



Review Article

Sustainable Intensification of Grain Legumes Optimizes Food Security on Smallholder Farms—A Review

Eliakira Kisetu Nassary^{1*}, Frederick Baijukya² and Patrick Alois Ndakidemi³

^{1,3}The Nelson Mandela African Institution of Science and Technology (NM-AIST), School of Life Sciences and Bioengineering, P.O. Box 447, Arusha, Tanzania

²International Institute of Tropical Agriculture (IITA), P.O. Box 34441, Dar es Salaam, Tanzania

*For correspondence: keliakira@yahoo.com

Abstract

Cereals and grain legumes are the staple and cash crops providing nutrition and cash to the smallholder farmers. Intercropping of these crops is more common than rotations in sub-Saharan Africa but options to optimize benefits from these practices are underutilized or unclear to the smallholder farmers. Understanding of the benefits and trade-offs associated with these practices is required to find suitable options for intensification of system productivity and to ensure food security. In this review, options for intensification of cereals and grain legumes in both intercrops and/or rotations are identified. Intercropping optimizes productivity of the crops in mixtures. The primary benefits derived are related to the greater resource capture through uptake of nutrients and utilization of light and water. Resource facilitation and complementarity explain the mechanisms by which crops in intercrop benefit each other. Facilitation includes increased availability of phosphate and micronutrients such as zinc, iron, and copper for uptake by plants through release of phytosiderophores. Facilitation is also realized through effects on nitrogen fixation – often legume dependence on nitrogen fixation increases (%N fixed) but the amount fixed decreases due to less legume present compared with the sole crop. On both rotations and intercrops, grain legumes have ‘N-effects’ and ‘non-N-effects’ effects on subsequent cereal crops. The ‘N-effects’ are explained by the improvement of N nutrition for the subsequent cereal crop. The ‘Non-N-effects’ are biotic factors such as suppression of insect pests, weeds, and diseases, and abiotic factors such as effects on soil moisture availability, nutrients other than N, pH, organic matter and improvements in soil structure. © 2020 Friends Science Publishers

Keywords: Agricultural systems; Food crops; Gender equity; Smallholder farmers; Sustainable intensification

Introduction

Agriculture is for food production and economic growth of the smallholders in Sub-Saharan Africa (SSA) and also employs over 70% of the labour force (Pretty *et al.*, 2011). Most of the production is for subsistence attributed to the small land owned and cultivated which vary from less than 1 to 3 ha (Sarris *et al.*, 2006; Vanlauwe *et al.*, 2014). The main food crops produced by smallholder farmers are maize (*Zea mays* L.), rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), sorghum (*Sorghum bicolor* L.), finger millet (*Eleusine coracana* L.), cassava (*Manihot esculenta* L.), grain legumes, potatoes (*Solanum tuberosum* sp. *Ipomoea batatas* and *Solanum tuberosum*) and bananas (*Musa* sp.) comprising over 80% of the total area cultivated (Sarris *et al.*, 2006).

Production of food crops on smallholder farms is always below potentials due to the effects of environments, crop management options and cultivar/variety of the crops

cultivated (Lyimo *et al.*, 2014; Nyaligwa *et al.*, 2017). Variations in climatic conditions and the major soil types is large and partly due to topography (Pretty, 2008; Vanlauwe *et al.*, 2017). Management including poor farming systems are often due to lack of access to resources such as little use of inorganic fertilizers and continuous cultivation of cereals crops with non-formalized rotations and/or intercrops (Pretty *et al.*, 2011). Lack of nutrients means that farmers cannot get the yield benefits that better varieties can provide (Tittonell and Giller, 2013). There are other constraints related to poor access to market information and low prices of crops in local markets, an outbreak of diseases and pests, both insects and invasive weeds (Carter and Zimmerman, 2000). Another important constraint to crop production in smallholder farms is low purchasing power of fertilizers to meet nutrients demand of the crop and this is associated with high prices and easy of accessibility (Giller, 2001).

Grain legumes are produced by smallholder farmers as food and provide important source of protein (38%) and

14% of daily calorific requirements, vitamins, nutrients including iron (Fe), zinc (Zn), phosphorus (P), calcium (Ca), copper (Cu), potassium (K), and magnesium (Mg) and complex carbohydrates to both human being and livestock (Vance, 2002; Xavery *et al.*, 2006; Considine *et al.*, 2017; Stagnari *et al.*, 2017). In SSA, for instance, grain legumes are produced by over 75% of rural farming households mainly for subsistence and little surplus is sold to generate cash income (Considine *et al.*, 2017). Improvement of soil fertility through biological symbiosis of grain legumes with rhizobium under favourable conditions and upon incorporation of residues into soils has been widely reported (Giller *et al.*, 1991; Leidi and Rodriguez-Navarro, 2000). Despite their importance, yields of these legumes have remained below their potentials (Smithson *et al.*, 1993; Giller *et al.*, 1994; Hillocks *et al.*, 2006).

The population growth worldwide is estimated to be around 9 billion by 2050 and the SSA leads in this increase (Stagnari *et al.*, 2017; Loboguerrero *et al.*, 2019). Global food demand is also expected to increase concomitantly (Loboguerrero *et al.*, 2019) thus, a need for intensification of agricultural systems and its sustainability (Raimi *et al.*, 2017). Intensification may ensure increase in food production on smallholder farmers by exploiting small pieces of lands owned (Pretty, 2008; Pretty *et al.*, 2011). Pretty *et al.* (2011) and Pretty and Bharucha (2014) defined agricultural intensification such as: - (1) optimizing yields per land area; (2) intensify plant population (*i.e.*, more crops at once) per land or other inputs in a season (water) and (3) increasing value for land with respect to crops cultivated. However, intensification of agricultural systems cannot necessarily ensure food security as the practice needs to be considered under sustainable basis (Pretty *et al.*, 2011; Bedoussac *et al.*, 2015; Stagnari *et al.*, 2017). The definition of sustainable intensification is given by many studies as a practice which involves increasing land productivity (Pretty, 2008; Giller *et al.*, 2011; Pretty *et al.*, 2011). However, sustainable intensification of agricultural systems should not confront the role of land and other land use types (Godfray *et al.*, 2010; Vanlauwe *et al.*, 2014).

Sustainable intensification of grain legumes as an option to food security on smallholder farms may be invested in the highly populated regions which are dominated by small owned lands for cultivation (Devendra, 2012; Rusinamhodzi *et al.*, 2012; Ronner and Giller, 2013; Bybee-Finley and Ryan, 2018; Dong *et al.*, 2018). Grain legumes are often intercropped with bananas, coffee (*Coffea sp.*), sorghum and maize and less-commonly grown as sole crops during short rainy seasons in regions which experience bimodal rainfall pattern (Giller *et al.*, 1998; Hillocks *et al.*, 2006; Ndakidemi *et al.*, 2006; Ronner and Giller, 2013). In addition, the inclusion of these grain legumes during short rainy season adopts rotational cropping with cereal crops such as maize (*Zea mays L.*), grown often during the long rainy season. The importance of maize and grain legumes such as common bean

(*Phaseolus vulgaris L.*) as food and cash crops on smallholder farms cannot be compromised (Ndakidemi *et al.*, 2006) hence a need for sustainable intensification for food security and scaling-up to agri-business entrepreneurship (Hillocks *et al.*, 2006; Venance *et al.*, 2016). Sustainable intensification in grain legumes would improve systems productivity in the farming settings and ensure food base for the households (Pretty, 2008; Pretty *et al.*, 2011; Raimi *et al.*, 2017). Therefore, the objective of this review is to identify options for sustainable food production through intensification of grain legumes producing systems through intercropping and/or rotations with food cereal crops. To do that the literature on various annual food crops commonly involved in intercrops and/or as part of a rotation on smallholder farms was reviewed. The review also examined principles underlying socio-economic and environmental importance and the mechanisms involved to achieve the benefits from these practices mostly undertaken by smallholder farmers in different parts of the world. The topic on the role of grain legumes intensification in improving food security under changing climate is included. In addition, concerns on gender equity in the production of various crops in these farming systems were raised.

Intercropping as an Element of Sustainable Agricultural Intensification

Intercropping involves growing of two or more crops simultaneously and during the same cropping season time but overall profitability is derived from sustainable intensification (Brooker *et al.*, 2015). Intercropping is considered sustainable only when it enhances food production from the component crops and does not have large negative impact to the natural resources in the environment during field operations and after harvesting of both crops (Lithourgidis *et al.*, 2011; Micheni *et al.*, 2015). Therefore, there is a need of understanding the ways by which food cereal crops and various varieties/cultivars of grain legumes can interact and result into additional benefits on diverse farming systems of smallholder farmers.

Benefits Derived from Intercropping Cereals and Grain Legumes

Food Productivity and Associated Benefits of Intercrops

Intercropping cereals with grain legumes has often recorded overall systems advantage compared with sole cropping of each crop (Zhang *et al.*, 2015). Intercrops are reported to give greater combined yields and monetary returns than their corresponding sole crops (Seran and Brintha, 2010). Cereal-legume intercropping is practised by smallholder farmers in order to mitigate risks of complete crop failure in monocropping (Kermah *et al.*, 2017). Sun *et al.* (2014) indicated that maize cultivated in mixture with alfalfa optimized their niche complementarity through efficient use

of growth resources. Intercropping maize with grain legumes is more advantageous over their respective sole crops when are grown on poor soils for both absolute yield and economic return (Rusinamhodzi *et al.*, 2012; Midega *et al.*, 2014; Kermah *et al.*, 2017).

The benefits derived from intercrops could be evaluated depending on the purpose and in most cases on relative, absolute, monetary and nutritional units of measurements (Willey, 1985). The overall intercropping system productivity was shown earlier by Dahmardeh *et al.* (2010) who found greater land equivalent ratio (LER) in all intercropping systems with modified planting densities of component crops (Fig. 2). Zhang *et al.* (2015) found that mixtures of maize and soybean gave higher LER (1.3), total N fixed (258 kg ha⁻¹), and economic return of 3408 USD per ha. The partial LERs of the component crops in maize-bean intercrop depicted more efficiently used land than sole cropping and attributed this observation to the better utilization of growth resources. Therefore, understanding of food and economic benefits derived from improved and local varieties of crops cultivated in mixtures would increase awareness to appropriate system combination of these crops and optimize food productivity in smallholder farms.

Resource Facilitation, Complementarity, Sharing and Utilization in Intercrops

Intercropping of cereal-legume improves utilization of plant growth resources (Willey, 1979; Jensen, 1996). Intercropping optimizes crop productivity in a unit land area where the crops in mixtures are grown depending on the seasons of the year, resource inputs, and appropriateness of the planting density of each crop species. Willey (1979) and Chowdhury and Rosario (1994) indicated that higher uptake of nutrients and utilization of other growth factors by the intercropped component crops are the primary benefits gained from intercropping. Temporal and spatial arrangements of intercrops can be chosen to enhance the complementarity of resources such as space, light, water, and nutrients. The spatial arrangement needs to be carefully selected so as to improve radiation interception through maximization of ground cover (Li *et al.*, 2014).

Enhanced productivity of intercrops compared with their sole crops is shown to improve utilization of limited resources through complementarity and facilitation (Hinsinger, 2001; Tilman *et al.*, 2001; Li *et al.*, 2014). According to Hinsinger *et al.* (2011) and Li *et al.* (2014), there is always a decrease in interspecific competition between intercrops thereby increasing their complementarities for the growth resources. This is attributed to differences in utilization of these resources in space, time and forms; for example, the cereals in association with legumes complement each other for N use. Cereals and legumes compete for the soil N but the legume can also obtain additional N from N₂-fixation. Niche complementarity between intercrops is determined by root

(deep and shallow) and canopy (tall and short) architecture, which allow exploitation of light and soil resources (Hinsinger, 2001; Hauggaard-Nielsen and Jensen, 2005; Li *et al.*, 2014).

Productivity of intercrops is achieved with less competition within species than competition between contrasting species for the limited resources (Zhang *et al.*, 2015). The competition between cereals and legumes enhances atmospheric N₂ fixation by a legume in symbiosis with rhizobium (Corre-Hellou *et al.*, 2006). Inter-specific competition causes complementarity for N in an intercrop where N-fixing legume is included (Brooker *et al.*, 2015; Zhang *et al.*, 2015). In intercrops of maize and common bean there is an increase in mycorrhizal colonization as well as higher shoot N concentration in the maize (Dawo *et al.*, 2008; Brooker *et al.*, 2015). According to Connolly *et al.* (2001) and Latati *et al.* (2016), there is more positive interaction in cereal-legume intercrops although the resulted yield increase in a cereal crop was due to other non-N enhancing factors. The facilitation for resources between component intercrops has also been realized in situations where the cereal crop improves availability of Fe for the legume and the later enhances N and P uptake by the former (Zhang and Li, 2003; Li *et al.*, 2016).

Facilitation (Fig. 1 and Table 1) is the positive interaction between intercrops and it is well explained by situations where growth and survival of intercrops are interdependent (Brooker *et al.*, 2015). Phytoavailability and acquisition of micronutrients such as Zn, Fe and Cu on alkaline or calcareous soils is a good example of a facilitative interaction. Plants such as maize and beans release acids and enzymes (phosphatases) that enhance availability of P in the soil while a legume bean also facilitates N availability through N₂-fixation (Dotaniya *et al.*, 2013; Brooker *et al.*, 2015). Aluminium (Al) and manganese (Mn) associated toxicities to plants are reduced through root secretions of proton in the rhizosphere (Ryan *et al.*, 2011). On the other hand, plants adapted to soils higher in pH (mildly alkaline) such as maize increase the availability of P and possibly of Fe, Zn, Mn and Cu through their root secretions (Zhang *et al.*, 2010).

Phytosiderophores, the anti-binding agents such as nicotianamine, mugineic acids (MAs) and avenic acid (Dotaniya *et al.*, 2013) dissolve micronutrients Mn, Zn, Cu, and Fe, in soils and enhance their solubility for crop utilization (Zhang *et al.*, 2010). According to Li *et al.* (2014), the Fe³⁺-phytosiderophore deoxymugineic acid released by maize or another cereal in intercrop is mostly absorbed directly by dicotyledonous crops. Sharing of the resources between component crops in intercrops is also highly documented (Brooker *et al.*, 2015; Li *et al.*, 2016). We, therefore, foresee that there is a need of evaluating interaction between contrasting varieties of crops cultivated mixtures as different crop species and/or varieties/cultivars may have different properties which may positively or negatively influence their coexistence.

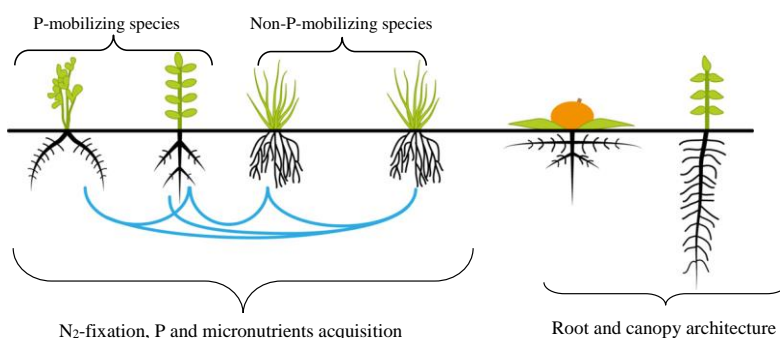


Fig. 1: Facilitation of growth resources, sharing and niche complementarity enable polyculture systems to yield more than their corresponding monocultures. Facilitation of P acquisition for both component crops when one is P-mobilizing and another is non-P-mobilizing. The P-mobilizing species may mobilize sparingly soluble inorganic P in soil through carboxylates or protons or organic P by acid phosphatases enzymes. These substances hydrolyze soil organic P into soluble inorganic P, which may be shared by both plant species. There is also facilitation of acquisition of minerals Fe and Zn by a dicotyledonous (*e.g.* common bean) or non-graminaceous monocotyledonous. In the non-Fe-/or Zn- mobilizing plant species and in graminaceous monocotyledonous (*e.g.* maize) the Fe and Zn acquisition is facilitated by the Fe-/Zn- mobilizing species

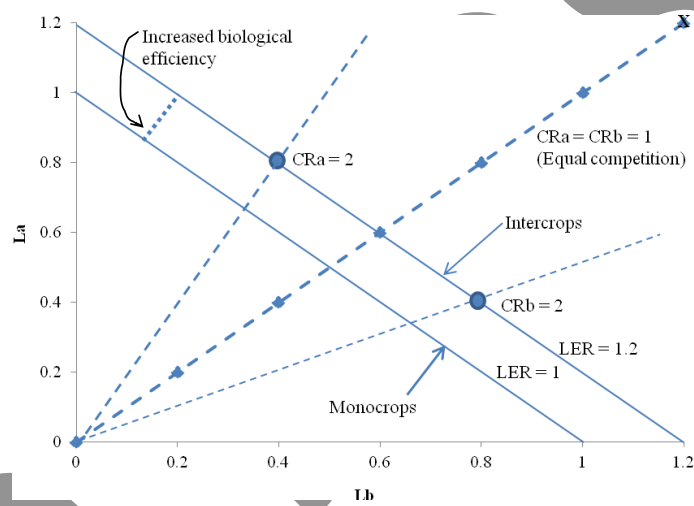


Fig. 2: Competitive ratios of two different crops when sown in intercrops compared with their sole crops. The values above line X indicates that crop *a* is more competitive than crop *b* when sown in intercrops. Similarly, below this line, crop *b* has higher competitive advantage over crop *a* when are intercropped. At $CR_a = 2$ means that crop *a* is twice as much as competitive as crop *b*; likewise, when the $CR_b = 2$ means that crop *b* has twice competitive advantage over crop *a*. Key: L_a and L_b are land equivalent ratios of crops *a* and *b*, respectively; LER is the land equivalent ratio; CR_a and CR_b are competitive ratios of crops *a* and *b*, respectively. Source: Modified from Willey (1985)

Control of Insects and Diseases by Intercrops

Crops in mixtures may have a small niche for insect pests that are specific to certain plant species and therefore might not proliferate (Table 2). Foliage beetle incidence is significantly reduced by 15% in mixed bean varieties and/or in intercrops with other crops compared with when each bean variety is sown alone (Wortmann *et al.*, 1998; Hillocks *et al.*, 2006; Obanyi *et al.*, 2017). Abdullah and Fouad (2016) found that the population of the aphids decreased significantly in faba bean + fenugreek intercrop than faba bean + onion or sole faba bean crop.

The reduced pest abundance in mixed cropping systems compared with monocrops has been attributed to efficacy and abundance of natural enemies and in differences in food or resource concentration that limits the insect pests to locate the host plants (Ogenga-Latigo *et al.*, 1992). Mulumba *et al.* (2012) found that the damages caused by insect pest and disease and their incidence on crops decreased with higher levels of diversity in production systems in four contrasting agro-ecologies in Uganda. According to Ssekandi *et al.* (2016), damage of resistant varieties of common bean caused by bean fly in intercrops was reduced using different cropping patterns compared with when the same varieties were sown as sole crops.

Table 1: Acquisition, sharing, and utilization of growth resources (space, light, water, and nutrients) between component crops in mixtures

Character	Contribution of intercrops			References
Resource Facilitation	1. Protection against mineral toxicities in saline, sodic or metalliferous soils			Li <i>et al.</i> (2014); Brooker <i>et al.</i> (2015)
	2. Attraction of beneficial organisms such as natural enemies and pollinators			
	3. Deterrence of pests and pathogens			
	4. Suppression of weeds			
Resource Sharing	Benefits	Nitrogen UE	Phosphorus UE	Babikova <i>et al.</i> (2013)
		Mycorrhizal fungi connections		
		1. Leaf litter		
		2. Root turnover		
	Benefits	1. Water (WUE)		
		2. Carbon (RUE)		
		3. Minerals (MUE)		
Complementarity between plant species		Traits: 1. Root architecture		
		2. Canopy architecture		
	Benefits	Root architecture	1. Humidity (WUE)	
			2. Temperature (WUE)	
			3. Light harvesting (LUE)	
			4. Weed competition (RUE)	
			1. Hydraulic lift (WUE)	
			2. Minerals acquisition (MUE)	
			3. Reduced leaching (WUE & MUE)	
		Canopy architecture		

UE = use efficiency

Intercropping enhances the abundance of predators and parasites of pests and diseases as the modified environments can delay spread of pathogens and the introduction of diseases (Seran and Brintha, 2010). Understanding the dynamics of insect pests and diseases of common bean and maize when grown in mixtures in the field is crucial for prevention and control by smallholder farmers. Evaluation of the interactions between contrasting varieties of common bean and maize mixtures and their effects on occurrence, prevalence, and severity of these reducing factors on crop productivity is also important in the farmers' field settings.

In phenomenological studies comparing disease in monocultures and intercrops, primarily due to foliar fungi, intercropping reduce diseases. The important sources of these diseases and the various studies involved as references are presented in Table 3. According to Boudreau (2013), the mechanisms by which intercrops affect disease dynamics include alteration of wind, rain, and vector dispersal; modification of microclimate, especially temperature and moisture; changes in host morphology and physiology; and direct pathogen inhibition. Chen *et al.* (2007) reported a 26 to 49% reduction in wheat powdery mildew when wheat was sown in association with faba bean. The rate of disease progress and delayed epidemic onset was observed in common bacterial blight of bean caused by *Xanthomonas campestris* pv. *phaseoli* in several additive patterns of maize and sorghum mixtures with beans (Fininsa, 1996).

Weed Suppression by Intercrops

Intercropping of cereals and legumes are reported to suppress competition from weeds. Kwiecinska-Poppe *et al.* (2009) found that many broadleaf weeds were suppressed

by the intercrops and their biomass was reduced. Previous studies have revealed that intercrops compete with weeds for the light capture, space, water and nutrients (Wanic *et al.*, 2005) and given good canopy created by intensified cropping systems sprouting and the establishment of weeds are suppressed.

Allelopathic compounds released by intercrops interfere with weeds occurrence and establishment (Ndakidemi and Dakora, 2003; Kwiecinska-Poppe *et al.*, 2009; Makoi and Ndakidemi, 2012; Shahzad *et al.*, 2016a, b). Maize-bean mixtures have been reported to reduce weed biomass by 50-66% when bean population was varied (Seran and Brintha, 2010). A study that evaluates allelochemicals from contrasting species of crops cultivated in mixtures is required since different crop species may release different allelochemicals with allelopathic properties useful in the natural control of associated weed species to one or more crops. It is important to examine how different varieties of grain legumes when cultivated in mixtures with cereals can be helpful in the suppression of weeds in order to avoid costs that would be incurred from chemicals and the likely negative environmental and health impacts of these chemicals.

Soil Erosion Control by Intercrops

Soil erosion is caused by water and wind, which degrades land and its productivity potential as physical and chemical characteristics are negatively affected (Dregne, 2002). Soil erosion is determined by various factors but the important ones include amount of rainfall, erodibility of the soil, topography of the area, cropping systems and the existing land conservation measures (Adekalu *et al.*, 2006). The measures that control or reduce soil erosion are helpful in sustaining soil fertility and its overall productivity.

Table 2: Major pests of grain legumes in the field, the plant parts that they damage, their global distribution and their control by crop rotation and/or intercropping

Insect pests	Crops attacked ^a	Plant parts damaged ^b	Distribution	Control measure ^w	References
<i>Acyrtosiphon pisum</i> (Harris) ^f	CP, FB, Le, FP	V, Re	A,B,C	I & R	Clement et al. (2000)
<i>Aphis craccivora</i> (Koch) ^f	All Legumes	V, Re	A,B,C,D	R	Clement et al. (2000); Dar et al. (2012)
<i>Aphis fabae</i> Scopoli ^f	FB	V	B,C	I & R	Clement et al. (2000)
Bean bugs [<i>Riptortus pedestris</i> (F.), <i>R. clavatus</i> (Thunberg)] ^a	Sb, Cb	V, Re	G, H	I	Wada et al. (2006)
Bean flies [<i>Ophiomyia phaseoli</i> Tryon, <i>O. centrosematis</i> , de Meijere, <i>O. spencerella</i> Greathead, <i>Melanagromyza sojae</i> Zehntner, <i>M. obtusa</i> Malloch] ^e	All Legumes	V	B, D, Oceania	I	Srinivasan (2014)
Bean foliage beetles [<i>Ootheca sp.</i>] ^a	CW, Cb	V, Re	I, J	I & R	Srinivasan (2014)
Beet army worm [<i>Spodoptera exigua</i> Hubner] ^m	Sb	V, Re	Widely	I & R	Srinivasan (2014)
Blue butterfly [<i>Lampides boeticus</i> (L.), <i>Euchrysops cnejus</i> (F.)] ^u	All Legumes	V, Re	A, B, D, Pacific	I & R	Srinivasan (2014)
<i>Bruchus pisorum</i> L. ⁱ	FP	Re	A,B,C,D	I & R	Clement et al. (2000)
Common armyworm [<i>Spodoptera litura</i> Fabricius] ^m	All Legumes	V	E, G, H	I & R	Srinivasan (2014)
<i>Halotydeus destructor</i> Tucker ^j	FP, Lu, FP	V	D	I & R	Clement et al. (2000)
<i>Helicoverpa armigera</i> Hiibner ^d	C, Mb, Lu, PP, Sb	V, Re	B,C,D	R	Clement et al. (2000); Srinivasan (2014)
<i>Helicoverpa punctigera</i> (Wallengren) ^d	All Legumes	V, Re	D	I & R	Clement et al. (2000)
<i>Helicoverpa/Maruca</i>	CP, CW, PP	V, Re	B, D, Oceania	I & R	Dar et al. (2012)
Leafhoppers [<i>Empoasca kerri</i> Puthi, <i>E. facialis</i> Jacobi, <i>E. fabae</i> Hari] ^l	All Legumes	V	A, B	I	Ranga Rao et al. (2013); Srinivasan (2014)
Legume pod borer [<i>Maruca vitrata</i> (F.)] ^s	CW, PP, Cb	V, Re	A,B,D,H	I & R	Srinivasan (2014)
Lima bean pod borer [<i>Etiella zinckenella</i> Treitschke] ^t	Le, FP, Sb	V, Re	A, B, D, Caribbean	I	Wada et al. (2006)
<i>Liriomyza cicerina</i> (Rondani) ^e	CP	V	B	I & R	Clement et al. (2000)
<i>Lygus hesperus</i> Knigh ^e	Le	Re	A	I & R	Clement et al. (2000)
<i>Myzus persicae</i> (Sulzer) ^f	Lu	V	D	I & R	Clement et al. (2000)
Pod bugs [<i>Clavigralla gibbosa</i> Spinola, <i>C. scutellaris</i> (Westwood), <i>C. tomentosicollis</i> (Stal.)] ^p	All Legumes	V, Re	B ^A , K	I	Srinivasan (2014)
<i>Sitona crinitus</i> Herbst ^h	Le	R, V	B	I & R	Clement et al. (2000)
<i>Sitona lineatus</i> (L.) ^h	FB, FP	R, V	A,B	I & R	Clement et al. (2000)
Southern green stink bug [<i>Nezara viridula</i> (L.)] ^r	All Legumes	V, Re	G, H	I & R	Muniappan et al. (2012)
Spider mite [<i>Tetranychus sp.</i>] ^v	All Legumes	V, Re	B, Mediterranean	C, I & R	Srinivasan (2014)
Thrips [<i>Megalurothrips distalis</i> Kany, <i>M. usitatus</i> (Bagnall), <i>M. sjostedti</i> (Tribom)] ^o	All Legumes	V, Re	G, H, B ^A , Oceania	I & R	Srinivasan (2014)
Whitefly [<i>Bemisia tabaci</i> Gennadius] ^k	All Legumes	V	E, F	I	Srinivasan (2014)

Here ^aLegume crops: Cb=Common bean; Sb= Soyabean; CP=Chickpea; CW= Cowpea; Mb=mungbean; PP= Pigeon pea; FB=Faba bean; Le=Lentil; Lu=Lupins; FP=Field pea. ^bPlant parts: R=Root; V=Vegetative organs (stems, leaves); Re=Reproductive organs (flower, pod and/or seed damaged). ^cInsect species on legumes in: A=America; B=Europe, Africa, W. Asia; BA=Africa; C=Southeast Asia including Indian subcontinent; D=Australia; E=Tropics; F=Sub-tropics; G=South Asia; H=Asia; I=Eastern Africa; J=Southern Africa; K=Asia. ^dLepidoptera: Noctuidae; ^eDiptera: Agromyzidae; ^fHomoptera: Aphididae; ^gHeteroptera: Miridae; ^hColeoptera: Curculionidae; ⁱColeoptera: Bruchidae; ^jAcarina: Penthaleidae; ^kHemiptera: Aleyrodidae; ^lHomoptera: Cicadellidae; ^mLepidoptera: Noctuidae; ⁿColeoptera: Chrysomelidae; ^oThysanoptera: Thripidae; ^pHemiptera: Coreidae; ^qHemiptera: Alydidae; ^rHemiptera: Pentatomidae; ^sLepidoptera: Crambidae; ^tLepidoptera: Pyralidae; ^uLepidoptera: Lycaenidae; ^vAcari: Tetranychidae. ^wLocally available option of controlling insects: I=Intercropping; R=Rotation

Canopies of plants for the crops sown in mixtures prevent the action of rain drops from hitting and destructing structure of the bare soil thereby checking for surface runoff, rapid underground seepage, development of rills and gullies on land (Adekalu et al., 2006). Dense vegetation cover and/or use of green manure in intercrops prevent or reduced impact of rain drop to the soil surface, reduce surface runoff and prevent sweeping of detached soil particles (Dogliotti et al., 2005). Sowing of maize + cowpea (1:1) mixture reduced surface runoff as well as loses of surface soil compared with sowing maize alone (Sharma et al., 2017). This is attributed to the good ground cover created by the overlapping canopies of both crops in the mixture.

Intercropping taller plants such as maize and shorter grain legumes like the common bean, the taller plants act as a wind barrier for the shorter crops, which both improve the ability of the soil to resist erosion by wind or runoff

(Reddy and Reddi, 2007). It is, therefore, important to study how crops differing in species and/or in varieties when are cultivated in mixtures would prevent impact of soil erosion on land degradation and maintain suitability of the soil for sustainable crop production.

Disadvantages of Intercropping

The component crops in intercropping may produce less total individual yield compared with their sole crops due to incompatibility and/or high interspecific competition and lack of niche complementarity between them. There is high labour demand for field operations during sowing, weeding, spraying and harvesting, since mechanization is not possible in intercrops. For instance, in most cases the main crop when crops are sown in association will not reach as high yield as in a monoculture due to competition among component plants for light, soil nutrients and water (Willey, 1979).

Table 3: Important foliar diseases of legumes in the field, causal agents, their distribution, likely economic losses, and some cultural control measures

Legume	Disease	Causal agent	Distribution	Losses	Control measure	References
Chickpea (<i>Cicer arietinum</i> L.)	Stunt	Bean leaf roll luteovirus (BLRV)	North Africa, Middle East, India, Spain, Turkey, USA	N/I	Rotation	Makkouk <i>et al.</i> (2003); Pande <i>et al.</i> (2006; 2009); Darai <i>et al.</i> (2017)
	Ascochyta blight	<i>Ascochyta rabiei</i>	West Asia, northern Africa, Mediterranean region	> 50%		
	Botrytis gray mold	<i>Botrytis cinerea</i>	India, Nepal, Bangladesh, Pakistan, North Africa, Australia, America	50-100%		
Lentil (<i>Lens culinaris</i> Medik.)	Stemphylium blight	<i>Stemphylium botryosum</i>	Bangladesh, Egypt, Syria, USA	Up to 70%	Rotation	Makkouk <i>et al.</i> (2003); Pande <i>et al.</i> (2009)
	Rust	<i>Uromyces viciae-fabae</i>	Bangladesh, Chile, Ecuador, Ethiopia, India, Morocco, Nepal, Pakistan	50-100%		
	Ascochyta blight	<i>Ascochyta lentis</i>	Argentina, Australia, Brazil, Canada, Chile, Cyprus, Ethiopia, Greece, Iran, Jordan, New Zealand, Pakistan, Russia, Spain, Syria, USA	Up to 70%		
Faba bean (<i>Vicia faba</i> L.)	Rust	Faba bean necrotic yellows virus	Mediterranean countries	Up to 50%	Rotation	Makkouk <i>et al.</i> (2003); Pande <i>et al.</i> (2009)
	Ascochyta blight	<i>Ascochyta fabae</i>	Mediterranean countries	5-50%		
	Necrotic yellows	N/I	West Asia, North Africa	Up to 80%		
Field pea (<i>Pisum sativum</i> L.)	Downy mildew	<i>Peronospora viciae</i>	N/I	Up to 50%	Intercropping	Pande <i>et al.</i> (2009); Darai <i>et al.</i> (2017)
	Powdery mildew	<i>Erysiphe polygoni</i>	India, Nepal	10%	Rotation	
	Sterility mosaic	Pigeonpea sterility mosaic virus	Bangladesh, India, Myanmar, Nepal, Sri Lanka, Thailand	N/I	Rotation	Pande <i>et al.</i> (2009)
Pigeon pea (Cajanus cajan [L.] Millsp.)	Powdery mildew	<i>Erysiphe polygoni</i>	India, southeast Asian countries	9-50%	Intercropping	Pande <i>et al.</i> (2009)
	Cercospora leaf spot	<i>Cercospora cruenta</i> , <i>C. canescens</i>	Bangladesh, India, Indonesia, Taiwan, Thailand, Philippines, Malaysia	Up to 50%	Rotation	
	Yellow vein mosaic	Mungbean yellow mosaic virus	Bangladesh, India	10-100%		
Mungbean (<i>Vigna radiata</i> [L.] Wilczek and black gram (Vigna mungo [L.] Hepper)	Powdery mildew	<i>Erysiphe polygoni</i>	India, southeast Asian countries	9-50%	Intercropping	Pande <i>et al.</i> (2009)
	Cercospora leaf spot	<i>Cercospora cruenta</i> , <i>C. canescens</i>	Bangladesh, India, Indonesia, Taiwan, Thailand, Philippines, Malaysia	Up to 50%	Rotation	
	Yellow vein mosaic	Mungbean yellow mosaic virus	Bangladesh, India	10-100%		
Cowpea (<i>Vigna unguiculata</i> Walp.)	Cowpea aphid-borne mosaic	Cowpea aphid-borne mosaic virus	Europe, Africa, Mediterranean basin, Turkey, Iran, India, Indonesia, China, Japan, Australia, Brazil, USA	13-87%	Intercropping & Rotation	Pande <i>et al.</i> (2009)
	Cowpea golden mosaic	Cowpea golden mosaic virus	Kenya, Nigeria, Tanzania, Cuba, Surinam, USA	60-100%		
	Cercospora leaf spot	<i>Cercospora canescens</i> and <i>Pseudocercospora cruenta</i>	Fiji, Brazil, Kenya, Nigeria, Zimbabwe, India, Bangladesh, Egypt, Iran, Japan, Malaysia, Thailand	18-42%		
Common bean (<i>Phaseolus vulgaris</i> L.) (Fungal diseases)	Anthracnose	<i>Colletotrichum lindemuthianum</i>	Widely	N/I	Use of disease-free seed, crop rotation, intercropping	Kelly <i>et al.</i> (2003); Miklas <i>et al.</i> (2006); Singh and Schwartz (2010); Schwartz and Singh (2013); Porch <i>et al.</i> (2013); OECD (2016)
	Fusarium wilt	<i>Fusarium oxysporum</i>		N/I		
	Fusarium root rot	<i>Fusarium solani</i>		N/I		
	Angular leaf spot	<i>Phaeoisariopsis griseola</i>		N/I		
	Ascochyta blight	<i>Phoma exigua</i> var. <i>diversispora</i> , <i>P. exigua</i> var. <i>exigua</i>		N/I		
	Rhizoctonia root rot	<i>Rhizoctonia solani</i>		N/I		
	White mold	<i>Sclerotinia sclerotiorum</i>		N/I		
	Web blight	<i>Thanatephorus cucumeris</i>		N/I		
Common bean (<i>P. vulgaris</i> L.) (Bacterial diseases)	Halo blight	<i>Pseudomonas syringae</i> pv. <i>phaseolicola</i> or <i>Pseudomonas savastanoi</i> pv. <i>Phaseolicola</i>	Widely	N/I	Use of disease-free seed, crop rotation, intercropping	Kelly <i>et al.</i> (2003); Liebenberg (2009); Singh and Schwartz (2010); Porch <i>et al.</i> (2013); OECD (2016)
	Bacterial brown spot	<i>Pseudomonas syringae</i> pv. <i>Syringae</i>		N/I		
	Common bean blight	<i>Xanthomonas campestris</i> pv. <i>phaseoli</i> or <i>Xanthomonas axonopodis</i> pv. <i>Phaseoli</i>		N/I		
Common bean (<i>P. vulgaris</i> L.) (Viral diseases)	Bean common mosaic virus	Potyvirus	Widely	N/I	Use of disease-free seed, intercropping	Miklas <i>et al.</i> (2006); Bonfim <i>et al.</i> (2007); Singh <i>et al.</i> (2009); Singh and Schwartz (2010); Faria <i>et al.</i> (2014); OECD (2016)
	Bean common mosaic virus	Potyvirus		N/I		
	Bean golden mosaic virus	Geminivirus		N/I		
	Bean yellow virus	Potyvirus		N/I		
	Beet curly top virus	Curtovirus		N/I		

Here N/I = Not identified

Reduction in yield may be economically significant if the main crop has a high market value than its associate crop. The canopy cover of intercrops may result in a microclimate with a higher relative humidity conducive to disease outbreak, especially of fungal pathogens, which however, happens within the same cropping season when the plants are in the field (Li *et al.*, 2014). The selection of the appropriate crop species to be included in the intercrops and the time of sowing one crop relative to the other or simultaneously is also a big challenge in intercropping. Therefore, it is important to design intercrops to avoid these potential disadvantages.

Crop Rotation as an Element of Agricultural Intensification

Crop rotation involves a practice of cultivating two or more crop species in the same piece of land but after one has been harvested *i.e.*, in sequence or a definite sequence of crops grown in successive cropping seasons. The sequence of rotating the crops in the same piece of land with differing cropping seasons is repetitive. The practice unveils its profitability by improving the productivity of the subsequent crop through improving soil fertility, minimization of diseases and pests. The previous study by Yusuf *et al.* (2009) indicates that crop rotation is usually superior to both monoculture and intercropping. Decomposition of plant residues in cultivated fields is also the most important source of soil N used by plants, with the exception of those having the ability to fix atmospheric N₂. Cereal yield decline under intensive continuous cultivation with little or no use of inorganic N-containing fertilizers has been attributed to soils depleted of fertility (Papastylianou, 2004). The productivity of cereal crops on such soils can be improved sustainably by including it as part of a rotation with N₂-fixing legumes (Gathumbi *et al.*, 2002). The benefits derived from cereals and legumes cultivated in rotations as well as the associated trade-offs from these practices are important to be examined, understood and established.

The main benefits derived from crop rotations are related with improvement in soil fertility and disruption of life cycle for insect pests, disease pathogens and weeds. This discussion brings to a critical need of evaluating the benefits of rotational cultivations of cereals with different legumes in systems intensification with an overall focus on sustainable food security.

Crop Rotation Improves Soil Fertility

Inclusion of grain legumes on rotational cropping has been benefiting subsequent cereal crops. The benefits derived from crop rotation have been due to both 'N-effects' and 'non-N-effects', also termed as 'other rotational effects' (Franke *et al.*, 2018; Kermah *et al.*, 2018). According to Franke *et al.* (2018), 'N-effects' explain the improvement in N nutrition for the subsequent non-legume crop as well as

reduced N fertilizer requirements as it is facilitated by the legumes included in rotation. The N balance of a legume crop in the field becomes close to zero or even negative in situations where most of the fixed N₂ is removed at crop harvest, escalating availability of more N for the subsequent crop than after a cereal (Chen *et al.*, 2014). The N-effects depend on the initial amount of N-fertilizer applied to the subsequent crop in soils with low N (Giller, 2001).

On the other hand, the 'non-N-effects' of legumes refers to the effects of biotic and abiotic factors determining crop growth and development. The biotic factors include the occurrence of insect pests, weeds and diseases. In addition, the abiotic factors include changes in soil moisture as well as plant nutrients other than N, changes in soil pH, or changes in soil organic matter and soil structure (Chan and Heenan, 1996; Rusinamhodzi *et al.*, 2012; Shahzad *et al.*, 2016c; Franke *et al.*, 2018). The positive effects realized from rotations of legumes on the productivity of subsequent cereal have been attributed to the additional residual N from BNF and high decomposition of legumes residues due to lower C/N ratio (Sanginga *et al.*, 2001). On the other hand, P and K distribution to the soil surface for easy plant uptake from beyond the root zone is one of the advantages of including deep-rooted cover crops in rotations (Marschner, 1990). It is important to clearly know the ways sustainability of soil productivity optimizes crop performance as an influence of rotational cultivations of cereals with grain legumes.

Crop Rotation Disrupts Disease Cycle and Suppresses Weeds

Diseases and insect pests are also major constraints to legume production, especially in the tropics and subtropics. For the efficient impact of crop rotation on the control of insect pest and diseases plants of the same family are grouped together as related crops are vulnerable to the same problem associated with soil-living pests and diseases. Some of the disease pathogens survive in the soil from year to year as sclerotia, spores, or hyphae. Crop rotation can effectively be a measure of suppressing crop diseases caused by fungal and bacterial pathogens, which survive in soil with the help of crop debris. There is a need to establish the positive contribution of rotational cultivation of cereals with legumes in preventing proliferation of disease pathogens.

Manipulation of cropping systems improves weed control options and requires a better understanding of the spatial and temporal dynamics of weeds and their likely seed banks (Bastiaans *et al.*, 2008; Belde *et al.*, 2008). According to Bastiaans *et al.* (2008), applicability, reliability, acceptability, efficacy and the adoption of most non-chemical strategies of controlling weeds are dependent on combinations of various measures resulting in systems complexity. Rotational cropping systems of various crops where legumes are included negatively affect weed

population, biomass, seed production and seed bank. Crop rotations altered seed bank density and species composition more in annual grass weeds than in broadleaf weeds (Koochecki *et al.*, 2009). According to Koochecki *et al.* (2009), rotations in which crops with different life cycles are included could result in a reduction in the weed seed bank. The inclusion of plants with allelopathic effects in rotational systems has also shown a promising and sustainable option for weed control in agricultural systems (Ndakidemi and Dakora, 2003; Ndakidemi, 2006; Makoi and Ndakidemi, 2012).

Striga infestation was reduced by 35% in the legume-maize rotation and the reduction was doubled when the rotation was repeated (Kureh *et al.*, 2006). Comparing soybean and cowpea in rotations with maize, these authors found that the former was superior to the latter in reducing *Striga* infestation. The reason for the differences observed between the two legumes could be attributed to the superiority of soybean in fixing atmospheric N, but both improving soil fertility, which does not favour germination and survival of *Striga* (Gworgwor and Weber, 1991; Ikie *et al.*, 2007; Gacheru and Rao, 2011). It is, therefore, important to understand how the rotational cultivations of cereals with different legumes can be the feasible option towards weed control in cropping systems.

Nitrogen Budget in Grain Legume Cropping Systems

The cereal-legume cropping systems have gained prominence in increasing yields of maize as a major crop relative to sole maize cropping (Sanginga *et al.*, 2001). The increased maize yields in legume associated systems are due to N contributed by the legumes through biological N₂ fixation to improve soil fertility (Giller, 2001). The sustained benefits with large N applications like 60–120 kg N ha⁻¹ equal to cereal grain yield of 0.32 t ha⁻¹ or 59% of the response have been reported to indicate the importance of non-N effects (Franke *et al.*, 2018). There are also, however, non-N benefits such as the reduced impact of pests and diseases, increased soil microbial biomass and activity and improved soil properties (Giller, 2001; Franke *et al.*, 2018; Kermah *et al.*, 2018).

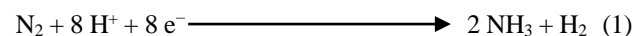
The amount of N input from biological N₂ fixation (BNF) is reported to be as high as 360 kg N ha⁻¹ (Giller, 2001). The N contributions from non symbiotic such as free-living/associative organisms are relatively low ranging from 10–160 kg N ha⁻¹ (Urquiaga *et al.*, 1989; Roger and Ladha, 1992). Peoples *et al.* (1989; 2009) depicted that environmental conditions such as temperature, water availability, soil pH, soil bulk density, etc., the level of availability of mineral nutrients in the soil, pests, and diseases of legumes may affect nodulation and/or N₂ fixation. Soil low in mineral N favours effective legume-rhizobia symbiosis. On contrast, a legume growing on soils higher in mineral-N content is likely to compensate for poor N₂ fixation by scavenging N from the soil. In both

intercrops and rotations of cereals with legumes, it is expected that there is improvement of soil fertility through N₂-fixation as well as microbial activities and soil structure (Giller, 2001).

The translocation, fates, and distribution of N in legumes influence soil fertility and productivity of the next crop. The residues of legumes contain some of the N that they have fixed and this becomes available to subsequent crops if are retained back in the field after harvest although part of it remains in plant system (Carranca *et al.*, 2015). The N-fixed which remains in soil/plant parts in the same field have economic importance of reducing N-fertilizers needed in subsequent crops. Maingi *et al.* (2001) found a slight increase and maintenance of total N (%) levels in maize-common bean intercropped fields after one cropping season compared with the pure maize fields where N declined in the soil.

N₂-fixation is affected by the factors that affect the host plant during its growth and development such as water, temperature, pH, nutrients, and light. Rondon *et al.* (2006) found that greater boron (B) and molybdenum (Mo) availability from bio-char increased BNF in common bean. The greater K, Ca and P availability, lower N availability, higher pH levels and Al saturation decreased BNF in common bean (Rondon *et al.*, 2006). It is reported that higher levels of P increase symbiotic N₂-fixation in common bean at low N (Leidi and Rodriguez-Navarro, 2000). Giller *et al.* (1998) found that P- fertilizer at 26 kg P ha⁻¹ increased the number of root nodules and seed yields of *Phaseolus* bean on farmers' fields in the West Usambara Mountains in northern Tanzania. There has been realized improvement in seed yields by addition of P or N fertilizers in Kilimanjaro and Arusha regions (Giller *et al.*, 1998).

Selection of common bean varieties to be cultivated by farmers is important since they differ in their abilities to fix and utilize atmospheric N to optimize yield and improve soil fertility (Manrique *et al.*, 1993). Phosphorus is also a very important macronutrient during N₂-fixation acting as a source of energy when adenosine triphosphate (ATP) is converted to adenosine diphosphate (ADP) as N₂ is reduced to NH₃ as the overall reaction of BNF (Armstrong *et al.*, 1999; Giller, 2001). Inadequate P in soil restricts root growth, the process of photosynthesis, translocation of sugars, and other functions which directly or indirectly influence N fixation by legume plants.



The released H₂ stimulates the growth of hydrogen-fixing bacteria in the rhizosphere, and these compete successfully for living space with other rhizosphere organisms, including many pathogens (Armstrong *et al.*, 1999). It is, therefore, important to evaluate the amounts of N in plants (both in non-fixing and fixing plants) as well as in soils when the crops are cultivated as components of intercrops or in rotations.

Effectiveness of nodulation is best studied at or near to 50% flowering but immediately before pod formation. In each individual plant the number of nodules and presence or absence of crown nodulation will be noted. Nodule number and nodule mass or nodule weight per unit dry weight of the whole plant or root system are often used in trial comparisons. Similar comparison information can be obtained by visually scoring nodulation on a 0–5 basis by considering nodule number, size, colour, distribution, and longevity of the nodule population (Peoples *et al.*, 1989). From the study plants a few nodules are randomly selected and cut open for assessment of the inner colour of the nodule such as red, pink or brown for active and green, grey, white for inactive.

The pink/brown colour of the nodule is caused by a protein leghaemoglobin containing both micronutrient iron (Fe) and it is responsible for binding of oxygen (Armstrong *et al.*, 1999). This creates a low oxygen environment within the nodule which allows rhizobium bacteria to live and to fix N₂. The practice involves carefully digging-up plants at random across a crop while ensuring the root system and nodules are recovered and scoring each plant using predetermined classification criteria. A mean nodule score of 4–5 excellent nodulation and potential for N₂ fixation, 3–4 good nodulation and potential for fixation, 2–3 fair nodulation but N₂ fixation may not be sufficient to supply the N demand of the crop, 0–2 poor nodulation, little or no N₂-fixation (Peoples *et al.*, 1989). Knowledge of nodulation characteristics in legumes is important as it provides an indication of N₂-fixing legume at certain stages of plant growth. This also provides an insight of the time for sowing a component crop in an intercrop relative to their growing cycles and/or the likely amount of residual N₂-fixed for the subsequent crop in the same land.

Quantifying Amount of N₂-fixed by the Legumes

The widely acceptable methods of quantifying the amount of N₂-fixed by a legume are enrichment (¹⁵N-enriched) and natural abundance (δ¹⁵N) (Unkovich *et al.*, 2008). The ¹⁵N-enriched method is useful where N-containing materials e.g. N-carrying fertilizers and organic substrates have been added into the experimental ecosystem while δ¹⁵N method is applicable in environments where no inclusion of N-containing materials (Giller, 2001; Unkovich *et al.*, 2010). The δ¹⁵N method uses small differences between the ¹⁵N/¹⁴N ratio of the N-source being examined and the ¹⁵N/¹⁴N ratio of N already existing in the system to follow the N-source through the soil, water and plants. The advantage of the δ¹⁵N approach is that, in principle, it can be used in any ecosystem, but it has analytical, assumptions and interpretative limitations (Unkovich *et al.*, 2010).

Natural abundance method uses N₂-fixing legume and a no N₂-fixing reference plant growing together with the N₂-fixing legume. Cadisch *et al.* (2000) found that δ¹⁵N method was less sensitive between the reference and

N₂-fixing plant compared to the ¹⁵N-enrichment method but signals for the same precautions as for the ¹⁵N-enrichment method because of the N₂-fixing legume and the reference plant and accounting for ¹⁵N variation within the plant. According to Unkovich *et al.* (2010), the ¹⁵N content of the plant lies between the ¹⁵N signature of the plant-available soil N (%Nd_{fa} of zero) and a value close to 0.3663 atom% ¹⁵N (%Nd_{fa} of 100%). Carranca *et al.* (2015) reported that whole legume plant *i.e.*, top plant and visible roots and nodules should be involved in N₂-fixation studies in order to avoid underestimating the role of legumes for soil N fertility. Grain yields in legumes are a useful parameter in estimating biomass yield by taking into account harvest index and root/shoot ratio. Data on N concentrations in seeds, straw and roots of the main species allows quantification of the amount of N accumulated in the plant. Fustec *et al.* (2010) indicated that deposition of N in the root zone from dead cells, root exudates and shed fragments of roots, and the amount of N derived from biological fixation are important in considering the amount of N in the plant.

Several formulae for calculating the amount of N₂-fixed by a legume have been put in place but they depend on the method employed (Cadisch *et al.*, 2000; Giller, 2001; Unkovich *et al.*, 2010). The natural abundance method relies on the different natural abundance of ¹⁵N in soil N and atmospheric N. The ¹⁵N abundance in a non-N₂-fixing (reference) plant, which is all derived from the soil, is larger than that of a N₂-fixing plant, which derives some of its N from atmospheric N through symbiotic nitrogen fixation (Shearer and Kohl, 1986). The reference plant is a non-N₂-fixing but useful in measuring the ¹⁵N-enrichment of the available soil N (Giller, 2001). The total N is then analyzed for ¹⁵N, and the percentage of N derived from the atmosphere (%Nd_{fa}) by the legume is calculated using the equation 2.

$$\%Nd_{fa} = \left(1 - \frac{\text{atom\% } ^{15}\text{N excess from N}_2\text{fixing plant}}{\text{atom\% } ^{15}\text{N excess from a reference plant}}\right) \times 100 \dots (2)$$

Boddey *et al.* (1995) deduced a computational equation for %Nd_{fa} based on the whole plants *i.e.* the whole plant δ¹⁵N by considering the weight of seed and stover/straws (equation 3).

$$\%^{15}\text{N}_{d_{fa, \text{whole plant}}} = \left(\frac{\text{total seed N} \times \delta^{15}\text{N}_{\text{seed}} - \text{total straw N} \times \delta^{15}\text{N}_{\text{straw}}}{\text{total seed N} + \text{total straw N}}\right) \times 100 \dots (3)$$

The natural ¹⁵N abundance is expressed as delta δ¹⁵N in parts per thousand or per mill (‰) ¹⁵N excess over a standard (equation 4).

$$\delta^{15}\text{N}(\text{‰}) = \left(\frac{\text{atom\% } ^{15}\text{N sample} - \text{atom\% } ^{15}\text{N standard}}{\text{atom\% } ^{15}\text{N standard}}\right) \times 1000 \dots (4)$$

A slightly different expression for δ¹⁵N (‰) uses the R-values of the isotope ratios (equation 5).

$$\delta^{15}\text{N}(\text{‰}) = \left(\frac{R_{\text{sample}} - R_{\text{standard}}}{R_{\text{standard}}}\right) \times 1000 \dots (5)$$

Where $\delta^{15}\text{N}$ (%) is the isotope ratio of the sample relative to the atmospheric air standard and R_{sample} and R_{standard} is the molar ratios of ^{15}N to ^{14}N from the atmosphere. According to Giller (2001), the value of R is calculated as indicated in equation 6.

$$R = \frac{15_{\text{N}} + 14_{\text{N}}}{14_{\text{N}} + 14_{\text{N}}} \dots \dots \dots (6)$$

The proportion of ^{15}N atoms in the atmospheric N_2 is constant, around 0.3663 atom% ^{15}N and Ojiem *et al.* (2007) indicated that the $\delta^{15}\text{N}$ of the atmosphere is zero. However, the majority of N_2 transformed in the soil is in the ^{15}N isotopic form of N. The amount of N_2 -fixed can be calculated (Cadisch *et al.*, 2000; Somado and Kuehne, 2006) as in equation 7.

$$\text{Amount of } N_2 \text{ fixed} = \left(\frac{\%N_{\text{dfa}} \times \text{total N from } N_2 \text{ fixing crop}}{100} \right) \dots \dots \dots (7)$$

The amount of N_2 -fixed by a legume crop can also be calculated from measures of DM and N content (%N) in more simplified formula (Hauggaard-Nielsen *et al.*, 2009) as in equation 8.

$$\text{Amount of } N_2 \text{ fixed} = \left(\frac{\%N_{\text{dfa}}}{100} \right) \times DM \times \left(\frac{\%N}{100} \right) \dots (8)$$

Where DM is the dry weight of shoot

In the case of annual field crops, *e.g.* common bean, the %N from N_2 -fixation calculated using the equation of Shearer and Kohl (1986), Peoples *et al.* (1997) and Ojiem *et al.* (2007) as in equation 9.

$$\%N \text{ from } N_2 \text{ fixation} = \left(\frac{\delta^{15}N_{\text{reference plant}} - \delta^{15}N_{N_2 \text{ fixing plant}}}{\delta^{15}N_{\text{reference plant}} - B} \right) \times 100 \dots (9)$$

Where B is the $\delta^{15}\text{N}$ of the growing legume deriving its entire N from N_2 -fixation in an N-free medium and the B -value measured in common bean is -1.00 (Peoples *et al.*, 2002; Ojiem *et al.*, 2007). This value is obtained by taking the average of $\delta^{15}\text{N}$ measurements of a total of randomly selected bean genotypes and recombinant inbred lines from a cross between low symbiotic N_2 -fixing genotype and high symbiotic N_2 -fixing genotype grown in a greenhouse (Peoples *et al.*, 2002). The N (%) obtained in equation 8 is converted into land area (kg N ha^{-1}) basis of N contributed by an N_2 -fixing legume. It is important to quantify the amounts of N_2 -fixed by grain legumes by referring to non- N_2 -fixing plants such as C4-plants such as cereals (*e.g.* maize) as are growing together with legumes but cereals do not have closely related growth habits (acquisition of growth factors) with these legumes. It is therefore practical to choose a reference plant with the same growth habit and duration as the test legume. The use of C3-plants (*e.g.* broadleaved weeds as reference plants) growing together with both maize and legume crops in the same land is important as these C3-plants have some similarities in

growth habit with the test legume. Ojiem *et al.* (2007) indicated that the inclusion of C4-plants underestimated quantities of N_2 -fixed relative to the use of C3-plants as reference. It is important to understand the appropriate method of quantifying the amount of N_2 -fixed by legumes in cereal-legume cropping systems under field conditions and the associated N economy in the soil. The ^{15}N natural abundance method is superior to the ^{15}N -enrichment method because there is no application of N-containing fertilizer. The non- N_2 -fixing reference plants need to be well matched with the N_2 -fixing legumes.

The amount of N in soil as a result of fixation by a legume is also quantified in order to understand residual N that would be available for the subsequent crop. However, it is unlikely that N in soil would change over one cropping season as a contribution of including a legume. However, total N in soil before and after experimentation (given a long-term), soil sampling depth and bulk density are important in estimating the amount of mineral N (NH_4^+ and NO_3^-) in soil (Giller, 2001; Cresswell and Hamilton, 2002; Casanova *et al.*, 2016). Therefore, it is important to quantify the amounts of N_2 -fixed by grain legumes and added to the soil in order to understand the likely availability of N to the subsequent crop when cultivated in the same land and its overall influence on soil health.

Role of Grain Legumes Intensification in Improving Food Security under Changing Climate

Grain legumes are the important crops in sustaining natural resources, improvement of food security, improving nutrition and health status, and reduction of poverty (Dar *et al.*, 2012; Loboguerrero *et al.*, 2019). Grain legumes provide affordable nutritionally-balanced diets. Smallholder farmers diversify and intensify grain legumes with tubers, cereals, and root crops through rotations and intercrops. With the impact of climate change there are chances that some crops may fail in a season but diversification of different crop species ensures food security for the family's livelihood (Bedoussac *et al.*, 2015). Grain legumes like other legumes also play role in breaking cycles of weed, pest and disease of other subsequent crops, and provide massive soil cover (Franke *et al.*, 2018; Loboguerrero *et al.*, 2019).

Climate change is explained by the increase in temperatures and rainfall, which affect association among crop species, weeds, disease pathogens and pests (Saina *et al.*, 2013; Myers *et al.*, 2017; Stagnari *et al.*, 2017). Grain legumes such as common bean and soybean and cereals including rice and wheat operate with a C3 photosynthetic pathway. The growth of C3 crops is more stimulated by increases in CO_2 due to climate change than a C4 photosynthetic pathway crops such as sugarcane, sorghum, and maize (Leakey *et al.*, 2009; Considine *et al.*, 2017). It has been reported that the changes in climate since 1980 have reduced global food production (Myers *et al.*, 2017).

However, there is no evidence that the production of common bean, soybeans and rice has been affected by the trends of climate change (Lobell *et al.*, 2011; Saina *et al.*, 2013; Myers *et al.*, 2017). This is an important area of concern that common bean would play role in sustaining food security on smallholder farms. Lipiec *et al.* (2013) indicated that plants with C3 pathways are more sensitive to higher temperatures during photosynthesis compared with the plants characterized by C4 pathways.

Accessibility as well as availability of food both physically and economically at all times ensures food security where the people are sufficiently provided with dietary safe and nutritious food (Ericksen, 2008; Saina *et al.*, 2013; Loboguerrero *et al.*, 2019). Grain legumes including common bean are locally produced and/or available at farmer's level, safe and healthy, provide dietary proteins and vitamins, and acceptable at all households on smallholder farms (Hillocks *et al.*, 2006; Ndakidemi *et al.*, 2006; Ronner and Giller, 2013). However, production of these grain legumes and their dependence as an important source of food security should be considered consciously along with the influence of changes in climatic trends (Bishop *et al.*, 2017; Considine *et al.*, 2017) although there is no direct evidence reported. Therefore, it is important that options are designed for adaptation and mitigation of the impact of climate change on crops considered for food security. Some of the available options include intensification of cropping systems using improved varieties, sowing based on the onset of rains, improvement of irrigation and water use efficiency, diversification of the farming systems and adoption of crop rotations and intercropping (Ericksen, 2008; Devendra, 2012; Loboguerrero *et al.*, 2019). Grain legumes have importance on improvement and sustainability of soil quality, which dedicates production of food crops. Depending on the legume species, climatic conditions, and variation in soil properties grain legumes differently influence rhizospheric levels of soil N supply, soil organic carbon (SOC) and availability of P (Stagnari *et al.*, 2017).

Soil Health and Fertility Status and Associated Environmental Benefits of Intercrops or Rotations

Intercrops and rotations which involve grain legumes improve soil health by reducing amount of N losses that cause pollution (Sanderson *et al.*, 2013; Lemaire *et al.*, 2014). The SOC and N contents sequestration rates are reported to increase in intercropped and/or rotated wheat, maize, and faba beans (*Vicia faba* L.) compared with the quantities of SOC measured in the monocultures of these crops (Cong *et al.*, 2014).

Inclusion of different crop species during or in successive cropping seasons in the same piece of land is reported to increase the diversity of soil microbes such as rhizobacteria and arbuscular mycorrhizal fungi (Cong *et al.*, 2014; Bybee-Finley and Ryan, 2018). The practices also

increase microbial activities with the additional benefits of influencing nutrient availability in soils and facilitate their uptakes for the component and/or subsequent crops (Cong *et al.*, 2014; Vukicevich *et al.*, 2016). Due to the ability of grain legume to fix atmospheric N in symbiosis with the rhizobium, the cereal-legume based systems have self-regulatory abilities on the amounts of soil total N (Chapman *et al.*, 1996; Vukicevich *et al.*, 2016). These self-regulating mechanisms reduce the fates of denitrification and leaching of NO₃⁻ through reduction of the reactive N in the soil. This in turn, reduces the problems associated with emissions of greenhouse gases and water quality in cropping systems (Tang *et al.*, 2017).

Socio-economic Implications of Intercrops and Rotations

Despite that the benefits derived from intercropping and/or rotations would outperform sole cultivations of each crop either during the season (monocropping) or throughout the cropping seasons (monoculture), there are also some economic implications of these systems (Ndakidemi *et al.*, 2006; Kermah *et al.*, 2017). The demand of labour for field operations such as sowing, weeding, spraying, and harvesting may be higher in intercropping compared with monocropping and this increases operational costs due time consumed and might affect the rate of adoption of the practice by farmers (Ndiritu *et al.*, 2014; Kermah *et al.*, 2017). However, costs related to large seed quantities are reduced under intercrops due to relatively low seeding rate at sowing (Kermah *et al.*, 2017). In addition, component crops complement each other in the season in cases one of them fails to complete its maturity cycle, probably, due to bad climates, poor soil fertility, diseases and pests (Trenbath, 1993). Similarly, in crop rotation although costs related to field operations might not be as higher as those incurred in intercrops, the practice often involves one crop in a cropping season (Kermah *et al.*, 2017; Shahzad *et al.*, 2017). In situations where this singly cultivated crop fails to complete its life cycle, farmers relying on it for food and income will suffer from food insecurity. With this in mind, it is likely that farmers may prefer continuous intercropping of contrasting plant species as an alternative to avoid risks of one crop failure in a season.

Gender preference in farming activities intersects most of the socio-economic aspects to be considered in intensification of crop production and sustainability of food security in smallholder settings. For example, cereals and only highly commercialized grain legumes are often considered as crops for male whereas less commercialized grain and vegetable legumes are regarded as crops for women (Bationo *et al.*, 2011). Women are the most important group, which affects the execution of agricultural activities and the outcomes unveiled since are obedient and fully involved in field operations, processing and storage, and trading where applicable.

However, women are less entitled to property ownership including access to and control of production assets such as land and the funds earned from farming activities and constitute a group inferiorly considered in decision making (Wakhungu, 2010).

It is a major concern that women are given priority and great consideration in decision making on designing appropriate practices to be adopted for sustainable intensification of systems productivity as this may increase awareness for gender equity in food security. Me-Nsope and Larkins (2016) indicated that farmers' adoption/cultivation of legume-cereal was highly affected by the gender element. Where only men are involved in marketing of farm products, the sales do not translate into improvements of the household's food security (Me-Nsope and Larkins, 2016). Development efforts towards food security through farming need to consider interventions on gender equity such that women are involved at every stage. According to Rubin *et al.* (2009), systems productivity and access to commodities from farming, funds from sales, human resources, time, information, and skills are affected by the gender equity. This suggests that there should be co-sharing of decision making, execution of the idea or activity and benefits derived from farming for both men and women right from the household level. It is important that farmers' perception is evaluated based on the options for sustainable intensification of common bean cultivation through rotations and/or intercropping while considering gender equity and its sensitization.

Conclusion

Cereals and grain legumes are the important staple crops of the smallholders. Grain legumes also supplement dietary protein and the surplus from both crops is sold for cash generation. Rotation and intercropping are the common farming systems of these crops on smallholder farms. Both practices are intended for improvement of system productivity on crop itself for food security and sustainability of soil fertility. Land size used for crop cultivation, socio-economic differences, climatic conditions, access to agro-inputs and seasons of the year affect the type of cropping system to be practised. Farmers are also unaware of the appropriate practices such as plant population (sowing density as for spacing and pattern) and time of introducing a legume crop relative to a cereal crop in intercrops. Farmers also do not use fertilizers in legumes-based cropping and for cereals they use little or sometimes do not apply any fertilizers. Locally adapted low yielding varieties are also used without guidance on the suitability of such varieties to varying agro-ecological zones. Literature synthesis revealed that well designed cereal-grain legume intercrops and/or rotations present elements for sustainable intensification of food security for smallholder farmers and they dedicate environmental friendly practices. The overall performance of these farming activities, ownership of assets

from farming, and marketing of surplus products is gender driven although women constitute the most vulnerable group in the system, escalating an area for further investigation and need for sensitization.

Acknowledgements

The Bill & Melinda Gates Foundation through a grant to Wageningen University is acknowledged for funding this study through the *Putting Nitrogen Fixation to Work for Smallholder Farmers in Africa* (N2Africa) Project, (www.N2Africa.org). Author Eliakira Kisetu Nassary gratefully acknowledges additional financial and guidance support from the International Institute of Tropical Agriculture (IITA) through the Graduate Research Internship. Authors are highly indebted to anonymous reviewers and the handling Editor of International Journal of Agriculture and Biology Dr. Mubshar Hussain – Associate Professor of Bahauddin Zakariya University Multan, Pakistan for their constructive comments which improved the final version of this manuscript.

References

- Abdullah, S.S. and H.A. Fouad, 2016. Effect of intercropping agro-ecosystem on the population of black legume aphid, *Aphis craccivora* Koch and yield of faba bean crop. *J. Entomol. Zool. Stud.*, 4: 1367–1371
- Adekalu, K.O., D.A. Okunade and J.A. Osunbitan, 2006. Compaction and mulching effects on soil loss and runoff from two southwestern Nigeria agricultural soils. *Geoderma*, 37: 226–230
- Armstrong, D.L., K.P. Griffin, M. Danner, M.C. Carol and D.S.O.H.O. Nguyen, 1999. Phosphorus for Agriculture. *Better Crops Food Plant*, 83:40
- Babikova, Z., L. Gilbert, T.J. Bruce, M. Birkett, J.C. Caulfield, C. Woodcock, J. Pickett and D. Johnson, 2013. Underground signals carried through common mycelia networks warn neighbouring plants of aphid attack. *Ecol. Lett.*, 16: 835–843
- Bastiaans, L., R. Paolini and D.T. Baumann, 2008. Focus on ecological weed management: What is hindering adoption? *Weed Res.*, 48: 481–491
- Bationo, A., B. Waswa, J.M. Okeyo, F. Maina, J. Kihara and U. Mokwunye, 2011. *Fighting poverty in Sub-Saharan Africa: The Multiple Roles of Legumes in Integrated Soil Fertility Management*. 1st edition. Springer
- Belde, M., A. Mattheis, B. Sprenger and H. Albrecht, 2000. Long-term development of yield affecting weeds after the change from conventional to integrated and organic farming. *J. Plant Dis. Protect.*, 291–301
- Bedoussac, L., E.P. Journet, H. Hauggaard-Nielsen, C. Naudin, G. Corré-Hellou, E.S. Jensen, L. Prieur and E. Justes, 2015. Ecological principles underlying the increase of productivity achieved by cereal-grain legume intercrops in organic farming. A review. *Agron. Sustain. Dev.*, 35: 911–935
- Bishop, J., H.E. Jones, D.M. O'Sullivan and S.G. Potts, 2017. Elevated temperature drives a shift from selfing to outcrossing in the insect pollinated legume, faba bean (*Vicia faba*). *J. Exp. Bot.*, 68: 2055–2063
- Boddey, R.M., O.C. de Oliveira, B.J.R. Alves and S. Urquiaga, 1995. Field application of the ¹⁵N isotope dilution technique for the reliable quantification of plant-associated biological nitrogen fixation. *Fertilizer Res.*, 42: 77–87
- Bonfim, K., J.C. Faria, E.O. Nogueira, E.A. Mendes and F.J. Aragão, 2007. RNAi-mediated resistance to bean golden mosaic virus in genetically engineered common bean (*Phaseolus vulgaris*). *Mol. Plant-Microbe Inter.*, 20: 717–726

- Boudreau, M.A., 2013. Diseases in intercropping systems. *Ann. Rev. Phytopathol.*, 51: 499–519
- Brooker, R.W., A.E. Bennett, W.F. Cong, T.J. Daniell, T.S. George, P.D. Hallett, C. Hawes, P.P.M. Iannetta, H.G. Jones, A.J. Karley, L. Li, B.M. McKenzie, R.J. Pakeman, E. Paterson, C. Schöb, J. Shen, G. Squire, C.A. Watson, C. Zhang, F. Zhang, J. Zhang and P.J. White, 2015. Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. *New Phytol.*, 206: 107–117
- Bybee-Finley, K.A. and R.M. Ryan, 2018. Advancing intercropping research and practices in industrialized agricultural landscapes. *Agriculture*, 8: 80
- Cadisch, G., K. Hairiah and K.E. Giller, 2000. Applicability of the natural ¹⁵N abundance technique to measure N₂ fixation in *Arachis hypogaea* grown on an Ultisol. *NJAS - Wageningen J. Life Sci.*, 48: 31–45
- Carranca, C., M.O. Torres and M. Madeira, 2015. Underestimated role of legume roots for soil N fertility. *Agron. Sustain. Dev.*, 1–13
- Carter, M.R. and F.J. Zimmerman, 2000. The dynamic cost and persistence of asset inequality in an agrarian economy. *J. Dev. Econ.*, 63: 265–302
- Casanova, M., E. Tapia, O. Seguel and O. Salazar, 2016. Direct measurement and prediction of bulk density on alluvial soils of central Chile. *Chil. J. Agric. Res.*, 76: 105–113
- Chan, K.Y. and D.P. Heenan, 1996. The influence of crop rotation on soil structure and soil physical properties under conventional tillage. *Soil Tillage Res.*, 37: 113–125
- Chapman, D.F., A.J. Parsons and S. Schwinning, 1996. Management of clover in grazed pastures: Expectations, limitations and opportunities. *Spec. Publ.-Agron. Soc. N.Z.*, 11: 55–64
- Chen, B., E. Liu, Q. Tian, C. Yan and Y. Zhang, 2014. Soil nitrogen dynamics and crop residues. A review. *Agron. Sustain. Dev.*, 34: 429–442
- Chen, Y., F. Zhang, L. Tang, Y. Zheng, Y. Li, P. Christie and L. Li, 2007. Wheat powdery mildew and foliar N concentrations as influenced by N fertilization and belowground interactions with intercropped faba bean. *Plant Soil*, 291: 1–13
- Chowdhury, M.K. and E.L. Rosario, 1994. Comparison of nitrogen, phosphorus and potassium utilization efficiency in maize/mungbean intercropping. *J. Agric. Sci.*, 122: 193–199
- Clement, S.L., J.A. Wightman, D.C. Hardie, P. Bailey, G. Baker and G. McDonald, 2000. Opportunities for integrated management of insect pests of grain legumes. In: *Linking Research and Marketing Opportunities for Pulses in the 21st Century*, pp: 467–480. Knight, R. (ed.). Kluwer Academic Publishers
- Cong, W.F., E. Hoffland, L. Li, J. Six, J.H. Sun, X.G. Bao, F.S. Zhang and W. Van DerWerf, 2015. Intercropping enhances soil carbon and nitrogen. *Glob. Chang. Biol.*, 21: 1715–1726
- Connolly, J., H.C. Goma and K. Rahim, 2001. The information content of indicators in intercropping research. *Agric. Ecosyst. Environ.*, 87: 191–207
- Considine, M.J., K.H.M. Siddique and C.H. Foyer, 2017. Nature's pulse power: legumes, food security and climate change. *J. Exp. Bot.*, 68: 1815–1818
- Corre-Hellou, G., J. Fustec and Y. Crozat, 2006. Interspecific competition for soil N and its interaction with N₂ fixation, leaf expansion and crop growth in pea-barley intercrops. *Plant Soil*, 282: 195–208
- Cresswell, H.P. and G.J. Hamilton, 2002. Bulk density and pore space relations. In: *Soil Physical Measurement and Interpretation for Land Evaluation*, pp: 35–58. McKenzie, N.J., H. Cresswell and K. Coughlan (eds.). Australian Soil and Land Survey Handbook. Melbourne: CSIRO
- Dahmardeh, M., A. Ghanbari, B.A. Syahsar and M. Ramrodi, 2010. The role of intercropping maize (*Zea mays* L.) and cowpea (*Vigna unguiculata* L.) on yield and soil chemical properties. *Afr. J. Agric. Res.*, 5: 631–636
- Dar, W.D., R.G. Echeverria, M. Solh and N. Sanginga, 2012. GRAIN LEGUMES: Leveraging legumes to combat poverty, hunger, malnutrition and environmental degradation. A CGIAR Research Program submitted by ICRISAT-lead, CIAT, ICARDA and IITA), 03 February 2012, 290 p
- Darai, R., B.R. Ojha and K.H. Dhakal, 2017. Disease management of major grain legumes and breeding strategies in Nepal. *Adv. Plants Agric. Res.*, 6: 1–7
- Dawo, M.I., M.J. Wilkinson and D.J. Philbeam, 2008. Interactions between plants in intercropped maize and common bean. *J. Sci. Food Agric.*, 89: 41–48
- Devendra, C., 2012. Climate change threats and effects: challenges for agriculture and food security. *Academy of Sciences Malaysia (ASM) Series on Climate Change*, p: 66
- Dogliotti, S., M.K. van Ittersum and W.A.H. Rossing, 2005. A method for exploring sustainable development options at farm scale: a case study for vegetable farms in South Uruguay. *Agric. Syst.*, 86: 29–51
- Dong, N., M.M. Tang, W.P. Zhang, X.G. Bao, Y. Wang, P. Christie and L. Li, 2018. Temporal differentiation of crop growth as one of the drivers of intercropping yield advantage. *Sci. Rep.*, 8: 3110
- Dotaniya, M.L., D. Prasad, H.M. Meena, D.K. Jajoria, G.P. Narolia, K.K. Pingoliya, O.P. Meena, K. Kumar, B.P. Meena, A. Ram, H. Das, M.S. Chari and S. Pal, 2013. Influence of phytosiderophore on iron and zinc uptake and rhizospheric microbial activity. *Afr. J. Microbiol. Res.*, 7: 5781–5788
- Dregne, H.E., 2002. Land degradation in the drylands. *Arid Land Res. Manag.*, 16: 99–132
- Erickson, P.J., 2008. Conceptualizing food systems for global environmental change research. *Glob. Environ. Chang.*, 18: 234–245
- Faria, J.C., P.A.M.R. Valdisser, E.O.P.L. Nogueira and F.J.L. Aragão, 2014. RNAi-based bean golden mosaic virus-resistant common bean (Embrapa 51) shows simple inheritance for both transgene and disease resistance. *Plant Breed.*, 133: 649–653
- Fininsa, C., 1996. Effect of intercropping bean with maize on bean common bacterial blight and rust diseases. *Intl. J. Pest Manage.*, 42: 51–54
- Franke, A.C., G.J. van den Brand, B. Vanlauwe and K.E. Giller, 2018. Sustainable intensification through rotations with grain legumes in sub-Saharan Africa: a review. *Agric. Ecosyst. Environ.*, 261: 172–185
- Fustec, J., F. Lesuffleur, S. Mahieu and J.B. Cliquet, 2010. Nitrogen rhizodeposition of legumes. A review. *Agron. Sustain. Dev.*, 30: 57–66
- Gacheru, E. and M.R. Rao, 2001. Managing Striga infestation on maize using organic and inorganic nutrient sources in western Kenya. *Intl. J. Pest Manage.*, 47: 233–239
- Gathumbi, S.M., J.K. Ndufa, K.E. Giller and G. Cadisch, 2002. Do species mixtures increase above- and belowground resource capture in woody and herbaceous tropical legumes? *Agron. J. Abstract-Cropping Syst.*, 94: 518–526
- Giller, K.E., J. Ormisher and F.M. Awah, 1991. Nitrogen transfer from Phaseolus bean to intercropped maize measured using ¹⁵N-enrichment and ¹⁵N-isotope dilution methods. *Soil Biol. Biochem.*, 23: 339–346
- Giller, K.E., 2001. *Nitrogen Fixation in Tropical Cropping Systems*, 2nd edition. CAB International, Wallingford, UK
- Giller, K.E., F. Amijee, S.J. Brodrick and O.T. Edje, 1998. Environmental constraints to nodulation and nitrogen fixation of *Phaseolus vulgaris* L. in Tanzania II. Response to N and P fertilisers and inoculation with *Rhizobium*. *Afr. Crop Sci. J.*, 16: 171–178
- Giller, K.E., J.F. McDonagh and G. Cadisch, 1994. Can biological nitrogen fixation sustain agriculture in the tropics? In: *Soil Science and Sustainable Land Management in the Tropics*, pp: 173–191. Syers, J.K. and D.L. Rimmer (eds.). Wallingford, U.K.: CAB International
- Giller, K.E., M.S. Murwira, D.K.C. Dhliwayo, P.L. Mafongoya and S. Mpepereki, 2011. Soyabean and sustainable agriculture in Southern Africa. *Intl. J. Agric. Sustain.*, 9: 50–58
- Godfray, C., J.R. Beddington, I.R. Crute, L. Haddad, D. Lawrence, J.F. Muir, J. Pretty, S. Robinson, S.M. Thomas and C. Toulmin, 2010. Food security: the challenge of feeding 9 billion people. *Science*, 327: 812–818
- Gworgwor, N.A. and H.C. Weber, 1991. Effect of N application on sorghum growth, Striga infestation and osmotic pressure of the parasite in relation to the host. *J. Plant Physiol.*, 139: 194–198

- Hauggaard-Nielsen, H., M. Gooding, P. Ambus, G. Corre-Hellou, Y. Crozat, C. Dahlmann, A. Dibet, P. von Fragstein, A. Pristeri, M. Monti and E.S. Jensen, 2009. Pea–barley intercropping for efficient symbiotic N₂-fixation, soil N acquisition and use of other nutrients in European organic cropping systems. *Field Crops Res.*, 113: 64–71
- Hauggaard-Nielsen, H. and E.S. Jensen, 2005. Facilitative root interaction in intercrops. *Plant Soil*, 274: 237–250
- Hillocks, R.J., C.S. Madata, R. Chirwa, E.M. Minja and S. Msolla, 2006. Phaseolus bean improvement in Tanzania, 1959–2005. *Euphyt.*, 150: 215–231
- Hinsinger, P., 2001. Bioavailability of soil inorganic P in the rhizosphere as affected by root-induced chemical changes: a review. *Plant Soil*, 237: 173–195
- Hinsinger, P., E. Betencourt, L. Bernard, A. Brauman, C. Plassard, J. Shen, X. Tang and F. Zhang, 2011. P for two, sharing a scarce resource – soil phosphorus acquisition in the rhizosphere of intercropped species. *Plant Phys.*, 156: 1078–1086
- Jensen, E.S., 1996. Grain yield, symbiotic N₂ fixation and interspecific competition for inorganic N in pea-barley intercrops. *Plant Soil*, 182: 25–38
- Kelly, J.D., P. Gepts and P.N. Miklas, 2003. Tagging and mapping of genes and QTL and molecular marker-assisted selection for traits of economic importance in bean and cowpea. *Field Crops Res.*, 82: 135–154
- Kermah, M., A.C. Franke, S. Adjei-Nsiah, B.D.K. Ahiabor, R.C. Abaidoo and K.E. Giller, 2017. Maize-grain legume intercropping for enhanced resource use efficiency and crop productivity in the Guinea savanna of northern Ghana. *Field Crops Res.*, 213: 38–50
- Kermah, M., A.C. Franke, S. Adjei-Nsiah, B.D.K. Ahiabor, R.C. Abaidoo and K.E. Giller, 2018. *Legume–maize Rotation or Relay? Options for Ecological Intensification of Smallholder Farms in the Guinea Savanna of Northern Ghana*, pp: 1–19. Exp. Agric. Cambridge University Press 2018
- Koochechi, A., M. Nassiri, L. Alimoradi and R. Ghorbani, 2009. Effect of cropping systems and crop rotations on weeds. *Agron. Sustain. Dev.*, 29: 401–408
- Kureh, I., A.Y. Kamara and B.D. Tarfa, 2006. Influence of cereal-legume rotation on Striga control and maize grain yield in farmers' fields in the northern Guinea savanna of Nigeria. *J. Agric. Rural Dev. Trop.*, 107: 41–54
- Kwiecinska-Poppe, E., P. Kraska and E. Palys, 2009. The effect of intercropping on weed infestation of a spring barley crop cultivated in monoculture. *Acta Agrobot.*, 62: 163–170
- Latati, M., A. Bargaz, B. Belarbi, M. Lazali, S. Benlahrech, S. Tellah, G. Kaci, J.J. Drevon and S.M. Ounane, 2016. The intercropping common bean with maize improves the rhizobial efficiency, resource use and grain yield under low phosphorus availability. *Eur. J. Agron.*, 72: 80–90
- Leakey, A.D.B., E.A. Ainsworth, C.J. Bernacchi, A. Rogers, S.P. Long and D.R. Ort, 2009. Elevated CO₂ effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. *J. Exp. Bot.*, 60: 2859–2876
- Leidi, E.O. and D.N. Rodriguez-Navarro, 2000. Nitrogen and phosphorus availability limit N₂-fixation in bean. *New Phytol.*, 147: 337–346
- Lemaire, G., A. Franzluebbers, P.C. de Faccio Carvalho and B. Dedieu, 2014. Integrated crop–livestock systems: Strategies to achieve synergy between agricultural production and environmental quality. *Agric. Ecosyst. Environ.*, 190: 4–8
- Liebenberg, A.J., 2009. *Dry bean production. Department: Agriculture, Forestry and Fisheries*. Republic of South Africa, www.nda.agric.za/docs/drybean/drybean.pdf
- Lipiec, J., C. Doussan, A. Nosalewicz and K. Kondracka, 2013. Effect of drought and heat stresses on plant growth and yield: A review. *Inst. Agrophys.*, 27: 463–477
- Lithourgidis, A.S., C.A. Dordas, C.A. Damalas and D.N. Vlachostergios, 2011. Annual intercrops: an alternative pathway for sustainable agriculture. *Aust. J. Crop Sci.*, 5: 396–410
- Li, B., Y.Y. Li, H.M. Wu, F.F. Zhang, C.J. Li, X.X. Li, H. Lambers and L. Li, 2016. Root exudates drive interspecific facilitation by enhancing nodulation and N₂ fixation. *PNAS*, 113: 6496–6501
- Li, L., D. Tilman, H. Lambers and Fu-Suo. Zhang, 2014. Plant diversity and overyielding: insights from belowground facilitation of intercropping in agriculture. *New Phytol.*, 203: 63–69
- Ikie, F.O., S. Schulz, Ogunyemi, A.M. Emechebe and A.O. Togun, 2007. Influence of legume cropping patterns and organic/inorganic soil amendments on Striga seedbank and subsequent sorghum performance. *Adv. Environ. Biol.*, 1: 11–19
- Lobell, D.B., W. Schlenker and J. Costa-Roberts, 2011. Climate trends and global crop production since 1980. *Science*, 333: 616–20
- Loboguerrero, A.M., B.M. Campbell, P.J.M. Cooper, J.W. Hansen, T. Rosenstock and E. Wollenberg, 2019. Food and earth systems: priorities for climate change adaptation and mitigation for agriculture and food systems. *Sustainability*, 11: 1372
- Lyimo, S., Z. Mduruma and H. De Groote, 2014. The use of improved maize varieties in Tanzania. *Afr. J. Agric. Res.*, 9: 643–657
- Maingi, J.M., C.A. Shisanya, N.M. Gitonga and B. Hornetz, 2001. Nitrogen fixation by common bean (*Phaseolus vulgaris* L.) in pure and mixed stands in semi-arid south-east Kenya. *Eur. J. Agron.*, 14: 1–12
- Makkouk, K.M., S.G. Kumari, J.A. Hughes, V. Muniyappa and N.K. Kulkarni, 2003. Other legumes: Faba bean, chickpea, lentil, pigeonpea, mungbean, blackgram, lima bean, horegram, bambara groundnut and winged bean. In: *Virus and Virus-like Diseases of Major Crops in Developing Countries*, pp: 447–476. Loebenstein, G. and G. Thottappilly (eds.). Kluwer Academic Publishers, Dordrecht, The Netherlands
- Makoi, J.H.J.R. and P.A. Ndakidemi, 2012. Allelopathy as protectant, defence and growth stimulants in legume cereal mixed culture systems. *N.Z. J. Crop Hortic. Sci.*, 40: 161–186
- Manrique, A., K. Manrique and J. Nakahodo, 1993. Yield and biological nitrogen fixation of common bean (*Phaseolus vulgaris* L.) in Peru. *Plant Soil*, 152: 1: 87–91
- Marschner, H., 1990. *Mineral Nutrition of Higher Plants*, 4th edition. Academic Press Limited, London
- Me-Nsope, N. and M. Larkins, 2016. Beyond crop production: Gender relations along the pigeon pea value chain and implications for income and food security in Malawi. *J. Gender Agric. Food Sec.*, 1: 1–22
- Midega, C.A.O., D. Salifu, T.J. Bruce, J. Pittchar, J.A. Pickett and Z.R. Khan, 2014. Cumulative effects and economic benefits of intercropping maize with food legumes on *Striga hermonthica* infestation. *Field Crops Res.*, 155: 144–152
- Micheni, A.N., F. Kanampiu, O. Kitonyo, D.M. Mburu, E.N. Mugai, D. Makumbi and M. Kassie, 2015. On-farm experimentation on conservation agriculture in maize-legume based cropping systems in Kenya: water use efficiency and economic impacts. *Exp. Agric.*, 1–18
- Miklas, P.N., J.D. Kelly, S.E. Beebe and M.W. Blair, 2006. Common bean breeding for resistance against biotic and abiotic stresses: From classical to MAS breeding. *Euphyt.*, 147: 105–131
- Mulumba, J.W., R. Nankya, J. Adokororach, C.F. Kiwuke, C. Fadda, P. Desantis and I.D. Jarvis, 2012. A risk minimizing argument for traditional crop varietal diversity use to reduce pest and disease damage in agricultural ecosystems of Uganda. *Agric. Ecosyst. Environ.*, 157: 70–86
- Muniappan, R., B.M. Shepard, G.R. Carner and P.A.C. Ooi, 2012. *Arthropod Pests of Horticultural Crops in Tropical Asia*. Wallingford, Oxfordshire, CABI
- Myers, S.S., M.R. Smith, S. Guth, C.D. Golden, B. Vaitla, N.D. Mueller, A.D. Dangour and P. Huybers, 2017. Climate change and global food systems: potential impacts on food security and undernutrition. *Annu. Rev. Public Health*, 38: 259–277
- Ndakidemi, P.A., 2006. Manipulating legume/cereal mixtures to optimize the above and below ground interactions in the traditional African cropping systems. *Afr. J. Biotech.*, 5: 2526–2533
- Ndakidemi, P.A. and F.D. Dakora, 2003. Legume seed flavonoids and nitrogenous metabolites as signals and protectants in early seedling development. *Funct. Plant Biol.*, 30: 729–745

- Ndakidemi, P.A., F.D. Dakora, E.M. Nkonya, D. Ringo and H. Mansoor, 2006. Yield and economic benefits of common bean (*Phaseolus vulgaris*) and soybean (*Glycine max*) inoculation in northern Tanzania. *Australian J. Exp. Agric.*, 46: 571–577
- Ndiritu, S.W., M. Kassie and B. Shiferaw, 2014. Are there systematic gender differences in the adoption of sustainable agricultural intensification practices? Evidence from Kenya. *Food Policy*, 49: 117–127
- Nyaligwa, L., S. Hussein, M. Laing, H. Ghebrehiwot and B.A. Amelework, 2017. Key maize production constraints and farmers' preferred traits in the mid-altitude maize agroecologies of northern Tanzania. *S. Afr. J. Plant Soil*, 34: 47–53
- Obanyi, J.N., A.W. Kamau and J.O. Ogecha, 2017. Effects of common bean (*Phaseolus vulgaris* L.) cultivars and their mixtures with other legume species on bean foliage beetle (*Ootheca spp*) incidence, severity and grain yield in Western Kenya. *World J. Agric. Res.*, 5: 156–161
- OECD, 2016. Common bean (*Phaseolus vulgaris*). In: *Safety Assessment of Transgenic Organisms in the Environment, Volume 6: OECD Consensus Documents*, OECD Publishing, Paris. <https://doi.org/10.1787/9789264253421-7-en>
- Ogenga-Latigo, M.W., J.K.O. Ampofo and C.W. Balidawa, 1992. Influence of maize row spacing on infestation and damage of intercropped beans by bean aphids (*Aphis fabae* Scop.) incidence of aphids. *Field Crops Res.*, 30: 111–121
- Ojiem, J.O., B. Vanlauwe, N. de Ridder and K.E. Giller, 2007. Niche-based assessment of contributions of legumes to the nitrogen economy of Western Kenya smallholder farms. *Plant Soil*, 292: 119–135
- Pande, S., J. Galloway, P.M. Gaur, K.H.M. Siddique, H.S. Tripathi, P. Taylor, M.W.J. MacLeod, A.K. Basandrai, A. Bakr, S. Joshi, K.G. Krishna, D.A. Isenegger, J. Narayana Rao and M. Sharma, 2006. Botrytis grey mould of chickpea: A review of biology, epidemiology and disease management. *Aus. J. Agric. Res.*, 57: 1137–1150
- Pande, S., M. Sharma, S. Kumari, P.M. Gaur, W. Chen, L. Kaur, W. MacLeod, A. Basandrai, D. Basandrai, A. Bakr, J.S. Sandhu, H.S. Tripathi and C.L.L. Gowda, 2009. *Integrated foliar diseases management of legumes. International Conference on Grain Legumes: Quality Improvement, Value Addition and Trade, February 14–16, 2009*, pp: 143–161. Indian Society of Pulses Research and Development, Indian Institute of Pulses Research, Kanpur, India
- Papastylianou, I., 2004. Effect of rotation system and N fertilizer on barley and vetch grown in various crop combinations and cycle lengths. *J. Agric. Sci.*, 142: 41–48
- Peoples, M.B., J. Brockwell, D.F. Herridge, I.J. Rochester, B.J.R. Alves, S. Urquiaga, R.M. Boddey, F.D. Dakora, S. Bhattarai and S.L. Maskey, 2009. The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. *Symbiosis*, 48: 1–17
- Peoples, M.B., A.W. Faizah, B. Rerkasem and D.F. Herridge, 1989. *Methods for Evaluating Nitrogen Fixation by Nodulated Legumes in the Field*, p: 76. ACIAR Monograph No. 11, vii
- Peoples, M.B., G.L. Turner, Z. Shah, S.H. Shah, M. Aslam, S. Ali, S.L. Maskey, S. Bhattarai, F. Afandi, G.D. Schwenke and D.F. Herridge, 1997. Evaluation of the ¹⁵N natural abundance technique to measure N₂-fixation in experimental plots and farmers' fields. In: *Extending Nitrogen Fixation Research to Farmers' Field: Proc. Intl. Workshop Manag. Legume Nitrogen Fixation Cropping Syst. Asia*, pp. 57–75. Rupela, O.P., C. Johansen and D.F. Herridge. (ed.). ICRISAT, Hyderabad, India
- Peoples, M.B., M.J. Unkovich and D.F. Herridge, 2002. Measuring symbiotic nitrogen fixation by legumes. In: *Nitrogen Fixation in Crop Production*. Emerich, D.W. and H.B. Krishnan (eds.), Vol. 52, pp: 125–170. American Society of Agronomy and Crop Science
- Porch, T.G., J.S. Beaver, D.G. Debouck, S.A. Jackson, J.D. Kelly and H. Dempewolf, 2013. Use of wild relatives and closely related species to adapt common bean to climate change. *Agronom*, 3: 433–461
- Pretty, J., 2008. Agricultural sustainability: concepts, principles and evidence. *Phil. Trans. R. Soc. B.*, 363: 447–466
- Pretty, J. and Z.P. Bharucha, 2014. Sustainable intensification in agricultural systems. *Ann. Bot.*, 114: 1571–1596
- Pretty, J., C. Toulmin and S. Williams, 2011. Sustainable intensification in African agriculture. *Intl. J. Agric. Sustain.*, 9: 5–24
- Raimi, A., R. Adeleke and A. Roonnarain, 2017. Soil fertility challenges and biofertiliser as a viable alternative for increasing smallholder farmer crop productivity in sub-Saharan Africa. *Cogent Food Agric.*, 3: 1400933
- Ranga Rao, G.V., V. Rameshwar Rao and M.A. Ghaffar, 2013. *Handbook on Chickpea and Pigeonpea Insect Pest Identification and Management, Information Bulletin No. 57*, p: 96. Patancheru, Andhra Pradesh 502 324, India: International Crops Research Institute for the Semi-Arid Tropics
- Reddy, T.Y. and G.H.S. Reddi, 2007. *Principles of Agronomy*, pp: 468–489. Kalyani Publishers, India
- Roger, P.A. and J.K. Ladha, 1992. Biological N₂ fixation in wetland rice fields: Estimation and contribution to nitrogen balance. *Plant Soil*, 141: 41–55
- Ronner, E. and K.E. Giller, 2013. *Background Information on Agronomy, Farming Systems and Ongoing Projects on Grain Legumes in Tanzania*, p: 33. www.N2Africa.org
- Rondon, M.A., J. Lehmann, J. Juan-Ramirez and M. Hurtado, 2006. *Biological Nitrogen Fixation by Common Beans (Phaseolus vulgaris L.) Increases with Bio-char Additions*. Biology and Fertility of Soils. ©Springer-Verlag 2006
- Rubin, D., C. Manfre and K. Barrett, 2009. *Promoting Gender Equitable Opportunities in Agricultural Value Chains*. Handbook, Washington, CC, USA: USAID
- Rusinamhodzi, L., M. Corbeels, J. Nyamangara and K.E. Giller, 2012. Maize-grain legume intercropping is an attractive option for ecological intensification that reduces climatic risk for smallholder farmers in central Mozambique. *Field Crops Res.*, 136: 12–22
- Ryan, P.R., S.D. Tyerman, T. Sasaki, T. Furuichi, Y. Yamamoto, W.H. Zhang and E. Delhaize, 2011. The identification of aluminium-resistance genes provides opportunities for enhancing crop production on acid soils. *J. Exp. Bot.*, 62: 9–20
- Saina, C.K., D.K. Murgor and F.A.C. Murgor, 2013. Climate Change and Food Security. *Environ. Change Sust.*, pp: 235–257 <http://dx.doi.org/10.5772/55206>
- Sanderson, M.A., D. Archer, J. Hendrickson, S. Kronberg, M. Liebig, K. Nichols, M. Schmer, D. Tanaka and J. Aguilar, 2013. Diversification and ecosystem services for conservation agriculture: Outcomes from pastures and integrated crop–livestock systems. *Renew. Agric. Food Syst.*, 28: 129–144
- Sanginga, N., J.A. Okogun, B. Vanlauwe, J. Diels, R.J. Carsky and K. Dashiell, 2001. *Nitrogen Contribution of Promiscuous Soybeans in Maize-based Cropping Systems*, pp: 157–177. Sustaining Soil Fertility in West Africa. SSSA Special Publication No. 58. SSSA, Madison, WI, USA
- Sarris, S., S. Savastano and L. Christiaensen, 2006. The role of agriculture in reducing poverty in Tanzania. *A household perspective from Rural Kilimanjaro and Ruvuma*. FAO Commodity and Trade Policy Research Working Paper, No. 19
- Schwartz, H.F. and S.P. Singh, 2013. Breeding common bean for resistance to white mold: A review. *Crop Sci.*, 53: 1832–1844
- Seran, T.H. and I. Brintha, 2010. Review on maize based intercropping. *J. Agron.*, 9: 135–145
- Shahzad, M., M. Farooq, K. Jabran and M. Hussain, 2016a. Impact of different crop rotations and tillage systems on weed infestation and productivity of bread wheat. *Crop Prot.*, 89: 161–169
- Shahzad, M., M. Farooq and M. Hussain, 2016b. Weed spectrum in different wheat-based cropping systems under conservation and conventional tillage practices in Punjab, Pakistan. *Soil Till. Res.*, 163: 71–79
- Shahzad, M., M. Farooq, K. Jabran, T.A. Yasir and M. Hussain, 2016c. Influence of various tillage practices on soil physical properties and wheat performance in different wheat-based cropping systems. *Intl. J. Agric. Biol.*, 18: 821–829

- Shahzad, M., M. Hussain, M. Farooq, S. Farooq, K. Jabran and A. Nawaz, 2017. Economic assessment of conventional and conservation tillage practices in different wheat-based cropping systems of Punjab, Pakistan. *Environ. Sci. Poll. Res.*, 24: 24634–24643
- Sharma, N.K., R.J. Singh, D. Mandal, A. Kumar, N.M. Alam and S. Keesstra, 2017. Increasing farmer's income and reducing soil erosion using intercropping in rainfed maize-wheat rotation of Himalaya, India. *Agric. Ecosyst. Environ.*, 247: 43–53
- Shearer, G. and D.H. Kohl, 1986. N₂-fixation in field settings: estimations based on natural δ¹⁵N abundance. *Austr. J. Plant Phys.*, 13: 699–756
- Singh, S.P. and H.F. Schwartz, 2010. Breeding common bean for resistance to diseases: A review. *Crop Sci.*, 50: 2199–2223
- Singh, S.P., H. Terán and J.S. Beaver, 2009. Scarlet runner bean germplasm accessions G35006 and G35172 possess resistance to multiple diseases of common bean. *Annu. Rep. Bean Improv. Cooperative*, 52: 22–23
- Smithson, J.B., O.T. Edje and K.E. Giller, 1993. Diagnosis and correction of soil nutrient problems of common bean (*Phaseolus vulgaris*) in the Usambara Mountains of Tanzania. *J. Agric. Sci.*, 120: 233–240
- Somado, E.A. and R.F. Kuehne, 2006. Appraisal of the ¹⁵N-isotope dilution and ¹⁵N natural abundance methods for quantifying nitrogen fixation by flood-tolerant green manure legumes. *Afr. J. Biotech.*, 5: 1210–1214
- Srinivasan, R., 2014. *Insect and Mite Pests on Vegetable Legumes: a Field Guide for Identification and Management: AVRDC – The World Vegetable Center, Shanhua, Taiwan*, pp: 14–778. AVRDC Publication No. 92
- Ssekandi, W., J.W. Mulumba, P. Colangelo, R. Nankya, C. Fadda, J. Karungi, M. Otim, P. De Santis and D.I. Jarvis, 2016. The use of common bean (*Phaseolus vulgaris* L.) traditional varieties and their mixtures with commercial varieties to manage bean fly (*Ophiomyia* spp.) infestations in Uganda. *J. Pest Sci.*, 89: 45–57
- Stagnari, F., A. Maggio, A. Galieni and M. Pisante, 2017. Multiple benefits of legumes for agriculture sustainability: an overview. *Chem. Biol. Technol. Agric.*, 4: 2
- Sun, B., Y. Peng, H. Yang, Z. Li, Y. Gao, C. Wang, Y. Yan and Y. Liu, 2014. Alfalfa (*Medicago sativa* L.)/maize (*Zea mays* L.) intercropping provides a feasible way to improve yield and economic incomes in farming and pastoral areas of Northeast China. *PLoS One*, 9: e110556
- Tang, Y., L. Yu, A. Guan, X. Zhou, Z. Wang, Y. Gou and J. Wang, 2017. Soil mineral nitrogen and yield-scaled soil N₂O emissions lowered by reducing nitrogen application and intercropping with soybean for sweet maize production in southern China. *J. Integr. Agric.*, 16: 2586–2596
- Tilman, D., P.B. Reich, J. Knops, D. Wedin, T. Mielke and C. Lehman, 2001. Diversity and productivity in a long-term grassland experiment. *Science*, 294: 843–845
- Tittonell, P. and K.E. Giller, 2013. When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. *Field Crops Res.*, 143: 76–90
- Trenbath, B.R., 1993. Intercropping for the management of pests and diseases. *Field Crops Res.*, 34: 381–405
- Unkovich, M., D. Herridge, M. Peoples, G. Cadisch, R. Boddey, K.E. Giller, B. Alves and P. Chalk, 2008. *Measuring Plant-associated Nitrogen Fixation in Agricultural Systems*, pp: 136–258. ACIAR Monograph
- Unkovich, M.J., J. Baldock and M.B. Peoples, 2010. Prospects and problems of simple linear models for estimating symbiotic N₂ fixation by crop and pasture legumes. *Plant Soil*, 329: 75–89
- Urquiaga, S., P.B.L. Botteon and R.M. Boddey, 1989. Selection of sugarcane cultivars for associated biological nitrogen fixation using ¹⁵N labelled soil. In: *Nitrogen Fixation with Non-Legumes*, pp: 311–319. Skinner, F.A., R.M. Boddey, I. Fendrik. (eds.). Kluwer Academic Publisher, Dordrecht, The Netherlands
- Vance, C.P., 2002. Root-bacteria interactions: symbiotic nitrogen fixation. In: *Plant Roots*, pp. 839–867, Waisel, Y., A. Eshel, U. Kafkati, (eds.). The Hidden Half, edition 3. New York: Marcel Dekker
- Vanlauwe, B., A.H. Gadir, J. Adewopo, S. Adjei-Nsiah, T. Ampadu-Boakye, R. Asare, F. Baijukya, E. Baars, M. Bekunda, D. Coyne, M. Dianda, P.M. Donsop-Nguezet, P. Ebanyat, S. Hauser, J. Huising, A. Jalloh, L. Jassogne, N. Kamai, A. Kamara, F. Kanampiu, A. Kehbila, K. Kintche, C. Kreye, A. Larbi, C. Masso, P. Matungulu, I. Mohammed, L. Nabahungu, F. Nielsen, G. Nziguheba, P. Pypers, D. Roobroeck, M. Schut, G. Taulya, M. Thuita, V.N.E. Uzokwe, P. van Asten, L. Wairegi, M. Yemefack and H.J.W. Mutsaers, 2017. Looking back and moving forward: 50 years of soil and soil fertility management research in sub-Saharan Africa. *Intl. J. Agric. Sustain.*, 15: 613–631
- Vanlauwe, B., D. Coyne, J. Gockowski, S. Hauser, J. Huising, C. Masso, G. Nziguheba, M. Schut and P. van Asten, 2014. Sustainable intensification and the African smallholder farmer. *Curr. Opin. Environ. Sustain.*, 8: 15–22
- Venance, S.K., P. Mshenga and E.A. Birachi, 2016. Factors influencing on-farm common bean profitability: the case of smallholder bean farmers in Babati District, Tanzania. *J. Econ. Sustain. Dev.*, 7: 196–201
- Vukicevic, E., T. Lowery, P. Bowen, J.R. Urbez-Torres and M. Hart, 2016. Cover crops to increase soil microbial diversity and mitigate decline in perennial agriculture. A review. *Agron. Sustain. Dev.*, 36, 48
- Wada, T., N. Endo and M. Takahashi, 2006. Reducing seed damage by soybean bugs by growing small-seeded soybeans and delaying sowing time. *Crop Prot.*, 25: 726–731
- Wakhungu, J.W., 2010. *Gender Dimensions of Science and Technology: African Women in Agriculture*. Expert Paper. Expert group meeting Gender, science and technology. Paris, France 28 September – 1 October 2010. United Nations Division for the Advancement of Women (DAW, part of UN Women) United Nations Educational, Scientific and Cultural Organization (UNESCO). EGM/ST/2010/EP.2 October 2010
- Wanic, M., M. Jastrzebska and J. Nowicki, 2005. Intercropping and weeds growth in spring barley cultivated on different lots. *Fragment. Agron.*, 2: 238–248
- Wiley, R.W., 1985. Evaluation and presentation of intercropping advantages. *Exp. Agric.*, 21: 119–133
- Wiley, R.W., 1979. Intercropping: its importance and research needs. Part 1. Competition and yield advantages. *Field Crops Res.*, 32: 1–10
- Wortmann, C.S., R.A. Kirkby, C.A. Elude and D.J. Allen, 1998. Atlas of common bean (*Phaseolus vulgaris* L.) production in Africa. CIAT, Colombia. *Afr. Crop Sci. Soc.*, 8: 2087–2090
- Xavery, P., R. Kalyebara, S. Kasambala and F. Ngulu, 2006. *The impact of improved bean production technologies in Northern and North Western Tanzania*. Occasional Publication Series No. 43, Pan African Bean Research Alliance, CIAT Africa Region, Kampala, Uganda and Selian Agricultural Research Institute – Arusha, Tanzania. Available online: http://ciat-library.ciat.cgiar.org/articulos_ciat/highlight42.pdf
- Yusuf, A.A., E.N.O. Iwuafor, R.C. Abaidoo, O.O. Olufajo and N. Sanginga, 2009. Grain legume rotation benefits to maize in the northern Guinea savanna of Nigeria: fixed-nitrogen versus other rotation effects. *Nutr. Cycl. Agroecosys.*, 84: 129–139
- Zhang, F. and L. Li, 2003. Using competitive and facilitative interactions in intercropping systems enhances crop productivity and nutrient-use efficiency. *Plant Soil*, 248: 305–312
- Zhang, Y., J. Liu, J. Zhang, H. Liu, S. Liu, L. Zhai, H. Wang, Q. Lei, T. Ren and C. Yin, 2015. Row ratios of intercropping maize and soybean can affect agronomic efficiency of the system and subsequent wheat. *PLoS One*, 6: e0129245
- Zhang, F., J. Shen, J. Zhang, Y. Zuo, L. Li and X. Chen, 2010. Rhizosphere processes and management for improving nutrient use efficiency and crop productivity: implications for China. *Adv. Agron.*, 107: 1–32