.sativum* accounts for 13% of total grain legume production in Ethiopia covering over 203,990.64 ha producing 257,031.41 tons.

Pisum abyssinicum is known locally as Dekoko (minute seed) in Tigrigna and in Amharic as Yagere Ater (pea of my country) or Tinishu Ater (the smallest pea) (Yirga et al., 2013). It has the potential to produce up to 1.95 t ha^{-1} under good agronomic management and it has a high market price (doubles other pulses) and is highly preferred for food (Yemane and Skjelvåg, 2002). Due to its high nutritional value, farmers and consumers refer to it as "Dero-wot of the poor" meaning chicken stew of the poor. The annual consumption of field peas in Ethiopia, including dekoko per person stands at an estimate of 6-7kg (Messiaen et al, 2006; Sentayehu, 2009; Yirga et al., 2013). Just like lentil, dekoko also has a variety of ways it is consumed, as stew, soup and at times mixed with other pulses.

2.4.0 Intercropping, a global perspective

Even though there is no documented history for intercropping and multiple cropping, however, considering the available evidence planting two or more crops in a combined way has a long history (Mousavi and Eskandari, 2011). Traditional farmers throughout the world practiced different methods of intercropping (Lithourgidis et al., 2011), in fact, farmers have grown several crops in combination with one another for hundred years and intercropping probably represent some of the first farming systems practiced (Plucknett and Smith, 1986, Lithourgidis et al., 2011).

Earliest scientists believed that wheat, barley, and certain pulses could be planted at various times during the growing season often integrated with vines and olives, indicating knowledge of the use of intercropping (Papanastasis et al., 2004). In the United States and Europe, growing more than one crop in the same field was common practice as early as 1940s (Kass 1978; Andersen 2005; Machado, 2009). At present, many smallholder farmers in the tropical parts of the world practice intercropping (Altieri, 1991, Machado, 2009), most of these farmers have restricted access to inorganic fertilizers mechanized farming.

For instance, in Africa, corn (*Zea mays* L.), sorghum (*Sorghum bicolor* L.), or millet (*Panicum* and *Pennisetum* spp.) are intercropped with pumpkin (*Cucurbita* spp.) cowpeas (*Vigna unguiculata*), pigeon peas (*Cajanus cajan)*, or beans (*Phaseolus* spp.), as reported by Machado (2009); Cocoa (*Theobroma cacao* L.) is commonly grown with yams (*Dioscorea* spp.) or cassava (*Manihot esculenta* Crantz). In the tropical Americas, according to this source, maize (corn) is grown with beans and squash (*Cucurbita* spp.). In Africa, intercropping is practiced as a part of traditional farming systems (Dakora, 1996; Machado, 2009), commonly implemented due to declining land sizes and food security needs by smallholder farmers who lack the capacity to acquire inputs.

2.4.1 The status of intercropping in Ethiopia

In Ethiopia, the farmers predominantly practice a mixed crop-livestock kind of farming, which are done on small pieces of land ranging from 0.5-4.0 ha. The production of crop and livestock has been closely integrated and they complement each other as livestock provide labor for crop production whereas the crop residues provide 10-50% of livestock feed demand (Daniel, n.d.). Wheat straw is the dominant source of animal feeds, producing about 1 million tons of residues annually.

Intercropping has been a common practice in smallholder farming systems of Ethiopia, maize (*Zea mays* L.) being used as the main food crop (cereal) and intercropped with different component legumes for different reasons (Alemu and Tikunesh, 2014). However, the integration is not always restricted only to cereal-legumes as some farmers have the tendency of mixing different cereals, an example being maize-wheat or maize-sorghum in some areas. In areas where both crops and livestock farming are practiced, farmers usually integrate food and forage crops (Lulseged et al 1987; Alemu and Tikunesh, 2014). Intercropping wheat with forage legume was reported to improve soil fertility, increase wheat yield by 36%, straw by 21% and total feed availability by 65%over sole wheat (Daniel, n.d.).

Although intercropping is known to be an old system and has been practiced for long, most farmers in Ethiopia have in recent years abandoned the practice as "outdated" and "primitive", and are going for sole cropping (Douglas, 2014). Much as they practice crop rotation to a smaller extent, most farmers have separate fields/plots dedicated for maize, wheat, teff and legumes like faba beans, lentil, and dekoko where they practice continuous cropping, and intercropping has not been a common practice. This according to Douglas (2014) is to some extent has resulted from government and development partners' promotion of monoculture throughout the country. This has resulted in smallholder farmers gradually shifting from the traditional sustainable mixed farming systems to less sustainable continuous and monoculture practices.

Nevertheless, different studies on intercropping in the country have indicated the potential of the "old" system in improving soil fertility, increased crop yields and straw yields for feeding livestock (Daniel, n.d., Alemu and Tikunesh, 2014, Douglas, 2014, Temesgen and Wondimu, 2012). This points out the potential of the system in improving soil fertility, crop yields, and livelihoods of the smallholder mixed farmers in an environmentally friendly way by minimizing the use of agrochemicals like fertilizers. However, to date most intercropping research in the country emphasized mainly on the bigger cereals and the effects of agronomic practices like spacing, planting date, compatibility of different species on yield and yield components. Wheat has been tried with forages and not other food legumes like dekoko and lentil.

2.4.2.0 Types of intercropping

Unlike in sole cropping where only one crop species is planted at a time, intercropping involves planting two or more species at the same time. This can be annual crops intercropped with annual crops; annual crops with perennial crops; and perennial crops with perennial crops intercrop (Eskandari et al., 2009; Ghanbari and Lee, 2003; Keighobadi et al., 2014). The intercropping is categorized into the following four groups (Vandermeer, 1992; Ofori and Stern, 1987; Mousavi and Eskandari, 2011).

2.4.2.1 Row intercropping

Where two or more crops are grown simultaneously and one or more crops are planted in even rows, and one crop or other crops may be grown simultaneously in row or randomly with the first crop.

2.4.2.2 Mixed intercropping

This involves growing two or more crops concurrently with no distinctive row pattern, mainly through broadcasting.

2.4.2.3 Strip-intercropping

Planting two or more crops simultaneously in different strips wide enough to permit different operations like mechanization but narrow enough for the crops to interact.

2.4.2.4 Relay intercropping

Two or more crops are grown simultaneously during part of the life cycle of each. A second crop is planted after the first crop has reached its flowering stage but before it is ready for harvest.

In order to optimize plant density, the seedling rate of the component crops is adjusted below the full rate to reduce competition as a result of overcrowding (Ouma and Jeruto, 2010). The extent of spatial and temporal overlap in the component crops can vary to some extent, but both requirements must be fulfilled for a cropping system to be an intercrop (Lithourgidis *et al*., 2011).

The main concept of intercropping is increasing total output per unit area and time, besides sustainable and equitable utilization of land resources and farming inputs including the workforce (Marer *et al*., 2007; Keighobadi *et al*., 2014).

2.5.0 Cereal Crop-Legume Intercrop

As earlier defined, according to Hauggaard-Nielsen *et al.*, 2008, intercropping is regarded as the practical application of basic ecological principles such as diversity, competition and facilitation in a closed system. It can meet several ecological goals including increasing biological diversity, promoting species interaction and enabling natural nutrient regulation (Hauggaard-Nielsen *et al.*, 2008).

Notably, intercropping also has several related additional benefits; the most important being the achievement of greater yields in a given piece of land through efficient and complementary resource utilization (Lemlem, 2013). Others include reduction of soil erosion (Lithourgidis *et al.*, 2011; Chapagain, 2014), weed suppression, increasing moisture retention (Ghanbari *et al.,* 2010; Chapagain, 2014), maintaining soil fertility (Hauggaard-Nielsen *et al.,* 2009; Chapagain, 2014), and increasing nutrient cycling (Hauggaard-Nielsen *et al.,* 2003; Chapagain, 2014) and biological nitrogen fixation (Bulson *et al*., 1997; Jensen, 1996; Chapagain, 2014), which are long-term; and there are also short-term benefits as increasing crop yield and quality (Malezieux *et al*., 2009; Šarūnaitė *et al.,* 2010).

It provides an opportunity for farmers to improve agriculture through increased production (Hauggaard-Nielsen *et al*., 2007; Chapagain, 2014), enhanced soil conservation (Lithourgidis *et al.,* 2011) and significant labor savings among other benefits. Typically, the different components of intercrop range from different species or families with one crop of primary importance (e.g., food) and the other primarily provide some other benefit (e.g., N_2 fixation or livestock feeds). An effective intercrop combination is one that produces greater total yield on a piece of land and uses resources more efficiently than would otherwise be used when each crop is grown as a monoculture (Inal *et al*., 2007; Chapagain, 2014).

Cultivation of mixed crops also increase protein content in the seeds of cereal component increases the yield of crude protein in the biomass and increases the content of this component in the yield of the seeds mixture (Staniak *et al*., n.d). Mixtures of legumes with cereals may be used for the production of fodder for monogastric animals (pigs and poultry), if they are grown for seeds, because of the increased protein content compared to the grains of sole cereals. In turn, if they are cultivated for green forage, they provide valuable roughage for ruminants.

Intercropping in small grain cropping systems, (e.g. wheat) is being assessed with beans as a group of valuable legume species (Ghanbari-Bonjar and Lee, 2002; Gooding *et al.*, 2007; Haymes and Lee, 1999; Pristeri *et al.*, 2006; Chapagain, 2014). Other legumes used as an intercrop in sustainable wheat and barley production, according to Chapagain, 2014 include pea, (*Pisumsativum* L.; Ghaley *et al*., 2005; Subedi, 1997), lentil, (*Lens culinaris* L.; Dusa, 2009) and red clover, (*Trifoliumpratense* L.; Blaser *et al*., 2006).

The integration of a non-leguminous cereal (i.e., wheat, barley) with a leguminous species (i.e., bean, pea) can provide multiple benefits over monoculture production (Ofori and Stern, 1987; Trenbath, 1974; Chapagain, 2014) since legumes improve soil fertility through the legume-rhizobia nitrogen fixation. Therefore, growing small grains with grain legumes will help to improve soil fertility and yields in arid and semi-arid areas, a case of Ethiopia where the soils are severely degraded with low productivity.

Most research studies on wheat intercrop have included pea, and a few studies assessed common bean (*Phaseolus vulgaris* L.) or faba bean (*Viciafaba* L.) in temperate and tropical regions. However, the use of species that are used as livestock feeds, such as Lablab (*Lablab purpureus* L. Sweet) and Alfalfa *(Medicago sativa)* in the semi-arid and arid context is yet to be investigated and documented. Similarly, most of the previous research on intercropping systems has only assessed traditional performance metrics i.e., yield, disease and pest pressure, crop competition, and weed control (Ghaley *et al*., 2005; Gooding *et al*., 2007; Hauggaard-Nielsen *et al.*, 2003; 2009; Jensen, 1996; Lauk and Lauk, 2008; Subedi, 1997; Chapagain, 2014). However, there is also need to assess and measure the qualities related to environmental sustainability, use of supplementary irrigation and also predict the effects of this system in the face of the ever changing climatic conditions, with the use of appropriate tool for crop modeling and simulation.

2.5.1 The role of Cereal-Legume intercropping in improving soil fertility

The biological process of atmospheric nitrogen fixation by the bacteria of *Rhizobium* and *Bradyrhizobium* that live in symbiosis with legumes has great significance for agriculture (Staniak *et al*., n.d). However, the management of Nitrogen as an essential nutrient in small grains production is mainly challenging for farmers due to the witnessed escalations in inorganic fertilizer prices, emission of nitrous oxide (N_2O) from these fertilizers, and their potential to contaminate ground and surface water sources (Ferguson *et al*., 1999; Chapagain, 2014). Proper nitrogen management, therefore, is crucial in improving soil quality, environmental sustainability, and incomes from crop production. It is therefore important to understand crop nitrogen requirements and the amount of nitrogen present in the system so as to supply optimum N levels for gainful yields, while also protecting the environment (Campbell *et al*., 1995; Robertson, 1997; Chapagain, 2014).

In a cereal-legume intercrop, the legume component fixes nitrogen through biological nitrogen fixation (BNF) which helps to fulfill the nitrogen requirement of the companion species through improved soil fertility and the potential transfer of nitrogen through root exudates and root connections. Their green foliage parts and roots also can decompose and release nitrogen into the soil where it might be made available to succeeding crops (Lithourgidis *et al.,* 2011).

In line with the above, studies have shown that in vetch sown with oats, 90% of the total nitrogen uptake (about 53 kg ha^{-1}) comes from symbiosis, while oat uses about 28 kg of mineral N, which is one third of the nitrogen taken together by plants in the mixture (Triboi, 1985; (Staniak *et al.*,n.d). Keighobadi *et al.*, 2014 quoted, according to Sanginga and Woomer (2009); Peoples and Craswell, (1992) that intercropping cereal with grain legume crops such as cowpea, mung bean, soybean and groundnuts helps maintain and improve soil fertility, because these legumes accumulate about 80 to 350 kg nitrogen (N) ha-1. Therefore, cereal –legume intercropping has the possibility of addressing the soil nutrient depletion on small-holder farms (Sanginga and Woomer, 2009; Keighobadi *et al*., 2014).

2.5.2 The role of intercropping on soil moisture conservation and water use efficiency (WUE)

In order to enhance crop yields, soil moisture is a very important component in Agriculture. This is because soil water performs numerous important functions in soils, such as being essential for mineral weathering and organic matter decay and chemical reactions that give rise to soluble nutrients in the plant-soil system other than serving as a medium for nutrient translocation from plant roots (Ofori *et al.*, 2014).

Owing to the above, it is important that for the soil to retain a considerable amount of water after rainfall or irrigation. Therefore in rain fed agricultural systems, soil water infiltration and storage in the root zone determine the overall availability and use efficiency of water in crop production (Hsiao *et al*., 2007, Ofori *et al.*, 2014), and according to Ofori *et al.* (2014); Rockström *et al*. (2003), improving agricultural production will depend on efficient capture, management and use of rainwater resources. According to Hook and Gascho (1988); Matusso *et al*. (2014), improving the water use efficiency will lead to increases in resource use efficiency in this system.

Cereal-legume intercropping has been identified to conserve water largely because of early high leaf area index and higher leaf area (Ogindo and Walker, 2005, Ofori *et al.*, 2014). Zhang *et al.* (2012) reported that intercropping systems may possibly promote the full utilization of cropland water by plant roots, increase the water storage in root zone, reduce the inter-row evaporation and control excessive transpiration, and create a special microclimate beneficial to the plant for growth and development.

On the other hand, a research conducted by Ghanbari *et al*. (2010) indicated that the soil moisture content in the soil was dramatically reduced in the sole crop of maize than in the intercropped field, and on the contrary soil moisture content in the soil was high in the sole crop of cowpea due to high evapotranspiration potential in maize than in cowpea. Based on the above statements and evidences, intercropping of cereals with legumes may have a high contribution to the soil moisture conservation by providing adequate soil coverage and minimizing evaporative water loss hence resulting in high water use efficiency by the component crops, resulting to higher yields.

Agronomists define water use efficiency as the crop yield per unit of water consumed. Regardless of its definition, the growing shortage of and competition for water resources for agriculture is pressing us to design more water efficient production systems, especially for rainfed locations (Chapagain, 2014). This can be achieved by adopting crop management practices that lessen evapotranspiration, surface run-off and drainage, and by effective nitrogen management that stimulates rapid early crop growth that shades the soil thereby reducing additional evapotranspirative losses (Gaiser *et al*., 2004, Chapagain, 2014), and through breeding and selection to acquire more biomass for improved crop transpiration efficiency. Intercropping improves the production system's WUE as it increases water uptake and storage in root zones through the presence of diverse root systems, and reduces inter-row evaporation and excessive transpiration by promoting crop growth that shades the soil creating a protected microclimate (Zhang *et al*., 2012).

Chapagain, (2014) reported that the inherent WUE of wheat is improved when grown with common bean in an intercrop. Matusso *et al*. (2014) also cited in Garba and Renard (1991) that the continuous pearl millet/forage legume system was the best in terms of production and water use efficiency. Hulugalle and Lal (1986) also established that water use efficiency in a maize-cowpea intercrop was higher than in the sole crops, when soil water was not limiting. However, under water limiting conditions, this higher WUE in the intercrop compared to sole cereal can result in retarded growth and reduced crop yield (Ofori and Stern, 1987, Matusso *et al*., 2014). Therefore generally, improves the soil water retention capacity, water storage at the root zone and improves the water use efficiency of the crops, and therefore within the limited water resources, high yields can be achieved by the small-holder farmers.

2.5.3 The Roles of intercropping in minimizing soil erosion.

Soil erosion, the major forms being water and wind erosion the major causes of farmland degradation and desertification in dryland areas by either the effect of rain-splash and runoff of the soil surface layer, or by the effect of the wind. Wind erosion is a very serious problem in cultivated land in many parts of the world both for people and environment (Keay-Bright and Boardman, 2009; Saxton *et al*., 2000).

Intercropping systems help in controlling soil erosion by checking rain drops from striking the bare soil hence preventing them from sealing the surface pores, and reducing surface runoff (Seran and Brintha, 2010, Matusso *et al*., 2014). Kariaga (2004); Matusso *et al*. (2014) established that in maize-cowpea intercropping system, cowpea act as best cover crop and reduced soil erosion than maize-bean system. According to Reddy and Reddi (2007), taller crops act as wind barrier for short crops, in intercrops of taller cereals with short legume crops. Similarly, an intercrop of sorghum and cowpea reduced runoff by 20-30 percent compared with sorghum sole crop and by 45-55 percent compared with cowpea monoculture.

Furthermore, soil loss was reduced with intercropping by more than 50 percent compared with sorghum and cowpea monocultures (Zougmore, Kambou, Ouattara, Guillobez, 2000), as cited by Matusso *et al*. (2014). In Nigeria, the findings from an experiment conducted at 5% slope indicated that soil loss declined from 87 ton/ha/year to 50 ton/ha/year when cassava is grown in sole and intercropped with maize, respectively (Lal, 1984, Kassie, 2011).

2.6.0 Supplementary Irrigation (SI); Aconceptual framework

There are many reasons why we use irrigation but the basic one is to supply crops with water when natural precipitation is not sufficient to satisfy the evapotranspiration demand of the atmosphere (Caliandro and Boari, n.d). This water supply can be permanent or temporal, depending mainly on the rainfall quality and the availability of water for the purpose. According to Caliandro and Boari (n.d), the optimal crop water requirement can be ensured through a temporal irrigation regime in environments where rainfall partially satisfies crop water requirements, as it is the case in arid and semiarid regions where the yearly rainfall is between 500-600 mm and it is concentrated in the rainy season. On the contrary, permanent irrigation regime is used in desert environments, where rainfall can only slightly contribute to crop water requirements.

Therefore in environments where the daily rainfall is adequate to support crop growth, but with frequent dry spells, the stable optimal crop water requirement can be ensured through a temporal and discontinuous provision of water, also referred to as supplementary irrigation. Supplementary is irrigation thus defined as the application of a limited quantity of water to the crops when rainfall is inadequate to meet plant growth and increased yield requirements (Owesis *et al.,* 1999). The quantity and timing of SI are not aimed to provide the crops a water stress-free condition over the growing season, but to provide adequate water during the critical growth stages to ensure optimal yields per unit of water used (Oweis 1997; Owesis *et al.,* 1999).

The three major effects of Supplementary Irrigation are yield improvement, stabilization of production over time (increasing reliability) and it also provides suitable conditions for economic use of other technology inputs, like improved varieties, fertilizers, and herbicides, irrespective of seasonal rainfall.

2.6.1 The need for, and status of supplementary irrigation in the study area

Rainfall is the primary source of water for agricultural productivity in Ethiopia. For the last three decades, there has been erratic occurrence of rainfall in Ethiopia which immensely affected the country's economy and food production (Araya and Stroosnijder, 2011). This rainfall variability has been reported to be a major cause of insufficient food production and food insecurity in the country (Awulachew *et al.,* 2005).

Even when there is adequate rains during crop growth, the yields still remains low, perhaps due to the early cessation of the rains during the yield formation stages. This may also be attributed to the poor water holding capacity of the soils due to the shallow nature and low organic matter content. In other words, rainfall is always insufficient during high growth demand stages, furthermore, Tesfaye (2004); Bello (2008) observed that water shortage in crop production is as a result of water scarcity and mismatches with its crop demand. Thus, a well-planned and timely application of supplementary irrigation will moderate the effect of terminal water shortages in the country and increase agricultural yields and food sufficiency in the country.

In Tigray region where more than 80 % of agriculture is rainfed, crop failure mainly results from the frequent dry spells of about 10 days long, as well as a shorter growing period due to the late onset and/or early cessation of rainfall (Segele and Lamb, 2005; Araya *et al.,* 2010). This problem extremely reduces crop yields, especially when the available rainfall does not meet half of the crop water demand (Doorenbos and Kassam, 1979; Araya and Stroosnijder, 2011).

Since the rainy season in the region starts in early July and ends in early or mid-September, crops are normally subjected to water stress during the critical growth stage, hence the need for supplementary irrigation if potential yields are to be realized in the highlands of Tigray. Different studies have reported that application of irrigation water at critical growth stages of crops result in higher yields. According to Caliandro and Boari (n.d), wheat yields greatly increase when irrigated at the booting stage.

In general, studies have shown that rainfed agriculture with supplementary irrigation significantly increases crop yields. For instance, a study conducted in Mekelle, Tigray showed that supplementary irrigation increased the yield of maize by around 50% (Bello, 2008). Similarly, Allam *et al*. (2007) reported that a double application of supplementary irrigation increased the yield of lentil by 72.7% over that grown under rainfed in the west cost of Libya.

CHAPTER 3: MATERIALS AND METHODS

3.1 Description of study area

The field experiment was conducted at Mekelle University Main Campus, Southern Tigray in Northern Ethiopia (Figure 4.1). Mekelle is located at a longitude of 13^0 $30^{'}$N and latitude of 39^0 $29^{'}$E and on altitude ranging from 2100-2600m above sea level (Solomon, 2001). It is located around 780 kilometers north of the Ethiopian capital, Addis Ababa. This area is characterized by a highly variable bimodal type of rainfall,70–80% of which falls in between June–September, also referred to as *Kiremt* season (Araya *et al*., 2010). The study area receives between 400mm and 700 mm of rainfall annually with an average temperature of 18.8^0C (NMA, 2004).

The growing season in the study area starts in early July and ends in early to late September, rainy period being a maximum of 80 days (Araya *et al*., 2010; Araya and Stroosnijder, 2010), and more than 95% of the farm land is cultivated without irrigation. Farmers in this area practice mixed crop and livestock farming and the major crops grown are wheat, teff, sorghum, chickpea and barley (Araya and Stroosnijder, 2010), and soil fertility is deteriorating besides the soil being shallow (<0.5m) and with poor water-holding capacity.

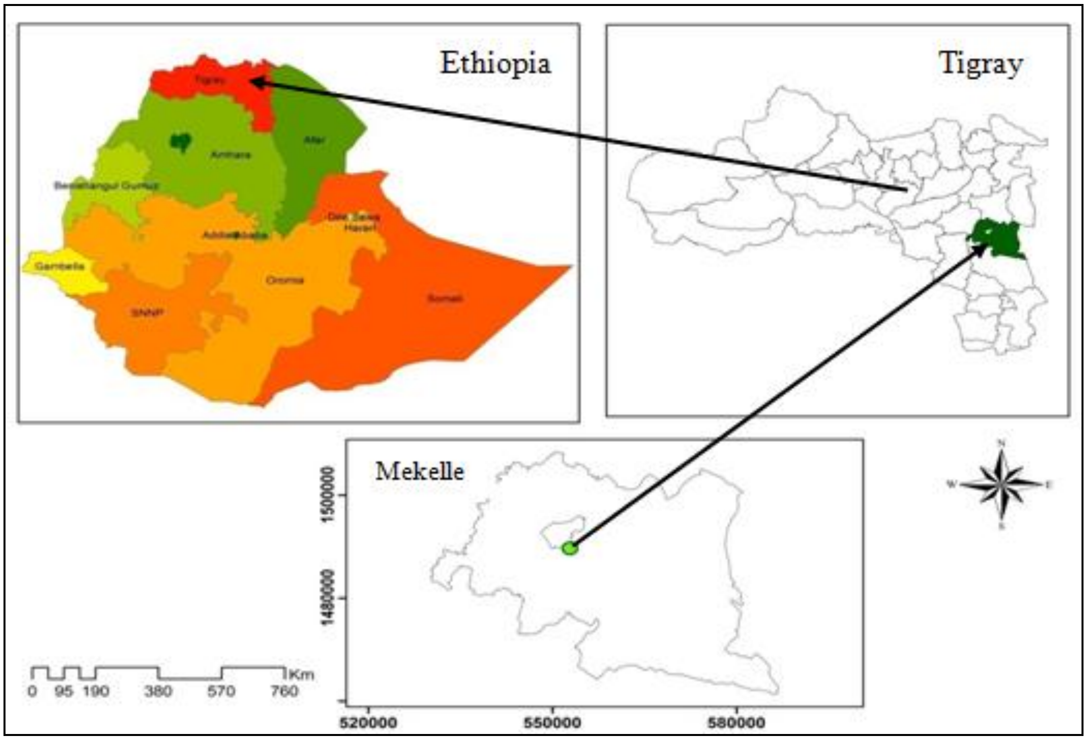
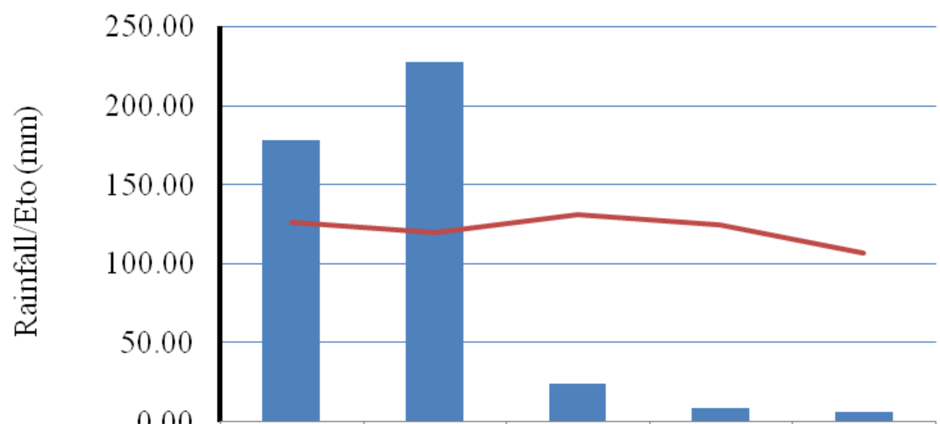


Figure 4.1: Location of the study area



	Jul	Aug	Sep	Oct	Nov
Rainfall(mm)	178.39	227.06	24.48	8.87	6.49
Eto (mm)	126.73	119.84	131.28	124.94	107.09

Figure 4.2: Rainfall and reference evapotranspiration (ETo) of Mekelle Airport from 1991-2010 (Source: EMA, 2010).

3.2 Soil sampling and site description

Five random soil samples were collected at 30 cm depth from each treatment plot (7.2 m^2) before planting at the time of plot establishment. The samples were then reduced to a working sample size (100 g) analyzed differently in the laboratory at Mekelle Soil Laboratory to characterize soil physical and chemical properties (Table 3.1). Another soil sample was taken at planting using core sampler to determine the moisture content. Soil samples were also taken from the respective plots after harvest and analyzed for the same physiochemical properties.

Table 3.1 Analyzed soil characteristics and method of analysis.

Soil Parameters	Methods	References
Soil Texture	Hydrometer	FAO (2008)
Soil Organic matter	Volumetric method	Walkley and Black, (1934)
Soil pH	pH meter	Von Reeuwijk, (1992)
EC	1:2.5 water suspension	Jackson, (1967)
CEC	Ammonium acetate	Chapman, (1965)
Total Nitrogen	Micro-Kjeldahl	Jackson, (1962)
Available Phosphorus	Olsen	Olsen, (1954)

3.3 Experimental details

The study was laid in a 5 x 2 factorial experiment in a split-plot design where intercropping treatment were assigned in the main plots and supplemental irrigation treatments to the sub-plots. The site was laid into blocks measuring 6.5m x 20.5m. The block was divided into two sub-plots measuring 20.5m x 3m and each sub-plot into treatment plots measuring 2.5m x 3m. The treatment was then assigned to the treatment plots in three replications.

Bread wheat (*Triticum aestivum* L.) variety Mekelle-01/HUW-468 was obtained from the Tigray Agricultural Research Institute (TARI); dekoko (*pisum sativuum var. abyssinicum)* variety Raya-01, was sourced from Alamata Agricultural Research Centre, Tigray and lentil (*Lens culinaris*) was sourced from farmers in Mekelle area. The planting details are listed below (see Table 3.1 below). Bread wheat was used as a principal crop and intercropped with both dekoko and lentil. A sole stand of each crop types were planted for comparison of the two cropping systems. All the grain legumes were grown in dual intercrop with wheat in raw planting, with alternating rows of wheat and legumes sown at the same depth at a ratio of 1:1. The treatments were arranged as follows;

i. Pure stand wheat (*Triticum aestivum* L.),
ii. Pure stand dekoko (*psium aestivum var. abyssinicum*),
iii. Pure stand lentil (*Lens culinaris* Medik),
iv. Single row wheat (*Triticum aestivum* L.) alternating with single row of dekoko (*psium aestivum var. abyssinicum*)
v. Single row wheat (*Triticum aestivum* L.) alternating with single row of lentil (*Lens culinaris* Medik)

Table 3.2 Different cultivars used in the experiment, sowing details and their sources

Crop	**Variety**	**Seeding rate (kgha^{-1})**	**Source**
Wheat	Mekelle-1	125	TARI
Pea (Dekoko)	Raya-1	150	Alamata Agricultural Research Center
Lentil	-	25	Farmers' stored seeds

3.4 Seedbed preparation and sowing

The seedbed was ploughed three times using the farmers’ practice common in the area. Primary cultivation was done by ploughing using oxen in the first week of June, 2015; secondary tillage to a finer tilth and leveling of the plots were done using hand hoe.

Wheat and legume grain seeds were sown on July 14th, 2015 by hand drilling at a constant depth of 3-4 cm. Wheat seeds were planted at a spacing of 20 cm at the rate of 125 kg ha^{-1} in both pure stand and intercropped plots, while dekoko was planted at the rate of 150 kg ha^{-1} at a spacing of 40 cm x 10 cm. Lentil seeds was planted at the rate of 25 kg ha^{-1} by drilling. The space between the rows of wheat and any of the legume rows was 20 cm. A recommended amount (i.e., 100 kg/ha) of DAP and Urea was applied to all treatments, full doze of DAP at planting, and Urea in two splits; at planting and at tillering stage.

3.5 Supplementary irrigation

A supplementary irrigation was applied to each of the replications from booting stage till physiological maturity during the dry periods to avoid water stress. Since not all the rainfall received is consumed by crops due to losses by vegetation interception, runoff and deep percolation among others, in this study, the effective rainfall was considered in the calculation of net irrigation (In). The net irrigation requirement for the mid and late season was computed by considering the mean crop water requirement (ET_{crop}) for wheat and the dependable rainfall (P_{eff}) using the formulae (Eqn. 1, 2 and 3).

$$ETcrop = ET_o \times K_c \quad \text{………………………………………..(Eqn. 1)}$$

Where; ET_{crop} = Crop evapotranspiration (mm)

ET_o = Reference evapotranspiration for the area (mm)

K_c = Crop coefficient (mm);

The effective rainfall was calculated using the USDA SCS empirical formula, given as;

$P_{eff} = P_{tot}(125-0.2P_{tot})/125$ – for $P_{tot}<250$mm/month, and

$P_{eff} = 125+0.1P_{tot}$ __for $P_{tot}>250$mm/month ...………………..(Eqn. 2)

And $I_n = ET_{crop} - P_{eff}$ ……………………………………(Eqn. 3)

Where;- I_n = Net irrigation (mm)

P_{eff} = Effective rainfall (mm)

Basing on the above calculation, 135 mm of irrigation water was applied to the irrigated subplots from booting stage till physiological maturity was attained. Supplementary irrigation was applied by use of pressure pipes at a pre-determined time interval per plot. Water losses by runoff and deep percolation was minimal, therefore an efficiency of 90% was considered for this method due to the precise water delivery and this value was used to determine the gross water requirement (GWR), using the following equation;

$$\mathrm{GWR} = \frac{\mathrm{NWR}}{\mathrm{Ea}} \quad \text{………………………………………(Eqn. 4)}$$

Where;- GWR = Gross water requirement (mm)

NWR = Net water requirement (mm)

Ea = Irrigation efficiency (%)

To quantify the degree to which the major phenological and yield attributes varied and the degree of association between any two variables or how they affected each other, a bivariate linear correlation (r) was performed for these major yield determining traits. It was assumed that the difference in the water regimes could affect differently the relationship between the yield and yield traits, thus a separate correlation was done for rainfed and irrigated conditions.

3.6 Data collection and analysis

The data collected in the research includes soil data and plant-based phenological and yield and yield components data. Soil samples were taken from pre-planting and postharvest according to the procedures described in section 2. Plant-based data was collected from germination to harvest maturity. The recorded data included the following;

3.6.1 Phenological data

i. Days to 50% germination and 50% flowering scored per plot basis.
ii. Days to 50% heading was recorded when 50% of spikes pop out in 50% of the plots
iii. Days to 90% physiological maturity of all the crops was recorded as the number of days taken by the crops from the date of planting to the date when 90% of the plants in each plot were at physiological maturity.

3.6.2 Growth and yield parameters

i. Plant height was determined by measuring in centimeters (cm) from ground level to the tip of the awn from five randomly selected plants for both wheat and the legumes.
ii. Number of effective/productive tillers was taken from five randomly selected plants by counting the number of headed tillers per stand excluding the main plant.

iii. Spike length was measured from the base of the panicle to its tip using meter rule.
iv. Number of spikelets per spike of five randomly selected plants was done by counting.
v. Number of seeds per spike was counted from five randomly selected plants.
vi. For legumes, the number of pods per plant and pod length (cm), number of seeds per pod was also taken from ten (10) randomly selected plants.
vii. Above ground biomass yield (t/ha), grain yield (t/ha) and thousand grain weight (g) were also taken from the harvested net plot area.

Maturity for wheat was determined by the spike color and was considered matured when the spikelets turned straw-colored with 80 percent of grains in hard dough stage, while the legume grains were considered matured when the leaves turned yellowish-brown and pods start to dry at the tip. Destructive sampling was done for the legumes for nodule counting and examination. The crop biomass and grains were sun-dried and threshed before taking grain yield data. The grains were adjusted to 12.5 % moisture content before weighing.

3.6.3 Legume nodulation

Legume nodulation was assessed by examination of the roots of ten (10) randomly selected plants from each plot at 30 and 70 days after sowing (DAS) (Chapagain, 2014). The parameters measured included earliness, total number, color and distribution of the root nodules. The nodulation was then scored visually as described in Appendix 8. Scores ranging from 0-5 were assigned basing on nodule number, size, color and distribution as described by Corbin et al. (1977). These were then averaged to obtain the mean nodule score per treatment.

3.7 Competition indices

To establish the benefit of intercropping system and the effect of interspecific competition between the intercropped species, land equivalent ration (LER), Land Equivalent Coefficient (LEC) and the relative crowding coefficient (K) were calculated. This was calculated using the grain yield of the wheat and the component crops grown under the two different water regimes. These mathematical indices can be used in intercropping trials to summarize and provide an interpretation from inter-plant competition,

3.7.1 Land Equivalent Ratio

LER was used as the first criteria to show the advantages of sole and mixed cropping over the other among the different species (Willey 1979). It is used to show the effectiveness of intercropping in resource utilization in the environment in comparison with monocropping (Mead and Willey 1980). In other words, LER can be used to indicate complementarities among species in the intercrop (Yayeh et al. 2014). A unitary value of LER is the reference value. LER value greater than one indicates that intercropping is advantageous over sole cropping in terms of growth and yield of both species. A value of LER less than one, indicates the negative effect of the interaction on the species in the mixture (Ofori and Stern, 1987). Therefore, LER was calculated according to (Willey and Osiru, 1972), as;

LER = LER Wheat (A) + LER Legume (B);

where, LER wheat = $\left(\frac{Y_A I}{Y_A S}\right)$ and LER Legume = $\left(\frac{Y_B I}{Y_B S}\right)$

Where Y_AI and Y_BI are yields of wheat and legume in the intercrop respectively while Y_AS and Y_BS are the sole crop yields of wheat and the legumes respectively.

3.7.2 Land Equivalent Coefficient (LEC)

Land equivalent coefficient (LEC), a measure of interaction concerned with the strength of relationship in terms of mixture productivity. LEC, also referred to as Productivity coefficient (PC) was used because it is a more superior index for the evaluation of a crop mixture performance. For a dual-crop mixture the minimum expected productivity coefficient (PC) is 25%,i.e. a yield advantage is obtained if LEC value exceeds 0.25.

It was calculated as,

$$LEC = La \times Lb$$

Where, L*a* = LER of main crop and L*b* = LER of intercrop (Adetiloye *et al*.,1983).

3.7.3 Crowding Coefficient (K)

Furthermore, relative crowding coefficient was one of the indices used in the computation of competition effect of intercropping. Crowding coefficient is used to measure the relative dominance of one species over the other in multiple cropping (Banik et al., 2006). In order to determine the dominance of the different species, when the value of K is greater than 1, there is a yield advantage, when K is equal to 1, it indicates no yield advantage and K values less than one shows a disadvantage of intercropping.

Therefore, by considering species "a" and "b" for the legumes and cereals respectively intercropped in the ratio 1:1, the relative crowding coefficient K was formulated as follows (De Wit 1960);

$$Kab = \frac{\mathrm{Yab}}{\mathrm{Yaa-Yab}} \quad \text{and} \quad Kba = \frac{\mathrm{Yba}}{\mathrm{Ybb-Yba}}$$

where K = relative crowding coefficient

Kab = relative crowding effect of the cereal-legume intercropping

Kba = relative crowding effect of the legume-cereal intercropping

Yab = yield of cereal intercropped with the legumes

Yba = yield of legumes intercropped with cereals

Yaa = yield of the cereal in monocropping

Ybb = yield of the legume in monocropping

3.8 Economic benefits of intercropping

The economic advantage of the intercropping system was calculated to give information of the economic benefits of intercropping using monetary advantage index (MAI). This is because the LER simply give the yield advantage of intercropping over sole cropping but it does not provide for comparison of economic benefits of the system. Therefore the economic advantage of the cropping systems was compared as below:

The economic advantage, monetary advantage index (MAI) was calculated as:

MAI = (value of combined intercrops) x (LER - 1) / LER.

The higher MAI value will indicate more profitable cropping system over the other (Muhammad *et al.*, 2008).

3.9 Data analysis

The collected data was analyzed using GenStat Release 14th Edition (Payne et al., 2014), according to standard analysis of variance procedures (Gomez and Gomez, 1984) and least significant difference (LSD) test at 5% probability level to compare the treatment means. Bivariate correlation was used to test the relationship and significance between the selected treatment parameters.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Soil physical and chemical properties

The values revealed from the analysis are listed below (Table 4.1). In accordance with the soil particle size analysis, sand (57%), silt (25%) and clay (28%), the soil can be classified as sandy clay loam with very low organic matter (0.04%). This indicates that the soil was severely degraded, with low ability to hold nutrients, especially nitrogen. The soil has low fertility as confirmed by the low amount of total nitrogen (0.056%) and 5.78 ppm of available P. It had a neutral pH (7.0) and was quite homogeneous. The cation exchange capacity (CEC) of the soil was very low (1.2 meq/100g), implying that the soil has very low resistance to changes to soil chemical properties inflicted by changes in land use (Hazelton and Murphy, 2007). The site was sown with sole wheat in the previous season and the record of any fertilizer used was not available.

Table 4. 1. Soil physical and chemical properties

Parameter Determination	Unit	Quantity	Status
Physical analysis			
Sand	%	57	-
Silt	%	25	-
Clay	%	28	-
Soil texture (class)	-	-	Sandy clay loam
Chemical analysis			
Soil pH	-	7.010	Neutral
Electrical Conductivity	ms/cm	0.220	Negligible
Cation Exchange Capacity	meq/100g	1.200	Very low
Soil Organic matter	%	0.040	Extremely low
Soil organic carbon	%	0.023	Extremely low
Total N	%	0.056	Low
Available P	Ppm	5.780	Low

Soil data analyzed at Mekelle Soil Research Center

Table 4. 2. The effect of intercropping on soil total nitrogen and available phosphorus.

	Sole Wheat		Sole Lentil		Sole Dekoko		Wheat+Dekoko		Wheat+Lentil	
Chemical properties	Before	After	Before	After	Before	After	Before	After	Before	After
Total N	0.056	0.058	0.056	0.08	0.056	0.068	0.056	0.068	0.056	0.07
Available P	5.78	6.18	5.78	10.5	5.78	6.86	5.78	13.34	5.78	10.3

Intercropping had a significant positive effect on soil chemical properties (Table 4.2). The soil nitrogen and phosphorus levels were seen to slightly increase with intercropping in reference to sole wheat. This could be as a result of nitrogen fixation by the legumes as induced by competition for the available nitrogen in the soil (Chapagain, 2014). For this reason, pea was shown to fix 9-8% in barley intercropping which was reported to promote pea's reliance on the symbiotic N-fixation (Chapagain and Riseman, 2014). Thus intercropping small cereals with legumes offers better opportunities of complementary nitrogen use under low input farming systems without compromising yield.

4.2 The phenology of wheat and legumes as affected by intercropping and supplementary irrigation.

The response of wheat and component legumes on the major phenological parameters as affected by intercropping and supplementary irrigation treatments are shown (Table 4.3). Generally, the results of ANOVA (Appendix 1) has shown that whereas days to 90% physiological maturity was significantly affected by both intercropping and supplementary irrigation, the days to emergence and 50% flowering were not significantly affected by application of supplementary irrigation (Table 4.3). The maximum days to emergence of 10.33 and 1.13 days were recorded in sole lentil and sole dekoko treatments with no statistical difference. The lowest number of days (8) was recorded in both sole wheat and wheat dekoko treated plots. From the results, it was shown that the legumes took more days to emergence compared to wheat. The greatest number of days to 90% emergence under supplementary irrigation was 8 days.

The days to 50% flowering was highest (54.33) in wheat intercropped with lentils whereas sole dekoko took the least (36.17) days to flower. Whereas supplementary irrigation had no significant effect on the days to 50% flowering. The most probable reason for maximum days under wheat-lentil intercropping could be as a result of moisture conservation by the legume due to its bushy growth habit at the lower sphere of wheat.

The results of this study showed that the days to 90% physiological maturity was maximum (83.17) in wheat intercropped with lentil and the least number of days (66) was registered in sole dekoko. Generally, intercropping was shown to increase the number of days to maturity for moth the legumes and cereal species. This could be as a result of moisture conservation due to the reduced soil water evaporation provided by the legumes in the intercropped treatments and reduced the severity of moisture stress. Supplementary irrigation generally gave the maximum days to maturity (79.2) as compared to rainfed conditions (Table 4.3). The possible reason for this could be a result of prolonged grain filling as a result of sufficient moisture enhanced by the additional water.

By considering the effects of the interaction between the treatments, the maximum days to 50% flowering under rainfed condition (54 days) was attained when wheat was intercropped with lentil (Table 4.3), whereas the lowest was recorded in sole dekoko, which took only 36 days to 50% flowering. The same trend was recorded with the application of supplementary irrigation. This can be attributed to the difference in the physiology of the two species concerning water imbibition and germination process since there was no moisture difference at this stage. Wheat intercropping with lentil registered the highest number of days to 90% physiological maturity (79.67) under rainfed conditions as compared to the lowest (63) days under sole dekoko. With application of supplementary irrigation, the interaction with wheat-lentil intercropping also produced similar results, taking longest (86.67) days to 90% physiological maturity. Sole dekoko matured earliest (68 days) under supplementary irrigation.

Table 4. 3. The effects of intercropping and supplemental irrigation on the phenology of wheat and component legumes

Treatment	Days to 90% emergence	Days to 50% flowering	Days to 90% physiological maturity
Cropping system			
Sole wheat	8.00[b]	53.17[b]	81.67[b]
Sole lentil	10.33[a]	46.42[c]	68.67[c]
Sole dekoko	11.17[a]	36.17[d]	66.00[d]
Wheat + Lentil	7.83[b]	54.33[a]	83.17[a]
Wheat + Dekoko	8.00[b]	53.00[b]	81.50[b]
SEm±	0.28	0.40	0.34
$LSD_{0.05}$	0.91	0.91	0.77
Water regime			
Rainfed	8.00	48.47	73.2
Supplemental irrigation	7.89	48.77	79.2
SEm±	0.23	0.42	0.14
$LSD_{0.05}$	0.39	0.93	0.32
CV%	5.3	2.4	0.5

Means followed by same letters are not statistically significant (Duncan 5%); S = Significant at $p < 0.05$ probability levels; NS = Non Significant; CV = Coefficient of variation; LSD = Least Significant Difference; SEm = Standard Error of mean

The interaction of intercropping and supplementary irrigation had no significant effect on the days to emergence and 50% flowering. However, the effect of this interaction on the days to 90% physiological maturity was significant (Table 4.4). Wheat took the highest number of days (86.67) to reach 90% physiological maturity when intercropped with lentil under supplementary irrigation, while the sole stand matured earlier under rainfed condition (79 days). Generally, intercropping extended the number of days for wheat to reach physiological maturity and as well supplementary irrigation for both wheat and the component legumes. Possible reasons could be the availability of extra moisture that enhanced further vegetative growth that slowed senescence.

Table 4. 4. The interaction effects of intercropping and supplementary irrigation on the phenology of wheat and component legumes.

Treatments	Rainfed	Supplementary irrigation
Days to 50% flowering		
Sole wheat	53.33	53.00
Sole lentil	46.67	46.17
Sole dekoko	36.00	36.33
Wheat + lentil	54.00	54.67
Wheat + dekoko	52.33	53.67
Days to 90% physiological maturity		
Sole wheat	79.00	84.33
Sole lentil	65.00	72.33
Sole dekoko	63.33	68.67
Wheat + lentil	79.67	86.67
Wheat + dekoko	79.00	84.00

4.3 The effects of intercropping and supplementary irrigation on growth, yield and yield components of wheat and component legumes.

4.3.1 Plant height

The results from AOVA (Appendix 2) showed that there was a highly significant variation in plant height between the wheat and the legume species. The growth height of wheat was also affected differently by intercropping according to the legume species it was intercropped with. Wheat generally produced taller plants in intercropping as compared sole cropping. The tallest wheat plants (69.63 cm) were registered in wheat-lentil intercropping whereas sole wheat produced the shortest plants (59.43 cm). Dekoko produced taller plants than the lentils (Table 4.5). Possible reasons for taller wheat plants under intercropping could be a result of moisture conservation by the legumes and competition for sunlight with the leguminous species. These findings are in accordance with that reported by Khan et al. (2005) who reported that leguminous intercropping significantly increased the growth height of wheat when it was intercropped with lentils, canola and chickpea at the same ratio.

Supplemental irrigation also significantly increased the plant height for both wheat and the legumes showing the importance of supplementing rain water in dryland areas. An average plant height of 53.2 cm was recorded under supplementary irrigation compared to 50.31 cm for rainfed conditions. Thus, supplementary irrigation could have promoted more vegetative growth due to sufficient soil moisture. Research results from Egypt by Attia and Barsoum (2013) also showed the increase in plant height and other growth parameters on application of supplemental irrigation. Khourgami et al. (2012) also reported that the application of supplemental irrigation at flowering stage significantly increased the growth height of lentils. This study therefore reveals that lentil is the most preferred legume for intercropping with wheat since its growth is less affected by intercropping.

4.3.2 Biomass yield.

The results from analysis of variance showed that intercropping and supplementary irrigation both had a highly significant effect on the biomass yield of wheat and component legumes. Generally in this study, higher biomass was produced in intercropping than in wheat pure stand. It was shown that higher biomass (2.08 and 1.83 t/ha) was produced in wheat-lentil and wheat-dekoko treatments respectively (Table 4.5). Hence, higher land and biomass productivity was reported in wheat intercropped with lentil. This could be associated to the possibility of the symbiotic benefit from nitrogen fixation by the legumes as well as reduced soil moisture loss. Hellou et al. (2006) attributed this to the fact that that cereals outcompete legumes for soil nitrogen utilization.

Supplementary irrigation also had an increasing effect on above ground biomass. Higher biomass (2.14 t/ha) was registered under supplementary irrigation while rainfed cropping produced 26.7% less. This could be attributed to enhanced vegetative growth and stem elongation due to sufficient moisture and nutrient uptake as was showed by taller plants in irrigated plots. This is in agreement with results by Khourgami et al. (2012) who attributed increased biomass production to increased growth traits resulting from supplementary irrigation.

4.3.3 Grain yield.

In response to the main effects of intercropping and supplementary irrigation, the grain yield of wheat and component legumes were significantly affected according to this study. Similarly, higher grain yields in wheat was obtained in intercropped plots and the least in sole wheat. The maximum grain yield (0.77 t/ha) was registered in wheat intercropped with lentils as compared to 0.59 t/ha in sole wheat. Whereas among the leguminous species, the lowest grain yield (0.29 t/ha) was registered in sole lentil. This could be due maximum competitive ability of wheat and its effective utilization of resources like nutrients and moisture in the environment (Chen et al., 2004) and reduced interspecific competition (Yayeh et al., 2014). Hauggaard-Nielsen et al. (2009) reported that cereals used nitrogen sources 32% more efficiently in intercropping than in monocropping. They further put forward that this could partially be due to the increased acquisition of soil N by the cereal crop which promoted the legumes to rely more on internal N-fixation. In addition, the legumes could have contributed to reduced moisture loss aside of fixing nitrogen. Sarunaite et al. (2009) also reported significant wheat yield increase in a wheat-lupine, wheat-bean and wheat-pea intercropping study. This result also conforms to the study by Yayeh et al. (2014) who reported the cereal yield increase in wheat-lupine intercropping.

Supplementary irrigation generally led to an 81.4 % increase in grain yield compared with rainfed conditions (Table 4.5). This might be as a result of sufficient soil moisture that was availed during the seed setting and grain filling stage, hence facilitating nutrient uptake and assimilate translocation to the major sinks, and producing heavier kernels. In the absence of irrigation, there wheat might have suffered moisture stress that resulted in a remarkable grain yield reduction due to reduced nitrogen uptake from the soil. From this observation, it can be inferred that the booting and grain filling stages of wheat are sensitive to moisture stress and in dryland areas, significant yield increase can be attained by supplying supplementary water at this stage.

Table 4. 5. The effect of Lentil and Dekoko intercropping and Supplemental irrigation on yield components of wheat.

	Yield and yield components				
Treatment	P H (cm)	BMY (t ha^{-1})	GY (t ha^{-1})	TGW (g)	HI
Cropping system					
Sole wheat	59.43^{b}	1.23^{e}	0.59^{d}	26.83^{c}	0.48^{a}
Sole lentil	29.90^{d}	2.80^{a}	0.29^{e}	27.00^{bc}	0.10^{c}
Sole dekoko	39.33^{c}	1.61^{d}	0.73^{b}	24.50^{d}	0.48^{a}
Wheat + Lentil	69.63^{a}	2.08^{b}	0.77^{a}	27.83^{b}	0.36^{b}
Wheat + Dekoko	60.47^{b}	1.83^{c}	0.67^{c}	29.83^{a}	0.51^{a}
SEm$\pm$	0.72	0.08	0.01	0.37	0.02
LSD $_{0.05}$	1.67	0.17	0.02	0.86	0.05
Management					
Rainfed	50.31	1.69	0.43	21.23	0.31
Supplemental irrigation	53.20	2.14	0.78	33.17	0.46
SEm$\pm$	0.47	0.05	0.02	0.30	0.02
LSD $_{0.05}$	1.04	0.10	0.04	0.66	0.04
CV%	2.5	3.5	7.6	3.0	13

Means followed by same letters are not statistically significant (Duncan 5%); S = Significant at p < 0.05 probability levels; NS = Non Significant; SEm = Standard Error of means; LSD = Least Significant Difference; CV = Coefficient of variation; PH = plant height; BMY= biomass yield; TGW = thousand grain weight; GY = grain yield; HI = harvest index

4.3.4 Thousand grain weight (TGW)

From the ANOVA, TGW was shown to be significant ($p < 0.001$) for both intercropping and supplementary irrigation for both wheat and the leguminous species. Intercropping wheat with dekoko gave the highest TGW (29.83 g) while sole wheat gave the least with 26.83 g (Table 4.5). This could be because wheat out competed dekoko for sunlight and other resources and enhanced sufficient grain filling which resulted in heavier grains. On the other hand concerning the legumes, lentil produced heavier weight of a thousand seeds (27 g) compared to dekoko

(Table 4.5). This is in line with Khan et al (2014) who argued that denser canopy in legumes due to intercropping results in the lower TGW.

Supplementary irrigation also increased significantly the TGW and a higher weight of 33.17 g was recorded as compared to rainfed treatment. This shows that the thousand grain weight was increased by up to 57% which was so noticeable and this could be because the availability of sufficient moisture offered favorable conditions grain filling, hence the seeds had larger starch reserves hence higher TGW. The findings above indicate that water is a vital growth requirement during grain filling and show that water stress at this stage can result in significant grain loss.

4.3.5 Harvest index (HI)

The current study revealed that intercropping and application of supplementary irrigation both significantly affected the harvest index of wheat and component legumes at $p < 0.001$ and the same effect was observed from their interaction. Generally, the highest harvest index (0.51 and 0.48) were registered in wheat-lentil, and sole wheat respectively with no statistical significance (Table 4.5). Sole dekoko also produced the highest harvest index (0.48) of the legumes whereas the lowest harvest index was recorded in sole lentil.

Supplementary irrigation also positively affected the HI hence a higher value of 46% was noted as compared to rainfed treatment. This probably was because the crops were not subjected to moisture stress and they experienced continuous growth and yield formation. Since supplementary irrigation led to adequate soil moisture availability for the biomass formation, there was an efficient conversion of biomass to grain yield hence the higher value of HI was recorded.

Table 4 6. Interaction effects of intercropping and supplementary irrigation yield and yield components of wheat and component legumes.

Treatments	Rainfed	Supplementary irrigation
Plant height (cm)		
Sole wheat	53.4	65.47
Sole lentil	28.93	30.87
Sole dekoko	39.2	39.47
Wheat + lentil	68.33	70.93
Wheat + dekoko	61.67	59.27
Biomass yield (t/ha)		
Sole wheat	1.15	1.32
Sole lentil	2.79	2.81
Sole dekoko	1.1	2.13
Wheat + lentil	1.93	2.23
Wheat + dekoko	1.47	2.2
Grain yield (t/ha)		
Sole wheat	0.47	0.7
Sole lentil	0.22	0.37
Sole dekoko	0.62	0.83
Wheat + lentil	0.5	1.03
Wheat + dekoko	0.37	0.97

4.4 Effects of the interaction between intercropping and supplementary irrigation on yield and yield components in wheat based intercropping.

The present study showed that intercropping and supplementary irrigation had significant combined effects on the plant height, biomass yield and grain yield of wheat and the component legumes. From the table (Table 4.6) above, the highest values of the yield and yield components were registered when intercropping interacted with supplementary irrigation.

The greatest plant height for wheat (70.93 cm), biomass yield (2.23 t/ha) and grain yield (1.03 t/ha) for wheat were registered in wheat-lentil intercropping in the presence of supplementary irrigation and the least were in sole wheat under rainfed conditions. However, it was demonstrated that the greatest growth height of wheat in the absence of supplementary irrigation (68.33 cm) was attained in wheat-lentil intercropping. The same intercropping combination also gave maximum values for biomass (1.93t/ha) and grain yield (0.5 t/ha) respectively under rainfed conditions. The possible reason for this is that sufficient moisture from supplementary irrigation enhanced more nutrient uptake, more so the legume component fixed its own nitrogen allowing more nitrogen availability for the wheat. Chapagain and Riseman (2014) reported that intercropping barley with pea increased N-uptake for barley due to competition. However, in the absence of supplementary irrigation, wheat-lentil combination was ideal and this could be attributed to reduced soil moisture loss by the component legume.

4.5 The effect of intercropping and supplementary irrigation on the biological and agronomic yield

In order to compare the maximum yield obtainable per unit area between monocropping and intercropping, a cumulative analysis of variance was done with a combination of total biomass and grain yields per plot. This was instrumental in determining the total grain yield (kg ha^{-1}) that the smallholder farmers can obtain per unit area in either farming practices so as to guide decision making.

The results presented below shows a highly significant ($p < 0.001$) difference in cumulative biomass and grain yield as influenced by intercropping and supplementary irrigation of wheat. According to the table (Table 4.8), the combined biomass yield was highest (5.1 t ha^{-1}) in irrigated wheat-lentil whereas grain yield combined was highest in wheat-dekoko (1.4 t ha^{-1}). Hence it can be observed that intercropping wheat with lentil provided favorable conditions for biomass accumulation compared to monocropping and wheat-dekoko mixtures. This could be explained by the growth habit of lentil at the lower sphere of wheat and did not experience much competition for light and therefore was able to capture optimum light for its biomass accumulation. In other words, there was minimal competition for sunlight and other growth resources between wheat and lentil compared to wheat-dekoko, the latter being more erect in nature hence was almost completely dominated by wheat. Therefore intercropping wheat with lentil in dryland areas could be one of the strategies to increase soil biomass in addition to providing nutritious straws for livestock feeding. This combination is also suitable for rainfed conditions since it gave higher biomass (4.3 t ha^{-1}) in the absence of supplementary irrigation compared to wheat-lentil supplemented with irrigation (Table 4.8). This could be so because lentil acted as a good cover crop and with high biomass fall which maintained a favorable eco-environment for the growth of wheat.

On the contrary, intercropping wheat with dekoko gave a slightly higher grain yield (1.4 t ha^{-1}) than wheat-lentil mixture (1.36 t ha^{-1}) under supplementary irrigation although they were statistically similar. However, under rainfed conditions, the combined grain yield was higher (0.67 t ha^{-1}) in wheat-lentil mixture. This indicates that, in the absence of supplementary irrigation, intercropping wheat with lentils can be a more suitable cropping system for drylands since it has proven to be superior over wheat-dekoko intercropping and monocropping in terms of combined biomass and grain yield. However to maximize yields, it is advisable to supplement this with supplementary irrigation at booting stage of wheat.

Table 4. 7. The interaction effect of intercropping and supplementary irrigation on the total biomass and grain yield of wheat based intercropping with the legumes.

Management	Biomass yield (t ha^{-1})			Grain yield (t ha^{-1})		
	Sole wheat	Wheat + Lentil	Wheat + Dekoko	Sole wheat	Wheat + Lentil	Wheat + Dekoko
Rainfed	0.517e	4.323b	2.323c	0.470c	0.667b	0.650b
Supplemental irrigation	0.833d	5.057a	4.300b	0.700b	1.363a	1.400a
SEm	0.03			0.03		
LSD	0.09			0.08		
CV%	3.1			4.7		

Means followed by same letters are not statistically significant (Duncan 5%); SEm = Standard Error of means; LSD = Least Significant Difference; CV = Coefficient of variation.

4.6. Competition Indices

4.6.1 Land equivalent ratio (LER) and Land equivalent coefficient (LEC)

Generally, the partial LER for wheat (1.06) was higher than wheat in combination with lentil and (1.47) in the case of rainfed and supplementary irrigation compared to wheat-dekoko mixtures (Table 4.8). As shown in the Table 4.8 these values of partial LER for wheat increased with supplementary irrigation and the highest was recorded in wheat-lentil mixture (1.47). This indicates that intercropping wheat with lentil enhanced its effectiveness of resource use to produce the same yield. In other words about 6% more area would be required for sole wheat under rainfed and as high as 47% more area under cultivation with supplementary irrigation to produce the same amount of yield. An advantage in wheat yield in wheat-dekoko mixture was only realized with addition of supplementary water. Conversely, the LER for legumes was higher for lentil in both cases against that of dekoko but generally was lower than 1, meaning that intercropping legumes were disadvantageous on yield than solitary cropping. This could be owed to the high competition by wheat for resources. Accordingly, the total LER was higher in the mixture of wheat and lentil in both water regimes (1.83 and 2.38) respectively for rainfed and supplementary irrigated conditions (Table 4.8) and was generally greater than 1. This showed that intercropping was superior to sole cropping in terms of resource use efficiency and this could be attributed to the mutual complementary resource utilization relationship by the species in the mixtures. Therefore it is worth recommending intercropping in this semi-arid area in order to maximize the use of the scarce land resources. More so, supplementary irrigation could be an important input to enhance the superiority of this system to address the insufficient rain received in these areas.

The present study also showed that LEC was generally greater than 25% in both rainfed and supplementary irrigated treatments (Table 4.8). The results demonstrated that LEC was higher in the mixture of wheat with lentil at 0.82 and 1.34 for rainfed and supplementary irrigated plots in that order. The lowest value of LEC (0.36) was recorded in wheat-dekoko intercropping. As expected, higher LEC values were recorded in supplementary irrigated plots with the highest (1.34) in wheat-lentil intercropping whereas the lowest (0.34) was recorded in rainfed wheat-dekoko intercropping (Table 4.8).

4.6.2 The Relative crowding Coefficient (K)

Lentil and dekoko had higher values of partial K than the intercropped wheat in the wheat-legume mixtures (Table 4.8). The partial K for wheat was much higher (3.55) in wheat-dekoko mixtures under rainfed condition and the lowest partial K for wheat was registered in wheat-lentil mixtures without supplementary irrigation. The total K was greater than 1 in the case of wheat-dekoko intercropping exclusive of supplementary irrigation and it tended to 1 in the same mixture when irrigation was applied. Wheat-lentil mixtures had the lowest values of total K. The results below indicate that lentil generally was more competitive than wheat. This translates to more competitive use of resources by lentils, and since it occupies a lower sphere of the canopy, there was no much competition for light as compared to dekoko which is more erect. It also shows that with supplementary irrigation, dekoko becomes more competitive over wheat, demonstrated by the higher partial K value (1.08) for dekoko.

Generally, comparison using LER and LEC gave similar outcomes while the K values was slightly deviated. Land equivalent Coefficient (LEC) however is a relatively better index since it takes into account the strength of the interaction in terms of mixture productivity.

Table 4 8. The Land equivalent ratio (LER) and Land equivalent coefficient (LEC) for grain yield of wheat - legume intercrop under rain fed and supplementary irrigation.

	Rainfed					**Supplementary irrigation**				
	LER			LEC	K	LER			LEC	K
Treatment	Wheat	Legume	Total	-	-	Wheat	Legume	Total	-	-
Wheat+lentil	1.06	0.77	1.83	0.82	-55.56	1.47	0.91	2.38	1.34	-31.21
Wheat+dekoko	0.78	0.46	1.24	3.02	3.02	1.38	0.52	1.9	0.72	-3.93

Table 4. 9. The MAI for wheat - legume intercrop under rain fed and supplementary irrigation in Mekelle, Ethiopia.

	Monetary advantage index (MAI) (ETBr)*	
Treatment	Rainfed	Supplementary Irrigation
Wheat + Lentil	7,937.2	20,642
Wheat + Dekoko	4,983.9	22,500

** Exchange rate: 1 USD = 22.5 ETBr*

4.7.0 Economic advantage of intercropping under rainfed and supplementary irrigation

4.7.1 Monetary Advantage index (MAI)

In order to best recommend a cropping system or pattern to farmers, it is worth to conduct a cost benefit analysis, more especially the profit or monetary gain and the more profitable system tends to be more attractive to the farming community. Therefore, the yield advantage of intercropping patterns over monocropping and their economic return and profitability was estimated using the monetary advantage index (MAI). A higher value of MAI is associated with the more profitable cropping system.

Results from this study indicated that the MAI was higher above one in all the intercropping combinations, both rainfed and with supplementary irrigation showing that intercropping was superior to monocropping in terms of profitability. However, wheat-lentil association proved to be more profitable (ETBr 7,937.2) per hectare under rainfed conditions over wheat-dekoko mixture (Table 4.9). This may perhaps be due to the significantly higher LER value. With supplementary irrigation, dekoko-wheat was more profitable, supported by higher values of MAI (ETBr 22,500). The same observation was reported by Muhammad et al. (2008), Ghosh et al. (2009) and Mahapatra (2010). Compared to rainfed conditions, supplementary irrigation was shown to produce better economic results. Lentil-wheat mixture however, could be more recommended to farmers in Mekelle area who are mainly dependent on erratic rainfall.

4.8. Partial budget analysis

The study showed that smallholder farmers can get more profits per hectare in intercropping than sole cropping (Table 4.10). Generally, by considering the variable costs, intercropping wheat with dekoko was shown to be more profitable (13,185.05 ETB) under rainfed conditions whereas sole wheat was shown to be the least profitable as it gave the least returns (3,023.35 ETB) per hectare. Similar results were obtained under supplementary irrigation (Table 4.10). This could be as a result of the differences in the monetary value of the different species, dekoko having a higher market price (65 ETB) as compared to 14 and 45 for wheat and lentil respectively.

Table 4 10. Partial budget analysis for wheat and component legumes under intercropping and supplementary irrigation.

Treatment	Rainfed			Supplementary Irrigation		
	Gross income	Variable costs	Net income	Gross income	Variable costs	Net income
Sole wheat	11,180.54	7,212.5	3,968.04	22,438.92	18,412.50	4,026.42
Sole lentil	11,548.35	6,525	5,023.35	20,833.20	17,125.00	3,708.20
Sole dekoko	24,460.76	15,150	9,310.76	44,851.29	26,350.00	18,501.29
Wheat + Lentil	22,728.89	1,3831.25	8,897.64	43,272.12	25,031.25	18,240.87
Wheat + Dekoko	35,641.30	22,456.25	13,185.05	67,290.21	31,656.25	35,633.96

Variable costs: cost of seeds, cost of harvesting, cost of threshing, labor cost for irrigation

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Rainfed mixed crop-livestock subsistence farming is a major source of food security and livelihood to smallholder farmers in Ethiopia. Due to the escalating rate of population increase in the country, there is a crucial need to increase production of food and fodder to sustain the rising population, and food insecurity is increasingly becoming a threat to the country's development.

This therefore calls for adoption of farming systems and technologies that ensures sustainable production of crops and increase the total biomass production for livestock feeding. This should include availing the crops with supplementary water during periods of short dry spells during the grain filling stage since water stress at this stage has been reported to result in significant yield reduction.

Soil total nitrogen and available phosphorus increases when wheat is intercropped with lentil and dekoko.

Intercropping wheat with lentil and dekoko increases the yield of wheat whereas it negatively affects the yield of component legumes.

The highest yield of wheat under rainfed conditions can be obtained in wheat-lentil intercropping and in wheat-dekoko under supplementary irrigation

Intercropping was shown to be more efficient in resource utilization and productivity over sole cropping as was indicated by LER and LEC.

The partial budget indicated that it was more profitable for smallholder farmers to intercrop wheat with dekoko under rainfed conditions and supplementary irrigation.

In a nutshell, intercropping was shown as a more sustainable technology for low-input smallholder farmers in the study area and similar agroecolgies to sustainably improve soil productivity, crop yields and profitability.

5.2 Recommendations

Small grains like wheat and other related species can give maximum yields under dryland-rainfed conditions when grown in a mixture with nitrogen-fixing leguminous species; however their yield can be optimized when intercropping is supported with supplementary irrigation, mainly at booting stage of wheat. Therefore, farmers in the study area and related agro ecologies can adopt this practice to sustainably increase yield and productivity.

In this study area, intercropping wheat with lentil is recommended since it can give maximum yield and economic returns, even under rainfed conditions. This is more appropriate for resource-poor farmers who cannot afford the cost of irrigation.

If farmers are to maximize profits from their farm operations, intercropping is recommended over sole cropping. Wheat-lentil is also more recommended for this cause.

Since low soil fertility is one of the leading drawbacks to yield increase in the area, cereal legume intercropping could help to sustainably increase soil fertility and consequently crop yields.

However, this study was conducted in only one agroecology over a single season and using only two leguminous species out of the many in the farmers' practice. It is therefore recommended that a similar study be conducted in a different location and over seasons to draw a more concrete conclusion.

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APPENDICES

Appendix 1. Summary of ANOVA with respect to mean squares and coefficient of variation for the phenology of wheat and component legumes.

Source of variation	Degrees of freedom	Mean squares		
		Days to 90% emergence	Days to 50% flowering	Days to 90% physiological maturity
Rep.	2	0.6333	1.658	0.9000
Cropping_sys. (A)	4	14.7167	348.658	400.950
Error (a)	8	0.4667	0.471	0.3375
Water_regime (B)	1	0.0000	0.675	270.000
A*B	4	0.4167	0.842	1.7500
Error (b)	10	0.2333	1.308	1.5000
F pr. (a)		<0.001**	<0.001**	<.001**
F pr. (b)		1.000^{NS}	0.489^{NS}	<.001**
F pr. (a*b)		0.208^{NS}	0.644^{NS}	<.001**
CV%		5.3	2.4	0.5

*Rep. = Replication; A = intercropping; B = supplementary irrigation; F pr = F-probability; CV = Coefficient of variation; ** = significant at p <0.01 probability levels; * = significant at p <0.001 probability levels; NS = non significant at p <0.05 probability levels.*

Appendix 2. Summary of ANOVA with respect to mean squares and coefficient of variation for the yield and yield components of wheat and component legumes.

Source of variation	Degrees of freedom	Mean squares				
		PH	BMY	TGW	GY	HI
Rep.	2	2.089	0.00870	0.2250	0.000703	0.000611
Cropping_sys. (A)	4	1629.635	2.06081	22.2000	0.213550	0.167371
Error (a)	8	1.572	0.01667	0.4125	0.000132	0.001243
Water_regime (b)	1	62.785	1.52325	1068.0333	0.894413	0.159573
A*B	4	45.029	0.26055	23.2833	0.062613	0.088969
Error (b)	10	1.650	0.01619	0.6583	0.002153	0.002539
F pr. (a)		<.001**	<.001**	<.001**	<.001**	<.001**
F pr. (b)		<.001**	<.001**	<.001**	<.001**	<.001**
F pr. (a*b)		<.001**	<.001**	<.001**	<.001**	<.001**
CV%		2.5	6.7	7.6	7.6	3.0

*Rep. = Replication; A = cropping system; B = water regime; F pr = F-probability; CV = Coefficient of variation; ** = significant at p <0.01 probability levels; * = significant at p <0.001 probability levels; PH = plant height; BM Y= biomass yield; TGW = thousand grain weight; GY = grain yield; HI = harvest index*

Appendix 3. Rating key for nodule assessment (after Corbin et al., 1977) in legume during 2010 cropping season at UBC Farm, Vancouver, Canada.

Field assessment key		**Mean score and indication**	
Score	***Visual Observation***	**Mean nodule score**	***Indication***
0	No nodulation	0	No nodulation and no N_2 fixation
1	<5 in the crown-root zone (regarded as the region up to 5 cm below the first lateral roots) with no nodules on elsewhere on the root system	0-1	Very poor nodulation and probably little or no N_2 fixation
2	5-10 in the crown-root zone with <5 nodules on elsewhere on the root system	1-2	Poor nodulation and probably little N_2 fixation
3	>10 in the crown-root zone with <5 nodules on elsewhere on the root system	2-3	Fair nodulation; N_2 fixation may not be sufficient to supply the N demand of the crop
4	>10 in the crown-root zone with 5-10 nodules on elsewhere on the root system	3-4	Good nodulation and good potential for N_2 fixation
5	*>10 in the crown-root zone with >10 nodules on elsewhere on the root system*	4-5	Excellent nodulation; excellent potential for N_2 fixation