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Review Article

Sustainable Intensification of Grain Legumes Optimizes Food Security on Smallholder Farms in Sub-Saharan Africa–A Review

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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.

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* spp. *Ipomoea batatas* and *Solanum tuberosum*) and bananas (*Musa* spp.) 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).

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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* spp.), 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 N_2–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 N_2 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 N_2-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 nicotinamine, 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 Fe^{3+}-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.

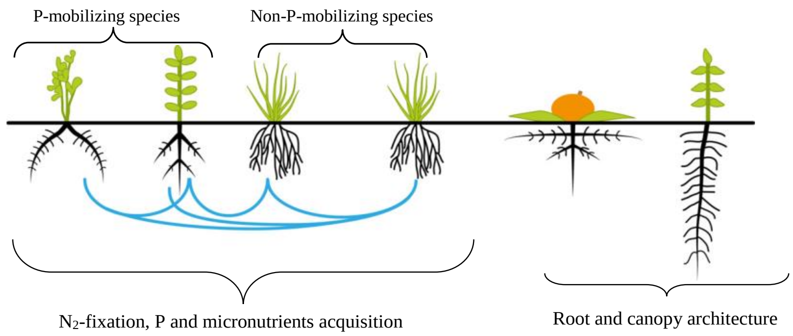

Fig. 1: Facilitation of growth resources, sharing and niche complementarity enable polyculture systems to yield more than their corresponding monocultures. Facilitation of P acquisition for both component crops when one is P-mobilizing and another is non-P-mobilizing. The P-mobilizing species may mobilize sparingly soluble inorganic P in soil through carboxylates or protons or organic P by acid phosphatises 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

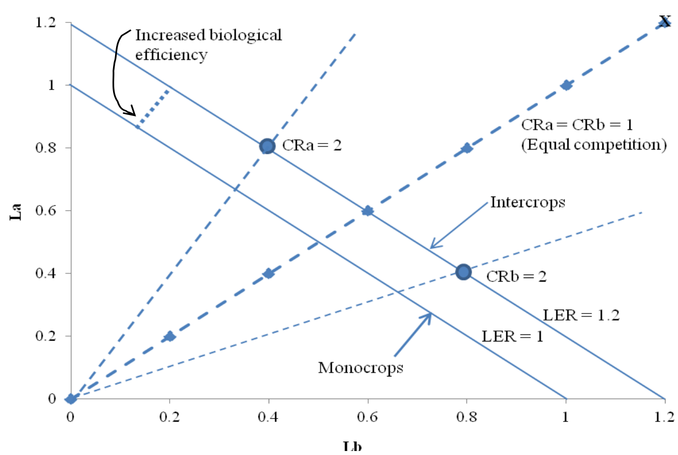

Fig. 2: Competitive ratios of two different crops when sown in intercrops compared with their sole crops. The values above line X indicates that crop *a* is more competitive than crop *b* when sown in intercrops. Similarly, below this line, crop *b* has higher competitive advantage over crop *a* when are intercropped. At CRa =2 means that crop *a* is twice as much as competitive as crop *b*; likewise, when the CRb =2 means that crop *b* has twice competitive advantage over crop *a*. Key: La and Lb are land equivalent ratios of crops *a* and *b*, respectively; LER is the land equivalent ratio; CRa and CRb 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. Intercropping enhances the abundance of predators and parasites of pests and diseases as the modified environments

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			
		2. Attraction of beneficial organisms such as natural enemies and pollinators			Li *et al*. (2014); Brooker *et al*. (2015)
		3. Deterrence of pests and pathogens			
		4. Suppression of weeds			
	Benefits	Nitrogen UE	Phosphorus UE	Micronutrients UE	
Resource Sharing		Mycorrhizal fungi connections			Babikova *et al*. (2013)
		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)		
		Canopy architecture	1. Hydraulic lift (WUE)		
			2. Minerals acquisition (MUE)		
			3. Reduced leaching (WUE & MUE)		

UE = use efficiency

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. Canopies of plants for the crops sown in mixtures prevent the action of rain drops from hitting and destructing

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

Here [a]Legume 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. [b]Plant parts: R=Root; V=Vegetative organs (stems, leaves); Re=Reproductive organs (flower, pod and/or seed damaged). [c]Insect 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. [d]Lepidoptera: Noctuidae; [e]Diptera: Agromyzidae; [f]Homoptera: Aphididae; [g]Heteroptera: Miridae; [h]Coleoptera: Curculionidae; [i]Coleoptera: Bruchidae; [j]Acarina: Penthaleidae; [k]Hemiptera: Aleyrodidae; [l]Homoptera: Cicadellidae; [m]Lepidoptera: Noctuidae; [n]Coleoptera: Chrysomelidae; [o]Thysanoptera: Thripidae; [p]Hemiptera: Coreidae; [q]Hemiptera: Alydidae; [r]Hemiptera: Pentatomidae; [s]Lepidoptera: Crambidae; [t]Lepidoptera: Pyralidae; [u]Lepidoptera: Lycaenidae; [v]Acari: Tetranychidae. [w]Locally available option of controlling insects: I=Intercropping; R=Rotation

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). Reduction in yield may be economically significant if the main crop has a high market value than its associate crop.

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 (*Cicer arietinum* L.)	Stunt	Bean leaf roll luteovirus (BLRV)	North Africa, Middle East, India, Spain, Turkey, U.S.A.	N/I	Rotation	Makkouk *et al*. (2003); Pande *et al*. (2006, 2009); Darai *et al*. (2017)
	Ascochyta blight	*Ascochyta rabiei*	West Asia, northern Africa, Mediterranean region	> 50%		
	Botrytis gray mold	*Botrytis cinerea*	India, Nepal, Bangladesh, Pakistan, North Africa, Australia, America	50-100%		
Lentil (*Lens culinaris* Medik.)	*Stemphylium blight*	*Stemphylium botryosum*	Bangladesh, Egypt, Syria, UzSA	Up to 70%	Rotation	Makkouk *et al*. (2003); Pande *et al*. (2009)
	Rust	*Uromyces viciae-fabae*	Bangladesh, Chile, Ecuador, Ethiopia, India, Morocco, Nepal, Pakistan	50-100%		
	Ascochyta blight	*Ascochyta lentis*	Argentina, Australia, Brazil, Canada, Chile, Cyprus, Ethiopia, Greece, Iran, Jordan, New Zealand, Pakistan, Russia, Spain, Syria, U.S.A.	Up to 70%		
Faba bean (*Viciae faba* L.)	Rust	Faba bean necrotic yellows virus	Mediterranean countries	Up to 50%	Rotation	Makkouk *et al*. (2003); Pande *et al*. (2009)
	Ascochyta blight	*Ascochyta fabae*	Mediterranean countries	5-50%		
	Necrotic yellows	N/I	West Asia, North Africa	Up to 80%		
	Chocolate leaf spot	*Uromyces viciae-fabae*	Mediterranean countries	Up to 50%		
Field pea (*Pisum sativum* L.)	Downy mildew	*Peronospora viciae*	N/I	30%	Intercropping &	Pande *et al*. (2009);
	Powdery mildew	*Erysiphe polygoni*	India, Nepal	10%	Rotation	Darai *et al*. (2017)
Pigeon pea (*Cajanus cajan* [L.] Millsp.)	Sterility mosaic	Pigeonpea sterility mosaic virus	Bangladesh, India, Myanmar, Nepal, Sri Lanka, Thailand	N/I	Rotation	Pande *et al*. (2009)
Mungbean (*Vigna radiata* [L.] Wilczek and black gram (*Vigna mungo* [L.] Hepper)	Powdery mildew	*Erysiphe polygoni*	India, southeast Asian countries	9-50%	Intercropping & Rotation	Pande *et al*. (2009)
	Cercospora leaf spot	*Cercospora cruenta*, *C. canescens*	Bangladesh, India, Indonesia, Taiwan, Thailand, Philippines, Malaysia	Up to 50%		
	Yellow vein mosaic	Mungbean yellow mosaic virus	Bangladesh, India	10-100%		
Cowpea (*Vigna ungiculata* [L.] 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 *et al*. (2009)
	Cowpea golden mosaic	Cowpea golden mosaic virus	Kenya, Nigeria, Tanzania, Cuba, Surinam, USA	60-100%		
	Cercospora leaf spot	*Cercospora canescens* and *Pseudocercospora cruenta*	Fiji, Brazil, Kenya, Nigeria, Zimbabwe, India, Bangladesh, Egypt, Iran, Japan, Malaysia, Thailand	18-42%		
Common bean (*Phaseolus vulgaris* L.) (Fungal diseases)	Anthracnose	*Colletotrichum lindemuthianum*	Widely	N/I	Use of disease-free seed, crop rotation, intercropping	Kelly *et al*. (2003); Miklas *et al*. (2006); Singh and Schwartz (2010); Schwartz and Singh (2013); Porch *et al*. (2013); OECD (2016)
	Fusarium wilt	*Fusarium oxysporum*		N/I		
	Fusarium root rot	*Fusarium solani*		N/I		
	Angular leaf spot	*Phaeoisariopsis griseola*		N/I		
	Ascochyta blight	*Phoma exigua* var. *diversispora*, *P. exigua* var. *exigua*		N/I		
	Rhizoctonia root rot	*Rhizoctonia solani*		N/I		
	White mold	*Sclerotinia sclerotiorum*		N/I		
	Web blight	*Thanatephorus cucumeris*		N/I		
	Bean rust	*Uromyces phaseoli, U. appendiculatus*		N/I		
Common bean (*P. vulgaris* L.) (Bacterial diseases)	Halo blight	*Pseudomonas syringae* pv. *phaseolicola* or *Pseudomonas savastonoi* pv. *Phaseolicola*	Widely	N/I	Use of disease-free seed, crop rotation, intercropping	Kelly *et al*. (2003); Liebenberg (2009); Singh and Schwartz (2010); Porch *et al*. (2013); OECD (2016)
	Bacterial brown spot	*Pseudomonas syringae* pv. *Syringae*		N/I		
	Common bean blight	*Xanthomonas campestris* pv. *phaseoli* or *Xanthomonas axonopodis* pv. *Phaseoli*		N/I		
Common bean (*P. vulgaris* L.) (Viral diseases)	Bean common mosaic necrosis virus	Potyvirus	Widely	N/I	Use of disease-free seed, intercropping	Miklas *et al*. (2006); Bonfim *et al*. (2007); Singh *et al*. (2009); Singh and Schwartz (2010); Faria *et al*. (2014); OECD (2016)
	Bean common mosaic virus	Potyvirus		N/I		
	Bean golden mosaic virus	Geminivirus		N/I		
	Bean yellow mosaic virus	Potyvirus		N/I		
	Beet curly top virus	Curtovirus		N/I		

Here N/I = Not identified

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 N_2. 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 N_2-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 N_2 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 for 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 N_2 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 N_2 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 N_2 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 N_2 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 N_2–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.

N_2-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 N_2-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 N_2-fixation acting as a source of energy when adenosine triphosphate (ATP) is converted to adenosine diphosphate (ADP) as N_2 is reduced to NH_3 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.

$$N_2 + 8\,H^+ + 8\,e^- \longrightarrow 2\,NH_3 + H_2 \quad (1)$$

The released H_2 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 N_2. 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 N_2 fixation, 3–4 good nodulation and potential for fixation, 2–3 fair nodulation but N_2 fixation may not be sufficient to supply the N demand of the crop, 0–2 poor nodulation, little or no N_2–fixation (Peoples *et al*. 1989). Knowledge of nodulation characteristics in legumes is important as it provides an indication of N_2–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 N_2–fixed for the subsequent crop in the same land.

Quantifying amount of N_2–fixed by the legumes

The widely acceptable methods of quantifying the amount of N_2–fixed by a legume are enrichment (^{15}N-enriched) and natural abundance ($\delta^{15}N$) (Unkovich *et al*. 2008). The ^{15}N-enriched method is useful where N-containing materials e.g. N-carrying fertilizers and organic substrates have been added into the experimental ecosystem while $\delta^{15}N$ method is applicable in environments where no inclusion of N-containing materials (Giller, 2001; Unkovich *et al*. 2010). The $\delta^{15}N$ method uses small differences between the $^{15}N/^{14}N$ ratio of the N-source being examined and the $^{15}N/^{14}N$ ratio of N already existing in the system to follow the N-source through the soil, water and plants. The advantage of the $\delta^{15}N$ 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 N_2–fixing legume and a no N_2–fixing reference plant growing together with the N_2–fixing legume. Cadisch *et al*. (2000) found that $\delta^{15}N$ method was less sensitive between the reference and N_2-fixing plant compared to the ^{15}N-enrichment method but signals for the same precautions as for the ^{15}N-enrichment method because of the N_2–fixing legume and the reference plant and accounting for ^{15}N variation within the plant. According to Unkovich *et al*. (2010), the ^{15}N content of the plant lies between the ^{15}N signature of the plant-available soil N (%Ndfa of zero) and a value close to 0.3663 atom% ^{15}N (%Ndfa of 100%). Carranca *et al*. (2015) reported that whole legume plant *i.e*., top plant and visible roots and nodules should be involved in N_2–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 considering 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 N_2–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 ^{15}N in soil N and atmospheric N. The ^{15}N abundance in a non-N_2–fixing plant, which is all derived from the soil, is larger than that of a N_2–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-N_2-fixing but useful in measuring the ^{15}N-enrichment of the available soil N (Giller 2001). The total N is then analyzed for ^{15}N, and the percentage of N derived from the atmosphere (%Ndfa) by the legume is calculated using the equation 2.

$$\%\text{Ndfa} = \left(1 - \frac{\text{atom\% } 15_N \text{ excess from N2fixing plant}}{\text{atom\%} 15_N \text{ excess from a reference plant}}\right) \times 100 \ldots (2)$$

Boddey *et al*. (1995) deduced a computational equation for %Ndfa based on the whole plants *i.e*. the whole plant $\delta^{15}N$ by considering the weight of seed and stover/straws (equation 3).

$$\%15_N\text{dfa}_{whole\ plant} = \left(\frac{(\text{total seed N} \times \delta 15_{N_{seed}}) - (\text{total straw N} \times \delta 15_{N_{straw}})}{\text{total seed N} + \text{total straw N}}\right) \times 100 \ldots (3)$$

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

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

A slightly different expression for $\delta^{15}N$ (‰) uses the R-values of the isotope ratios (equation 5).

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

Where $\delta^{15}N$ (‰) is the isotope ratio of the sample relative to the atmospheric air standard and $R_{\text{-sample}}$ and $R_{\text{-standard}}$ 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.

$$\mathrm{R} = \frac{15_{\mathrm{N}} + 14_{\mathrm{N}}}{14_{\mathrm{N}} + 14_{\mathrm{N}}} \ldots\ldots\ldots (6)$$

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 δ^{15}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.

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

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.

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

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.

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

Where *B* is the δ^{15}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 δ^{15}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 on-set 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*. 2015).

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*. 2015; 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*. 2015; 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 NO_3^- 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 environmentally 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.

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