Mungbean [*Vigna radiata* (L.) Wilczek]: Protein-rich legume for improving soil fertility and diversifying cropping systems

Andre Amakobo Diatta

Dissertation submitted to the faculty of the Virginia Polytechnic Institute and State
University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
In
Crop and Soil Environmental Sciences

Ozzie Abaye
Wade Thomason
Thomas Thompson
Larry Vaughan
Mamadou Lo

March 24th, 2020
Blacksburg, Virginia

Keywords: Mungbean, intercropping, millet yield, soil fertility, nitrogen fixation, %Ndfa, *Bradyrhizobium* inoculation, soil texture, sustainable agriculture, Senegal

Mungbean [*Vigna radiata* (L.) Wilczek]: Protein-rich legume for improving soil fertility and diversifying cropping systems

Andre Amakobo Diatta

ABSTRACT

Drought, salinity, and low soil fertility have negative impacts on agricultural productivity, resulting in food scarcity and nutritional insecurity, particularly in Sub-Saharan Africa. Mungbean [*Vigna radiata* (L.) R. Wilczek] has seen increased interest as a short-duration and drought tolerant legume crop, capable of atmospheric N_2 fixation. Mungbean is a protein and iron-rich legume and can be used as vegetable or grain for human consumption or multipurpose crop. At present, few studies have simultaneously explored the best agronomic practices for mungbean cultivation and evaluated its potential for increasing crop yields via intercropping systems and improving soil fertility through biological N_2 fixation. To understand the agronomic practices and soil physical properties limiting mungbean production, the impacts of two mungbean cultivars (Berken and OK2000) with and without inoculation with *Bradyrhizobium* spp. grown in loamy sand and silt loam soils on mungbean growth and yield were investigated under glasshouse conditions. Promising results from this study led to the introduction of mungbean into pearl millet systems in Senegal and evaluation of the effects of intercropping on growth, yields, land equivalent ratio (LER), canopy cover estimates, and normalized difference vegetation index (NDVI). Finally, we evaluated plant growth and N_2 fixation of five mungbean genotypes grown in two soil textures using the ^{15}N natural abundance technique leading to recommendations for those with the greatest overall benefit to the cropping system.

The literature review shows mungbean often proposed as a strategic crop for increasing legume diversification within current cropping systems and providing increased food security as well as market diversification and economic sustainability. The greenhouse study revealed that OK2000 cultivar produced significantly higher yield when inoculated and planted on a silt loam soil than other treatments, indicating the importance of inoculation and soil texture in mungbean establishment. Intercropping mungbean and millet significantly ($p \leq 0.05$) increased combined yields (35% to 100% increase) and LER compared to sole millet cropping systems. Canopy cover estimates and NDVI values significantly increased up to 60% and 30%, respectively, in millet-mungbean intercropping over millet alone. The N_2 fixation study showed that %Ndfa of mungbean was higher when grown in the loamy sand soil (27% increase). However, soil N uptake (235 mg plant^{-1}) and amount of N fixed (67 mg plant^{-1}) were greater in the silt loam soil. Among genotypes, IC 8972-1 significantly ($p \leq 0.05$) derived less N from the atmosphere (23%) but took more soil N (155 mg plant^{-1}) which yielded significantly greater dry biomass (7.85 g plant^{-1}) and shoot N content (200 mg plant^{-1}). The results from the N_2 fixation study indicated that choice of mungbean genotype can contribute to reducing N needs of agricultural systems. Overall, this research project demonstrated that mungbean has the potential for diversifying smallholder agriculture and adding biologically fixed N into soils, in line with transformative adaptation strategies being promoted for sustainable agriculture. Further research and development programs on good cultural practices, adaptation to cropping systems, and nutritional benefits for human consumption can promote mungbean cultivation in SSA.

Mungbean [*Vigna radiata* (L.) Wilczek]: Protein-rich legume for improving soil fertility and diversifying cropping systems

Andre Amakobo Diatta

GENERAL AUDIENCE ABSTRACT

Global population growth is expected to reach 9.8 billion in 2050 while climate change is predicted to reduce food production. Sustainable solutions are needed for increasing food availability and satisfying nutritional needs under changing climatic conditions. Mungbean is a viable option because it is a legume crop capable of restoring soil fertility and has low water requirements. Mungbean also contains high levels of protein and iron and can, therefore, provide a nutritious and healthy food. Although the agronomic benefits of mungbean have been studied, best cultural practices and its impact on farming systems and soil fertility are scattered. The objectives of this research were to identify the best agronomic practices for mungbean production, assess its effects when grown together with millet, and measure its nitrogen contribution to the soil. The results showed that selecting the best genotypes to be grown in a particular soil texture can significantly increase mungbean growth and yield. In addition, incorporation of mungbean into cereal-based farming systems demonstrated its capacity for improving agricultural production in a low-input environment. Assessment of nitrogen fixation by mungbean showed that it can naturally add nitrogen into the soils, the most limiting plant nutrient, reducing nitrogen application needs. Thus, the ability of mungbean to diversify farming systems, improve soil fertility, and deliver nutritious food will provide agronomic, environmental, and economic benefits to farmers, especially in food-insecure households. However, exploitation of the full potential of mungbean won't be achieved without understanding the major factors influencing mungbean cultivation and production.

DEDICATION

To my parents, sister, brothers, and wife,
you certainly deserve better but I tried to do my best,
which you always advised me to do;
To my brother Bonaventure Lambal *in memoriam*,
gone forever, obedience is the memory that I keep of you;
I dedicate this modest work.

ACKNOWLEDGMENTS

My sincerest thanks go first to Dr. Ozzie Abaye and Dr. Wade Thomason, my co-advisors, for giving me the opportunity to work on this rewarding research program in Senegal. Your advice and suggestions, your spirit of conciseness and clarity have been very useful and will certainly still be. Your scientific rigor, pragmatism and human qualities were invaluable to me all these years.

I would also like to thank Dr. Thomas Thompson, Dr. Larry Vaughan, and Dr. Mamadou Lo, my committee members, for agreeing to assess this work. Your contributions allowed me to improve the quality of this research project.

I am pleased to express my gratitude to the various institutions for their financial, material and technical support. I am thinking in particular of the School of Plant and Environmental Sciences of Virginia Tech; USAID/ERA (Education & Research in Agriculture); College of Agriculture and Life Sciences Graduate Teaching Scholar (GTS) Program; Center for International Research, Education, and Development (CIRED); and the Senegalese Institute of Agricultural Research (ISRA).

I thank the staff members of USAID/ERA particularly Fatou Gueye and Abdoulaye Ba as well as my colleagues M.D. Thiam, M. Diaw, N.K. Diame, M. Doucoure, C. Diop for their support throughout the research activity in Senegal. The difficulties encountered during this study were the basis of a friendship which was consolidated over the field trials.

I express my profound gratitude to my parents Hyacinthe Diatta and Constance F. Mbodje Diedhiou, Marie Lambal, Noëlla Diatta, Bienvenu Sambou, my brothers, sisters, and friends for their support and confidence. Thank you to my wife Loryse C. Francisco for her understanding and support throughout this journey.

Finally, to all those who have contributed directly or indirectly to the accomplishment of this modest work, please find here the expression of my gratitude.

Table of Contents

List of Tables

List of Figures

Chapter I – Introduction

Context and justification

Climate change has been projected to reduce agricultural productivity globally, but especially across sub-Saharan Africa (SSA) where severe droughts negatively impact the livelihoods of rural populations (Ramírez Villegas and Thornton, 2015; Tadele, 2017). The vulnerability of the SSA region is due to its dependence on rain-fed agriculture and natural resources, high vulnerability to climate variability (Roudier et al., 2011; Niang et al., 2014), low soil fertility (Connolly-Boutin and Smit, 2016; Vanlauwe et al., 2019), and low focus on transformative adaptation strategies to climate change (Grist, 2014).

Most of the research on increasing agricultural production has focused on improving yields of cereal crops, but not on developing transformative adaptation strategies for resilient multi-crop production systems that can improve the livelihoods of the most vulnerable populations. The literature about agriculture in SSA shows that food security is dependent not only on crop production but also on nutritional security. Research on sustainable intensification of production systems demonstrates that adaptation and mitigation strategies must address the challenges of agricultural productivity, climate change, food security, and poverty. The aim of this research project is to assess the potential of inclusion of mungbean, a legume crop, for diversifying cropping systems to promote sustainable adaptation strategies and reduce food insecurity.

Legumes for sustainable intensification

The important role of legumes for diversifying and intensifying production systems and ultimately promoting sustainable agriculture has been extensively reviewed by several authors (Franke et al., 2018; Snapp et al., 2019; Vanlauwe et al., 2019). Legumes, in symbiosis with rhizobia, can fix atmospheric nitrogen, thus contributing to improve soil fertility and reduce inorganic nitrogen fertilizer needs (Giller, 2001; Smith et al., 2016). Legumes can also reduce N_2O emissions compared to cereal crops and decrease the carbon footprint associated with the production of protein, making legume crops a mitigation strategy to greenhouse gas emissions from agriculture (Foyer et al., 2016; Magrini et al., 2016). Legumes in association or rotation with cereal crops have also resulted in improved nitrogen-use efficiency and soil phosphorus uptake as well as enhanced soil physical and biological properties, thus increasing combined seed yields (Li et al., 2009). Other reported benefits include reduction of insect pests, disease and weed incidence (Matusso et al., 2014). Legume crops are also a cheap and available source of protein and minerals which could help in reducing malnutrition in SSA (Nair et al., 2013; Dahiya et al., 2015; Pataczek et al., 2018).

Yet, despite these agronomic, environmental, and nutritional benefits, cultivation of legume crops still remains low in Sub-Saharan Africa, particularly in West Africa (Vanlauwe et al., 2019). Although, research has demonstrated the advantages of including legumes into cropping systems, little to no-research has focused on the potential of introducing new legume crops to new localities such as mungbean to Senegal. In this dissertation, I hypothesize that: 1) inoculation with *Bradyrhizobium* spp. improve plant growth, nodulation and yield components, and the magnitude of this effect will vary by cultivar and soil texture; 2) optimized density of mungbean in millet-based systems will increase the growth and yields and plant health status compared to monoculture; and 3) selected high yielding and nutrient-dense cultivars will exhibit greater potential for N_2 fixation.

Mungbean is a short-duration and drought-tolerant legume crop capable of improving soil fertility through biological N_2 fixation, maintaining crop productivity under variable climatic conditions, and sustaining the livelihood and nutritional security of smallholder farmers (Keatinge et al., 2011; Foyer et al., 2016). Shah et al. (2003) reported that mungbean can fix up to 110 kg N ha^{-1} which can be used to satisfy the N needs of the companion or subsequent crops. Li et al. (2009) found that intercropping mungbean with rice could increase the formation of mycorrhiza and nodules, thus increasing N and P uptake and N transfer to associated crops. The only reported mungbean study in intercropping systems in Senegal demonstrated that mungbean was a compatible legume crop in millet systems (Trail et al., 2016). Studies on the benefits of mungbean consumption in Senegal also reported agricultural advantages from its cultivation which improved dietary diversity of women and also provided financial opportunities (Vashro et al., 2018). With the projected increase of semi-arid areas in Senegal, the introduction of mungbean to Senegalese agriculture could help sustain agricultural production through diversification of agricultural systems. It also represents an opportunity to produce nutrient-rich foods in an area that faces serious food insecurity issues.

The primary goal of this proposed research is, therefore, to enhance the productivity of cropping systems and to improve soil fertility and food security in Senegal. Specifically, the objectives of the proposed experiments are: 1) to evaluate the effect of inoculation of mungbean with *Bradyrhizobium* (group I) on growth, yield, yield components of two mungbean genotypes in greenhouse studies; 2) evaluate the effect of millet and mungbean intercropping on the yield of combined crops in Senegal; and 3) screen the best adapted lines for inherent N fixation capacity under favorable conditions in the greenhouse.

Dissertation structure

The dissertation begins with the rationale and significance of mungbean (Chapter 1) as a highly productive legume crop in N-impoverished soils and under highly variable climatic conditions. Chapter 2 reviews the potential of mungbean for diversity cropping systems and improving soil fertility in SSA. On the basis of the great potential of mungbean for production in SSA for restoring soil fertility and nutritional security, a greenhouse study (Chapter 3) was conducted to investigate the effects of *Bradyrhizobium* (group I) inoculation and soil texture on mungbean establishment, yield and yield components. To assess the effects of mungbean association with millet systems (Chapter 4), field-based research trials were conducted in Senegal. The results showed that the successful inclusion of mungbean in cropping systems can improve household food security and dietary diversity for smallholders. As a legume crop, mungbean is capable of fixing atmospheric N_2 for its own N requirements and the N needs of the companion crops. Thus, mungbean genotypes were used to estimate biological N_2 fixation using the ^{15}N natural abundance method (Chapter 5). Overall, this research project proposes a legume diversification of cropping systems which provides economically sustainable advantages for farming through biological nitrogen fixation in Sub-Saharan Africa.

References

Connolly-Boutin L, Smit B (2016) Climate change, food security, and livelihoods in sub-Saharan Africa Regional Environmental Change 16:385-399 doi:https://doi.org/10.1007/s10113-015-0761-x

Dahiya PK, Linnemann AR, Van Boekel MAJS, Khetarpaul N, Grewal RB, Nout MJR (2015) Mung bean: Technological and nutritional potential Critical Reviews in Food Science and Nutrition 55:670-688 doi:https://doi.org/10.1080/10408398.2012.671202

Foyer CH et al. (2016) Neglecting legumes has compromised human health and sustainable food production Nature Plants 2:16112 doi:https://doi.org/10.1038/nplants.2016.112

Franke A, Van den Brand G, Vanlauwe B, Giller K (2018) Sustainable intensification through rotations with grain legumes in Sub-Saharan Africa: A review Agriculture, ecosystems & environment 261:172-185 doi:https://doi.org/10.1016/j.agee.2017.09.029

Giller KE (2001) Nitrogen fixation in tropical cropping systems. Cabi. doi:https://doi.org/10.1079/9780851994178.0000

Grist N Transformative adaptation in Africa's agriculture. In: Contribution Note for Africa Progress Panel meeting.“Expert Consultation: an African Agenda for Green, Low Carbon Development”, Geneva, 2014.

Keatinge J, Easdown W, Yang R, Chadha M, Shanmugasundaram S (2011) Overcoming chronic malnutrition in a future warming world: the key importance of mungbean and vegetable soybean Euphytica 180:129-141 doi:https://doi.org/10.1007/s10681-011-0401-6

Li Y, Ran W, Zhang R, Sun S, Xu G (2009) Facilitated legume nodulation, phosphate uptake and nitrogen transfer by arbuscular inoculation in an upland rice and mung bean intercropping system Plant and Soil 315:285-296 doi:https://doi.org/10.1007/s11104-008-9751-9

Magrini M-B et al. (2016) Why are grain-legumes rarely present in cropping systems despite their environmental and nutritional benefits? Analyzing lock-in in the French agrifood system Ecological Economics 126:152-162 doi:https://doi.org/10.1016/j.ecolecon.2016.03.024

Matusso J, Mugwe J, Mucheru-Muna M (2014) Potential role of cereal-legume intercropping systems in integrated soil fertility management in smallholder farming systems of sub-Saharan Africa Journal of Agriculture and Environmental Management 3:162-174

Nair RM, Yang RY, Easdown WJ, Thavarajah D, Thavarajah P, Hughes JdA, Keatinge J (2013) Biofortification of mungbean (*Vigna radiata*) as a whole food to enhance human health Journal of the Science of Food and Agriculture 93:1805-1813 doi:https://doi.org/10.1002/jsfa.6110

Niang I, Ruppel O, Abdrabo M, Essel A, Lennard C, Padgham J, Urquhart P (2014) Africa, climate change 2014: impacts, adaptation and vulnerability—Contributions of the

Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. 1199–1265.

Pataczek L et al. (2018) Beans with benefits—the role of mungbean (*Vigna radiata*) in a changing environment American Journal of Plant Sciences 9:1577 doi:https://doi.org/10.4236/ajps.2018.97115

Ramírez Villegas J, Thornton PK (2015) Climate change impacts on African crop production

Roudier P, Sultan B, Quirion P, Berg A (2011) The impact of future climate change on West African crop yields: What does the recent literature say? Global Environmental Change 21:1073-1083 doi:https://doi.org/10.1016/j.gloenvcha.2011.04.007

Shah Z, Shah SH, Peoples MB, Schwenke GD, Herridge DF (2003) Crop residue and fertiliser N effects on nitrogen fixation and yields of legume–cereal rotations and soil organic fertility Field Crops Research 83:1-11 doi:http://dx.doi.org/10.1016/S0378-4290(03)00005-4

Smith A, Snapp S, Dimes J, Gwenambira C, Chikowo R (2016) Doubled-up legume rotations improve soil fertility and maintain productivity under variable conditions in maize-based cropping systems in Malawi Agricultural Systems 145:139-149 doi:https://doi.org/10.1016/j.agsy.2016.03.008

Snapp SS, Cox CM, Peter BG (2019) Multipurpose legumes for smallholders in sub-Saharan Africa: Identification of promising ‘scale out’options Global Food Security 23:22-32 doi:https://doi.org/10.1016/j.gfs.2019.03.002

Tadele Z (2017) Raising crop productivity in Africa through intensification Agronomy 7:22 doi:https://doi.org/10.3390/agronomy7010022

Trail P et al. (2016) Evaluating intercropping (living cover) and mulching (desiccated cover) practices for increasing millet yields in Senegal Agronomy Journal doi:https://doi.org/10.2134/agronj2015.0422

Vanlauwe B, Hungria M, Kanampiu F, Giller K (2019) The role of legumes in the sustainable intensification of African smallholder agriculture: Lessons learnt and challenges for the future Agriculture, Ecosystems & Environment 284:106583 doi:https://doi.org/10.1016/j.agee.2019.106583

Vashro TN, Farris A, Kraak VI, Hulver MW, Gueye F, Abaye AO (2018) Effects of mung bean consumption on dietary diversity of women and children in Senegal Journal of Nutritional Ecology and Food Research 5:40-46 doi:https://doi.org/10.1166/jnef.2018.1181

Chapter 2 – Potential of mungbean [*Vigna radiata* (L.) Wilczek] in Sub-Saharan Africa. A review

Abstract

Mungbean [*Vigna radiata* (L.) Wilczek] is an important tropical legume mainly cultivated in South and East Asia. Despite being a minor grain legume in Sub-Sahara Africa (SSA), mungbean has a considerable potential for improving soil fertility and enhancing food security of smallholder farmers. Mungbean is a short-duration and drought-tolerant crop, capable of symbiotic atmospheric nitrogen fixation. It has low water and input requirements, making it suitable to rainfed smallholder production systems. Having similar nutritional content to cowpea and dry beans, mungbean could perform better than them under semi-arid conditions due its lower rate of flower and pod abscission. The legume is an important source of protein, carbohydrates, minerals (particularly iron), and vitamins and has lower phytic acid content than other legumes and staple cereals in SSA. Mungbean seeds can be eaten with cereals, processed to make dhals, sprouts, noodles, soups, desserts, and protein- and iron-rich supplements for children. This review summarizes (1) the advantages of mungbean cultivation and (2) its potential for improved nutrition in SSA as well as (3) constraints, highlighting (4) the potential characteristics for mungbean improvement in SSA.

Keywords: Mungbean, Sub-Saharan Africa, soil fertility, food security.

Introduction

In Sub-Saharan Africa (SSA), the projected increase in climate variability, as well as increased frequency and intensity of extreme weather events, is expected to have a negative impact on agricultural production (Ogallo, 1984; Kotir, 2011; Niang et al., 2014). Rainfall variability and persistent droughts and floods are reported to contribute to decreased crop yields (Lloyd et al., 2011), fluctuation and volatility of food prices (Terdoo and Feola, 2016), negative impacts on livelihoods (Connolly-Boutin and Smit, 2016; Diatta et al., 2016a), and increased poverty and malnutrition (Barrett and Bevis, 2015; Tirado et al., 2015). Adaptation strategies must occur within the context of both sustainable agricultural production and growing consumer demand.

Development of climate adaptation strategies and mitigation efforts that would anticipate effective responses and interventions will be important in Sub-Saharan Africa where are located the most vulnerable populations (Kotir, 2011; Niang et al., 2014; Zewdie, 2014). Such strategies include improvement of agricultural management practices (Brooker et al., 2015) and sustainable intensification (Lal et al., 2015; Snapp et al., 2019), use of high-yielding (Brown et al., 2009; Cairns et al., 2013) and drought and heat-resistant crop genotypes (Odeny, 2007; Ramírez Villegas and Thornton, 2015), intensified use of technology inputs (Shishaye, 2015), natural resource stewardship (Mbow et al., 2008; Diatta et al., 2016b; Faye et al., 2019), and development of policy and community programs (Connolly-Boutin and Smit, 2016). Growing mungbean, a species with low water and input requirements and wide adaptability into crop rotations, is a potentially promising way of increasing crop production under adverse soil, water, and climatic conditions. Furthermore, the high protein, mineral, and vitamin content of mungbean represent an opportunity for improving nutrition security in SSA. However, while mungbean has played an important role in improving soil fertility and sustaining the livelihood and nutritional security of smallholder farmers in other regions (Smith et al., 2016; Ullah et al., 2016), it represents an understudied crop in SSA (Naylor et al., 2004; Foyer et al., 2016).

Mungbean is an important tropical food legume that has an optimum temperature range for growth of 28-30^{o}C and is extensively grown in areas that are prone to drought and high temperatures (Sangakkara et al., 2001; Kumar and Kumar, 2014; Raina et al., 2016). Global annual production of mungbean in 2017 was estimated to be approximately 2.7 mill metric tons, which represented about 3% of global pulse production that year (IMARC, 2018). Mungbean global production is expected to be 5.3 million metric tons by 2023, representing a 15% increase due to an increased demand from the food industry (IMARC, 2018).

Mungbean is a self-pollinated diploid (2n = 22), erect plant with branches carrying pods (8-15 seed grains) in clusters near the top of the plant (Kaur et al., 2015), belonging to the *Papilionoideae* in the *Fabaceae* (Van et al., 2013). It belongs to the *Phaseoleae* tribe, which contains soybean (*Glycine max*) and cowpea (*Vigna unguiculata*) (Stefanović et al., 2009). The genus *Vigna* includes more than 100 species in three sub-specific taxa: *radiata* (green grams and golden grams including the cultivated mungbean), *sublobata* and *glabra* (Van et al., 2013; Sakai et al., 2015). Improved mungbean varieties reach maturity in 60 to 65 days (Fig. 1) (Keatinge et al., 2011) while traditional varieties mature in 65 to 90 days (HanumanthaRao et al., 2016). Mungbean varieties have determinate growth but flower and fruit over a period of several weeks, which can result in multiple harvests (Fig. 1) (Diatta et al., 2018). In semi-arid regions, mungbean grain yields exceeding 1.5 Mg ha^{-1} have been reported for improved varieties (Chadha, 2001; Mbeyagala et al., 2017; Kassa et al., 2018), while traditional varieties average about 0.5 Mg ha^{-1} (Mogotsi, 2006; Nair et al., 2012). Mungbean is classified by the Food and Agriculture Organization (FAO), as a “dry bean”. Few studies have been conducted to assess the adaptation, growth, and yield of introduced mungbean genotypes in Africa. No prior article has reviewed the potential of mungbean in Sub-Saharan Africa to our knowledge.

Geographic distribution and production of mungbean

Genetic diversity data and archaeological studies revealed mungbean to be a native crop of India and the Indo-Burma region where the early domestication processes began (Morton et al., 1982). From this region, selection of species resulted in the introduction of cultivated types of mungbean by Asian emigrants or by traders to the Middle East, Africa, Latin and South America, and Australia (Smartt, 1984). *Vigna radiata* var. *sublobata* is believed to be the wild progenitor of mungbean.

Mungbean is cultivated on more than 6 million ha (HanumanthaRao et al., 2016). Ninety percent of global production occurs in south, east, and southeast Asia (Kang et al., 2014). India represents the major legume producing country in south Asia and the largest producer of mungbean worldwide followed by China and Myanmar. India's annual mungbean production is estimated to be around 3 million metric tons, which represents over 50% of the total world production (Nair et al., 2015). Because of both the limited increase in mungbean production over the past years combined with limited access to high quality seeds, current demand is high in India. Myanmar (83%), Tanzania (4%), Kenya (4%), Australia (3%), and Mozambique (2%) export mungbean to India (Raina et al., 2016).

Figure 1. A guide to the growth stages and agronomic advantages of mungbean.

In Sub-Saharan Africa, legume production is dominated by peanut, cowpea, and dry bean (Fig. 2). However, limitations on these primary legume crops in coping with drought provide an opportunity for mungbean production. In Africa, mungbean is cultivated in at least 22 countries but still remains as a minor crop in the continent, except in Kenya where it represents a valuable source of protein, nutrients and income to rural communities (Mogotsi, 2006). Among eight pulses tracked by FAOSTAT, aggregate production in SSA doubled to 30 million metric tons in the 21 years from 1997 to 2017. Peanut production grew only a little, but most of the other pulses more than doubled production (Fig. 2).

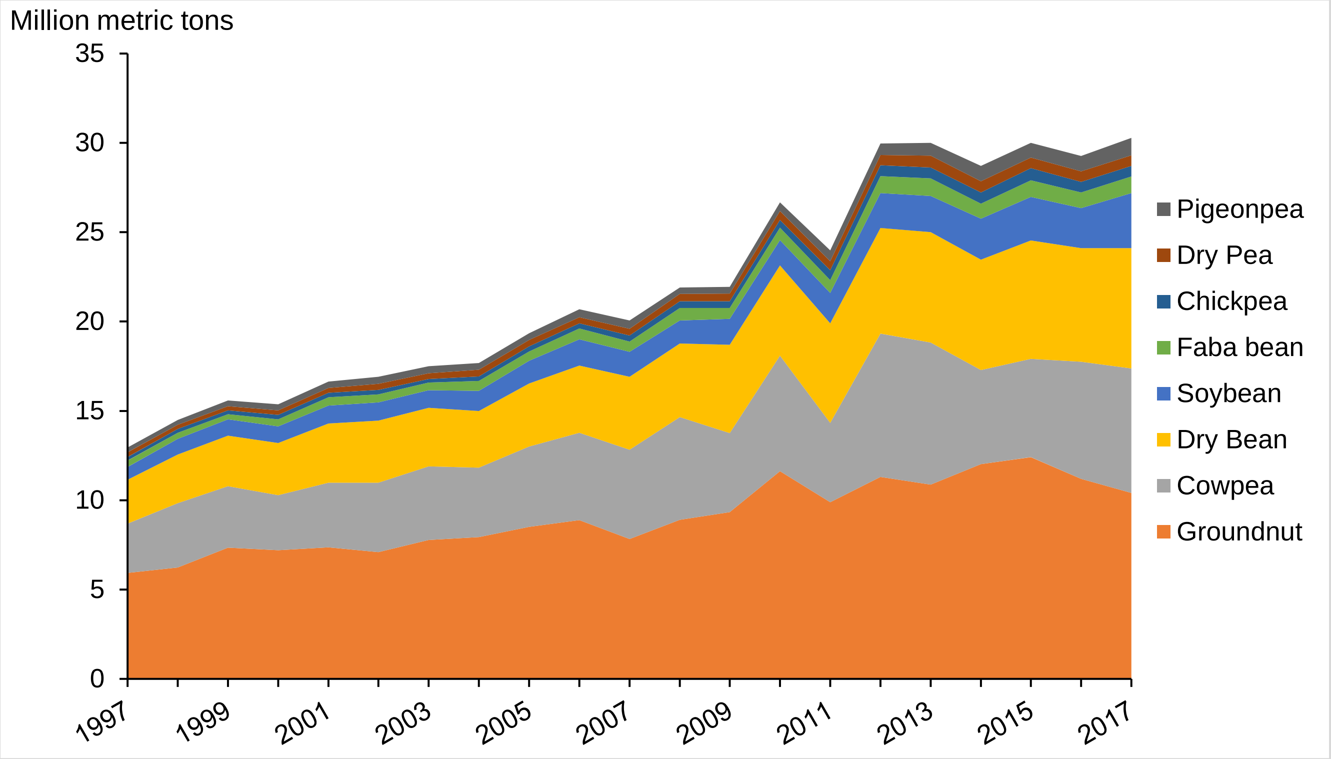

Figure 2. Annual production of major pulse crops in Sub-Saharan Africa during the period between 1997 and 2017 (Mill metric tons). *Source*: FAOSTAT (2019)

While production of major legume crops such as groundnut, cowpea and common beans has seen an important increase in Sub-Saharan Africa in the last 20 years, mungbean production has remained low and stable (Keatinge et al., 2011). One of the reasons behind this phenomenon could be explained by the low adoption of superior genetics by farmers in SSA. In major mungbean-producing countries in this region, recent reported average yields fluctuated between 0.2 to 0.5 Mg ha^{-1} (Waniale et al., 2014) while potential yields of 2.0 Mg ha^{-1} have been reported in trials (Herridge et al., 2005). Although use of improved mungbean lines developed by The World Vegetable Center have shown promising results in Asia, African farmers still use traditional varieties that are low-yielding, small-seeded, and pod shattering (Waniale et al., 2014). A participatory selection study of mungbean genotypes conducted in Uganda has revealed farmers' preferences for high-yielding and large-seeded genotypes compared to landraces (Mbeyagala et al., 2017). These findings suggest that breeding efforts to enhance mungbean productivity need to focus on farmers' needs in addition to genotypes with superior traits (Mbeyagala et al., 2016).

Agronomic performance of mungbean

Mungbean is usually grown on marginal lands under rainfed conditions. It is well adapted to arid and semiarid conditions and is suitable for planting on a range of altitudes, temperatures, and soil types. However, it grows best in subtropical regions with average annual rainfall in the range 600-900 mm and at altitude not exceeding 2000 m on well-drained loams or sandy loam soils (Mogotsi, 2006). Mungbean is well-suited to many cropping systems due to its ability to improve soil fertility and sustain productivity of subsequent crops in subsistence agriculture (Senaratne et al., 1995; Dey et al., 2016). In Sub-Saharan Africa, where reside the world's most vulnerable food production systems, recurrent droughts are projected to increase in frequency and intensity (Kotir, 2011; Zewdie, 2014; Connolly-Boutin and Smit, 2016). As a result of this, 60 to 90 million ha could be transformed into new arid and semi-arid areas in the following years, threatening food security for local farmers (UNDP, 2007; Juana et al., 2013; Rao et al., 2019). Under such a scenario, a highly nutritious crop like mungbean, which can sustain high rates of productivity under moderate to accentuated drought conditions, deserves special consideration. Multiple factors contribute to mungbean's drought-tolerance, such as early seedling growth stage (significantly positive correlation ($P<0.05$) with drought-tolerance (Zhongxiao et al., 2012)), important overall root system mass and length of main root, efficient stomatal conductance, and good photosynthetic capacity under water stress (Oo et al., 2005). Mungbean also has a low rate of flowers or pods abortion (14-37% compared to 43-81%, 48-76%, and 70-88% in soybean, common bean, and cowpea, respectively) (Ojehomon, 1968; Avav and Ugese, 2009).

Mungbean is an environmentally sustainable food legume, maintaining or enhancing soil fertility and reducing inorganic nitrogen needs. However, application of nitrogen fertilizer has been reported to improve mungbean growth and yield under low soil fertility conditions (Yin et al., 2018). To assess the effects of six nitrogen fertilizer rates (0, 20, 40, 60, 80 and 100 kg N ha^{-1}) on growth and yield of mungbean, Razzaque et al. (2017) conducted a pot study in a low-nutrient environment. They reported that 60 kg N ha^{-1} recorded 14.2 g plant^{-1}, which was a 48% increase over control. Under field conditions, Khan et al. (2008) investigated the effects 0, 30, 60, and 90 kg ha^{-1} of N on yield and yield components of mungbean and found that N fertilizers significantly increased N-content of nodules and shoots, number of pods and yield (11%, 9%, and 9% increase) compared to control. They also performed an economic analysis on N fertilizers vs control which revealed that N applications gave net higher income ha^{-1} than control under these conditions.

Like other legumes crops, seed inoculation of mungbean with an appropriate stain of *Rhizobium* spp. can result in a 10-12% increase in productivity (Ali and Gupta, 2012; Diatta et al., 2018). In addition, arbuscular mycorrhizal fungi have increased the productivity of mungbean and other legumes. Mycorrhizal dependence of blackgram, bushbean, chickpea, cowpea, gardenpea, grasspea, lentil, and mungbean revealed a dependence ranging from 25 to 51% for legume crops (Molla et al., 2011). This symbiotic relationship between mungbean, *Rhizobium* ssp. and arbuscular mycorrhizal fungi can promote and sustain mungbean productivity, even under drought conditions (Song, 2005; Habibzadeh et al., 2013). Arbuscular mycorrhizal fungi, with a 50% dependence recorded in mungbean (Molla et al., 2011), improves the uptake of slowly diffusing soil nutrients like phosphorus and micronutrients such as zinc (Tajini et al., 2011).

Intercropping systems are common agronomic techniques extensively practiced by subsistence farmers in Sub-Saharan Africa (Matusso et al., 2014; Corbeels et al., 2019).

Intercropping cereals with legume crops such as mungbean could increase the productivity of the land and also minimize the risk of crop failure (Brooker et al., 2015; Sabbagh and Lakzayi, 2016; Moswetsi et al., 2017). In Senegal, Trail et al. (2016) intercropped pearl millet [*Pennisetum glaucum* (L.) R. Br.] with mungbean and noted a 36% increase in millet grain yield compared to millet alone. Roy et al. (2016) reported that intercropping systems of maize and mungbean resulted in greater growth and higher number of cobs per plant, and grains per cob for maize, and pods per plant and seeds per pod for mungbean. High yield was attributed to a lower competition for light, water, and nutrients in these systems. Shaker-Koohi et al. (2014) intercropped mungbean with sorghum in a field experiment conducted in Iran and reported that intercropping treatments had higher intercropping advantage (3.22), relative yield totals (1.36) and land equivalent ratio (>1) compared to monocropping.

From an environmental standpoint, mungbean can improve agricultural systems in Sub-Saharan Africa through *in-situ* moisture conservation and addition of nutrient and organic matter to soil when grown as a green manure and/or cover crops (Morton et al., 1982; Samal et al., 2017). Among others, characteristics such as early establishment, high seedling vigor and N_2 fixation efficiency, short growing season with significant biomass production, favorable nitrogen to carbon balance, and easy incorporation and quick degradation into the soil, make mungbean a suitable crop for soil improvement in the Sub-Saharan Africa (Peoples and Herridge, 1990). Using mungbean as cover crop in semi-arid watersheds has resulted in reduced soil erosion through a decrease of runoff (28%) and sediment (30%) losses compared to bare soil (Rashid et al., 2015). Using mungbean as a cover crop may also reduce weed infestation in the companion crop (Dwivedi et al., 2016). Weed density and fresh weed biomass were reduced by 34% and 54%, respectively, when maize was intercropped with mungbean (6:10 row ratio) compared to maize alone in

Pakistan (Shahida and Khan, 2016). Planting mungbean at 35 cm row spacing + hand weeding at 25 days after sowing also reduced weed density and fresh weed biomass by 41 and 79%, respectively, compared to control (Awan et al., 2009). Moreover, mungbean has been used as an environmentally sound and sustainable approach for managing insects in cropping systems. A study conducted by Lu et al. (2009) to assess the potential of mungbean as trap crop revealed a 50% decrease in mirid bug [*Apolygus lucorum* (Meyer-Dür) (Heteroptera: Miridae)] population densities compared to cotton fields without mungbean plants (36 individuals per 100 plants). Similar findings were also reported by Geng et al. (2012) who observed not only significantly higher number of adults and first instar nymphs of *A. lucorum* but also higher adult longevity and fecundity on mungbean compared to cotton plants ($P < 0.05$). To understand the migration of *A. lucorum* adults between neighboring cotton and mungbean fields, Wang et al. (2017) developed a DNA-based polymerase chain reaction (PCR) approach. Findings from this study revealed a detection of cotton DNA in the guts of *A. lucorum* collected from mungbean plots evidencing the migration *A. lucorum* from cotton to mungbean plots. Results from these studies could help in developing mungbean-based trap-cropping strategies for controlling *A. lucorum* on agricultural crops.

Mungbean is also highly efficient in the use of nutrients, especially nitrogen, allowing smallholder farmers in Sub-Saharan Africa to achieve acceptable grain yields on marginal lands and under low fertility management. While mungbean crop has been successfully grown in SSA under low technology schemes to date, ensuring a timely and efficient nitrogen availability to the crop will represent a key management decision to increase grain yields in a region where little to none could be done regarding water availability to the crop. Nitrogen is the most essential nutrient and is a major component of protein, amino acids, enzymes, phospholipids, and nucleic acids. It promotes plant growth and enhances the production of biomass and grain yield of legumes (Mian and Hossain, 2014; Carranca et al., 2015; Bibi et al., 2016; Fu and Shen, 2016). In the case of mungbean, field and lab research has demonstrated that, in symbiosis with *Rhizobium,* the crop can derive up to 75% of its total N requirement from N_2 fixation (Shah et al., 2003), fix up to 110 kg N ha^{-1} (Dakora et al., 2015), and transfer 10% of fixed N to companion or following crops (Zang et al., 2015). However, studies within the SSA measuring N_2 fixation by mungbean have not been reported.

Estimated values of biological N_2 fixation for common legume crops in SSA reveal large variations in amount of N fixed (Fig. 3). In south, east, and southeast Asia, measurements of N_2 fixation revealed large variation (Table 1). In intercropping studies with maize and mungbean in Sri Lanka, Senaratne et al. (1995) reported that mungbean has the ability to fix up to 197 mg N $plant^{-1}$ which represents a 7 to 11% of N transfer to maize in an intercropped system. In Pakistan, Hayat et al. (2008) reported values ranging between 19 and 47 kg N ha^{-1}, which represented between 32% to 49% of the total N requirement of the crop across the whole growing season. However, a study conducted by Shah et al. (2003) in Pakistan revealed that a higher percentage of the total N requirement of the crop may be derived from N_2 fixation (i.e., 54 to 82%, or 55 to 86 kg N ha^{-1}). In the Philippines, George et al. (1995) reported that N_2 fixation by mungbean ranged from 61 to 90 kg N ha^{-1} while Rosales et al. (1995) found N fixation values ranging from 21 to 85 kg N ha^{-1}. In other cases, data obtained from field experiments was less variable. Peoples et al. (1991) investigated N fixation using the ^{15}N natural abundance method in Thailand and documented N fixation rates ranging between 64 to 66 kg N ha^{-1}, which represented around 90% of the total N requirement of the crop in this study.

Table 1. Estimates of fixed N by mungbean in field trials.

Country	N fixed kg N ha^{-1}	N method used†	Reference
Pakistan	55–86	N balance	Shah et al. (2003)
Pakistan	35–83	^{15}N isotope dilution	Mohammad et al. (2010)
Philippines	25–47	^{15}N isotope dilution	Delfin et al. (2008)
Philippines	21–85	^{15}N isotope dilution	Rosales et al. (1998)
Philippines	61–90	^{15}N isotope dilution	George et al. (1995)
Philippines	21–85	^{15}N isotope dilution	Rosales et al. (1995)
Thailand	35–50	^{15}N isotope dilution	Phoomthaisong et al. (2003)
Thailand	10	^{15}N isotope dilution	Toomsan et al. (2000)
Australia	20–83	^{15}N natural abundance	Rochester et al. (1998)
Ethiopia	8–25	^{15}N natural abundance	Raji et al. (2019)
Pakistan	32–46	^{15}N natural abundance	Umair et al. (2011)
Pakistan	41	^{15}N natural abundance	Hayat and Ali (2004)
Thailand	64–66	^{15}N natural abundance	Peoples et al. (1991)
Pakistan	6–32	Ureide	Ali et al. (2013b)
Pakistan	17–47	Ureide	Hayat and Ali (2010)
Pakistan	55	Ureide	Hayat and Ali (2004)
Pakistan	19–47	Ureide	Hayat et al. (2008)
Pakistan	13–26	Ureide	Tariq et al. (2007)

† See Unkovich et al. (2008) for description of techniques for measuring biological N_2 fixation.

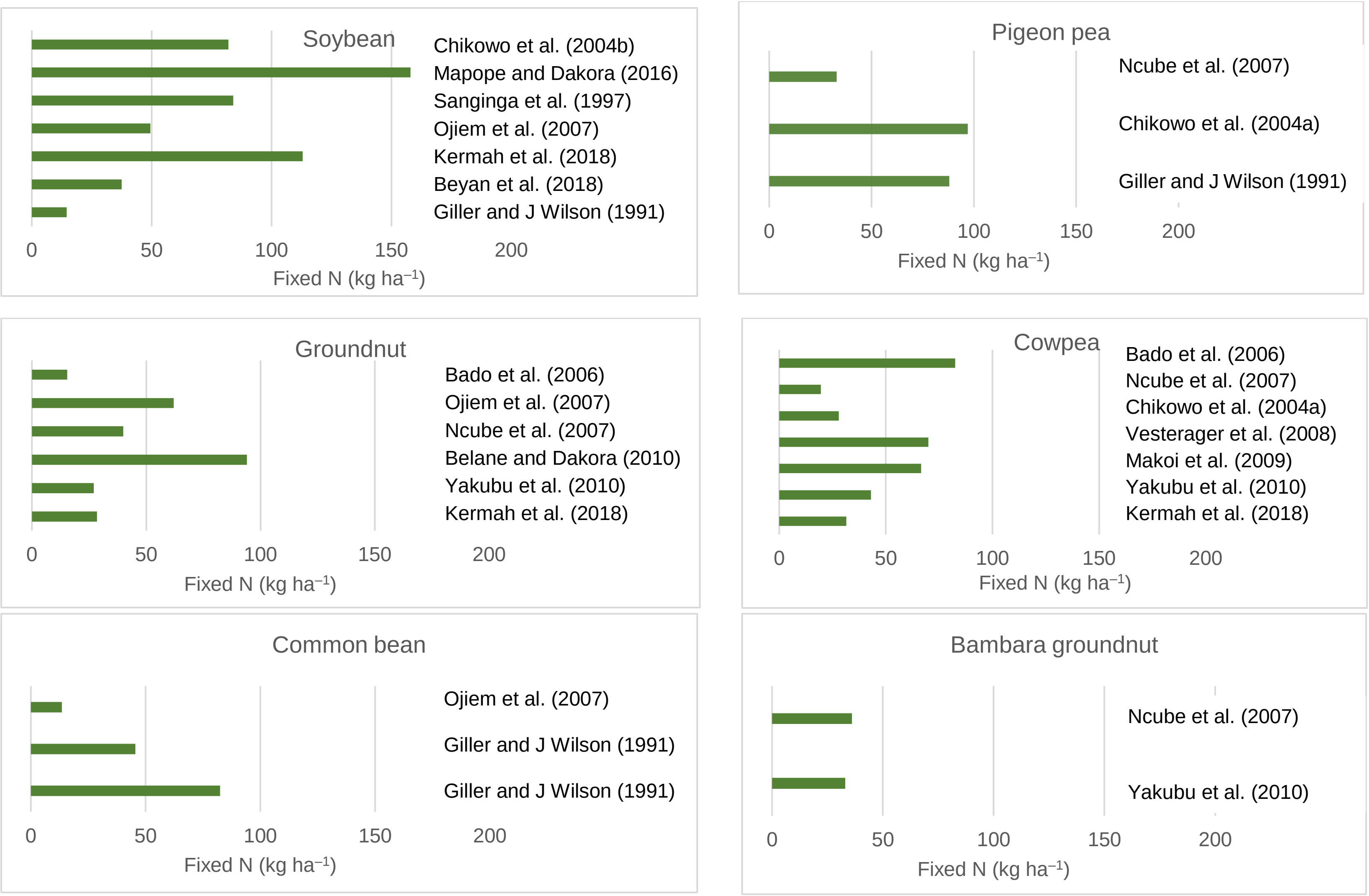

Figure 3. Estimates of fixed N (kg ha^{-1}) for some legume crops commonly grown in Sub-Saharan Africa.

Nutritional value of mungbean

The high nutritional value of mungbean makes it a good source of protein, minerals, and vitamins to smallholder households. Mungbean has a high protein content, complementing to deficiencies of cereal-based diets in SSA (Keatinge et al., 2011). Studies determining the proximate composition of mungbean report a wide variation in protein values (15% to 33%) (Paul et al., 2011; Shaheen et al., 2012; Dahiya et al., 2015; Ganesan and Xu, 2017). Mungbean has a comparable protein content to chickpea, kidney bean, cowpea, groundnut, and pigeon pea (Table 2) (USDA, 2010). Although mungbean is an important source of protein, its protein nutritional quality is limited by low concentration of sulfur-containing amino acids such as methionine and cysteine with 0.29 g and 0.21g in 100 g of raw edible portion (Nair et al., 2012; Ganesan and Xu, 2017).

Table 2. Absolute nutritional content (in g or mg) of major crop legumes grown in Africa and Asia. †

Crop	Protein (g)	Oil (g)	Calcium (mg)	Iron (mg)	Zinc (mg)	Vitamin A (mcg-RAE)	Vitamin C (mg)	Folate (mcg)
Chickpea	22	7	119	7	4	3	5	630
Cowpea	27	2	96	11	7	2	2	718
Groundnut	28	53	98	5	3	0	0	257
Kidney bean	27	1	162	9	3	0	5	446
Mungbean	26	1	145	7	3	7	5	687
Mungbean sprout	32	2	135	9	4	10	138	635
Pigeon pea	21	5	123	5	3	9	114	507
Soybean	40	22	303	17	5	1	7	410
Soybean, green	40	21	606	11	3	28	89	508

† Value per 100 g raw product (dry weight basis).

Source: (USDA, 2010)

Anti-nutritional compounds reduce the nutritive value of food due to limited digestibility, bioavailability, and bioconversion of nutrients. Anti-nutritional compounds reported in mungbean include tannins, phytic acid, hemagglutinins, polyphenols, trypsin inhibitor, and proteinase inhibitor (Dahiya et al., 2015). However, the reported amount of anti-nutritional components in mungbean like trypsin, hemagglutination, saponins, pythic acid and insoluble dietary fiber, are been relatively low compared to other legume crops such as soybean and cowpea (Elkowicz and Sosulski, 1982; Gupta, 1987) (Table 3). Variation in the amount of anti-nutritional components in mungbean can likely be explained by differences in genetic variation among cultivars (Dhole and Reddy, 2015). Processing techniques to decrease the concentration of anti-nutritional factors in mungbean include breeding research, agronomic techniques, and food preparation processes such as sprouting, dehulling, soaking, germination, boiling and cooking (Mubarak, 2005; Hemalatha et al., 2007; Ganesan and Xu, 2017). Preparing mungbean seeds with vegetables lowers the concentrations of anti-nutritional factors such as those displayed in Table 3 (Kumar Dahiya et al., 2014). Split seeds consumed with rice are beneficial for children and elderly people.

Table 3. Anti-nutritional factors in eleven legume flours.

Crop	Trypsin (TUI mg^{-1})	Hemagglutination activity (HU mg^{-1})	Saponin (HA g^{-1})	Phytic acid (mg g^{-1})	Insoluble fiber (%)
Chickpea	18.8	7.9	0.5	5.2	3.8
Cowpea	12.2	2	12.8	7.6	4.3
Faba bean	4.8	10.6	0	3.7	2.7
Field pea	7.6	15.1	0	7.4	3.2
Lentil	5.1	14.6	5.6	6.4	3.7
Lima bean	46.8	0.9	6	5.2	3.9
Lupin	0	--	0.8	8.2	5.6
Mungbean	10	3.4	0.8	5.1	2.8
Navy bean	18.2	46.1	12.6	10	4.6
Northern bean	18.1	16.8	7.8	10.6	3.2
Soybean	41.6	77.4	0	11.6	5.9

Source: (Elkowicz and Sosulski, 1982)

Additionally, mungbean seeds are an important source of carbohydrates (59-65%), minerals (particularly iron), vitamins and amino acids in human diets (Dahiya et al., 2015) (Table 2). Minerals present in mungbean seeds include iron, calcium, phosphorous, magnesium, and potassium (Puranik et al., 2011). Mungbean seeds contain 1-1.5% fat, and 3.5-4.5% fiber, (Nair et al., 2013). Adding to its highly desirable nutritive composition, mungbean is also considered valuable for good health and human development because of the high digestibility of its protein and carbohydrates (Anwar et al., 2007). The digestibility value of mungbean (67-72%) is comparable to chickpea (65-79%), pigeonpea (60-74%), soybean (63-72%), and urd bean (56-63%) (Chitra et al., 1995). Mungbean is also a rich source of amino acids like arginine, isoleucine, leucine, lysine, phenylalanine, valine, aspartic acid, glutamic acid and serine (Table 4) (Dahiya et al., 2015). The relatively high protein and lysine content, added to the low content of methionine in mungbean makes it a good complement for cereals with high carbohydrate, low lysine and high methionine concentrations (Arvind et al., 2013).

Table 4. Amino acid composition of mungbean seeds.

Amino acid (g/16 g of nitrogen)	Average†	Minimum	Maximum
Alanine	4.1	3.6	4.5
Arginine	5.8	4.5	6.7
Aspartic acid	13	12	15.1
Cysteic acid	13.5	13.5	13.5
Glutamic acid	18.3	13.6	21.7
Glycine	3.6	3.2	4.3
Histidine	3.2	2.4	5.6
Isoleucine	4.3	3.6	5.4
Leucine	7.6	6.9	8.7
Lysine	6.5	4.1	8.1

Methionine	1.2	0.5	1.9
Phenylalanine	5.4	4.6	6.2
Proline	4.5	3.7	5.6
Serine	4.9	4	5.8
Threonine	3.2	2.7	4
Tryptophan	1.2	0.5	3.4
Tyrosine	2.7	2.2	3.3
Valine	5.1	4.1	6.4

† Mean value of all collected data.

Source: Dahiya et al. (2015)

Food, feed and non-food uses of mungbean

Mungbean is an important food and livestock feed legume crop in tropical and subtropical regions and is extensively consumed for its protein-rich grains (Ramanujam, 1981; Bhardwaj et al., 1999; Khattak et al., 2007). Mungbean grains are typically consumed as boiled or cooked with vegetables or meat (Keatinge et al., 2011). It can also be used to make sprouts, soups, noodles, dessert and several other food products (Dhayal et al., 2015). In East Africa, mungbean is a major food crop and is commonly consumed as vegetable and processed seed. In Kenya and Tanzania, mungbean green pods and immature seeds are consumed with a popular thick maize porridge called "ugali" (Nair et al., 2013). Mature seeds of mungbean are also commonly boiled together with maize, sorghum and other cereals or fried with meat or vegetables in Kenya (Nair et al., 2013). In Uganda, mungbean represents an important food product and source of income for smallholder farmers (Waniale et al., 2014). Consumption of cooked mungbean seeds in sauces and as a side dish is common in Ethiopia and Malawi, respectively (Mogotsi, 2006). In West Africa, recent efforts to improve food security and soil fertility through crop diversification have resulted in the development and introduction of mungbean (Ngwuta et al., 2010; Diatta et al., 2019a). In Nigeria, mungbean is consumed as sprouts in salad or processed into biscuits (Akaerue and Onwuka, 2005; Okweche and Avav, 2013). Mungbean seeds and leaves are boiled and consumed with rice or millet in Senegal (Abaye et al., 2018). A study on dietary diversity of women and children conducted in Senegal revealed that inclusion of mungbean into the Senegalese diet could be a major addition to limited legume consumption and supplement cereal-based diets (Vashro, 2017).

In India, mungbean is consumed as whole or split seeds which are transformed into a thick soup called “dhal” (Chadha, 2001). In China, food products made of mungbean include soup, porridge of mungbean and rice, sprouts, starch noodles, and cakes. Cold jellies and cakes represent the popular food products in Thailand (Nair et al., 2013). After removing the seed coat, mungbean seeds may also be ground into flour. Mungbean flour can be further transformed into various products such as noodles, bread, biscuits, and vegetable cheese, used to fortify wheat flour, or to formulate high-protein food supplements for children (Nair et al., 2013). Imtiaz et al. (2011) revealed that 44% wheat flour with 36% mungbean flour or 56% wheat flour with 24% mungbean flour combined with 10% skim milk powder and 10% sugar in both cases can be used as weaning food. However, work on the effects of processing methods on protein concentration has shown that processing could improve the nutrient composition of mungbean flours (Akaerue and Onwuka, 2010).

Mungbean may provide opportunities for improving the health of rural populations in Sub-Saharan Africa. The relatively high concentration of proteins, amino acids, oligosaccharides, and polyphenols in mungbean make it suitable for antioxidant, antimicrobial, anti-inflammatory and anti-tumor use (Tang et al., 2014). Mungbean soup has been successfully used to increase total antioxidant capacity and glutathione levels, and to subsequently alleviate heat stress in rats (Cao et al., 2011). Results from the study demonstrated the potential of mungbean soup in reducing the risk of heat stress in humans.

Mungbean crop residues are a good quality forage for livestock, particularly as a high-protein supplement to produce high-quality meat and milk. Sherasia et al. (2017) reported that fresh forage mungbean contains 13-21% of protein on a dry matter basis and mungbean straw has 9-12% protein content. Forage yields of non-fertilized mungbean plants averaged 0.64 t ha^{-1} while 1.4 t ha^{-1} was recorded under fertilized conditions (Sherasia et al., 2017). However, aboveground samples of mung bean for forage yielded 2.9 t ha^{-1} in the Southern Great Plains (Rao and Northup, 2009). Because mungbean matures quickly, it offers forage while other legume crops such as cowpea or velvet bean are still maturing (Lambrides and Godwin, 2007).

Major constraints to mungbean production

The productivity of mungbean in Sub-Saharan Africa, widely grown over a range of environments, is constrained by abiotic and biotic stresses (Tuba et al., 2010; HanumanthaRao et al., 2016). Among abiotic stresses, drought and flooding are two of the major constraints to mungbean production in SSA. High rainfall variability has led to a reduction in suitable lands for bean production and a subsequent decrease in agricultural production (Foyer et al., 2016). Drought and flooding stresses have been reported to limit growth and yield of mungbean (Lalinia et al., 2012; Amin et al., 2016). To understand the effects of water stress on phenological and agronomic traits of mungbean, Lalinia et al. (2012) applied four irrigation regimes (no water stress, drought stress at the flowering, during pod and seed formation) to five mungbean cultivars. They found that drought stress manifested in mungbean through decreased plant height, 100-grain weight, number of grains per pod, number of pods per plant, days to flowering and physiological maturity. This decrease in mungbean growth and yield components when grown under drought stress conditions could be explained by inefficient stomatal regulation and low photosynthetic capacity under limited soil moisture stress conditions (Sunil et al., 2015; Raina et al., 2016). It could be also due to low xylem water potential, low transpiration resistance, high leaf diffusive resistance, and high canopy minus air temperature differential (Naresh et al., 2013). An excess of water can be detrimental to mungbean productivity. Working with five mungbean genotypes in Bangladesh, Amin et al. (2016) found that a 4-day flooding imposed at 24 days after emergence induced a decrease in total dry matter and seed yield through a reduction in the pods per plant and the seed size of all genotypes. The decrease in mungbean productivity could be explained by the reduction in leaf photosynthesis, stomatal closure, and growth inhibition (Oo et al., 2005).

Low productivity of mungbean could be explained by poor agronomic practices such as growing mungbean under low soil moisture and fertility conditions, absence of appropriate rhizobial strains, and inefficient weed control. Increases in mungbean productivity are often limited by an insufficient supply of suitable cultivars and high-quality seed (Keatinge et al., 2011; Foyer et al., 2016). Fewer pest and disease problems have been reported in mungbean compared to other legumes such as soybean, common bean and cowpea resulting in more stable yields (Keatinge et al., 2011).

Yield loss of mungbean can be caused by field pests such as whitefly, *Bemisia tabaci* Genn, leaf hopper, *Empoasca kerri* Pruthi, black aphid, *Aphis craccivora* Koch, Bihar hairy caterpillar, *Diacrisia obliqua* (WIK), galerucid beetle, *Madurasia obscurella* Jacoby, stem fly, *Ophiomyia (Melanagromyza) phaseoli* (Tryon), lycaenid borer, *Euchrysops cnezus* Fabr, and spotted caterpillar, *Maruca testulalis* Geyer (Lal, 1985). Integrated management strategies of mungbean pests include resistant cultivars, clean seeds, cultural practices, and biological control and chemical pesticides (Swaminathan et al., 2012). The major viral disease that constrains mungbean production is Mungbean Yellow Mosaic Virus (MYMV) (Anjum et al., 2010; Dubey and Birendra, 2013; Nair et al., 2019). MYMV is caused by *Begomovirus* species transmitted by whitefly (*Bemisia tabaci* Gennadius) (Sugandh et al., 2015). Mungbean plants infected by MYMV have small and scattered yellow colored leaves, reduced flower production, and small immature seeds in shrunken pods (Patel and Mahatma, 2016), resulting in a drastic reduction of mungbean yield from 30 to 100% (Kumar and Singh, 2008). Reduced yield can cause substantial economic losses (Dubey and Birendra, 2013). The prevalence of MYMV has been reported to be favored by high temperatures, high humidity (Safdar et al., 2015) and abundant whiteflies population (Munawwar et al., 2014). The development of high-yielding and disease-resistant mungbean varieties resulted in its introduction in rice/wheat rotations in Asia and a subsequent increase in crop production (Keatinge et al., 2011). Breeding efforts against MYMV also resulted in the development of high-yielding disease-resistant varieties (Kumar and Singh, 2008). Munawwar et al. (2014); Munawwar et al., 2014; Sugandh et al. (2015) identified mungbean genotypes resistant to MYMV through a screening trial. They reported that these genotypes could be used for development of MYMV-resistant varieties. However, Mohan et al. (2014) and (Munawwar et al., 2014) conducted a screening of mungbean genotypes for resistance to MYMV under field conditions and reported that most of the studied germplasms exhibited moderate to high susceptibility. Similarly, immune or highly resistant genotypes against MYMV under field conditions were not found by Binyamin et al. (2015) during a screening experiment. However, MYMV in mungbean has not been reported in SSA.

Additional major diseases of mungbean include powdery mildew [*Podosphaera fusca* (Fr.) U. Braun & Shishkoff], anthracnose [*Colletotrichum acutatum* (J.H. Simmonds)], cercospora leaf spots [*Cercospora canescens* Ellis & G. Martin], *Erysiphe polygoni* (Vaňha) Weltzien), *C. truncatum* (Schwein.) Andrus & Moore, *C. gloeosporioides* (Penz.) Penz. & Sacc), and wet root rot [*Rhizoctonia solani* (Kuhn)] (Anjum et al., 2010; Dubey and Birendra, 2013; Nair et al., 2019). Options to reduce the impacts of mungbean pathogens involve integrated disease management such as combinations of insecticides, fungicides, and bio-formulation as seed treatment. Dubey and Birendra (2013) revealed that mungbean seeds treated with a combination of thiamethoxam (insecticide) at 4 g kg^1, carboxin (fungicide) at 2 g kg^1 and Pusa 5SD (*Trichoderma virens*) at 4 g kg^1 recorded a low incidence of cercospora leaf spots, MYMV, and wet root rot.

Lack of policy and research attention can also constrain the productivity of mungbean in Sub-Saharan Africa (Akibode, 2011). Increases in mungbean productivity are often limited by an insufficient supply of suitable cultivars and high-quality seed coupled with the lack of training programs on mungbean potential benefits for agricultural productivity, soil, and human health (Shanmugasundaram et al., 2010; Keatinge et al., 2011; Foyer et al., 2016). As a result, adaptive and strategic research associated with the development of strong network and financial support will be helpful to promote mungbean from being a marginal crop to become one of the major grain legume crops in SSA, as was the case in Asia (Nair et al., 2012).

Potential for mungbean improvement

Agronomic practices for improving mungbean yields include optimization of row spacing and plant density in order to increase mungbean production through increased cumulative intercepted radiation and increased water use efficiency for specific environments (Rachaputi et al., 2015). The available, limited mungbean literature for SSA highlights the importance of investigating the potential of mungbean production (Table 5). Diatta et al. (2018) reported that inoculation of mungbean with *Bradyrhizobium* inoculum (group I) increased the number of pods per plant, number of seeds per plant, and seed yield by 15%, 18%, and 14%, respectively over uninoculated mungbean. HanumanthaRao et al. (2016) and Trail et al. (2016) suggested that surface organic mulch could also be used to alleviate heat stress of mungbean under semi-arid conditions through a decrease in soil temperature and reduced loss of soil water.

Promotion and utilization of mungbean in agriculture in Sub-Saharan Africa will require enhancement of production and nutritional value through breeding and better management practices under environmental and economic constraints (Nadarajan and Chaturvedi, 2010; Auti, 2012; Dahiya et al., 2015; HanumanthaRao et al., 2016). In order to fully utilize mungbean to increase agricultural resiliency in SSA, the changing climatic conditions will need concomitant screening of existing varieties and genetic improvements to develop high yielding varieties with short growing season, disease-resistant, and tolerant to waterlogging and salinity (Kumar and Kumar, 2014; Raina et al., 2016). To this point, efforts to develop improved varieties of mungbean with synchronous maturity, short growing season (60-75 days), higher yields (>2 Mg ha^{-1}) under different biotic and abiotic stresses, and better nutritional composition across various environments were recently initiated in South Asia (Kumar and Kumar, 2014). Despite these efforts, limited data on the genome sequence for *Vigna* species in developing countries resulted in a limited advancement of the molecular breeding research in these regions, particularly in SSA (Kang et al., 2014). Participatory selection of high-yielding and nutrient-dense cultivars should be continued in Eastern Africa but also encouraged in other Sub-Saharan regions (Mbeyagala et al., 2017).

In addition, breeding efforts should include sequencing of mungbean genome from existing germplasm collection and development of markers for traits of interest such as high yield, reduced photoperiod sensitivity, and synchronous maturity (60-65 days) (Kang et al., 2014; Pataczek et al., 2018). The availability of the complete genome sequence of mungbean represents an opportunity to facilitate the construction of genetic maps and the identification of important agronomic traits for crop improvement (Kim et al., 2015). Sustainability of mungbean in SSA will also require resistance to specific diseases such as cercospora leaf spot, powdery mildew, and MYMV and insects such as bruchids (*Callosobruchus* spp.), bean fly [*Ophiomyia phaseoli* (Tryon)], and pod borer (*Maruca* spp.). The development of high-yield, short-duration, and disease-resistant varieties could result in widespread introduction across SSA. Alongside with these efforts, the development of testing multi-environments and coordination of testing across the region will be helpful to determine the adaptability and stability of improved mungbean genotypes in SSA (Mbeyagala et al., 2016).

Because of the wide genetic variability of mineral composition in mungbean varieties, biofortification has a great potential for enhancing micronutrient concentrations, and thus its nutritional quality (Kumar and Kumar, 2014; Dahiya et al., 2015). For example, interspecific breeding of mungbean with black gram [*V. mungo* (L.) Hepper], a close relative of mungbean, could be used to increase the low concentration of the essential amino acid methionine (Nair et al., 2013). The establishment of seed production and distribution systems and creation of agronomic and market opportunities will be necessary for smallholder farmers (Keatinge et al., 2011). The development of training programs in mungbean production such as the organization of field days and demonstration trials needs to be promoted to sustain food production in SSA (Keatinge et al., 2011). These training programs should also take into account the diversity of agro-ecological conditions and socio-economic factors in SSA (Moswetsi et al., 2017). Finally, expansion of mungbean in SSA may also require adequate financial support from national research institutes, international organizations, and the private sector in order to sustain and capitalize research findings on best agronomic practices, breeding efforts and adaptation strategies of mungbean to current agriculture systems in SSA.

Table 5. Summary of mungbean studies, including reported grain yield ranges, conducted across Sub-Saharan Africa.

Country	Region	Rainfall (mm)	Temperature (°C)	Soil type	Yield range (Mg ha^{-1})	Culture system	Fertilization	References
Ethiopia	North Shewa Zone Amhara Region	NA[a]	NA[a]	NA[a]	0.68 to 1.54	Participatory on-farm evaluation	NA[a]	Kassa et al. (2018)
Ethiopia	Semi-arid highlands (Northern Ethiopia)	635	13 - 24.4	Clay loam	0.49 to 1.37	Performance under deficit irrigation application	Diammonium phosphate at a rate of 18/46 N/P_2O_5 (100 kg/ha)	Ambachew et al. (2014)
Nigeria	Guinea savanna zone	NA[a]	NA[a]	Sandy loam	0.44 to 2.27	Screening of cultivars	NA[a]	Okweche and Avav (2013)
Nigeria	Rain forest zone of Southern Nigeria	NA[a]	22.3 - 31.5	Sandy loam	0.37 to 0.53	Preliminary field assessment	No fertilizer	Agugo et al. (2010)
Nigeria	Sub-humid savanna of Nigeria.	NA[a]	NA[a]	NA[a]	0.54 to 2.00	Reproductive abscission and seed yield	NA[a]	Avav and Ugese (2009)
Senegal	Central millet-peanut basin	398-529	NA[a]	Loamy sand	0.25 to 0.65	Intercropping with millet	No fertilizer	Trail et al. (2016)
Uganda	North Western Farmland- Wooded Savanna	468	18.7 - 30.8	Sandy	0.14 to 0.40	Multi-environment trials	No fertilizer	Mbeyagala et al. (2016)
	Northern Moist Farmlands	545	17.8 - 29.8	Sandy	0.47 to 0.63			
	Southern and Eastern Lake Kyoga Basin	494	17.4 - 29.3	Sandy loam	0.52 to 0.73			
	North Eastern Short Grass Plains	325.5	17.2 - 29.6	Sandy loam	0.32 to 0.46			
	Northern Moist Farmlands	560.5	16.8 - 29.3	Sandy	0.24 to 0.46			
	Southern and Eastern Lake Kyoga Basin	551	18.0 - 29.8	Loam	0.28 to 0.53			

[a] NA, not available.

Conclusion

This paper highlights the promising yet largely unexploited potential of mungbean for diversifying and increasing crop productivity, promoting sustainable adaptation strategies, and reducing food insecurity and poverty in Sub-Saharan Africa. Mungbean's symbiotic relationship with rhizobia, agronomic advantages and nutritional potential makes it a valuable crop for meeting the ever-increasing global need for food and nutritional security. Broad production and consumption of mungbean in SSA should be encouraged by an active promotion of both good agronomic practices and information about the nutritional value of mungbean for human health.

Nutritional and agronomic benefits should be also given research and development attention supported by a multidisciplinary approach. Existing germplasm needs to be extensively screened to find the best varieties for varied environments in SSA and acceptability for local cuisine. For this reason, 550 mungbean varieties from USDA and AVRDC are being screened for best agronomic and nutritional traits in Senegal. In addition, variety screening is relatively inexpensive and provides immediate resources for growers, thereby promoting adoption. Whereas screening for physical environmental factors may be transferrable to similar environments that are geographically distant, the biological factors need to be considered. Finding good varieties for the expected temperature/soil/water conditions, and then screening those best varieties to understand their vulnerabilities to expected pests/diseases should be initiated.

Upon identifying the suite of biological constraints, it will be important to set priorities for breeding programs focusing on incorporating disease resistance into the varieties identified as best adapted to the physical environment. Thus, innovative mungbean breeding and agronomic technologies can be utilized to develop new varieties with superior agronomic, adaptive, and nutritional traits suitable for current cropping systems in SSA. Increased production and adoption of mungbean can support sustainable production and improve the livelihoods of smallholder farmers in SSA.

Acknowledgements: The authors would like to acknowledge the contributions the School of Plant and Environmental Sciences (SPES) and the Center for International Research, Education, and Development (CIRED) of Virginia Polytechnic Institute & State University (Virginia Tech). Staff and management members in the Centre National de Recherches Agronomiques de Bambey are also gratefully acknowledged. The authors would also like to thank anonymous reviewers for their thoughtful suggestions that have considerably helped improving the manuscript.

Compliance with ethical standards

Conflict of interest: The authors declare that they have no conflict of interest.

References

Abaye AO, Archibald T, Vaughan L, Thompson T, Thomason WE, Mbaye DF, Mamadou L, Abdoulaye S, Gueye F, Snyder G (2018) Internationalizing the land grant mission: Lessons from Senegal.

Agugo B, Oguike P, Kanu B (2010) A preliminary field assessment of mungbean (*Vigna radiata* L. Wilczek) yield in the rain forest zone of southeastern Nigeria. American-Eurasian Journal of Agricultural and Environmental Science 8 (6):752-757

Akaerue B, Onwuka G (2005) The proximate composition, physical qualities, sensory attributes and microbial load of mungbean biscuits as affected by processing. Journal of Emerging Trends in Engineering and Applied Sciences 4 (2):250-257

Akaerue B, Onwuka G (2010) Evaluation of the yield, protein content and functional properties of mungbean [*Vigna radiata* (L.) Wilczek] protein isolates as affected by processing. Pakistan Journal of Nutrition 9 (8):728-735. doi:https://doi.org/10.3923/pjn.2010.728.735

Akibode CS (2011) Trends in the production, trade, and consumption of food legume crops in Sub-Saharan Africa. Michigan State University. Agricultural, Food and Resource Economics,

Ali M, Gupta S (2012) Carrying capacity of Indian agriculture: pulse crops. Current Science 102 (6):874-881

Ali S, Hasan A, Ijaz S, Ansar M (2013) Mungbean (*Vigna radiata*) yield and di-nitrogen fixation under minimum tillage at semi arid Pothwar, Pakistan. J Anim Plant Sci 23:198-202

Ambachew S, Alamirew T, Melese A (2014) Performance of mungbean under deficit irrigation application in the semi-arid highlands of Ethiopia. Agricultural water management 136:68-74. doi:https://doi.org/10.1016/j.agwat.2014.01.012

Amin M, Karim M, Islam M, Aktar S, Hossain M (2016) Effect of flooding on growth and yield of mungbean genotypes. Bangladesh Journal of Agricultural Research 41 (1):151-162. doi:https://doi.org/10.3329/bjar.v41i1.27680

Anjum T, Gupta KS, Datta S (2010) Mapping of mungbean yellow mosaic India virus (MYMIV) and powdery mildew resistant gene in black gram [*Vigna mungo* (L.) Hepper]. Electron J Plant Breed 1:1148-1152

Anwar F, Latif S, Przybylski R, Sultana B, Ashraf M (2007) Chemical composition and antioxidant activity of seeds of different cultivars of mungbean. Journal of food science 72 (7):S503-S510. doi:https://doi.org/10.1111/j.1750-3841.2007.00462.x

Arvind K, Sucheta S, Sital JS, Sarvjeet S (2013) Effect of sulfur and nitrogen nutrition on storage protein quality in mungbean [*Vigna radiata* (L.) Wilczek] seeds. Indian Journal of Agricultural Biochemistry 26 (1):86-91

Auti SG (2012) Induced morphological and quantitative mutations in mungbean. Bioremediation, Biodiversity and Bioavailability 6 (Special Issue 1):27-39

Avav T, Ugese F (2009) Studies on reproductive abscission and seed yield of mungbean (*Vigna radiata*) in sub-humid savanna of Nigeria. African Journal of Food, Agriculture, Nutrition and Development 9 (8). doi:https://doi.org/10.4314/ajfand.v9i8.48412

Awan FK, Ashraf Zahid M, Yaqoob M (2009) Weed management in mungbean (Vigna radiata (l.) R. wilczek) using different methods and row spacing. Pak J Weed Sci Res 15:269-274

Bado B, Bationo A, Cescas M (2006) Assessment of cowpea and groundnut contributions to soil fertility and succeeding sorghum yields in the Guinean savannah zone of Burkina Faso (West Africa). Biology and Fertility of Soils 43 (2):171-176. doi:https://doi.org/10.1007/s00374-006-0076-7

Barrett CB, Bevis LE (2015) The self-reinforcing feedback between low soil fertility and chronic poverty. Nature Geoscience 8 (12):907-912. doi:https://doi.org/10.1038/ngeo2591

Belane AK, Dakora FD (2010) Symbiotic N 2 fixation in 30 field-grown cowpea (*Vigna unguiculata* L. Walp.) genotypes in the Upper West Region of Ghana measured using 15 N natural abundance. Biology and Fertility of Soils 46 (2):191-198. doi:https://doi.org/10.1007/s00374-009-0415-6

Beyan SM, Wolde-meskel E, Dakora FD (2018) An assessment of plant growth and N 2 fixation in soybean genotypes grown in uninoculated soils collected from different locations in Ethiopia. Symbiosis:1-15. doi:https://doi.org/10.1007/s13199-018-0540-9

Bhardwaj HL, Rangappa M, Hamama AA (1999) Chickpea, faba bean, lupin, mungbean, and pigeonpea: potential new crops for the Mid-Atlantic Region of the United States. Perspectives on new crops and new uses:202

Bibi Z, Gohar A, Sajid S, Shah Z, Ehtesham J (2016) Response of brinjal (*Solanum melongena* L.) cultivars to nitrogen levels. Pure and Applied Biology 5 (1):134-141. doi:https://doi.org/10.19045/bspab.2016.50018

Binyamin R, Khan MA, Khan NA, Khan AI (2015) Application of SCAR markers linked with mungbean yellow mosaic virus disease-resistance gene in Pakistan mungbean germplasm. Genetics and Molecular Research 14 (1):2825-2830. doi:https://doi.org/10.4238/2015.march.31.13

Brooker RW, Bennett AE, Cong WF, Daniell TJ, George TS, Hallett PD, Hawes C, Iannetta PP, Jones HG, Karley AJ (2015) Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. New Phytologist 206 (1):107-117

Brown ME, Hintermann B, Higgins N (2009) Markets, climate change, and food security in West Africa. Environmental science & technology 43 (21):8016-8020. doi:https://doi.org/10.1111/nph.13132

Cairns JE, Hellin J, Sonder K, Araus JL, MacRobert JF, Thierfelder C, Prasanna B (2013) Adapting maize production to climate change in sub-Saharan Africa. Food Security 5 (3):345-360

Cao D, Li H, Yi J, Zhang J, Che H, Cao J, Yang L, Zhu C, Jiang W (2011) Antioxidant properties of the mung bean flavonoids on alleviating heat stress. PloS one 6 (6):e21071. doi:https://doi.org/10.1371/journal.pone.0021071

Carranca C, Torres MO, Madeira M (2015) Underestimated role of legume roots for soil N fertility. Agronomy for Sustainable Development 35 (3):1095-1102. doi:10.1007/s13593-015-0297-y

Chadha M (2001) Mungbean (*Vigna radiata* L.), a choice crop for improvement of human and soil health in southern Africa. In: Combating Desertification with Plants. Springer, pp 263-271. doi:https://doi.org/10.1007/978-1-4615-1327-8_25

Chikowo R, Mapfumo P, Nyamugafata P, Giller K (2004a) Woody legume fallow productivity, biological N 2-fixation and residual benefits to two successive maize crops in Zimbabwe. Plant and Soil 262 (1-2):303-315. doi:https://doi.org/10.1023/b:plso.0000037053.05902.60

Chikowo R, Mapfumo P, Nyamugafata P, Giller KE (2004b) Maize productivity and mineral N dynamics following different soil fertility management practices on a depleted sandy soil in Zimbabwe. Agriculture, ecosystems & environment 102 (2):119-131. doi:https://doi.org/10.1016/j.agee.2003.08.009

Chitra U, Vimala V, Singh U, Geervani P (1995) Variability in phytic acid content and protein digestibility of grain legumes. Plant Foods for Human Nutrition 47 (2):163-172. doi:https://doi.org/10.1007/bf01089266

Connolly-Boutin L, Smit B (2016) Climate change, food security, and livelihoods in sub-Saharan Africa. Regional Environmental Change 16 (2):385-399. doi:https://doi.org/10.1007/s10113-015-0761-x

Corbeels M, Cardinael R, Naudin K, Guibert H, Torquebiau E (2019) The 4 per 1000 goal and soil carbon storage under agroforestry and conservation agriculture systems in sub-Saharan Africa. Soil and Tillage Research 188:16-26. doi:https://doi.org/10.1016/j.still.2018.02.015

Dahiya PK, Linnemann AR, Van Boekel MAJS, Khetarpaul N, Grewal RB, Nout MJR (2015) Mung bean: Technological and nutritional potential. Critical Reviews in Food Science and Nutrition 55 (5):670-688. doi:https://doi.org/10.1080/10408398.2012.671202

Dakora FD, Belane AK, Mohale KC, Makhubedu TI, Makhura P, Pule-Meulenberg F, Mapope N, Mogkelhe SN, Gyogluu C, Phatlane GP (2015) Food grain legumes: their contribution to soil fertility, food security, and human nutrition/health in Africa. Biological nitrogen fixation:1063-1070. doi:https://doi.org/10.1002/9781119053095.ch105

Delfin EF, Paterno ES, Torres° FG, Santos PJA (2008) Biomass, nitrogen uptake and fixed nitrogen partitioningin field grown mungbean (*Vigna radiata* L. Wilczek) inoculated with Bradyrhizobium. Philippine Journal of Crop Science (PJCS) 33 (3):24-33

Dey SK, Chakrabarti B, Prasanna R, Mittal R, Singh SD, Pathak H (2016) Growth and biomass partitioning in mungbean with elevated carbon dioxide, phosphorus levels and cyanobacteria inoculation. Journal of Agrometeorology 18 (1):7-12

Dhayal BL, Patel CR, Mehta BM (2015) A study on constraints perceived by the farmers in adoption of moongbean production technology in Vadodara and Chhotaudaipur district of Gujarat. Agriculture Update 10 (4):343-350. doi:https://doi.org/10.15740/has/au/10.4/343-350

Dhole VJ, Reddy KS (2015) Genetic variation for phytic acid content in mungbean (*Vigna radiata* L. Wilczek). The Crop Journal 3 (2):157-162. doi:https://doi.org/10.1016/j.cj.2014.12.002

Diatta A, Abaye O, Thomason W, Lo M, Guèye F, Baldé A, Tine F, Vaughan L, Thompson T (2019) Effet de l'association du haricot mungo sur le rendement du mil dans le Bassin arachidier, Sénégal.

Diatta AA, Ndour N, Manga A, Sambou B, Faye CS, Diatta L, Goudiaby A, Mbow C, Dieng SD (2016a) Services ecosystémiques du parc agroforestier à *Cordyla pinnata* (Lepr. ex A. Rich.) Milne-Redh. dans le Sud du Bassin Arachidier (Sénégal). International Journal of Biological and Chemical Sciences 10 (6):2511-2525. doi:https://doi.org/10.4314/ijbcs.v10i6.9

Diatta AA, Ndour N, Manga A, Sambou B, Faye CS, Diatta L, Mbow C (2016b) Composition floristique et dynamique du parc agroforestier à *Cordyla pinnata* (Lepr. ex A. Rich.) Milne-Redh. dans le Sud du Bassin Arachidier (Sénégal). International Journal of Biological and Chemical Sciences 10 (4):1805-1822. doi:https://doi.org/10.4314/ijbcs.v10i4.29

Diatta AA, Thomason WE, Abaye O, Vaughan LJ, Thompson TL, Lo M, Chim BK, Bateman S (2018) Inoculation and soil texture effects on yield and yield components of mungbean. Journal of Agricultural Science (Toronto) 10 (9):6-16. doi:https://doi.org/10.5539/jas.v10n9p6

Dubey SC, Birendra S (2013) Integrated management of major diseases of mungbean by seed treatment and foliar application of insecticide, fungicides and bioagent. Crop Protection 47:55-60. doi:https://doi.org/10.1016/j.cropro.2012.12.025

Dwivedi A, Singh A, Naresh R, Kumar M, Kumar V, Bankoti P, Sharma DK, Thaneshwar AS, Singh O (2016) Towards sustainable intensification of maize (Zea mays L.)+ legume intercropping systems; experiences; challenges and opportunities in India; a critical review. Journal of Pure and Applied Microbiology 10 (1):725-741

Elkowicz K, Sosulski F (1982) Antinutritive factors in eleven legumes and their air-classified protein and starch fractions. Journal of Food Science 47 (4):1301-1304. doi:https://doi.org/10.1111/j.1365-2621.1982.tb07673.x

FAOSTAT (2019) Crops: production quantity. Available online: http://www.fao.org/faostat/en/#data/QC. (Accessed on 17 January 2019).

Faye C, Faye M, Sambou H, Diatta A, Diatta L, Manga A, Konate K (2019) Modélisation de la biomasse aérienne des parcs arborés à *Cordyla pinnata*: Keur Samba Guèye. Journal of Chemical, Biological and Physical Sciences 09:238-250. doi:https://doi.org/10.24214/jcbps.d.9.3.23849

Foyer CH, Lam H, Nguyen HT, Siddique KHM, Varshney RK, Colmer TD, Cowling W, Bramley H, Mori TA, Hodgson JM, Cooper JW, Miller AJ, Kunert K, Vorster J, Cullis C, Ozga JA, Wahlqvist ML, Liang Y, Shou H, Shi K, Yu J, Fodor N, Kaiser BN, Wong F, Valliyodan B, Considine MJ (2016) Neglecting legumes has compromised human health and sustainable food production. Nature Plants 2 (8):16112. doi:https://doi.org/10.1038/nplants.2016.112

Fu G, Shen Z-X (2016) Response of Alpine plants to nitrogen addition on the Tibetan Plateau: A Meta-analysis. Journal of Plant Growth Regulation 35 (4):974-979. doi:https://doi.org/10.1007/s00344-016-9595-0

Ganesan K, Xu B (2017) A critical review on phytochemical profile and health promoting effects of mung bean (Vigna radiata). Food Science and Human Wellness. doi:https://doi.org/10.1016/j.fshw.2017.11.002

Geng H, Pan H, Lu Y, Yang Y (2012) Nymphal and adult performance of Apolygus lucorum (Hemiptera: Miridae) on a preferred host plant, mungbean Vigna radiata. Applied entomology and zoology 47 (3):191-197

George T, Ladha JK, Garrity DP, Torres RO (1995) Nitrogen dynamics of grain legume-weedy fallow-flooded rice sequences in the tropics. Agronomy journal 87 (1):1-6. doi:https://doi.org/10.2134/agronj1995.00021962008700010001x

Giller K, J Wilson K (1991) Nitrogen fixation in tropical cropping systems. doi:https://doi.org/10.1079/9780851994178.0000

Gupta Y (1987) Anti-nutritional and toxic factors in food legumes: a review. Plant foods for human nutrition 37 (3):201-228. doi:https://doi.org/10.1007/bf01091786

Habibzadeh Y, Pirzad A, Zardashti MR, Jalilian J, Eini O (2013) Effects of arbuscular mycorrhizal fungi on seed and protein yield under water-deficit stress in mung bean. Agronomy Journal 105 (1):79-84. doi:https://doi.org/10.2134/agronj2012.0069

HanumanthaRao B, Nair RM, Nayyar H (2016) Salinity and high temperature tolerance in mungbean [*Vigna radiata* (L.) Wilczek] from a physiological perspective. Frontiers in Plant Science 7. doi:https://doi.org/10.3389/fpls.2016.00957

Hayat R, Ali S (2004) Potential of summer legumes to fix nitrogen and benefit wheat crop under rainfed condition. J Agron 3:273-281. doi:https://doi.org/10.3923/ja.2004.273.281

Hayat R, Ali S (2010) Nitrogen fixation of legumes and yield of wheat under legumes-wheat rotation in Pothwar. Pak J Bot 42 (4):2317-2326

Hayat R, Ali S, Ijaz SS, Chatha TH, Siddique MT (2008) Estimation of N2-fixation of mung bean and mash bean through xylem uriede technique under rainfed conditions. Pak J Bot 40 (2):723-734

Hemalatha S, Platel K, Srinivasan K (2007) Influence of germination and fermentation on bioaccessibility of zinc and iron from food grains. European journal of clinical nutrition 61 (3):342. doi:https://doi.org/10.1038/sj.ejcn.1602524

Herridge D, Robertson M, Cocks B, Peoples M, Holland J, Heuke L (2005) Low nodulation and nitrogen fixation of mungbean reduce biomass and grain yields. Australian Journal of Experimental Agriculture 45 (3):269-277. doi:https://doi.org/10.1071/ea03130

IMARC (2018) International Market Analysis Research and Consulting. Global mung beans market driven by various health benefits and multiple uses in the food industry. https://www.imarcgroup.com/global-mung-beans-market (Accessed on April 18, 2018).

Imtiaz H, BurhanUddin M, Gulzar MA (2011) Evaluation of weaning foods formulated from germinated wheat and mungbean from Bangladesh. African Journal of Food Science 5 (17):897-903. doi:https://doi.org/10.5897/ajfs11.180

Juana JS, Kahaka Z, Okurut FN (2013) Farmers' perceptions and adaptations to climate change in sub-Sahara Africa: A synthesis of empirical studies and implications for public policy in African agriculture. Journal of Agricultural Science 5 (4):121. doi:https://doi.org/10.5539/jas.v5n4p121

Kang YJ, Kim SK, Kim MY, Lestari P, Kim KH, Ha B-K, Jun TH, Hwang WJ, Lee T, Lee J, Shim S, Yoon MY, Jang YE, Han KS, Taeprayoon P, Yoon N, Somta P, Tanya P, Kim KS, Gwag J-G, Moon J-K, Lee Y-H, Park B-S, Bombarely A, Doyle JJ, Jackson SA, Schafleitner R, Srinives P, Varshney RK, Lee S-H (2014) Genome sequence of mungbean and insights into evolution within Vigna species. Nature Communications 5:5443. doi:https://doi.org/10.1038/ncomms6443

Kassa Y, Admasu D, Tigabe A, Abie A, Mamo D (2018) Participatory on farm evaluation of improved mungbean technologies in the low land areas of North Shewa Zone Amhara Region, Ethiopia. Journal of Agricultural Extension and Rural Development 10 (8):158-164. doi:https://doi.org/10.5897/jaerd2018.0962

Kaur R, Bains T, Bindumadhava H, Nayyar H (2015) Responses of mungbean (Vigna radiata L.) genotypes to heat stress: effects on reproductive biology, leaf function and yield traits. Scientia Horticulturae 197:527-541. doi:https://doi.org/10.1016/j.scienta.2015.10.015

Keatinge J, Easdown W, Yang R, Chadha M, Shanmugasundaram S (2011) Overcoming chronic malnutrition in a future warming world: the key importance of mungbean and vegetable soybean. Euphytica 180 (1):129-141. doi:https://doi.org/10.1007/s10681-011-0401-6

Kermah M, Franke A, Adjei-Nsiah S, Ahiabor B, Abaidoo RC, Giller K (2018) N2-fixation and N contribution by grain legumes under different soil fertility status and cropping systems in the Guinea savanna of northern Ghana. Agriculture, ecosystems & environment 261:201-210. doi:https://doi.org/10.1016/j.agee.2017.08.028

Khan F, Ahmed Z, Muhammad A, Hassnain S (2008) Response of mungbean genotypes to Rhizobium inoculum and varying levels of nitrogen fertilizer. Pakistan Journal of Agricultural Research 21 (1/4):33-44

Khattak AB, Nizakat B, Aurangzeb (2007) Quality assessment and consumers acceptability studies of newly evolved mungbean genotypes (*Vigna radiata* L.). American Journal of Food Technology 2 (6):536-542. doi:https://doi.org/10.3923/ajft.2007.536.542

Kim SK, Nair RM, Lee J, Lee S-H (2015) Genomic resources in mungbean for future breeding programs. Frontiers in plant science 6:626. doi:https://doi.org/10.3389/fpls.2015.00626

Kotir JH (2011) Climate change and variability in Sub-Saharan Africa: a review of current and future trends and impacts on agriculture and food security. Environment, Development and Sustainability 13 (3):587-605. doi:https://doi.org/10.1007/s10668-010-9278-0

Kumar Dahiya P, Nout M, A. van Boekel M, Khetarpaul N, Bala Grewal R, Linnemann A (2014) Nutritional characteristics of mung bean foods. British Food Journal 116 (6):1031-1046. doi:https://doi.org/10.1108/bfj-11-2012-0280

Kumar R, Singh R (2008) Improvement in mungbean: present scenario and future challenges. National Journal of Plant Improvement 10 (2):69-74

Kumar S, Kumar R (2014) Genetic improvement in mungbean [*Vigna radiata* (L). Wilzeck] for yield, nutrition and resistance to stresses-a review. International Journal of Tropical Agriculture 32 (3/4):683-687. doi:https://doi.org/10.1111/j.1439-0523.2012.01964.x

Lal R, Singh BR, Mwaseba DL, Kraybill D, Hansen DO, Eik LO (2015) Sustainable intensification to advance food security and enhance climate resilience in Africa. Springer International Publishing Switzerland, Heidelberg doi 10 (1007):978-973. doi:https://doi.org/10.1007/978-3-319-09360-4

Lal S (1985) A review of insect pests of mungbean and their control in India. International Journal of Pest Management 31 (2):105-114. doi:https://doi.org/10.1080/09670878509370960

Lalinia AA, Hoseini NM, Galostian M, Bahabadi SE, Khameneh MM (2012) Echophysiological impact of water stress on growth and development of mungbean. International Journal of Agronomy and Plant Production 3 (12):599-607

Lambrides C, Godwin I (2007) Mungbean. In: Pulses, sugar and tuber crops. Springer, pp 69-90. doi:https://doi.org/10.1007/978-3-540-34516-9_4

Lloyd SJ, Kovats RS, Chalabi Z (2011) Climate change, crop yields, and undernutrition: development of a model to quantify the impact of climate scenarios on child undernutrition. Environmental health perspectives 119 (12):1817. doi:https://doi.org/10.1289/ehp.1003311

Lu Y, Wu K, Wyckhuys K, Guo Y (2009) Potential of mungbean, *Vigna radiatus* as a trap crop for managing *Apolygus lucorum* (Hemiptera: Miridae) on Bt cotton. Crop Protection 28 (1):77-81. doi:https://doi.org/10.1016/j.cropro.2008.08.018

Makoi JH, Chimphango SB, Dakora FD (2009) Effect of legume plant density and mixed culture on symbiotic N 2 fixation in five cowpea (*Vigna unguiculata* L. Walp.) genotypes in South Africa. Symbiosis 48 (1-3):57-67. doi:https://doi.org/10.1007/bf03179985

Mapope N, Dakora FD (2016) N2 fixation, carbon accumulation, and plant water relations in soybean (*Glycine max* L. Merrill) varieties sampled from farmers’ fields in South Africa, measured using 15N and 13C natural abundance. Agriculture, Ecosystems & Environment 221:174-186. doi:https://doi.org/10.1016/j.agee.2016.01.023

Matusso J, Mugwe J, Mucheru-Muna M (2014) Potential role of cereal-legume intercropping systems in integrated soil fertility management in smallholder farming systems of sub-Saharan Africa. Journal of Agriculture and Environmental Management 3:162-174

Mbeyagala E, Amayo R, Obuo J (2016) Adaptation of introduced mungbean genotypes in Uganda. African Crop Science Journal 24 (2):155-166. doi:https://doi.org/10.4314/acsj.v24i2.4

Mbeyagala E, Kwikiriza N, Amayo R, Omadi J, Okwang D, Obuo J (2017) Participatory selection of mungbean genotypes in Uganda. African Crop Science Journal 25 (2):253-262. doi:https://doi.org/10.4314/acsj.v25i2.9

Mbow C, Mertz O, Diouf A, Rasmussen K, Reenberg A (2008) The history of environmental change and adaptation in eastern Saloum–Senegal—Driving forces and perceptions. Global and Planetary Change 64 (3):210-221. doi:https://doi.org/10.1016/j.gloplacha.2008.09.008

Mian MAK, Hossain J (2014) Nitrogen level and physiological basis of yield of mungbean at varying plant population in High Ganges River Flood Plain Soil of Bangladesh. Pakistan Journal of Biological Sciences 17 (7):925-930. doi:https://doi.org/10.3923/pjbs.2014.925.930

Mogotsi K (2006) Vigna radiata (L.) R. Wilczek.[Internet] Record from Protabase. Brink, M. & Belay, G.(Editors). PROTA (Plant Resources of Tropical Africa/Ressources végétales de l’Afrique tropicale), Wageningen, Netherlands.

Mohammad W, Shehzadi S, Shah SM, Shah Z (2010) Effect of tillage and crop residues management on mungbean (*Vigna radiata* (L.) Wilczek) crop yield, nitrogen fixation and water use efficiency in rain fed areas. Pak J Bot 42 (3):1781-1789

Mohan S, Sheeba A, Murugan E, Ibrahim S (2014) Screening of mungbean germplasm for resistance to Mungbean Yellow Mosaic Virus under natural condition. Indian Journal of Science and Technology 7 (7):891-896. doi:https://doi.org/10.15406/apar.2017.07.00276

Molla M, Solaiman A, Jahiruddin M, Mridha M, Khanam D (2011) Influence of different doses of phosphorus in the presence of arbuscular mycorrhiza and *Rhizobium* on the growth and yield of mungbean. Bulletin of the Institute of Tropical Agriculture, Kyushu University 34 (1):49-67

Morton F, Smith R, Poehlman JM (1982) The mungbean.

Moswetsi G, Fanadzo M, Ncube B (2017) Cropping systems and agronomic management practices in smallholder farms in South Africa: Constraints, challenges and opportunities. Journal of Agronomy 16:51-64. doi:https://doi.org/10.3923/ja.2017.51.64

Mubarak AE (2005) Nutritional composition and antinutritional factors of mung bean seeds (*Phaseolus aureus*) as affected by some home traditional processes. Food Chemistry 89 (4):489-495. doi:https://doi.org/10.1016/j.foodchem.2004.01.007

Munawwar MH, Asghar A, Malik SR (2014) Identification of resistance in mungbean and mashbean germplasm against mungbean yellow mosaic virus. Pakistan Journal of Agricultural Research 27 (2):129-135

Nadarajan N, Chaturvedi S (2010) Genetic options for enhancing productivity of major pulses–retrospect, issues and strategies. Journal of Food legumes 23 (1):1-8

Nair R, Schafleitner R, Kenyon L, Srinivasan R, Easdown W, Ebert A, Hanson P (2012) Genetic improvement of mungbean. SABRAO Journal of Breeding and Genetics 44 (2):177-190

Nair RM, Pandey AK, War AR, Hanumantharao B, Shwe T, Alam A, Pratap A, Malik SR, Karimi R, Mbeyagala EK (2019) Biotic and abiotic constraints in mungbean production—Progress in genetic improvement. Frontiers in plant science 10

Nair RM, Thavarajah P, Giri RR, Ledesma D, Yang R-Y, Hanson P, Easdown W, Hughes JdA (2015) Mineral and phenolic concentrations of mungbean [*Vigna radiata* (L.) R. Wilczek var. radiata] grown in semi-arid tropical India. Journal of Food Composition and Analysis 39:23-32. doi:https://doi.org/10.1016/j.jfca.2014.10.009

Nair RM, Yang RY, Easdown WJ, Thavarajah D, Thavarajah P, Hughes JdA, Keatinge J (2013) Biofortification of mungbean (*Vigna radiata*) as a whole food to enhance human health. Journal of the Science of Food and Agriculture 93 (8):1805-1813. doi:https://doi.org/10.1002/jsfa.6110

Naresh RK, Purushottam, Singh SP, Ashish D, Vineet K (2013) Effects of water stress on physiological processes and yield attributes of different mungbean (L.) varieties. African Journal of Biochemistry Research 7 (5):55-62

Naylor RL, Falcon WP, Goodman RM, Jahn MM, Sengooba T, Tefera H, Nelson RJ (2004) Biotechnology in the developing world: a case for increased investments in orphan crops. Food Policy 29 (1):15-44. doi:https://doi.org/10.1016/j.foodpol.2004.01.002

Ncube B, Twomlow SJ, Van Wijk MT, Dimes JP, Giller KE (2007) Productivity and residual benefits of grain legumes to sorghum under semi-arid conditions in southwestern Zimbabwe. Plant and Soil 299 (1-2):1-15. doi:https://doi.org/10.1007/s11104-007-9330-5

Ngwuta A, Okoro A, Agugo B, Odiyi A, Eke K, Ogoke I (2010) Variations in some morphological and yield characteristics of mungbean (*Vigna radiata* (L.) Wilczek) cultivars introduced into the rain-forest agroecology of Southeastern Nigeria. International Journal of Agriculture and Rural Development 13 (2). doi:https://doi.org/10.4314/ijard.v13i2.67392

Niang I, Ruppel O, Abdrabo M, Essel A, Lennard C, Padgham J, Urquhart P (2014) Africa, climate change 2014: impacts, adaptation and vulnerability—Contributions of the Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. 1199–1265.

Odeny DA The potential of pigeonpea (*Cajanus cajan* (L.) Millsp.) in Africa. In: Natural resources forum, 2007. vol 4. Wiley Online Library, pp 297-305. doi:https://doi.org/10.1111/j.1477-8947.2007.00157.x

Ogallo L Variation and change in climate in sub-Saharan Africa. In: Advancing agricultural production in Africa: proceedings of CAB's First Scientific Conference, Arusha, Tanzania, 12-18 February 1984/edited by DL Hawksworth, 1984. Farnham Royal, Slough,[England]: Commonwealth Agricultural Bureaux, c1984.,

Ojehomon O (1968) Flowering, fruit production and abscission in cowpea, *Vigna unguiculata* (L.) Walp. Journal of the West African Science Association

Ojiem JO, Vanlauwe B, de Ridder N, Giller KE (2007) Niche-based assessment of contributions of legumes to the nitrogen economy of Western Kenya smallholder farms. Plant and soil 292 (1-2):119-135. doi:https://doi.org/10.1007/s11104-007-9207-7

Okweche SI, Avav T-R (2013) Yield evaluation of some cultivars of mungbean (*Vigna radiata* (L.) Wilczek) in southern giunea savanna location of Nigeria. International Journal of Plant, Animal and Environmental Sciences 3 (3):85-88

Oo HH, Araki T, Kubota F (2005) Effects of drought and flooding stresses on growth and photosynthetic activity of mungbean, *Vigna radiata* (L.) Wilczek, cultivars.

Pataczek L, Zahir ZA, Ahmad M, Rani S, Nair R, Schafleitner R, Cadisch G, Hilger T (2018) Beans with benefits—the role of mungbean (*Vigna radiata*) in a changing environment.

American Journal of Plant Sciences 9 (07):1577. doi:https://doi.org/10.4236/ajps.2018.97115

Patel VD, Mahatma L (2016) Epidemiology of mungbean yellow mosaic virus (MYMV) disease in mungbean in south Gujarat. Journal of Agrometeorology 18 (1):140-141

Paul T, Mozumder N, Sayed M, Akhtaruzzaman M, Akhtaruzzaman MSM (2011) Proximate compositions, minerals contents and determination of protease activity from green gram (*Vigna radiata* L. Wilczek). Bangladesh Res J 5:207-213

Peoples M, Bergersen F, Turner G (1991) Use of the natural enrichment of 15 N in plant available soil N for the measurement of symbiotic N 2 fixation. In: Stable isotopes in plant nutrition, soil fertility and environmental studies.

Peoples MB, Herridge DF (1990) Nitrogen fixation by legumes in tropical and subtropical agriculture. Advances in agronomy 44:155-223. doi:https://doi.org/10.1016/s0065-2113(08)60822-6

Phoomthaisong J, Toomsan B, Limpinuntana V, Cadisch G, Patanothai A (2003) Attributes affecting residual benefits of N 2-fixing mungbean and groundnut cultivars. Biology and fertility of soils 39 (1):16-24. doi:https://doi.org/10.1007/s00374-003-0676-4

Puranik V, Mishra V, Singh N, Rai G (2011) Studies on development of protein rich germinated green gram pickle and its preservation by using class one preservatives. Am J Food Technol 6 (9):742-752. doi:https://doi.org/10.3923/ajft.2011.742.752

Rachaputi RC, Chauhan Y, Douglas C, Martin W, Krosch S, Agius P, King K (2015) Physiological basis of yield variation in response to row spacing and plant density of mungbean grown in subtropical environments. Field Crops Research 183:14-22. doi:https://doi.org/10.1016/j.fcr.2015.07.013

Raina SK, Venkadasamy G, Mahesh K, Singh AK, Jagadish R, Minhas PS (2016) Genetic variation in physiological responses of mungbeans (*Vigna radiata* (L.) Wilczek) to drought. Acta Physiologiae Plantarum 38 (11):263. doi:https://doi.org/10.1007/s11738-016-2280-x

Raji SG, Tzanakakis V, Dörsch P (2019) *Bradyrhizobial* inoculation and P application effects on haricot and mung beans in the Ethiopian Rift Valley. Plant and Soil 442 (1-2):271-284. doi:https://doi.org/10.1007/s11104-019-04170-2

Ramanujam S Biometrical basis for yield improvement in mungbean. In: Procedings 1st International Mung bean Symposium, 1981. p 210

Ramírez Villegas J, Thornton PK (2015) Climate change impacts on African crop production.

Rao N, Lawson ET, Raditloaneng WN, Solomon D, Angula MN (2019) Gendered vulnerabilities to climate change: insights from the semi-arid regions of Africa and Asia. Climate and Development 11 (1):14-26. doi:https://doi.org/10.1080/17565529.2017.1372266

Rao SC, Northup BK (2009) Capabilities of four novel warm-season legumes in the southern Great Plains: Biomass and forage quality. Crop science 49 (3):1096-1102. doi:https://doi.org/10.2135/cropsci2008.08.0499

Rashid M, Kausar R, Alvi S, Sajjad MR (2015) Assessment of runoff and sediment losses under different slope gradients and crop covers in semi-arid watersheds. Soil & Environment 34 (1)

Razzaque M, Haque M, Karim M (2017) Effect of nitrogen on growth and yield on mungbean in low nutrient soil. Bangladesh Journal of Agricultural Research 42 (1):77-85

Rochester I, Peoples M, Constable G, Gault R (1998) Faba beans and other legumes add nitrogen to irrigated cotton cropping systems. Australian Journal of Experimental Agriculture 38 (3):253-260. doi: https://doi.org/10.1071/ea97132

Rosales C, Rivera F, Hautea R, Del Rosario E (1998) Field evaluation of N 2 fixation by mung bean in the Philippines, and residual effects on maize.

Rosales C, Rivera F, Hautia R, Del Rosario E (1995) Nitrogen fixation by mung bean (*Vigna radiata* L.) under field conditions in the Philippines as quantified by 15N isotope dilution. Philippine Nuclear Research Inst.,

Roy S, Barman M, Puste A, Gunri S, Jana K (2016) Growth, yield, water use efficiency and competitive functions of intercropping system of maize (*Zea mays* L.) and mungbean (*Vigna radiata* L.) as influenced by irrigation. SAARC Journal of Agriculture 13 (2):94-107. doi:https://doi.org/10.3329/sja.v13i2.26571

Sabbagh E, Lakzayi M (2016) Influence of intercropping on weed control, soil fertility and forage quality. International Journal of Agriculture and Biosciences 5 (5):285-290

Safdar A, Khan MA, Zeshan MA, Amer H, Haider MS (2015) Characterization of conducive environmental conditions for mungbean yellow mosaic virus disease incidence on mungbean germplasm. Pakistan Journal of Phytopathology 27 (1):27-30

Sakai H, Naito K, Takahashi Y, Sato T, Yamamoto T, Muto I, Itoh T, Tomooka N (2015) The Vigna Genome Server,'Vig GS': A genomic knowledge base of the genus Vigna based on high-quality, annotated genome sequence of the Azuki Bean, Vigna angularis (Willd.) Ohwi & Ohashi. Plant and Cell Physiology 57 (1):e2-e2. doi:https://doi.org/10.1093/pcp/pcv189

Samal S, Rao K, Poonia S, Kumar R, Mishra J, Prakash V, Mondal S, Dwivedi S, Bhatt B, Naik SK (2017) Evaluation of long-term conservation agriculture and crop intensification in rice-wheat rotation of Indo-Gangetic Plains of South Asia: Carbon dynamics and productivity. European Journal of Agronomy 90:198-208. doi:https://doi.org/10.1016/j.eja.2017.08.006

Sangakkara U, Frehner M, Nösberger J (2001) Influence of soil moisture and fertilizer potassium on the vegetative growth of mungbean (*Vigna radiata* L. Wilczek) and cowpea (*Vigna* *unguiculata* L. Walp). Journal of Agronomy and Crop Science 186 (2):73-81. doi:https://doi.org/10.1046/j.1439-037x.2001.00433.x

Sanginga N, Dashiell K, Okogun J, Thottappilly G (1997) Nitrogen fixation and N contribution by promiscuous nodulating soybeans in the southern Guinea savanna of Nigeria. Plant and Soil 195 (2):257-266

Senaratne R, Liyanage NDL, Soper RJ (1995) Nitrogen fixation of and N transfer from cowpea, mungbean and groundnut when intercropped with maize. Fertilizer Research 40 (1):41-48. doi:https://doi.org/10.1007/bf00749861

Shah Z, Shah SH, Peoples MB, Schwenke GD, Herridge DF (2003) Crop residue and fertiliser N effects on nitrogen fixation and yields of legume–cereal rotations and soil organic fertility. Field Crops Research 83 (1):1-11. doi:http://dx.doi.org/10.1016/S0378-4290(03)00005-4

Shaheen S, Harun N, Khan F, Hussain RA, Ramzan S, Rani S, Khalid Z, Ahmad M, Zafar M (2012) Comparative nutritional analysis between *Vigna radiata* and *Vigna mungo* of Pakistan. African Journal of Biotechnology 11 (25):6694-6702. doi:https://doi.org/10.5897/ajb11.3496

Shahida B, Khan IA (2016) Impact of weed control techniques on intercropping of mungbean with maize under agro climate condition of Peshawar. Sarhad Journal of Agriculture 32 (2):62-69. doi:https://doi.org/10.17582/journal.sja/2016/32.2.62.69

Shaker-Koohi S, Nasrollahzadeh S, Raei Y (2014) Evaluation of chlorophyll value, protein content and yield of sorghum (*Sorghum bicolor* L.)/mungbean (*Vigna radiate* L.) intercropping. International Journal of Biosciences (IJB) 4 (8):136-143. doi:https://doi.org/10.12692/ijb/4.8.136-143

Shanmugasundaram S, Keatinge J, Hughes JdA (2010) The mungbean transformation: Diversifying crops, defeating malnutrition. Proven Successes in Agricultural Development:381

Sherasia P, Garg MR, Bhanderi B (2017) Pulses and their by-products as animal feed. Food and Agriculture Organization of the United Nations (FAO),

Shishaye HA (2015) The Negative impacts of climate change in Sub-Saharan Africa and their mitigation measures. doi:https://doi.org/10.9734/bjast/2015/17665

Smartt J (1984) Gene pools in grain legumes. Economic Botany 38 (1):24-35. doi:https://doi.org/10.1007/bf02904413

Smith A, Snapp S, Dimes J, Gwenambira C, Chikowo R (2016) Doubled-up legume rotations improve soil fertility and maintain productivity under variable conditions in maize-based cropping systems in Malawi. Agricultural Systems 145:139-149. doi:https://doi.org/10.1016/j.agsy.2016.03.008

Snapp SS, Cox CM, Peter BG (2019) Multipurpose legumes for smallholders in sub-Saharan Africa: Identification of promising 'scale out'options. Global Food Security 23:22-32. doi:https://doi.org/10.1016/j.gfs.2019.03.002

Song H (2005) Effects of VAM on host plant in the condition of drought stress and its mechanisms. Electronic Journal of Biology 1 (3):44-48

Stefanović S, Pfeil BE, Palmer JD, Doyle JJ (2009) Relationships among phaseoloid legumes based on sequences from eight chloroplast regions. Systematic Botany 34 (1):115-128. doi:https://doi.org/10.1600/036364409787602221

Sugandh S, Sharma VK, Harsh K, Shahi VK (2015) Screening of mungbean [*Vigna radiata* (L.) Wilczek] genotypes for resistance to mungbean yellow mosaic virus (MYMV). Environment and Ecology 33 (2A):855-859. doi:https://doi.org/10.15406/apar.2017.07.00276

Sunil K, Gokulakrishnan BJ, Prakash M (2015) Effect of drought stress on seed yield and bio-physical characters in mungbean (*Vigna radiata* L.) Wilczek. International Journal of Tropical Agriculture 33 (2 (Part II)):853-864

Swaminathan R, Singh K, Nepalia V (2012) Insect pests of green gram *Vigna radiata* (L.) Wilczek and their management. In: Agricultural Science. InTech,

Tajini F, Suriyakup P, Jansa J, Drevon J-J (2011) Assessing hydroaeroponic culture for the tripartite symbiosis of mungbean (*Vigna radiata* L.) with arbuscular mycorrhizal fungi and rhizobia. African Journal of Biotechnology 10 (38):7409-7415

Tang D, Dong Y, Ren H, Li L, He C (2014) A review of phytochemistry, metabolite changes, and medicinal uses of the common food mung bean and its sprouts (*Vigna radiata*). Chemistry Central Journal 8 (1):4. doi:https://doi.org/10.1186/1752-153x-8-4

Tariq S, Ali S, Ijaz SS (2007) Improving nitrogen fixation capacity and yield of mungbean and mashbean by phosphorous management in Pothowar. Sarhad Journal of Agriculture 23 (4):1027

Terdoo F, Feola G (2016) The vulnerability of rice value chains in Sub-Saharan Africa: a review. Climate 4 (3):47. doi:https://doi.org/10.3390/cli4030047

Tirado M, Hunnes D, Cohen M, Lartey A (2015) Climate change and nutrition in Africa. Journal of Hunger & Environmental Nutrition 10 (1):22-46

Toomsan B, Cadisch G, Srichantawong M, Thongsodsaeng C, Giller K, Limpinuntana V (2000) Biological N2 fixation and residual N benefit of pre-rice leguminous crops and green manures. NJAS-Wageningen Journal of Life Sciences 48 (1):19-29. doi:https://doi.org/10.1016/s1573-5214(00)80002-0

Trail P, Abaye O, Thomason WE, Thompson TL, Gueye F, Diedhiou I, Diatta MB, Faye A (2016) Evaluating intercropping (living cover) and mulching (desiccated cover) practices for increasing millet yields in Senegal. Agronomy Journal. doi:https://doi.org/10.2134/agronj2015.0422

Tuba A, Gupta KS, Subhojit D (2010) Mapping of Mungbean Yellow Mosaic India Virus (MYMIV) and powdery mildew resistant gene in black gram [*Vigna mungo* (L.) Hepper]. Electronic Journal of Plant Breeding 1 (4):1148-1152

Ullah MA, Hussain N, Schmeisky H, Muhammad R (2016) Enhancing soil fertility through intercropping, inoculation and fertilizer. Pakistan Journal of Scientific and Industrial Research, Series B: Biological Sciences 59 (1):1-5

Umair A, Ali S, Hayat R, Ansar M, Tareen MJ (2011) Evaluation of seed priming in mung bean (*Vigna radiata*) for yield, nodulation and biological nitrogen fixation under rainfed conditions. African Journal of Biotechnology 10 (79):18122-18129. doi:https://doi.org/10.5897/ajb11.1385

UNDP (2007) United Nations Development Programme. Fighting climate change: human solidarity in a divided world. Springer,

Unkovich M, Herridge D, Peoples M, Cadisch G, Boddey B, Giller K, Alves B, Chalk P (2008) Measuring plant-associated nitrogen fixation in agricultural systems. Australian Centre for International Agricultural Research (ACIAR),

USDA (2010) United States Department of Agriculture. National Nutrient Database. Agricultural Research Service, Nutrient Data Laboratory. http://www.nal.usda.gov/fnic/foodcomp/search/.

Van K, Kang Y, Han K, Lee Y, Gwag J, Moon J, Lee S (2013) Genome-wide SNP discovery in mungbean by Illumina HiSeq. TAG Theoretical and Applied Genetics 126 (8):2017-2027. doi:https://doi.org/10.1007/s00122-013-2114-9

Vashro TN (2017) The effect of mung bean on improving dietary diversity in women and children in Senegal. Virginia Tech,

Vesterager JM, Nielsen NE, Høgh-Jensen H (2008) Effects of cropping history and phosphorus source on yield and nitrogen fixation in sole and intercropped cowpea–maize systems. Nutrient Cycling in Agroecosystems 80 (1):61-73. doi:https://doi.org/10.1007/s10705-007-9121-7

Wang Q, Bao W-F, Yang F, Xu B, Yang Y-Z (2017) The specific host plant DNA detection suggests a potential migration of Apolygus lucorum from cotton to mungbean fields. PloS one 12 (6):e0177789

Waniale A, Wanyera N, Talwana H (2014) Morphological and agronomic traits variations for mungbean variety selection and improvement in Uganda. African Crop Science Journal 22 (2):123-136

Yakubu H, Kwari J, Ngala A (2010) N 2 Fixation by grain legume varieties as affected by *Rhizobia i*noculation in the sandy loam soil of Sudano-Sahelian Zone of North Eastern Nigeria. Nigerian Journal of Basic and Applied Sciences 18 (2). doi:https://doi.org/10.4314/njbas.v18i2.64325

Yin Z, Guo W, Xiao H, Liang J, Hao X, Dong N, Leng T, Wang Y, Wang Q, Yin F (2018) Nitrogen, phosphorus, and potassium fertilization to achieve expected yield and improve yield components of mung bean. PloS one 13 (10):e0206285

Zang H, Yang X, Feng X, Qian X, Hu Y, Ren C, Zeng Z (2015) Rhizodeposition of nitrogen and carbon by mungbean (*Vigna radiata* L.) and its contribution to intercropped oats (*Avena nuda* L.). PloS one 10 (3):e0121132. doi:https://doi.org/10.1371/journal.pone.0121132

Zewdie A (2014) Impacts of climate change on food security: a literature review in Sub Saharan Africa. Journal of Earth Science & Climatic Change 2014. doi:https://doi.org/10.4172/2157-7617.1000225

Zhongxiao G, Lianxue Z, Minghai W (2012) Study on early identification method of drought tolerance of mungbean cultivars. Journal of Northwest Agriculture and Forestry University

Chapter 3 – Inoculation and soil texture effects on yield and yield components of mungbean

Abstract

Mungbean [*Vigna radiata* (L.) Wilczek] is a short-duration and relatively drought-tolerant crop grown predominantly in the tropics. This grain legume can improve soil fertility through biological nitrogen (N) fixation. To assess the effects of *Bradyrhizobium* (group I) inoculation on yield and yield attributes of mungbean, a greenhouse study was conducted during Fall 2016 with two mungbean cultivars ('Berken' and 'OK2000'), two inoculum treatments (inoculated and uninoculated), and two soil textures (loamy sand and silt loam). Pots were laid out in a completely randomized design and treatment combinations were replicated seven times. The main effects of cultivar and soil texture significantly ($P \leq 0.05$) affected mungbean seed weight and plant residue mass. Seed yield (13%), plant residue (22%), and protein content (6%) of OK2000 were significantly higher than Berken cultivar. A 31% seed yield and 40% plant residue increase were recorded on silt loam soil compared to loamy sand soil. Significant increase in plant height (18%) and number of pods per plant (21%) were also recorded when mungbean plants were grown on silt loam compared to loamy sand soil. *Bradyrhizobium* inoculation significantly increased the number of pods per plant, the number of seeds per plant, and seed yield. [*Cultivar × inoculation*] and [*cultivar × soil texture*] interactions had significant ($P \leq 0.05$) effects on number of seeds per pods and plant height, respectively. Understanding the agronomic practices and soil physical properties that may limit mungbean production could help in optimizing its establishment and growth in non-traditional growing areas.

Keywords: *Bradyrhizobium* inoculation, yield, soil texture, *Vigna radiata* L., yield

Introduction

Mungbean [*Vigna radiata* (L.) Wilczek], also known as mung, moong, green gram, golden gram, chickasaw pea, oregon pea, and chop suey bean, is a pulse species widely grown in tropical and sub-tropical regions of the world (Nair et al., 2013). It is an ancient crop believed to be a native of India and is extensively cultivated in South, East, and Southeast Asia, as well as East Africa (Kim, Nair, J. Lee, & S.-H. Lee, 2015; Sharma, Priya, Bindumadhava, Nair, & Nayyar, 2016). Mungbean is an important food and livestock feed legume crop in these regions and is consumed for its protein-rich seeds (Dahiya et al., 2015; Foyer et al., 2016). Mungbean, a short growth duration legume (55-110 days), fixes atmospheric N through a symbiotic association with rhizobia living in its root nodules (Peoples & Herridge, 1990; Razzaque, Haque, Karim, & Solaiman, 2016). However, under unfavorable conditions such as very acidic and heavy-textured soils, or very hot, dry conditions, *Rhizobium* survival and crop establishment can be constrained, thereby limiting root nodulation and yield (Kirchhof & So, 1995; Rahmianna, Adisarwanto, Kirchhof, & So, 2000). Therefore, seed inoculation with a strain of *Rhizobium*, appropriate to the cultivar and soil texture is recommended for improving growth and yield of mungbean (Hussain et al., 2014; Sharma & Khanna, 2010).

Anjum, Ahmed, and Rauf (2006) reported that *Rhizobium* inoculation of mungbean seeds increased the number of pods per plant, number of seeds per plant, seed weight and seed yield over the control. *Rhizobium* inoculation also increased plant height, number of nodules per plant, number of pods per plant, number of seeds per pod and weight of seeds per plant, and N and phosphorous (P) accumalation compared to the control (Hussain et al., 2014). Molla, Solaiman, Jahiruddin, Mridha, and Khanam (2011) observed that inoculation of seed with *Rhizobium* produced a higher number of nodules per plant, plant height, number of pod per plant and seed yield. Travlos and Karamanos (2006) compared the responses of marama bean [*Tylosema esculentum* (Burch.) A. Schreib.], a perennial tropical grain legume of southern Africa on four different soil textures. They reported significant restriction in marama bean growth under clay and clay loam soils compared to sandy clay loam, and sandy soils. Thomson, Siddique, Barr, and Wilson (1997) evaluated the growth and seed yields of six commercially grown and eight potential new grain legumes species on a sandy clay loam and silty clay loam. They observed that faba bean (*Vicia faba*) cv. Fiord and field pea (*Pisum sativum* L.) cv. Dundale had the highest grain yield compared to other legume species on fine-textured, neutral to alkaline soils.

Most previous studies have shown that the use of a short-duration legume crop such as mungbean could be useful for producing nutrient-rich foods in regions facing food insecurity issues. However, few studies have investigated the yield performance of mungban cultivars as affected by *Bradyrhizobium* inoculants under various soil conditions. The present study evaluated the combined effects of *Bradyrhizobium* (group I) inoculation, cultivar, and soil texture on yield and yield components of mungbean under greenhouse conditions.

Materials and methods

Soil description

A Eunola loamy sand and a Guernsey silt loam soil from 0-15 cm depth were collected from Virginia Tech’s Tidewater Agricultural Research and Extension Center in Suffolk, VA (36°39′50.9″N latitude, 76°44′01.0″W longitude) and Kentland Agricultural Research Farm in Blacksburg, VA (37°11′47.3″N latitude, 80°34′49.7″W longitude), respectively. The site in Suffolk had been under a corn (*Zea mays* L.) and cotton (*Gossypium hirsutum* L.) rotation while the one in Blacksburg was subjected to a continuous corn system. The presence of naturally occurring symbiotic bacteria in these samples was not evaluated, but due to the lack of legumes in either of these rotations, the presence of high levels of native bacteria was deemed unlikely. The field capacity of the soil samples was determined as described by Gupta and Larson (1979). Soil pH and plant available Ca, Mg, P, and K and were determined as described by Maguire and Heckendorn (2011). Soil pH was determined using a 1:1 (vol/vol) soil-water mix. Phosphorus and potassium were determined via extraction with Mehlich 1 at a 1:1 solution:soil ratio, (Mehlich, 1976) filtered (Whatman #2), and analyzed via inductively coupled plasma atomic emission spectroscopy (ICP) (SPECTRO ARCOS, Kleve, Germany). Total C and N were analyzed by dry combustion using a vario MAX CNS Element Analyzer (Elementar Analysensysteme GmbH, Hanau, Germany). Prior to determining the concentrations of ammonium (NH_4^+) and nitrate (NO_3^-) using Lachat QuikChem AE flow-injection autoanalyzer and ion chromatography, the soil samples were prepared as described by Bremner and Keeney (1966). The physical and chemical properties of the two soil types are presented in Table 1.

Table 1. Chemical and physical characteristics of the Eunola soil and Guernsey soil

Soil properties	Eunola soil	Guernsey soil
Soil texture	Loamy sand	Silt loam
Field Capacity (%)	9	17
Soil pH	5.9	6.2
C (%)	0.98	0.93
N (%)	0.08	0.08
C/N	13	11
NO_3^- (mg/kg)	1.52	2.67
NH_4^+ (mg/kg)	0.32	0.25
P plant available (mg/kg)	37	25.67
K plant available (mg/kg)	62.67	61.33
Ca plant available (mg/kg)	575	858.67
Mg plant available (mg/kg)	72	167

Note. pH: soil (1:1 soil: deionized water mixture on a volumetric basis); Total carbon (C) and total nitrogen (N): vario MAX CNS Element Analyzer; Inorganic NO_3^- and NH_4^+: 2M KCl extraction; Plant available nutrients: soil (Mehlich 1 solution).

Experimental design and management

A greenhouse study was conducted at a Virginia Tech greenhouse in Blacksburg (Virginia, USA) to examine the yield responses of mungbean cultivars to *Bradyrhizobium* inoculation and soil type. The experiment consisted of two mungbean cultivars, 'Berken' and 'OK2000', two inoculum treatments (inoculated and uninoculated conditions), and two soil textures (loamy sand and silt loam). The treatments were a factorial combination of three factors and the experiment was laid out as a completely randomized design with seven replications (Table 2).

Table 2. Cultivars, inoculation treatments, and soil texture used in the pot experiment

No.	**Treatments**		
	Cultivars	Inoculation	Soil Texture
1.	Berken	Inoculated	Loamy sand
2.	Berken	Inoculated	Silt loam
3.	Berken	Uninoculated	Loamy sand
4.	Berken	Uninoculated	Silt loam
5.	OK2000	Inoculated	Loamy sand
6.	OK2000	Inoculated	Silt loam
7.	OK2000	Uninoculated	Loamy sand
8.	OK2000	Uninoculated	Silt loam

Bradyrhizobium inoculum (group I) purchased from Hancock Farm & Seed Co., Inc. (Dade City, FL, USA) was mixed with mungbean seeds at a rate of 10 g inoculant kg^{-1} seed with to allow thorough coating and sown in the pots. The seed inoculant contained less than 1% active ingredient by weight of *Bradyrhizobium* sp. (*Vigna*), *Bradyrhizobium japonicum*, *Rhizobium leguminosarum biovar phaseoli*, *Rhizobium leguminosarum biovar viceae*. Mungbean cultivars were obtained from Oklahoma Foundation Seed Stocks (Stillwater, OK, USA). Berken is a medium-large seeded cultivar while OK2000 is a large-seeded cultivar with good lodging and shattering resistance. Berken is widely grown in the U.S. and has 15% lower seed weight than OK2000 with similar seed yields. Experimental pots (19 cm tall, 19 cm outside diameter, and 3785 cm^3 volume) were lined with polythene bags to avoid loss of water and filled with 4 kg of soil. Three seeds were sown (immediately after inoculation if applicable) per pot by hand at 3-4 cm depth on December 9, 2016 and grown at 80% field capacity. After seedling emergence, density was thinned to one plant per pot. Plant height was measured with a ruler at harvest maturity (March 14, 2017) by stretching out the plant to the tip. At full maturity, mungbean pods were hand harvested twice and the number of pods per plant and number of seeds per pod were counted. Seed yield was calculated as dry matter of seeds from each plant at harvest and seed yield per plant was computed. For plant dry matter determination, aboveground plant material was collected after seed harvest and oven dried at 50 ºC to constant weight. Seed protein content was estimated using near infrared spectroscopy.

Analysis of variance (ANOVA) was used to test the effects of cultivar, *Bradyrhizobium* inoculation, and soil texture on plant parameters, seed yield and yield components using JMP Pro version 13.0.0 statistical software (SAS Institute Inc., Carey, NC). Differences among means were considered significant at the $\alpha = 0.05$ level of probability and were separated using Fisher's protected LSD. Most interactions were not significantly different for yield and yield components of mungbean, therefore most main effects were subjected to mean separation tests.

Results and Discussion

Plant height at maturity

The comparison of loamy sand with silt loam revealed that the average plant height (28.7 cm) of plants grown in silt loam soil was 18% greater than average height of plants grown in loamy sand soil (Figure 1). These results are in agreement with Singh et al. (2011) who reported differences on mungbean growth when grown in different soil textures. They observed greater plant height on a sandy loam soil compared to a loamy sand soil and attributed this to higher organic carbon and moisture content in the sandy loam. Results obtained by Ntukamazina et al. (2017) revealed that differences in mungbean growth under different soils may be due to variations in moisture retention of soils. Increased height of plants grown in silt loam soils can likely be explained by better tilth compared to the sandy loam soil. Previous findings have demonstrated that different soil structures can result in differences in particle composition, chemical properties, mechanical impedance and bulk density which affect crop growth and development (Cook, Gupta, Woodhead, & Larson, 1995; Travlos & Karamanos, 2006).

Table 3. Analysis of variance of the effects of *Bradyrhizobium* inoculation, cultivar, and soil texture and their interactions on yield and yield components of mungbean (n = 7 per treatment)

Treatments	Plant height	No. pods	No. seeds	Seed weight	Plant residue	Protein
	---- cm ----	-------- plant^{-1} --------		----------- g plant^{-1} -----------		-- % --
			Pr > f			
Cultivar	<.0001	0.8028	0.6637	0.0029	<.0001	0.0003
Inoculation	0.2831	0.0029	0.0032	0.0013	0.0583	0.3178
Soil Texture	<.0001	<.0001	<.0001	<.0001	<.0001	0.3520
Cultivar*Inoculation	0.0247	0.3838	0.5031	0.8632	0.3995	0.6197
Cultivar*Soil Texture	0.8587	0.0657	0.0066	0.1036	0.8453	0.6134
Inoculation*Soil Texture	0.3554	0.6178	0.3362	0.2497	0.3107	0.7109
Cultivar*Inoculation*Soil Texture	0.7590	0.1384	0.0501	0.0672	0.6806	0.9616

The cultivar and inoculation interaction was statistically significant for plant height (Table 3). Height of inoculated OK2000 plants was greater than uninoculated OK2000 plants (30.0 vs. 26.8 cm, respectively) while inoculated and uninoculated Berken plants did not differ from each other (mean = 23.9 cm) (Figure 2). Similar results were reported by Bhuiyan, Mian, and Islam (2008) who observed greater plant height for inoculated BARI Mung-2 cultivar due to increased nodulation resulting in enhanced vegetative growth.

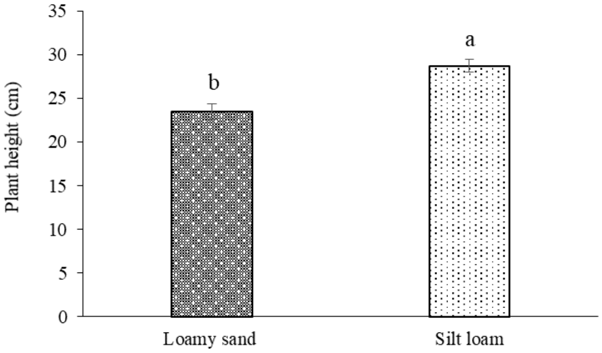

Figure 1. Effect of soil texture on plant height. Treatments with the same letter are not significantly different according to Fisher's protected LSD (α = 0.05). Error bars show standard error of the mean (*n* = 56)

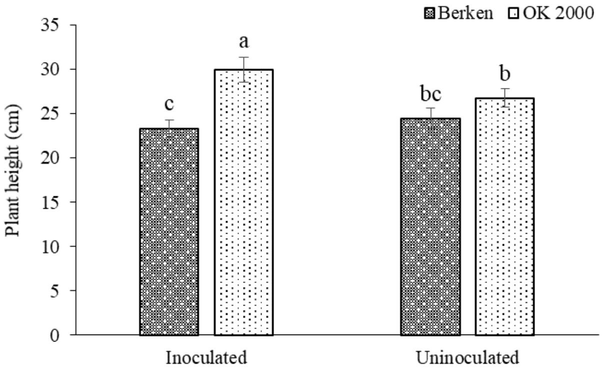

Figure 2. Effect of cultivar on plant height of mungbean grown in soil with and without *Bradyrhizobium* (group I) inoculation. Treatments with the same letter are not significantly different according to Fisher's protected LSD (α = 0.05). Error bars show standard error of the mean (*n* = 56)

Number of pods per plant

Bradyrhizobium inoculation and soil texture significantly affected mungbean pod formation (Table 3). Over cultivars and soil textures, the maximum number of pods (12 pods/plant) was observed for inoculated mungbean (a 15% increase) compared to uninoculated plants (Table 4). Anjum et al. (2006) found similar results when studying the impact of *Rhizobium* inoculation on mungbean and reported that inoculation with *Rhizobium* increased the number of pods per plant over the control. A pot experiment performed by Hussain et al. (2014) to determine the response of mungbean nodulation, growth and yield to *Rhizobium* inoculation revealed a 50% increase in the number of pods per plant compared to the control.

The comparison of the pod number per plant indicated that mungbean grown in silt loam soil had, on average, 12 pods/plant which represents a 21% increase compared to mungbean grown in loamy sand soil (Table 4). Similar results were obtained by Oke and Eyitayo (2010) when evaluating cowpea (*Vigna unguiculata* L. Walp.) growth under different fallow soils in Nigeria. They reported a significantly greater number of pods for plants grown in a sandy clay loam than a clay loam or sandy loam. Enhancement of pod formation under these soil textures could be attributed to greater concentration of organic matter, higher pH, greater percentage of exchangeable cations and greater water and fertilizer retention. The significant differences on number of pods per plant reported in our study can be attributed to the favorable conditions of silt loam soil for mungbean development. Some researchers, confirming our present results, also compared the number of pods per plant of legumes on different soil textures and reported a significant effect evidencing its importance on legume growth and yield (Ndema, Etame, Taffouo, & Bilong, 2010; Zhao, Jia, Y. Wang, M. Wang, & McGiffen Jr., 2015).

Table 4. Main effects of cultivar, inoculation, and soil texture on number of pods, seed weight, and plant residue weight per plant

Treatments		No. pods	Seed weight (g)	Plant residue (g)
Cultivar	Berken	10.79±0.40a	3.70±0.21b	2.48±0.18b
	OK2000	10.93±0.40a	4.25±0.18a	3.18±0.18a
Inoculation	Inoculated	11.75±0.50a	4.28±0.20a	2.99±0.12a
	Uninoculated	9.96±0.44b	3.68±0.20b	2.67±0.12a
Soil texture	Loamy sand	9.61±0.45b	3.24±0.16b	2.12±0.12b
	Silt loam	12.11±0.43a	4.72±0.13a	3.54±0.15a

Note. For each parameter, means within each treatment followed by different letter are significantly different [Fisher's protected LSD (α = 0.05)].

Number of seeds per plant

The number of seeds per plant was significantly affected by mungbean inoculation (Table 3). Mungbean inoculation increased the number of seeds per plant of inoculated plants by 18% compared to uninoculated plants to an average of 84 seeds/plant (Figure 3). Hussain et al. (2014) evaluated the effects of *Rhizobium* inoculation on yield and yield attributes of mungbean. They found that inoculation significantly increased (23%) the number of seeds per pods compared to uninoculated plants. However, a study conducted by Kyei-Boahen, Savala, Chikoye, and Abaidoo (2017) on growth and yield responses of cowpea revealed that inoculation did not significantly increase number of seeds per pod compared to uninoculated plants on a Rhodic Ferralsol. The differences in number of seeds per plant of mungbean reported in our study could be attributed to genotypic differences (Peksen, Toker, Ceylan, Aziz, & Farooq, 2015; Razzaque et al., 2016).

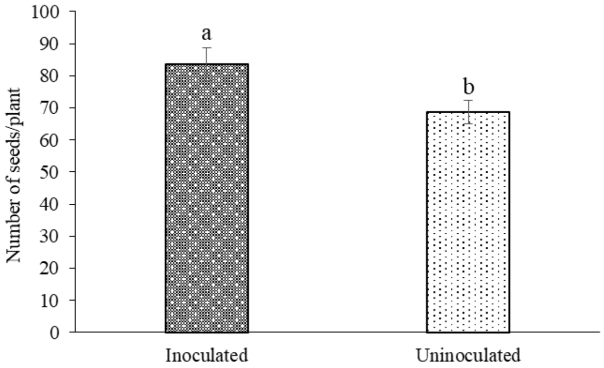

Figure 3. Effect of inoculation on number of seeds per plant of mungbean. Different letters on bars means significant difference between treatment according to Fisher's protected LSD (α = 0.05). Error bars show standard error of the mean (*n* = 56)

The interaction effect of cultivar and soil texture on number of seeds per plant was statistically significant (Table 3). Figure 4 shows that the greatest number of seeds was recorded for Berken grown in silt loam soil with 95 seeds per pod while Berken grown in loamy sand produced the lowest number of seeds per plant (55 seeds/plant). Eugegrave, Jacques, Désiré, and Paul (2010) showed in their study that yield of cowpea significantly increased in plots with sandy clay loam with high sand content (72%), organic matter and exchangeable cations. In our study, the difference in number of seeds per plant can be explained by better performance of Berken in silt loam soil. Previous findings (Ahmad et al., 2015; Kumar & Sharma, 2009) have shown that higher seed yield of mungbean cultivars under different soil textures might be due to greater root system development and a subsequent increase in water and nutrient uptake.

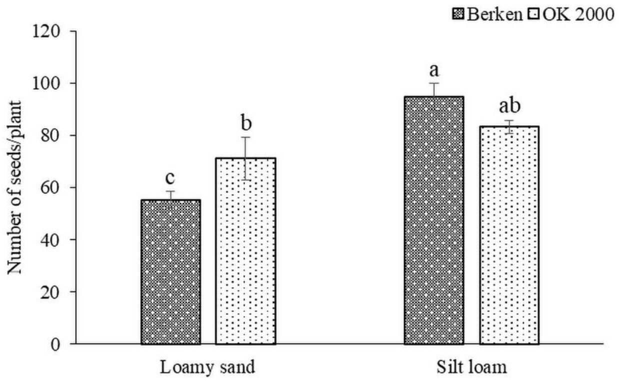

Figure 4. Effect of cultivar on number of seeds per plant of mungbean grown on a loamy sand and silt loam soils. For each soil texture, bars with the same letter are not significantly different according to Fisher's protected LSD (α = 0.05). Error bars show standard error of the mean (*n* = 56)

Seed weight

The seed weight of mungbean (g/plant) was significantly affected by cultivar, inoculation, and soil texture (Table 3). Among cultivars, the maximum seed weight of 4.25 g per plant was observed for OK2000 and represented a 13% increase compared to Berken (Table 4). M. Begum, M. Begum, Anwar, and Juraimi (2009) also studied the effect of cultivar on morphological characters, yield attributes and yield of mungbean varieties and reported BINA moog7 cultivar had the highest seed yield per plant compared to other varieties. Variations in yield among mungbean cultivars was explained by hereditary superiority, higher yield potential and greater translocation of nutrients (Ahmad et al., 2015; Sriphadet, Lambrides, & Srinives, 2007).

Inoculation of mungbean resulted in a 14% increase compared to uninoculated mungbean (3.68 g/plant) while growing in the silt loam soil resulted in a 31% increase in seed weight compared to the loamy sand (3.24 g/plant) (Table 4). Similar results were reported by Bhuiyan et al. (2008) who investigated the response of mungbean cultivars to *Bradyrhizobium* inoculation and reported a significant 27%increase in seed yield over control. The high yields of mungbean under bacterial inoculation could be attributed to plant growth promoting substances in the rhizosphere and efficient nutrient uptake resulting in increased dry matter accumulation and greater photosynthate translocation to the seed (Zaidi, Khan, & Aamil, 2004). The field study conducted by Stajković-Srbinović, Kuzmanović, Mrvić, and Knežević-Vukčević (2011) to explore growth and yield components of mungbean under different soil types showed a 24% increase in bean yield in a clay loam soil compared to a heavy clay soil. Low seed yield of mungbean in heavy clay could be explained by reduced infiltration and slow drainage due to the prevalence of small pores in soil.

Bean plant residue weight

The means presented in Table 4 showed that OK2000 had the highest plant residue biomass (3.18 g) which was 22% greater than Berken. This result is in accordance with Bhuiyan et al. (2008) who reported that BARI Mung-2 mungbean cultivar produced significantly higher stover yield than two local mungbean cultivars. Mondal et al. (2012) demonstrated that higher production of plant residue in mungbean was explained by larger leaf area, greater branches per plant and increased plant height.

Residue mass of mungbean plants was also significantly affected by soil texture. Mungbean plants grown in the silt loam soil produced 40% more residue (3.54 g) than those plants grown in loamy sand soil. Similar to our results, Stajković-Srbinović et al. (2011) reported differences in the shoot dry yield of mungbean when grown under different soil conditions. They noted greater shoot dry matter of mungbean in clay loam texture compared to heavy clay soil. Cook et al. (1995) demonstrated from growth chamber and field experiments that high soil resistance characteristic of fined-textured soils could explain constraints to biomass production of mungbean. Zhao et al. (2015) reported that lower dry matter accumulation of peanut (*Arachis hypogaea* L.) on sandy soil compared to loam and clay soils was likely due to poor soil fertility in the sandy soil.

Protein content

Seed protein content was significantly different between cultivars (Table 3). Maximum protein content (25%) was obtained with the mungbean cultivar OK2000 (Figure 5). The critical review on the technological and nutritional potential of mungbean conducted by Dahiya et al. (2015) revealed variations in the reported protein concentrations ranging from 15-33% with a mean of 24%. Bhardwaj and Hamama (2016) observed no significant effects of cultivar on protein concentration of Berken and TexSprout seeds. Varietal differences in mungbean seed protein content are likely explained by differences in genetic constitution as reported by Hussain, Malik, Haji, and Malghani (2011), and Paul, Mozumder, Sayed, Akhtaruzzaman, and Akhtaruzzaman (2011).

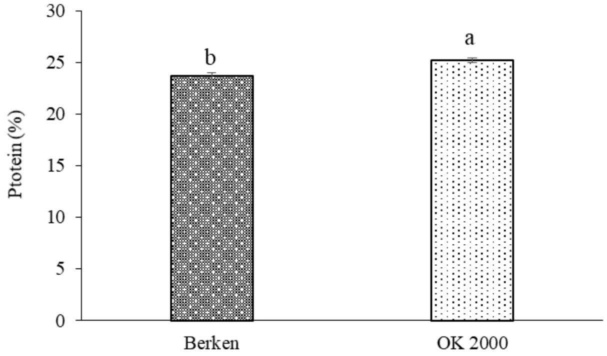

Figure 5. Effect of cultivar on protein content. Different letters on bars means significant difference between treatment according to Fisher’s protected LSD (α = 0.05). Error bars show standard error of the mean (*n* = 56)

Conclusion

Bradyrhizobium (group I) inoculation, cultivar, and soil texture affect yield and yield components of legume crops. There were significant differences in yield and yield attributes of mungbean due to the combined effects of variety (Berken and OK2000 cultivars), inoculum treatment, and soil texture under greenhouse conditions indicated. Inoculation of OK2000 cultivar grown on silt loam soil seems a promising agronomic practice for improving yield of mungbean. *Bradyrhizobium* inoculation increased the number of pods and the number of seeds per plant, but did not increase seed weight. Plant height at maturity was greater when OK2000 was inoculated, but inoculation did not affect mature height of Berken mungbean indicating differential response by cultivar. Mungbean productivity was frequently influenced by soil texture with greater number of pods, seed weight and plant residue weight for plants grown in silt loam soil. These results indicating the significant effects of soil texture, inoculation, and cultivar on mungbean yield need to be confirmed by field experiments.

Acknowledgements

The authors are grateful to the Department of Crop & Soil Environmental Sciences of Virginia Polytechnic Institute & State University for its contribution, technical expertise, and financial assistance. This publication was made possible by the United States Agency for International Development and the generous support of the American people through USAID Cooperative Agreement No. #685-A-00-10-00194-00.

References

Ahmad, S., Ali Khan, A., Ali, S., Ullah, I., Imran, M., & Habibullah, M. (2015). Impact of Phoshporus Levels on Yield and Yield Attributes of Mungbean Cultivars under Peshawar Valley Conditions. *J. Environ. Earth Sci.*, *5*, 18-24.

Anjum, M., Ahmed, Z., & Rauf, C. A. (2006). Effect of *Rhizobium* inoculation and nitrogen fertilizer on yield and yield components of mungbean. *Int. J. Agric & Biol.*, *8*(2), 238-240.

Begum, M., Begum, M., Anwar, M., & Juraimi, A. (2009). Optimizing seed rate for summer mungbean varieties. *J. Agric. Soc. Sci, 5*, 114-118.

Bhardwaj, H. L., & Hamama, A. A. (2016). Cultivar, planting date, and row spacing effects on mungbean seed composition. *Journal of Agricultural Science*, *8*(10), 26-32. https://doi.org/10.5539/jas.v8n10p26

Bhuiyan, M., Mian, M., & Islam, M. (2008). Studies on the effects of *Bradyrhizobium* inoculation on yield and yield attributes of mungbean. *Bangladesh Journal of Agricultural Research, 33*(3), 449-457. https://doi.org/10.3329/bjar.v33i3.1604

Bremner, J. M., & Keeney, D. R. (1966). Determination and isotope-ratio analysis of different forms of nitrogen in soils: 3. Exchangeable ammonium, nitrate, and nitrite by extraction-distillation methods. *Proceedings. Soil Science Society of America*, *30*, 577-582. https://doi.org/10.2136/sssaj1966.03615995003000050015x

Cook, S., Gupta, S., Woodhead, T., & Larson, W. (1995). Soil physical constraints to establishment of mungbeans (*Vigna radiata* L. Wilczek) in paddy rice (*Oryza sativa* L.) soils. *Soil and Tillage Research, 33*(1), 47-64. https://doi.org/10.1016/0167-1987(94)00431-D

Dahiya, P. K., Linnemann, A. R., Van Boekel, M. A. J. S., Khetarpaul, N., Grewal, R. B., & Nout, M. J. R. (2015). Mung Bean: Technological and Nutritional Potential. *Critical Reviews in Food Science and Nutrition*, *55*(5), 670-688. https://doi.org/10.1080/10408398.2012.671202

Eugegrave, N. N., Jacques, E., Désiré, T. V., & Paul, B. (2010). Effects of some physical and chemical characteristics of soil on productivity and yield of cowpea (*Vigna unguiculata* L. Walp.) in coastal region (Cameroon). *African Journal of Environmental Science and Technology*, *4*(3), 108-114. https://doi.org/10.5897/AJEST09.160

Foyer, C. H., Lam, H., Nguyen, H. T., Siddique, K. H. M., Varshney, R. K., Colmer, T. D., ... Considine, M. J. (2016). Neglecting legumes has compromised human health and sustainable food production. *Nature Plants*, *2*(8), 16112. https://doi.org/10.1038/nplants.2016.112

Gupta, S. C., & Larson, W. E. (1979). Estimating soil water retention characteristics from particle size distribution, organic matter percent, and bulk density. *Water Resources Research*, *15*(6), 1633-1635. https://doi.org/10.1029/WR015i006p01633

Hussain, A., Ali, A., Khaliq, T., Ahmad, A., Aslam, Z., & Asif, M. (2014). Growth, nodulation and yield components of mung bean (*Vigna radiata*) as affected by phosphorus in combination with rhizobium inoculation. *African Journal of Agricultural Research, 9*(30), 2319-2323. https://doi.org/10.5897/AJAR11.691

Hussain, F., Malik, A., Haji, M., & Malghani, A. (2011). Growth and yield response of two cultivars of mungbean (*Vigna radiata* L.) to different potassium levels. *J. Anim. Plant Sci, 21*(3), 622-625.

Kim, S. K., Nair, R. M., Lee, J., & Lee, S.-H. (2015). Genomic resources in mungbean for future breeding programs. *Frontiers in Plant Science, 6*, 626. https://doi.org/10.3389/fpls.2015.00626

Kirchhof, G., & So, H. (1995). The effect of puddling intensity and compaction on soil properties, rice and mungbean growth: A mini-ricebed study. In G. Kirchhof & H. B. So (Eds.), *Management of clay soils for rainfed lowland rice-based cropping systems* (pp. 51-70). Canberra: ACIAR.

Kumar, A., & Sharma, K. (2009). Physiological responses and dry matter partitioning of summer mungbean (*Vigna radiata* L.) genotypes subjected to drought conditions. *Journal of Agronomy and Crop Science, 195*(4), 270-277. https://doi.org/10.1111/j.1439-037X.2009.00373.x

Kyei-Boahen, S., Savala, C. E., Chikoye, D., & Abaidoo, R. (2017). Growth and yield responses of cowpea to inoculation and phosphorus fertilization in different environments. *Frontiers in Plant Science, 8*, 646. https://doi.org/10.3389/fpls.2017.00646

Maguire, R., & Heckendorn, S. E. (2011). *Laboratory procedures: Virginia Tech soil testing laboratory*. Virginia Cooperative Extension, Blacksburg, VA. Retrieved from http://pubs.ext.vt.edu/452/452-881/452-881_pdf.pdf

Mehlich, A. (1976). New buffer pH method for rapid estimation of exchangeable acidity and lime requirement of soils. *Communications in Soil Science and Plant Analysis*, *7*(7), 637-652. https://doi.org/10.1080/00103627609366673

Molla, M., Solaiman, A., Jahiruddin, M., Mridha, M., & Khanam, D. (2011). Influence of different doses of phosphorus in the presence of arbuscular mycorrhiza and *Rhizobium* on the growth and yield of mungbean. *Bulletin of the Institute of Tropical Agriculture, Kyushu University, 34*(1), 49-67.

Mondal, M., Puteh, A., Malek, M., Ismail, M., Rafii, M., & Latif, M. (2012). Seed yield of mungbean (*Vigna radiata* (L.) Wilczek) in relation to growth and developmental aspects. *The Scientific World Journal, 2012*. https://doi.org/10.1100/2012/425168

Nair, R. M., Yang, R. Y., Easdown, W. J., Thavarajah, D., Thavarajah, P., Hughes, J. D. A., & Keatinge, J. (2013). Biofortification of mungbean (*Vigna radiata*) as a whole food to enhance human health. *Journal of the Science of Food and Agriculture, 93*(8), 1805-1813. https://doi.org/10.1002/jsfa.6110

Ndema, N., Etame, J., Taffouo, V., & Bilong, P. (2010). Effects of some physical and chemical characteristics of soil on productivity and yield of cowpea (*Vigna unguiculata* L. Walp.) in coastal region (Cameroon). *African Journal of Environmental Science and Technology*, *4*(3). https://doi.org/10.5897/AJEST09.160

Ntukamazina, N., Onwonga, R. N., Sommer, R., Mukankusi, C. M., Mburu, J., & Rubyogo, J. C. (2017). Effect of excessive and minimal soil moisture stress on agronomic performance of bush and climbing bean (*Phaseolus vulgaris* L.). *Cogent Food & Agriculture, 3*(1), 1373414. https://doi.org/10.1080/23311932. 2017.1373414

Oke, S. O., & Eyitayo, D. L. (2010). Growth and yield response of cowpea (*Vigna unguiculata* L. Walp.) to soils from different fallow physiognomies in the rainforest zone of Nigeria. *Acta Botanica Croatica, 69*(2.), 291-297.

Paul, T., Mozumder, N., Sayed, M., Akhtaruzzaman, M., & Akhtaruzzaman, M. S. M. (2011). Proximate compositions, minerals contents and determination of protease activity from green gram (*Vigna radiata* I. Wilczek). *Bangladesh Res. J, 5*, 207-213.

Peksen, E., Toker, C., Ceylan, F. Ö., Aziz, T., & Farooq, M. (2015). Determination of promising high yielded mungbean (*Vigna radiata* (L.) Wilczek) genotypes under Middle Black Sea Region of Turkey. *Anadolu Tarim Bilimleri Dergisi, 30*(2), 169. https://doi.org/10.7161/anajas.2015.30.2.169-175

Peoples, M. B., & Herridge, D. F. (1990). Nitrogen fixation by legumes in tropical and subtropical agriculture. *Advances in Agronomy, 44*, 155-223. https://doi.org/10.1016/S0065-2113(08)60822-6

Rahmianna, A., Adisarwanto, T., Kirchhof, G., & So, H. (2000). Crop establishment of legumes in rainfed lowland rice-based cropping systems. *Soil and Tillage Research, 56*(1-2), 67-82. https://doi.org/10.1016/S0167-1987(00)00123-9

Razzaque, M. A., Haque, M. M., Karim, M. A., & Solaiman, A. R. M. (2016). Nitrogen fixating ability of mungbean genotypes under different levels of nitrogen application. *Bangladesh Journal of Agricultural Research, 41*(1), 163-171. https://doi.org/10.3329/bjar.v41i1.27681

Sharma, L., Priya, M., Bindumadhava, H., Nair, R., & Nayyar, H. (2016). Influence of high temperature stress on growth, phenology and yield performance of mungbean [*Vigna radiata* (L.) Wilczek] under managed growth conditions. *Scientia Horticulturae, 213*, 379-391. https://doi.org/10.1016/j.scienta.2016.10.033

Sharma, P., & Khanna, V. (2010). Influence of fluchloralin on growth of *Rhizobium* and PSB, symbiotic parameters and grain yield in mungbean. *Journal of Food legumes, 23*(1), 71-73.

Singh, G., Sekhon, H., Singh, G., Brar, J., Bains, T., & Shanmugasundaram, S. (2011). Effect of plant density on the growth and yield of mungbean [*Vigna radiata* (L.) Wilczek] genotypes under different environments in India and Taiwan. *International journal of agricultural research, 6*(7), 573-583. https://doi.org/10.3923/ijar.2011.573.583

Sriphadet, S., Lambrides, C. J., & Srinives, P. (2007). Inheritance of agronomic traits and their interrelationship in mungbean (*Vigna radiata* (L.) Wilczek). *Journal of Crop Science and Biotechnology, 10*(4), 123-132.

Stajković-Srbinović, O., Kuzmanović, D., Mrvić, V., & Knežević-Vukčević, J. (2011). Effect of bradyrhizobial inoculation on growth and seed yield of mungbean in Fluvisol and Humofluvisol. *African Journal of Microbiology Research, 5*(23), 3946-3957. https://doi.org/10.5897/AJMR11.689

Thomson, B., Siddique, K., Barr, M., & Wilson, J. (1997). Grain legume species in low rainfall Mediterranean-type environments I. Phenology and seed yield. *Field Crops Research, 54*(2-3), 173-187. https://doi.org/10.1016/S0378-4290(97)00047-6

Travlos, I., & Karamanos, A. (2006). Effects of soil texture on vegetative growth of tropical legume marama bean (*Tylosema esculentum*). *Journal of Agronomy*, *5*(4), 609-612. https://doi.org/10.3923/ja.2006.609.612

Zaidi, A., Khan, M. S., & Aamil, M. (2004). Bioassociative effect of rhizospheric microorganisms on growth, yield, and nutrient uptake of greengram. *Journal of plant Nutrition*, *27*(4), 601-612. https://doi.org/10.1081/PLN-120030370

Zhao, C., Jia, L., Wang, Y., Wang, M., & McGiffen Jr, M. (2015). Effects of Different Soil Texture on Peanut Growth and Development. *Communications in Soil Science and Plant Analysis*, *46*(18), 2249-2257. https://doi.org/10.1080/00103624.2015.1059845

Chapter 4 - Evaluation of pearl millet and mungbean intercropping systems in the semi-arid regions of Senegal

Abstract

Agricultural production in Senegal is constrained by rainfall variability, persistent droughts, and low soil fertility. These constraints have decreased pearl millet [*Pennisetum glaucum* (L.) R. Br.] yields in Senegal. Mungbean [*Vigna radiata* (L.) Wilczek], a short-duration and relatively drought-tolerant legume crop, is capable of improving soil fertility and performance of a companion crop. To investigate the potential of mungbean for increasing millet yields through intercropping, field experiments were conducted during the 2017 and 2018 growing seasons in Bambey (14°43′12″ N, 16°36′41″ W) and Nioro (13°45′0″ N, 15°48′0″ W) located within Senegal's west central (Peanut Basin) and Saloum agricultural regions, respectively. Intercropping treatments: sole millet (T_1), sole mungbean (T_2), and 23% (T_3), 43% (T_4), 47% (T_5), 62% (T_6), 125% (T_7) and 164% (T_8) of mungbean planting density in sole millet were laid out in a randomized complete block design and replicated four times. Measured parameters included yield parameters for millet panicle count and length, mungbean pod number, combined yields, land equivalent ratio (LER), canopy cover, and normalized difference vegetation index (NDVI). Combined millet and mungbean seed yields were 35% to 100% higher ($P \leq 0.05$) under intercropping systems compared to sole millet at Bambey and Nioro, respectively. Similarly, LER was always greater than unity (>1) for the various intercropping densities compared to monoculture. Mean canopy cover estimates and NDVI values increased by 60% and 30% in millet-mungbean intercropping over millet grown alone, respectively. These combined yield increases were obtained without fertilizer applications. They suggest that optimizing mungbean density in pearl-millet based systems can increase the combined yield in a low-input and/or high-risk environment in Senegal.

Keywords: Mungbean, Millet, Yields, Intercropping, Senegal

Core Ideas

- Intercropping millet with mungbean significantly increased combined seeds yield by 35% in the Senegalese West Central Agricultural Region and by 100% in the Saloum Agricultural Region compared to millet grown alone.
- Millet-mungbean intercropping significantly increased LER (always >1), canopy cover (up to 60%), and NDVI values (up to 30%) over sole millet and tended to increase with increasing mungbean density.
- Optimizing mungbean density in millet systems would improve the productivity of pearl millet-based systems in semi-arid regions of Senegal.

Introduction

In Senegal, agricultural production systems are of paramount importance to the national economy and the livelihoods of rural populations (Mertz et al., 2009; Diatta et al., 2016b; Tankari and Traore, 2017). However, these agricultural systems, like those of other sub-Saharan African countries, face various constraints which are mainly due to climate variability and increased frequency of extreme weather events, intrusion of salt water, and pest and disease incidence (Mbow et al., 2008; Kotir, 2011; Roudier et al., 2011; Diatta, 2016; Faye et al., 2019; Daryanto et al., 2020). In addition, poor agricultural practices which result in land degradation and stagnation or even a decline in agricultural production at a time when population growth is accelerating at 2.7% per year (The World Bank, 2018). Senegalese agriculture is still extensive and essentially rain-fed (Diangar et al., 2004; Fall and Lo, 2009; Gaudreau and Gibson, 2015). It is also characterized by small family farms whose access to inputs (e.g. fertilizers, pesticides, equipment) is limited by the low income of farmers (Barrett and Bevis, 2015), limited access to credit (Seck, 2017) but also the limited use of soil fertility improvement and management practices (Settle and Garba, 2011; Diatta et al., 2016a; Tounkara et al., 2020).

Several studies propose sustainable solutions to the deterioration of cropland fertility and the decline in yields of major crops such as pearl millet, peanut (*Arachis hypogaea* L.), maize (*Zea mays* L.), sorghum [*Sorghum bicolor* (L.) Moench], cowpea [*Vigna unguiculata* (L.) Walp.], and rice (*Oryza sativa* L.) in Senegal. Research has shown that the adoption of adequate soil restoration and management practices and the implementation of climate change adaptation strategies can slow and even reverse the degradation of agricultural production systems (Roudier et al., 2011; Connolly-Boutin and Smit, 2016).

Agricultural production is mainly intended to meet local needs (food crops and animal production) in Senegal. Millet, a dominant staple crop among cereals, covers more than 63.5% of the land under cereal production with an annual production estimated at 574,000 tonnes in 2018 for a yield of 0.7 t ha^{-1} (FAOSTAT, 2020). Unlike sorghum and maize, which are confined to more humid areas, millet is found throughout the country on all soil types and in all agro-ecological zones because of its broad adaptation. It is also usually grown under rainfed and extensive conditions with few or no inputs, resulting in on-farm yields ranging from 0.5 t to 0.6 t ha^{-1} in farmers' fields (Kouakou et al., 2015). Low yields of major crops such as millet have led to Senegal’s dependence on food imports (Van den Broeck et al., 2018). To offset the decline in millet productivity, it is therefore necessary to develop viable and accessible alternatives for farmers and innovative practices for good agricultural production (Trail et al., 2016).

Intercropping of cereals and legumes can restore and improve soil fertility, diversify millet production systems, and provide fodder for animal feed (Matusso et al., 2014; Diatta et al., 2019a; Daryanto et al., 2020). Intercropping, which means planting two or more crops in the same field simultaneously (Gomez and Gomez, 1983), is a very effective approach in the use of resources and the promotion of soil protection and the gradual restoration of natural soil fertility (Brooker et al., 2015). In addition, intercropping systems are well-known and very common, old practices to farmers in the tropics (Francis et al., 1976). Several studies have demonstrated the importance of legumes in improving biological, organic and even mineral soil quality (Gebru, 2015; Maman et al., 2017; Franke et al., 2018; Vanlauwe et al., 2019). Other authors have found that the combination of legumes with cereal crops promotes improved agronomic performance and yields of cereal crops (Trail et al., 2016; Diatta et al., 2019a). Despite the use of multiple crop combinations such as millet-peanut, millet-cowpea, and millet-sorghum-cowpea in Senegal, there is still a recurrent decline in millet yields (Diangar et al., 2004; Mbaye et al., 2014). This lack in yield improvement could be explained by the use of a limited number of legumes and lack of appropriate recommendations for species sowing densities and spatial arrangement.

Thus, the introduction of mungbean into Senegalese agriculture could help increase agricultural production through farming system diversification (Abaye et al., 2015; Diatta et al., 2018). Mungbean is an annual short-cycle (60-65 days) legume of the *Fabaceae* family and is widely grown in the tropical and subtropical regions of the world (Pataczek et al., 2018; Nair et al., 2019). It is mainly grown in rotation with cereals and, in symbiosis with *Rhizobium* ssp. fix up to 110 kg N/ha, which could help meet its own nitrogen needs and those of the associated or next crop (Shah et al., 2003; Shahida and Khan, 2016). Mungbean also represents an opportunity to produce protein-rich foods for smallholders under changing climatic conditions (Keatinge et al., 2011; Arsenault et al., 2015; Foyer et al., 2016). The only reported study in Senegal of millet-mungbean intercropping (1:1 row ratio) demonstrated yield improvement, particularly for the millet (Trail et al., 2016). However, the appropriate planting arrangement and density of mungbean in intercropped millet systems has not been studied in Senegal.

Our study evaluated the effects of intercropping mungbean on pearl millet yield and yield attributes in the semi-arid region of Senegal. Field experiments were conducted during the 2017 and 2018 growing seasons at the Senegalese Institute of Agricultural Research (ISRA) stations of Bambey and Nioro. Specifically, the objectives of the field studies were to: i) investigate the effects of intercropping millet with multiple planting densities of mungbean on millet and mungbean yield components; ii) evaluate millet-mungbean intercropping density and spacing on yields, combined yields, and LER; and iii) compare canopy ground cover and NDVI values of intercropped millet and grown alone.

Materials and methods

Site description

The field experiments were conducted in Bambey (14°43′12″ N, 16°36′41″ W; Diourbel region) and in Nioro du Rip (13°45′0″ N, 15°48′0″ W; Kaolack region). The climate in Diourbel is Sahelo-Sudanian and Coastal Sudanian and characterized by a mean annual temperature of 27 °C to 28 °C and mean annual rainfall values of about 520 mm from 1991 to 2016 (Climate Research Unit of East Anglia, 2019), most of which occurs during a three-month rainy season (Mbow et al., 2008; Mertz et al., 2009). The Kaolack region is characterized by a Coastal Sudanian climate with an average annual rainfall of 900 mm from 1991 to 2016 (Climate Research Unit of East Anglia, 2019). Table 1 summarizes monthly rainfall (mm), temperature (°C), and relative humidity (%) in Bambey 2017, Bambey 2018, and Nioro 2018 between June and November. The annual rainfall values were 527 mm in 2017 and 448 mm in 2018 for Bambey corresponding to 34 and 27 days of more than 1 mm of rainfall, respectively.

Situated in the West Central Agricultural Region or ‘‘Peanut Basin’’ (25,915 km^2), the soil types in Diourbel are iron-rich tropical sandy soils, and slightly leached (Tappan et al., 2004). The predominant soils in Kaolack located within the “Saloum Agricultural Region” (6413 km^2) are iron-rich tropical and ferralitic soils; loamy sands over fine sandy loam at depth (Tappan et al., 2004). Table 2 presents the chemical properties of the soil at each experimental site.

Table 1: Monthly rainfall (mm), temperature (°C), relative humidity (%) and number of days receiving more than 1 mm of rainfall (DoR) between June and November for Bambey 2017, Bambey 2018, and Nioro 2018.

Sites	Parameters	June	July	Aug.	Sep.	Oct.	Nov.	Total
Bambey 2017	Rainfall (mm)	125	120	177	88	18	0	528
	Temperature (°C)	31	30	28	29	31	29	
	Relative humidity (%)	71	82	84	79	71	65	
	DoR	3	9	13	6	3	0	34
Bambey 2018	Rainfall (mm)	33	14	161	205	33	2	448
	Temperature (°C)	30	30	30	29	30	28	
	Relative humidity (%)	65	70	74	82	75	55	
	DoR	1	2	9	11	3	1	27
Nioro 2018	Rainfall (mm)	16	99	205	314	49	0	683
	Temperature (°C)	na†	na	na	na	na	na	
	Relative humidity (%)	na	na	na	na	na	na	
	DoR	1	6	13	12	5	0	37

† na, not available.

Table 2. Summary of soil chemical properties at Bambey 2017, Bambey 2018, and Nioro 2018 sites.

Sites	pH†	Total N	Total C	C/N	NO_3^-	NH_4^+	P	K	Ca	Mg
		% ‡			mg kg^{-1} §		mg kg^{-1} ¶			
Bambey 2017	8.0	0.03	0.28	9.9	0.1	0.5	15.6	5.2	209.1	43.6
Bambey 2018	6.7	0.02	0.23	11.2	0.1	0.2	4.4	5.5	69.7	14.9
Nioro 2018	5.6	0.03	0.38	12.4	0.1	0.3	1.0	4.2	27.5	4.7

† pH: soil (1:1 soil: deionized water mixture on a volumetric basis).

‡ Total carbon (C) and total nitrogen (N): vario MAX CNS Element Analyzer.

§ Inorganic NO_3^- and NH_4^+: 2M KCl extraction.

¶ Plant available nutrients: soil (Mehlich 1 solution).

Experimental design

The experiment was laid out as a randomized complete block design composed of eight treatments replicated four times. The first treatment was millet only (control treatment, T_1) whose density and spacing would represent the conventional practice followed by farmers in Senegal (Gupta, 1984; Fall and Lo, 2009). Millet spaced 0.9 by 0.9 m is commonly practiced by smallholders to allow animal traction used to loosen the soil for a good circulation of water and air in depth, promote root development, infiltration of rains on the surface, and weed control, and to mix organic inputs and soil amendments (Nicou, 1977). Mungbean grown alone and intercropped with millet represented the following treatments summarized in Figure 1. The proportions of mungbean grown with millet corresponded to their relative density compared to mungbean density in pure cultivation (T_2). Experimental plots measured 4.5 by 2.7 m and were separated by 1.8 m buffer. Millet seeds were sown in hills with 0.9 by 0.9 m spacing and thinned to three plants per hill for a density of 12,346 hills per hectare. Three mungbean seeds were sown per hill at 0.5 by 0.5 m and thinned to one plant for a plant density of 40,000 hills per hectare when grown alone. Planting densities and arrangements for millet and mungbean grown alone and intercropped are illustrated in Figure 1.

Experimental plots were planted manually under rainfed conditions with no fertilizer additions. Millet and mungbean were planted on 19 July 2017 in Bambey. In 2018, all crops were planted on 27 and 30 of July in Nioro and Bambey, respectively. Prior to planting, mungbean seeds were mixed with arabic gum and inoculated with *Bradyrhizobium* spp. (group I) at a rate of 10 g inoculant kg^{-1} seed to allow thorough coating. All experimental sites had been under millet cultivation prior to initiation of these studies. During early vegetative stages, weed management system included manual weeding. Seeds of millet (Souna III) were obtained from National Center for Agronomic Research (CNRA) laboratory. Mungbean seed (Berken) was purchased from Oklahoma Foundation Seed Stocks (Stillwater, Oklahoma, USA).

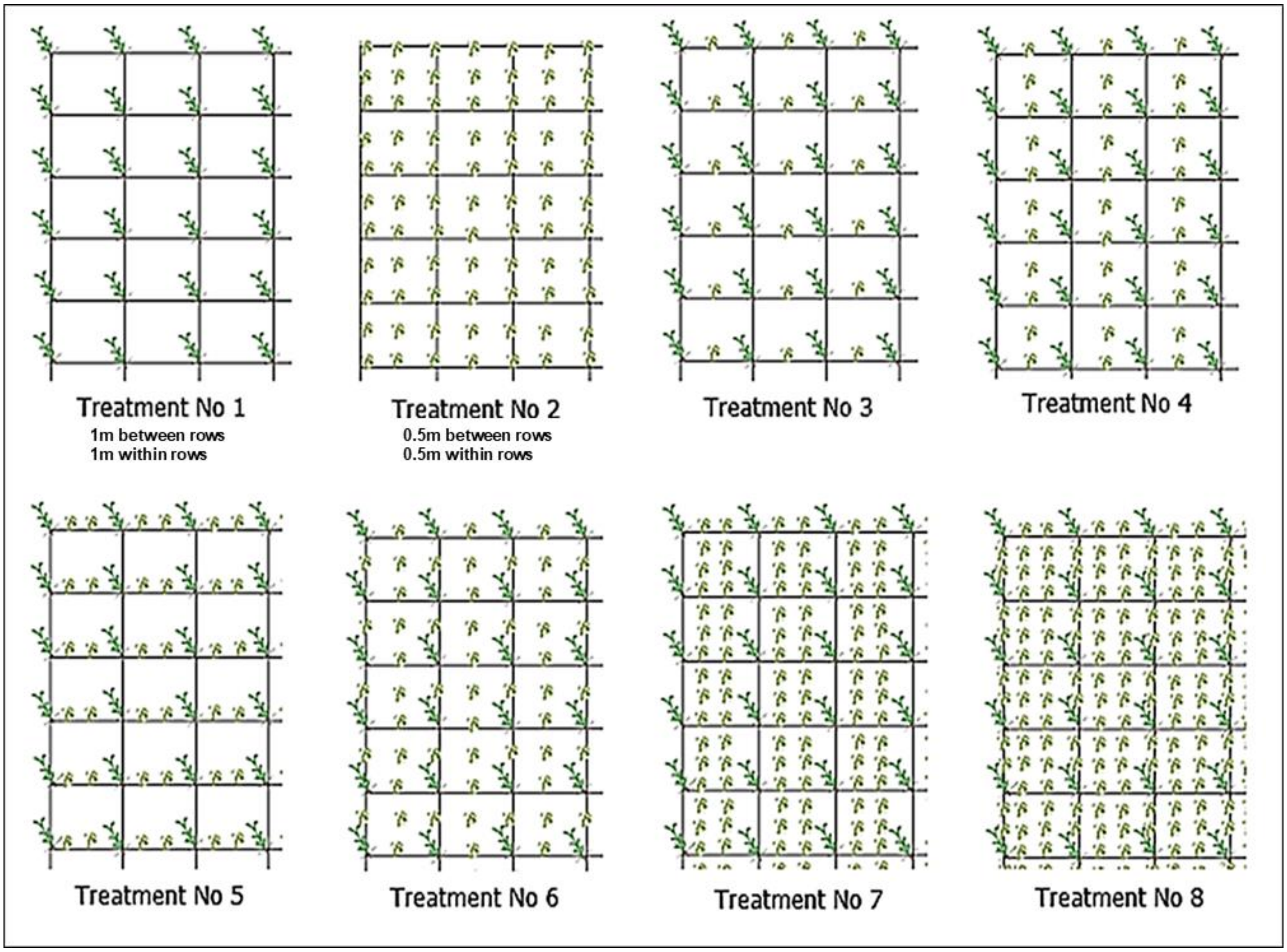

Figure 1. Planting densities and arrangements for millet and mungbean grown alone and intercropped. Millet alone (T_1), mungbean alone (100%, T_2), 23% mungbean (T_3), 43% mungbean (T_4), 47% mungbean (T_5), 62% mungbean (T_6), 125% mungbean (T_7) and 164% mungbean (T_8) grown in combination with the millet.

Data collection

Millet biomass and grains were hand-harvested from the center (7.6 m^2) of each plot at maturity and oven dried for 2-3 days at 60°C to constant weight and yields reported based on 12.5% moisture content. Additional millet parameters included plant height (cm), stem diameter (cm), number of panicles, and panicle length (cm). To determine the effects of mungbean intercropping on millet components, each millet plant was separated into inflorescence, leaf, and stem. Dry weight was measured for each parameter. Mungbean pods were hand harvested from the central rows (7.6 m^2) of each experimental plot. Mungbean yield was measured at 12.5% moisture content. Average plant height (cm) and number of pods were recorded at harvest.

To evaluate the advantage of intercropping millet with mungbean over millet grown alone, the total land equivalent ratio (LER) was calculated. LER is defined as a measure of crop productivity and resource-use efficiency of intercropped systems compared to sole cropping (Mead and Willey, 1980). LER greater than unity indicates greater land utilization efficiency and yield per unit area of intercropping over sole cropping, and is calculated as follow:

$$\mathrm{LER} = \mathrm{LER}_{\mathrm{Mung}} + \mathrm{LER}_{\mathrm{Mil}} = (\mathrm{Y}_{\mathrm{IMung}} / \mathrm{Y}_{\mathrm{SMung}}) + (\mathrm{Y}_{\mathrm{IMil}} / \mathrm{Y}_{\mathrm{SMil}})$$

where: $\mathrm{Y}_{\mathrm{IMung}}$ and $\mathrm{Y}_{\mathrm{IMil}}$ are mass yields per unit area of intercropped mungbean seeds and millet grains respectively and $\mathrm{Y}_{\mathrm{SMung}}$ and $\mathrm{Y}_{\mathrm{SMil}}$ are mass yield per unit area of sole cropped mungbean seeds and millet grains respectively.

Canopy cover measurements were taken at sowing, during vegetative growth, at flowering, during pod development, and at maturity with the Canopeo app (Shepherd et al., 2018). Canopeo, an image analysis application, uses color values based on the red-green-blue (RGB) system and fractional green canopy cover which ranges from 0 to 1 corresponding to no or 100% green canopy cover, respectively (Patrignani and Ochsner, 2015). Normalized difference vegetation index (NDVI) was also collected during the growing season with a Trimble Greenseeker hand-held optical sensor (Trimble Navigation, Sunnyvale, CA). To help determine N differences between millet grown alone and intercropped with mungbean, readings were taken on millet plants from the harvested area.

Statistical analysis

Millet and mungbean yields, canopy cover, and NDVI data were analyzed using SAS JMP Pro version 15.0.0 statistical software (SAS Institute Inc., Carey, NC). Prior to the analysis of variance (ANOVA), normal distribution of data was assessed using the Anderson-Darling goodness of fit test (Laio, 2004) and homogeneity of variance evaluated using Levene test (Gastwirth et al., 2009). When assumptions of normal distribution of data and homoscedasticity were not met, data were transformed using Box-Cox power transformation (Box and Cox, 1964; Osborne, 2010). ANOVA was then used to test the effects of the millet and mungbean intercropping on the studied parameters. Treatment means were separated using Fisher's protected LSD test at $\alpha = 0.05$ level of probability when values were significant. No data were collected at Nioro site in 2017 due to flooding. Due to interactions between sites and intercropping treatments, data are presented individually by site.

Results

Millet, mungbean, and combined intercropping yields

Pearl millet and mungbean yields under intercropping and monocropping systems are summarized in Table 3. Millet grain yields were not affected by intercropping treatments at either site, but there was a significant yield difference ($P < 0.05$) between sites (Table 3). Millet produced the highest grain yield of 1023 kg ha^{-1} at Nioro in 2018 which was 52% and 116% greater than millet yield at Bambey, 2017 or Bambey, 2018, respectively (Table 4).

There was a significant interaction between intercropping treatment and site for mungbean seed yield (Table 3), though seed yield tended to increase with increasing mungbean density, as expected. The mean mungbean seed yields in millet intercropped with 164% (T_8) and

125% (T_7) of mungbean were significantly ($P < 0.05$) greater (44%) than that in sole mungbean (T_2) in Bambey, 2017 (Fig. 2). At Bambey and Nioro in 2018, mungbean grown alone always produced the highest yields of 444 and 544 kg ha^{-1} compared to other intercropping treatments, respectively (Fig. 2).

Table 3. Analysis of variance of site, intercropping treatments, and interaction of main effects for yield and yield components of millet and mungbean, canopy cover, NDVI, LER.

		Millet					Mungbean			Combined	
Source	df	Yield	Panicle count	Plant height	Canopy cover	NDVI	Yield	Plant height	Number pods	Yield	LER
		kg ha^{-1}	per plot	cm	%		kg ha^{-1}	cm	per plot	kg ha^{-1}	
Site	2	***	***	***	***	***	***	***	***	***	ns
Treatment	7	ns†	ns	ns	***	***	***	***	***	***	***
Site × Treatment	14	ns	*	ns	ns	ns	*	***	**	*	ns
Model	23										
Error	72										
Total	95										

* Significant at α = 0.05.

** Significant at α = 0.01.

*** Significant at α = 0.001.

† ns– nonsignificant at α = 0.05.

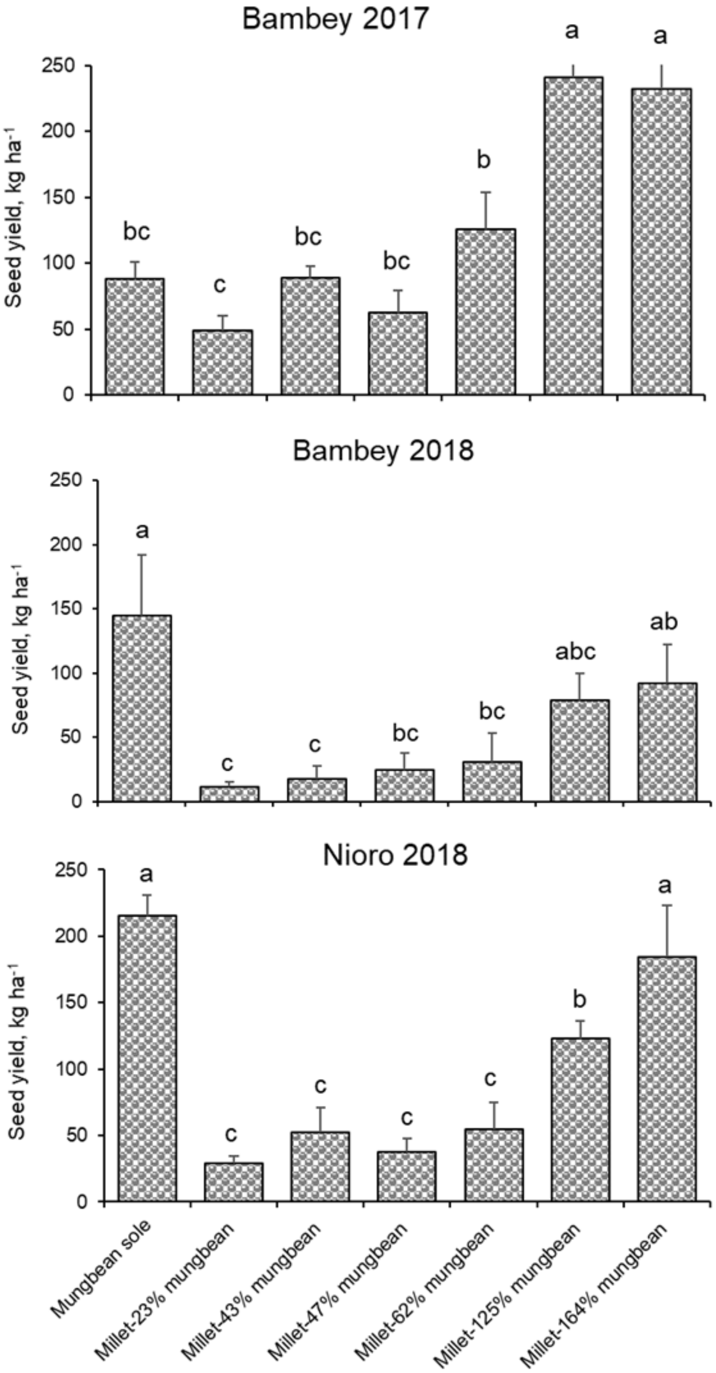

Figure 2. Mungbean yields in monocropping and intercropping at Bambey 2017, Bambey 2018, and Nioro 2018. Treatments connected by dissimilar letters are significantly different at α = 0.05 according to Fisher’s protected LSD and error bars represent standard error of the mean (n = 84).

Combined seed yields of millet and mungbean were significantly ($P < 0.05$) affected by an intercropping by site interaction (Table 3). At Bambey 2017, combined seed yields were significantly ($P < 0.05$) higher than those of monocropped systems. Maximum seed yields of 914 and 905 kg ha^{-1} were recorded for millet intercropped with 47% (T_5) and 62% (T_6), respectively, which corresponded to a 38 and 36% increase compared to millet grown alone (Fig. 3). Similarly, significant differences ($P < 0.05$) were observed for combined yields at Bambey 2018, where millet + 62% mungbean (T_6) intercropping treatment yielded 86% more than monocropped millet (452 kg ha^{-1}) (Fig. 3). At Nioro 2018, intercropping systems significantly ($P < 0.05$) produced more combined seed than millet grown alone (Fig. 3). A maximum combined seed yields of 1468 kg ha^{-1} in millet intercropped with 125% mungbean (T_7) was recorded, an 85% increase compared to millet alone (Fig. 3).

Intercropping mungbean with millet did not significantly ($P > 0.05$) influence the inflorescence, leaf, and stem dry biomass of millet plants despite its presence at high densities (up to 164% compared to T_2). Conversely, differences ($P < 0.05$) were observed for millet parameters among sites (Table 4). The highest recorded values for plant height and panicle length were in Nioro 2018 while greater stem diameter and dry biomass were recorded at Bambey 2017 (Table 4). At Bambey in 2018, millet grown alone produced more panicles than other intercropping treatments (Table 5). However, number of panicles was not significant ($P > 0.05$) between treatments at Bambey 2017 and Nioro 2018. At all sites, the number of panicles did not always significantly differ between treatments, but millet grain yields were significantly different. Statistical differences were found for millet panicle length between sites, with Nioro and Bambey 2018 recording the highest panicle length, 49 and 48 cm respectively, compared to Bambey 2017 (37 cm) (Table 4).

For mungbean, when the number of pods was significantly different between treatments, seed yield also differed between mungbean grown alone and intercropped. The greatest number of pods for Bambey 2017 was 125% (T_7) and 164% (T_8) of mungbean. Sole mungbean (T_2) and millet-125% mungbean (T_7) produced more pods at Bambey and Nioro in 2018 (Table 5). At Bambey in 2017, intercropped mungbean with millet had higher plant height than when mungbean was grown alone. Mungbean plants under 125% (T_7) and 164% (T_8) density recorded the highest plant heights of 149 and 144 cm, respectively, which corresponded to over 160% increase compared to mungbean grown alone (Table 5). Conversely in 2018, there was no significant difference for mungbean plant height between the two sites (Table 5).

Table 4. Millet panicle length, plant height, stem diameter, and dry biomass at Bambey 2017, Bambey 2018 and Nioro 2018.

Site / Parameters	Panicle length	Plant height	Stem diameter	Grain yield	Stem biomass	Leaf biomass	Panicle biomass	Dry biomass
		cm				kg ha^{-1}		
Bambey 2017	37b*	175b	2a	671c	4176a	4924a	8317a	17416a
Bambey 2018	48a	137c	1b	473b	1369c	305c	483c	2157c
Nioro 2018	49a	216a	2a	1023a	2534b	1144b	1926b	5604b

* Means within each column followed by dissimilar letters are significantly different according to Fisher’s protected LSD (α = 0.05).

Table 5. Number of millet panicles and mungbean pods by treatment at Bambey 2017, Bambey 2018 and Nioro 2018.

Site / Treatment	T_1†	T_2‡	T_3§	T_4¶	T_5††	T_6‡‡	T_7§§	T_8¶¶
				Number of panicles/7.6 m^2				
Bambey 2017	62a*	--	62a	57a	64a	60a	58a	60a
Bambey 2018	59a	--	38c	39bc	44bc	53ab	38c	31c
Nioro 2018	44a	--	49a	53a	45a	49a	53a	48a
				Number of pods per plot				
Bambey 2017	--	379bcd	287e	356cde	311de	404bc	509a	476ab
Bambey 2018	--	444a	158c	196c	205c	219bc	333ab	370a
Nioro 2018	--	544a	278c	321c	301c	347c	432b	530a
				Mungbean plant height, cm				
Bambey 2017	--	55bc	30c	55bc	39bc	78b	149a	144a
Bambey 2018	--	37a	36a	38a	36a	39a	40a	35a
Nioro 2018	--	45a	40a	41a	41a	42a	43a	47a

† T_1: Millet sole; ‡ T_2: Mungbean sole; § T_3: Millet-23% mungbean; ¶ T_4: Millet-43% mungbean; †† T_5: Millet-47% mungbean; ‡‡ T_6: Millet-62% mungbean; §§ T_7: Millet-125% mungbean; ¶¶ T_8: Millet-164% mungbean

* Means within each row followed by dissimilar letters are significantly different according to Fisher's protected LSD (α = 0.05).

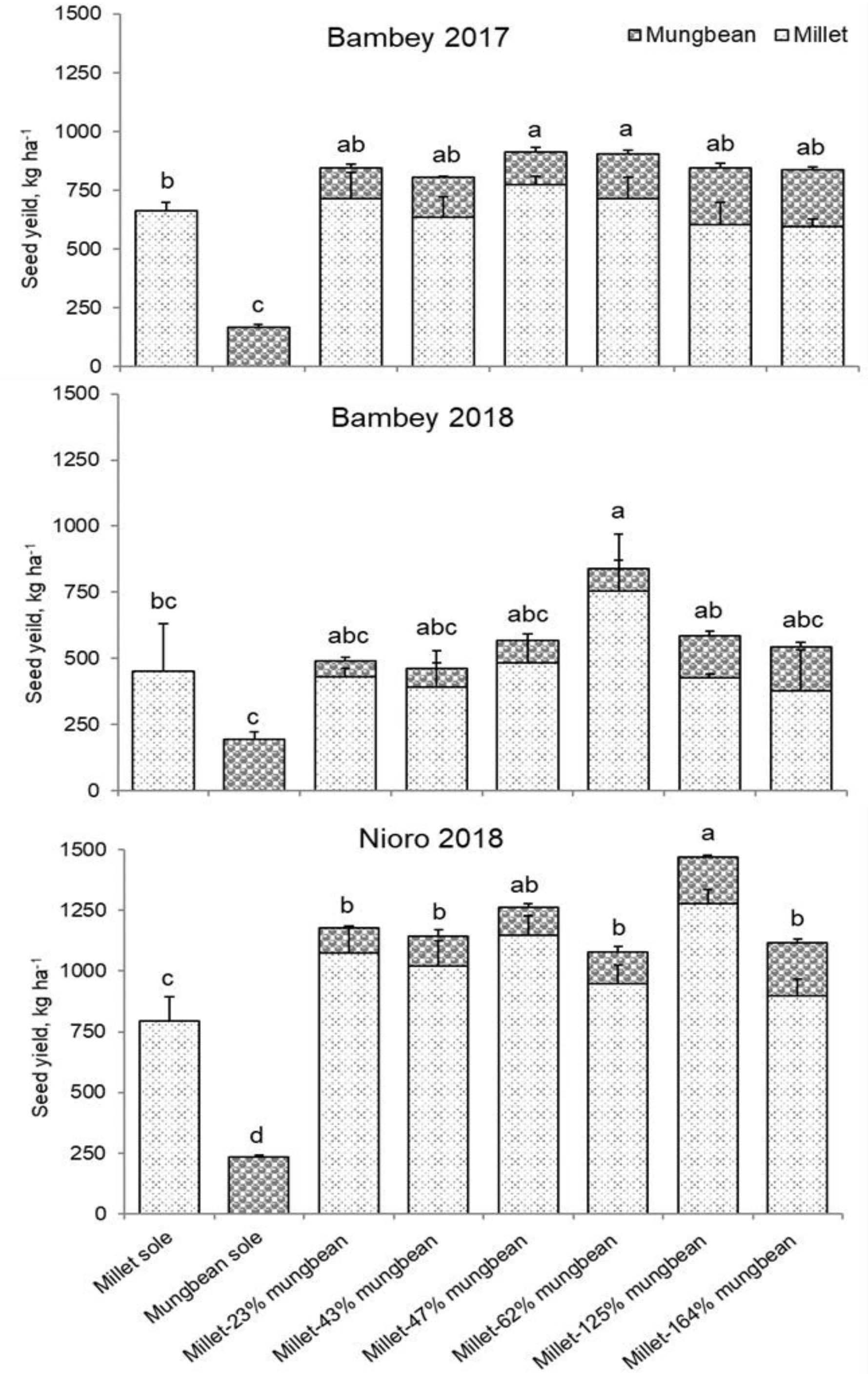

Figure 3. Millet and mungbean combined seed yield between treatments at Bambey 2017, Bambey 2018 and Nioro 2018. Treatments connected by dissimilar letters are significantly different at α = 0.05 according to Fisher's protected LSD and error bars represent standard error of the mean (n = 96).

Land equivalency ratios

Land equivalent ratio (LER) indicates the advantage of intercropping over a monocropping system (Oseni, 2010). In the present study, data for partial LER indicated yield advantage for all intercropped millet compared to monocropped millet, except for millet with 164% mungbean (Table 6). Partial LER of mungbean ranged from 0.51 to 1.09 for intercropped mungbean (Table 6). However, only partial LER of millet-125% mungbean (T_7) (1.04) and 164% of mungbean (T_8) (1.09) were greater than unity, indicating more seeds were produced per unit of land compared to mungbean grown alone.

Total LERs for the different intercropping systems were all greater than unity, demonstrating that intercropping was more efficient in land use than monocropping systems for seed yields. In addition, LER values showed an increasing trend with increasing mungbean density. The maximum LERs were 2.11 and 2.31 under millet-62% (T_6) and 125% mungbean (T_7) plant density, respectively, indicating that increasing mungbean density at 62% and 125% of standard mungbean plant density in millet increased land use productivity (Table 6).

Table 6. Land equivalency ratios for millet and mungbean in monocropping and intercropping systems.

	Land Equivalency Ratio		
Intercropping treatments	Millet	Mungbean	Total*
Millet sole	1.00	--	1.00b
Mungbean sole	--	1.00	1.00b
Millet-23% mungbean	1.25	0.51	1.76a
Millet-43% mungbean	1.10	0.63	1.74a
Millet-47% mungbean	1.39	0.60	1.99a
Millet-62% mungbean	1.39	0.72	2.11a
Millet-125% mungbean	1.26	1.04	2.31a
Millet-164% mungbean	0.94	1.09	2.03a

* Means within each column followed by dissimilar letters not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD.

Canopy cover

Percent canopy cover values differed among intercropping treatments at different stages of crop development, but followed the same pattern during the growing season (Table 3). Canopy cover increased with increasing mungbean density, and values were related to increasing density of mungbean ($r = 0.68$). The percent canopy cover of the monocropping systems was significantly lower ($P < 0.05$) than that of intercropping systems due to low shade cover from pearl millet. Millet grown alone generally recorded the lowest percent cover estimates, while intercropped millet with mungbean recorded, on average, 112% higher canopy cover over sole millet. The maximum canopy cover estimates for all treatments were recorded at flowering with T_8 reaching 63%, while millet grown alone (T_1) recorded 30% cover (Fig. 4). Maximum density of mungbean (T_8; 164%) in millet had the highest canopy cover estimates over the growing season and corresponded to a significant increase over millet alone of 237% at vegetative stage, 110% at flowering, 167% at pod development, and 182% at maturity stages (Fig. 4).

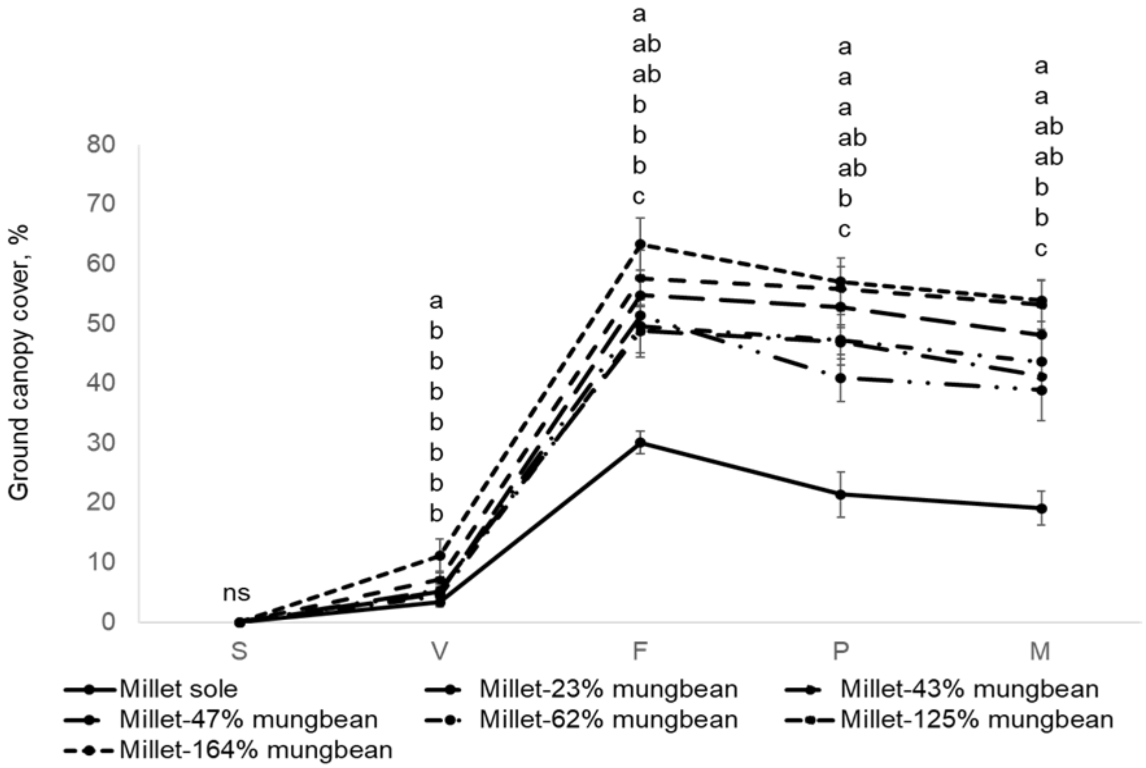

Figure 4. Percentage canopy cover of millet monocrop, mungbean monocrop, and millet + mungbean intercropping (S= Sowing, V= Vegetative, F= Flowering, P= pod development, M= Maturity). Treatments with dissimilar letters are significantly different at $\alpha = 0.05$ according to Fisher's protected LSD and error bars represent standard error of the mean (n = 96).

Normalized Difference Vegetation Index (NDVI)

NDVI is a standardized means of estimating plant health status (Gamon et al., 1995). Positive NDVI values correspond to green vegetation while negative values indicate little or no plant cover. NDVI values under intercropping treatments were significantly higher ($P < 0.05$) than that of sole millet at the same plant development stage. On average, a 16% increase was noted for intercropped millet with mungbean compared to millet monocrop (Fig. 5). However, NDVI values for sole millet and millet-mungbean intercropping reflected similar patterns from sowing to pod development stage. After the pod development stage, NDVI of millet intercropped with 47 and 62% of mungbean increased while values of the remaining treatments decreased at maturity. Significantly lower NDVI values were reported throughout the growing season for millet grown alone compared to intercropped millet. At the vegetative stage, pod development, and maturity, NDVI values of millet intercropped with the highest density of mungbean (T_8; 164%) had the highest NDVI values, which significantly increased 51%, 21%, and 27% over millet grown alone, respectively (Fig. 5).

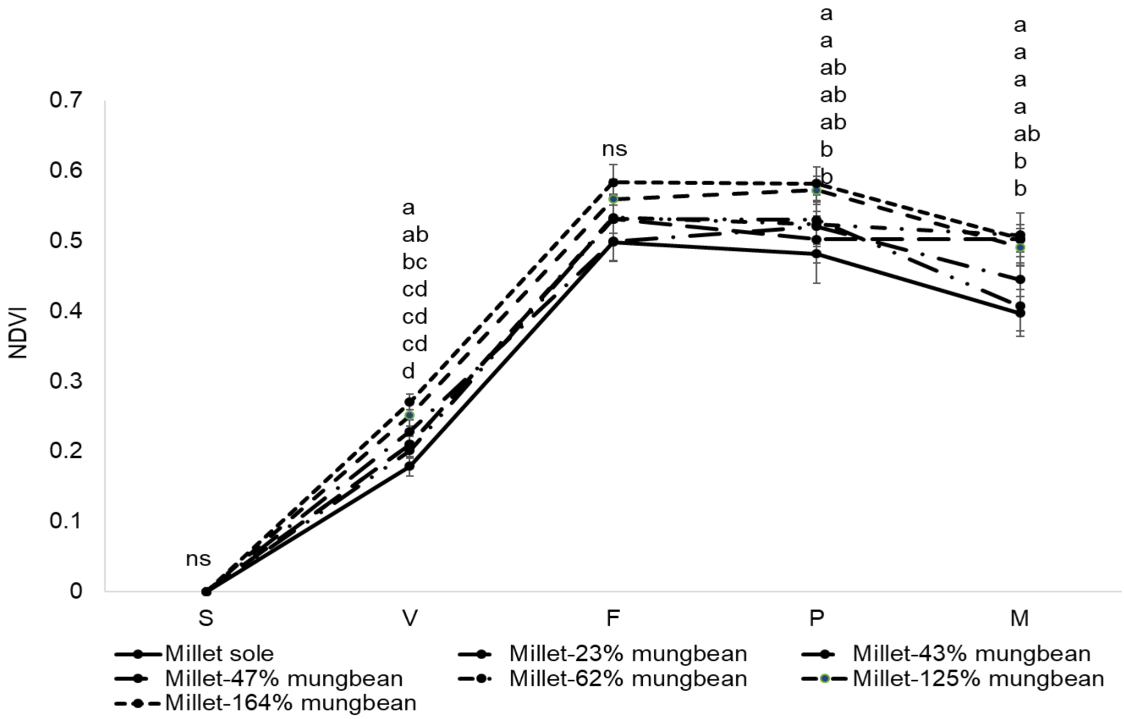

Figure 5. Normalized difference vegetation index (NDVI) of millet monocrop, mungbean monocrop, and millet + mungbean intercropping (S= Sowing, V= Vegetative, F= Flowering, P= pod development, M= Maturity). Treatments with dissimilar letters are significantly different at α = 0.05 according to Fisher's protected LSD and error bars represent standard error of the mean (n = 96).

Discussion

Intercropping millet with mungbean did not significantly increase millet yields. Yield varied by sites with Nioro 2018 recording the highest grain yields. Despite being intercropped at high mungbean density (up to 164%), millet yields were not significantly reduced, demonstrating that mungbean did not adversely affect millet grain yield at those sites. Trail et al. (2016) also studied the effect of 1:1 millet-mungbean intercropping in Senegal and reported a grain yield increased by 36% for intercropped millet with mungbean compared to monocropped millet. Similar results were reported by Reddy et al. (1992) and Bationo et al. (1998) who reported a 15% increase in Niger and 30% increase in West Africa for intercropped millet compared to millet grown alone. In contrast, others studies have revealed reduction in millet yields under millet-legume intercropping systems. Ntare (1990) reported yield decrease varying from 11 to 75% in Niger while Diangar et al. (2004) found up to 24% decrease in millet yields in Senegal. A recent study conducted by Maman et al. (2017) revealed that pearl millet intercropped with cowpea in Mali yielded 18% less than millet monocropping.

Intercropped mungbean generally had lower yield than mungbean grown alone except for mungbean grown at high density (over 125% plant density). Similar to our results, Trail et al. (2016) and Reddy et al. (1992) both reported decreases in intercropped legumes compared to monocropped legumes by 50% et 48%, respectively. Reduction of cowpea seed yield by 47% was reported by Mohammed et al. (2008) due to intercropping with millet. Ntare (1990) intercropped millet and cowpea and found significant reduction in cowpea yield when grown in association with millet. However, monocropped and intercropped legumes were grown at lower densities in these field trials than the present study. The differences in mungbean yield in the present study is explained by increased planting density in intercropping treatments. The T_8, which corresponds to 164% mungbean in millet sole, despite having the highest plant density, did not always result in the highest mungbean yield. The seeding rate of mungbean in intercropping could thus be reduced relative to its density in monoculture without significantly reducing yield (Matusso et al., 2014).

Combined seed yields of millet and mungbean were consistently higher in association than in monoculture. Nevertheless, we observed relatively low total yield in this study compared to yield reported in other intercropping experiments. The increase for total seed yield under intercropping in the present study is similar with Trail et al. (2016) when he intercropped millet with mungbean in Senegal and got a total seed yield of 2000 kg ha^{-1}. Naresh et al. (2017) reported greater yield of millet and mungbean under intercropping compared to monoculture and attributed it to beneficial interactions between millet and legumes. Ghilotia et al. (2015), by contrast, reported a decrease in combined grain yield compared to millet grown alone due to competition of associated crops for soil nutrients and environmental resources. In the present study, poor soil fertility associated with poor plant stand, insect pests, and low rainfall and early cessation might have resulted in relatively lower combined seed yields. Among intercropping treatments in Bambey, millet grown with 62% mungbean density (T_6) produced the highest combined seed yields both in 2017 and 2018, while millet-125% mungbean (T_8) yielded more at Nioro in 2018. The percentage yield increases were 60% in Bambey and 85% at Nioro 2018. Optimum mungbean density increased combined seed yields and is attributed to increased mungbean yield without decreasing millet yield. Differences in yields between sites could be due to variations in amounts of rainfall (488 mm at Bambey sites on average and 683 at Nioro 2018), indicating the need to consider site specificity for selecting the appropriate intercropping systems. Diangar et al. (2004) also reported higher pearl millet and cowpea yields in Central-south region compared to Central-north region in Senegal due lower rainfall in the north. Singh et al. (2011) and Begum et al. (2009) investigated the effects of mungbean plant density and concluded that optimum row and plant spacing significantly mungbean increased yield up to 30%. Rachaputi et al. (2015) demonstrated that optimum row spacing in mungbean grown in subtropical regions resulted in greater intercepted radiation and use of soil water. Proper mungbean density in cropping might reduce competition between species for growth factors such as water, nutrient, and solar radiation (Saleem et al., 2015; Sabbagh and Lakzayi, 2016).

This study reported total LER of all intercropped levels was always greater than monocropping. Partial LER of millet ranged from 0.94 to 1.39, while mungbean partial LER varied from 0.51 to 1.09 in the intercropping systems. Yield advantages of mungbean could be associated with significant variations in mungbean partial LER which generally increased with increasing density of mungbean in millet systems. Thus, intercropping millet with mungbean can result in a yield advantage and greater land use efficiency compared to millet grown alone. Mohammed et al. (2008) and Lithourgidis et al. (2011) reported that increasing legume proportion in intercropped systems with cereals significantly increased total LER due greater yield advantage. The yield advantage of millet-mungbean intercropping over sole millet has been also reported by Trail et al. (2016) in Senegal, Gong et al. (2019) in China, Ghilotia et al. (2015) and Ram and Meena (2015) in India. Sarr et al. (2008) and Diangar et al. (2004) reported LER of 1.68 and 1.37 under millet-cowpea intercropping, respectively, and concluded that intercropping systems can use less land area and produce more grain than monocropped millet in Senegal.

Intercropping systems significantly affected the estimates of millet and mungbean canopy cover. Intercropping increased canopy cover compared to monocropped millet. Similarly, Trail et al. (2016) reported that millet grown alone had lower ground cover compared to intercropped millet with mungbean. In contrast, Biriah et al. (2017) studied the effects of maize-cowpea intercropping on ground cover and reported greater percent ground cover (74% on average) for cowpea alone compared to maize grown alone and in association. The higher canopy cover reported for millet-164% mungbean (T_8) in our study could be attributed to increased plant density. In addition, increased canopy cover with increasing mungbean density could be due to the linear growth pattern of legume crops. Similar results were observed by Lithourgidis et al. (2011) who reported a quadratic growth for cereals while legumes showed a linear pattern. Higher coverage rate for T_8 could reduce water evaporation and thus improve water use efficiency (Ogindo and Walker, 2005). Treatments with the highest mungbean density had the lowest weed density compared to millet grown alone (Diatta, unpublished data, 2018). Reduction of pest/weed incidence was also observed in intercropping systems with high coverage compared to monocropping (Daryanto et al., 2020). This result could be attributed to the creation of adverse weed germination conditions such as light interception by associated crops (Saha, 2017). Other benefits from intercropping systems with high cover rates include control soil erosion by reducing surface runoff (Seran and Brintha, 2010).

Normalized difference vegetation index (NDVI) values were estimated over the growing season to detect N nutritional differences between millet monocrop and intercropped with mungbean. Millet grown with mungbean had significantly higher NDVI values than millet grown alone and tended to vary at different growth stages. Among intercropping treatments, NDVI values were highest for mungbean grown at the highest densities as reported by Erdle et al. (2011). Trail et al. (2016) found a 9% increase of NDVI on average for millet-mungbean intercropping compared to millet monocropping in Senegal. Similar results were observed in Senegal by Bogie et al. (2019). Conversely, the study conducted by Klimek-Kopyra et al. (2018)

revealed that a legume grown alone had a significantly higher NDVI values (up to 25%) than intercropped legume at developmental stages. In our study, an increase in NDVI values under intercropping can be attributed to increased availability of symbiotically fixed N which can be transferred from mungbean to millet plants (Thilakarathna et al., 2016). The glasshouse experiment conducted by Diatta et al. (unpublished data, 2019) to assess symbiotic performance of mungbean using the ^{15}N natural abundance method revealed that mungbean can fixed up to 75 mg plant^{-1}. However, research on nitrogen fixation by mungbean under field conditions is needed to assess its N_2 fixation potential and contribution to cropping systems. Shah et al. (2003) reported that mungbean can fix up to 110 kg N ha^{-1}, while Senaratne et al. (1995) found that maize grown with mungbean in intercropping systems could derive 7-11% of its N from the N fixed by mungbean. Li et al. (2009) revealed that formation of arbuscular mycorrhizas was enhanced by mungbean and rice intercropping, which in turn increased N transfer (up to 16%) from mungbean to rice plants.

Conclusion

Millet-mungbean intercropping systems can be promoted as a sustainable strategy for increasing yields in low-input agriculture and/or high-risk environment in the semi-arid regions of Senegal. This study aimed at evaluating the productivity of millet-mungbean intercropping system in the semi-arid regions of Senegal. Among intercropping systems, millet + 62% mungbean (T_6) and millet + 125% mungbean (T_7) recorded the highest combined grain yields compared to other treatments in Bambey and Nioro, respectively. This field experiment also revealed that intercropping systems significantly increased LER as a result of increased combined grain yields. LER data revealed that T_6 and T_7 increased mungbean yield without decreasing millet yield and thus was found to be more advantageous than millet monocropping and mungbean systems in the semi-arid regions of Senegal. Intercropping significantly increased ground canopy cover and NDVI values in millet systems. Treatments T_7 and millet + 164% mungbean (T_8) had higher canopy cover than millet and mungbean alone. Overall, the optimum mungbean plant density for increasing combined yield was T_6 in the West Central Agricultural Region and T_7 in the Saloum Agricultural Region of Senegal. These results demonstrated that intercropping millet with mungbean can improve the productivity of millet and increase its LER, canopy cover estimates, and NDVI values.

Acknowledgements

This publication was made possible by the United States Agency for International Development and the generous support of the American people through USAID Cooperative Agreement No. #685-A-00-10-00194-00. The authors are grateful to the staff of the USAID-Education and Research in Agriculture (ERA) project in Senegal for their support. The authors would like also to thank the School of Plant and Environmental Sciences (SPES) of Virginia Polytechnic Institute & State University and the “Centre National de Recherches Agronomiques de Bambey” for their technical assistance.

References

Abaye O., Trail P., Gueye T., Gueye F., Mbaye D., Guisse B. (2015) Mungbean as an alternative high protein source food legume for Senegal, Spanish Association for Legumes (AEL), Madrid. pp. 85-86.

Arsenault J.E., Hijmans R.J., Brown K.H. (2015) Improving nutrition security through agriculture: an analytical framework based on national food balance sheets to estimate nutritional adequacy of food supplies. Food Security 7:693-707. DOI: https://doi.org/10.1007/s12571-015-0452-y

Barrett C.B., Bevis L.E. (2015) The self-reinforcing feedback between low soil fertility and chronic poverty. Nature Geoscience 8:907-912. DOI: https://doi.org/10.1038/ngeo2591

Bationo A., Lompo F., Koala S. (1998) Research on nutrient flows and balances in West Africa: state-of-the-art. Agriculture, ecosystems & environment 71:19-35. DOI: https://doi.org/10.1016/s0167-8809(98)00129-7

Begum M., Begum M., Anwar M., Juraimi A. (2009) Optimizing seed rate for summer mungbean varieties. J. Agric. Soc. Sci 5:114-118.

Biriah N., Chemining'wa G., Olubayo F., Saha H. (2017) Effect of cropping system on soil moisture content, canopy temperature, growth and yield performance of maize and cowpea.

Bogie N., Bayala R., Diedhiou I., Dick R., Ghezzehei T. (2019) Intercropping with two native woody shrubs improves water status and development of interplanted groundnut and pearl millet in the Sahel. Plant and soil 435:143-159. DOI: https://doi.org/10.1007/s11104-018-3882-4

Box G.E., Cox D.R. (1964) An analysis of transformations. Journal of the Royal Statistical Society: Series B (Methodological) 26:211-243.

Brooker R.W., Bennett A.E., Cong W.F., Daniell T.J., George T.S., Hallett P.D., Hawes C., Iannetta P.P., Jones H.G., Karley A.J. (2015) Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. New Phytologist 206:107-117. DOI: https://doi.org/10.1111/nph.13132

Climate Research Unit of East Anglia. (2019) Average monthly temperature and rainfall for Senegal at locations (14.7,-16.46) and (13.74,-15.77) from 1990-2012. The World Bank Group, Climate Change Knowledge Portal. http://sdwebx.worldbank.org/climateportal/index.cfm?page=country_historical_climate&ThisRegion=Africa&ThisCCode=SEN (accessed 22 March 2016).

Connolly-Boutin L., Smit B. (2016) Climate change, food security, and livelihoods in sub-Saharan Africa. Regional Environmental Change 16:385-399. DOI: https://doi.org/10.1007/s10113-015-0761-x

Daryanto S., Fu B., Zhao W., Wang S., Jacinthe P.-A., Wang L. (2020) Ecosystem service provision of grain legume and cereal intercropping in Africa. Agricultural Systems 178:102761. DOI: https://doi.org/10.1016/j.agsy.2019.102761

Diangar S., Fofana A., Diagne M., Yamoah C.F., Dick R.P. (2004) Pearl millet-based intercropping systems in the semiarid areas of Senegal. African Crop Science Journal 12:133-139. DOI: https://doi.org/10.4314/acsj.v12i2.27671

Diatta A., Abaye O., Thomason W., Lo M., Guèye F., Baldé A., Tine F., Vaughan L., Thompson T. (2019) Effect of intercropping mungbean on millet yield in the Peanut basin, Senegal Innovations Agronomiques 74:69-81.

Diatta A.A. (2016) Effects of biochar application on soil fertility and pearl millet (*Pennisetum glaucum* L.) yield, Virginia Tech.

Diatta A.A., Ndour N., Manga A., Sambou B., Faye C.S., Diatta L., Goudiaby A., Mbow C., Dieng S.D. (2016a) Ecosystem services of *Cordyla pinnata* (Lepr. ex A. Rich.) Milne-Redh. agroforestry parkland of Senegal’s South Peanut Basin International Journal of Biological and Chemical Sciences 10:2511-2525. DOI: https://doi.org/10.4314/ijbcs.v10i6.9

Diatta A.A., Ndour N., Manga A., Sambou B., Faye C.S., Diatta L., Mbow C. (2016b) Floristic composition and dynamics of *Cordyla pinnata* (Lepr. ex A. Rich.) Milne-Redh. agroforestry parkland of Senegal’s South Peanut Basin International Journal of Biological and Chemical Sciences 10:1805-1822. DOI: https://doi.org/10.4314/ijbcs.v10i4.29

Diatta A.A., Thomason W.E., Abaye O., Vaughan L.J., Thompson T.L., Lo M., Chim B.K., Bateman S. (2018) Inoculation and soil texture effects on yield and yield components of mungbean. Journal of Agricultural Science (Toronto) 10:6-16. DOI: https://doi.org/10.5539/jas.v10n9p6

Erdle K., Mistele B., Schmidhalter U. (2011) Comparison of active and passive spectral sensors in discriminating biomass parameters and nitrogen status in wheat cultivars. Field Crops Research 124:74-84. DOI: https://doi.org/10.1016/j.fcr.2011.06.007

Fall A., Lo M. (2009) Etude de référence sur les céréales: mil, sorgho, maïs, et fonio au Sénégal. CORAF/WECARD, Sénégal.

FAOSTAT. (2020) Crops: production quantity. Available online: http://www.fao.org/faostat/en/#data/QC. (Accessed on 19 February 2020).

Faye C., Faye M., Sambou H., Diatta A., Diatta L., Manga A., Konate K. (2019) Modélisation de la biomasse aérienne des parcs arborés à *Cordyla pinnata*: Keur Samba Guèye. Journal of Chemical, Biological and Physical Sciences 09:238-250. DOI: https://doi.org/10.24214/jcbps.d.9.3.23849

Foyer C.H., Lam H., Nguyen H.T., Siddique K.H.M., Varshney R.K., Colmer T.D., Cowling W., Bramley H., Mori T.A., Hodgson J.M., Cooper J.W., Miller A.J., Kunert K., Vorster J., Cullis C., Ozga J.A., Wahlqvist M.L., Liang Y., Shou H., Shi K., Yu J., Fodor N., Kaiser B.N., Wong F., Valliyodan B., Considine M.J. (2016) Neglecting legumes has compromised human health and sustainable food production. Nature Plants 2:16112. DOI: https://doi.org/10.1038/nplants.2016.112

Francis C.A., Flor C., Temple S.R. (1976) Adapting varieties for intercropping systems in the tropics. Multiple cropping 27:235-253. DOI: https://doi.org/10.2134/asaspecpub27.c12

Franke A., Van den Brand G., Vanlauwe B., Giller K. (2018) Sustainable intensification through rotations with grain legumes in Sub-Saharan Africa: A review. Agriculture, ecosystems & environment 261:172-185. DOI: https://doi.org/10.1016/j.agee.2017.09.029

Gamon J.A., Field C.B., Goulden M.L., Griffin K.L., Hartley A.E., Joel G., Penuelas J., Valentini R. (1995) Relationships between NDVI, canopy structure, and photosynthesis in three Californian vegetation types. Ecological Applications 5:28-41. DOI: https://doi.org/10.2307/1942049

Gastwirth J.L., Gel Y.R., Miao W. (2009) The impact of Levene's test of equality of variances on statistical theory and practice. Statistical Science:343-360. DOI: https://doi.org/10.1214/09-sts301

Gaudreau K., Gibson R.B. (2015) Sustainability assessment of the agricultural and energy systems of Senegal. Energies 8:3503-3528. DOI: https://doi.org/10.3390/en8053503

Gebru H. (2015) A review on the comparative advantages of intercropping to mono-cropping system. Journal of Biology, Agriculture and Healthcare 5:1-13.

Ghilotia Y., Meena R., Singh L. (2015) Pearlmillet and mungbean intercropping as influenced by various row ratios under custard apple orchard of Vindhyan region. The Bioscan 10:87-91.

Gomez A.A., Gomez K.A. (1983) Multiple cropping in the humid tropics of Asia International development research centre.

Gong X., Ferdinand U., Dang K., Li J., Chen G., Luo Y., Yang P., Feng B. (2019) Boosting proso millet yield by altering canopy light distribution in proso millet/mung bean intercropping systems. The Crop Journal. DOI: https://doi.org/10.1016/j.cj.2019.09.009

Gupta S.C. (1984) Programme d'amélioration du mil: développement des pratiques culturales pour les nouvelles variétés. In: Rapport annuel 1983-1984. ISRA, CNRA Bambey, 32 p.

Keatinge J., Easdown W., Yang R., Chadha M., Shanmugasundaram S. (2011) Overcoming chronic malnutrition in a future warming world: the key importance of mungbean and vegetable soybean. Euphytica 180:129-141. DOI: https://doi.org/10.1007/s10681-011-0401-6

Klimek-Kopyra A., Zając T., Oleksy A., Kulig B. (2018) Biological and production responses of intercropped plants of pea, spring wheat, and linseed. Acta Agrobotanica 71. DOI: https://doi.org/10.5586/aa.1737

Kotir J.H. (2011) Climate change and variability in Sub-Saharan Africa: a review of current and future trends and impacts on agriculture and food security. Environment, Development and Sustainability 13:587-605. DOI: https://doi.org/10.1007/s10668-010-9278-0

Kouakou P.K., Muller B., Affholder F., Guisse A., Sultan B. (2015) Pearl millet yields and climate evolution across the last 20 years in central Senegal. A yield gap study.[P93].

Laio F. (2004) Cramer–von Mises and Anderson-Darling goodness of fit tests for extreme value distributions with unknown parameters. Water Resources Research 40. DOI: https://doi.org/10.1029/2004wr003204

Li Y., Ran W., Zhang R., Sun S., Xu G. (2009) Facilitated legume nodulation, phosphate uptake and nitrogen transfer by arbuscular inoculation in an upland rice and mung bean intercropping system. Plant and Soil 315:285-296. DOI: https://doi.org/10.1007/s11104-008-9751-9

Lithourgidis A., Vlachostergios D., Dordas C., Damalas C. (2011) Dry matter yield, nitrogen content, and competition in pea–cereal intercropping systems. European Journal of agronomy 34:287-294. DOI: https://doi.org/10.1016/j.eja.2011.02.007

Maman N., Dicko M., Abdou G., Kouyate Z., Wortmann C. (2017) Pearl millet and cowpea intercrop response to applied nutrients in West Africa. Agronomy Journal 109:2333-2342. DOI: https://doi.org/10.2134/agronj2017.03.0139

Matusso J., Mugwe J., Mucheru-Muna M. (2014) Potential role of cereal-legume intercropping systems in integrated soil fertility management in smallholder farming systems of sub-Saharan Africa. Journal of Agriculture and Environmental Management 3:162-174.

Mbaye M., Kane A., Gueye M., Bassene C., Ba N., Diop D., Sylla S., Noba K. (2014) Optimal sowing date and density of cowpea [*Vigna unguiculata* (L.) Walp.] in an intercropping system with millet [*Pennisetum glaucum* (L.) R. Br.]. Journal of Applied Biosciences 76:6305-6315.

Mbow C., Mertz O., Diouf A., Rasmussen K., Reenberg A. (2008) The history of environmental change and adaptation in eastern Saloum–Senegal—Driving forces and perceptions. Global and Planetary Change 64:210-221. DOI: https://doi.org/10.1016/j.gloplacha.2008.09.008

Mead R., Willey R. (1980) The concept of a 'land equivalent ratio'and advantages in yields from intercropping. Experimental Agriculture 16:217-228. DOI: https://doi.org/10.1017/s0014479700010978

Mertz O., Mbow C., Reenberg A., Diouf A. (2009) Farmers' perceptions of climate change and agricultural adaptation strategies in rural Sahel. Environmental management 43:804-816. DOI: https://doi.org/10.1007/s00267-008-9197-0

Mohammed I., Olufajo O., Singh B., Oluwasemire K., Chiezey U. (2008) Productivity of millet/cowpea intercrop as affected by cowpea genotype and row arrangement. World Journal of Agricultural Sciences 4.

Nair R.M., Pandey A.K., War A.R., Hanumantharao B., Shwe T., Alam A., Pratap A., Malik S.R., Karimi R., Mbeyagala E.K. (2019) Biotic and abiotic constraints in mungbean production—Progress in genetic improvement. Frontiers in plant science 10. DOI: https://doi.org/10.3389/fpls.2019.01340

Naresh K., Bairwa R., Yadav R., Singh S., Rakesh S. (2017) Evaluation of yield attributes and yield on pearl millet (Pennisetum glaucum) and mungbean (Vigna radiata L.) intercropping system under arid western plain zone in India. Annals of Agri Bio Research 22:188-191.

Nicou R. (1977) Le travail du sol dans les terres exondées du Sénégal motivations-contraintes, ISRA.

Ntare B.R. (1990) Intercropping morphologically different cowpeas with pearl millet in a short season environment in the Sahel. Experimental Agriculture 26:41-47. DOI: https://doi.org/10.1017/s0014479700015386

Ogindo H., Walker S. (2005) Comparison of measured changes in seasonal soil water content by rainfed maize-bean intercrop and component cropping systems in a semi-arid region of southern Africa. Physics and Chemistry of the Earth, Parts A/B/C 30:799-808.

Osborne J. (2010) Improving your data transformations: Applying the Box-Cox transformation. Practical Assessment, Research, and Evaluation 15:12.

Oseni T.O. (2010) Evaluation of sorghum-cowpea intercrop productivity in savanna agro-ecology using competition indices. Journal of Agricultural Science 2:229. DOI: https://doi.org/10.5539/jas.v2n3p229

Pataczek L., Zahir Z.A., Ahmad M., Rani S., Nair R., Schafleitner R., Cadisch G., Hilger T. (2018) Beans with benefits—the role of mungbean (*Vigna radiata*) in a changing environment. American Journal of Plant Sciences 9:1577. DOI: https://doi.org/10.4236/ajps.2018.97115

Patrignani A., Ochsner T.E. (2015) Canopeo: A powerful new tool for measuring fractional green canopy cover. Agronomy Journal 107:2312-2320. DOI: https://doi.org/10.2134/agronj15.0150

Rachaputi R.C., Chauhan Y., Douglas C., Martin W., Krosch S., Agius P., King K. (2015) Physiological basis of yield variation in response to row spacing and plant density of mungbean grown in subtropical environments. Field Crops Research 183:14-22. DOI: https://doi.org/10.1016/j.fcr.2015.07.013

Ram K., Meena R. (2015) Evaluation of pearl millet and mungbean intercropping systems in arid region of Rajasthan (India). Bangladesh Journal of Botany 43:367-370.

Reddy K., Visser P., Buckner P. (1992) Pearl millet and cowpea yields in sole and intercrop systems, and their after-effects on soil and crop productivity. Field Crops Research 28:315-326. DOI: https://doi.org/10.1016/0378-4290(92)90017-4

Roudier P., Sultan B., Quirion P., Berg A. (2011) The impact of future climate change on West African crop yields: What does the recent literature say? Global Environmental Change 21:1073-1083. DOI: https://doi.org/10.1016/j.gloenvcha.2011.04.007

Sabbagh E., Lakzayi M. (2016) Influence of intercropping on weed control, soil fertility and forage quality. International Journal of Agriculture and Biosciences 5:285-290.

Saha H. (2017) Effect of cropping system on soil moisture content, canopy temperature, growth and yield performance of maize and cowpea.

Saleem R., Ahmad Z.I., Anees M.A., Razzaq A., Saleem A. (2015) Productivity and land use efficiency of maize mungbean intercropping under different fertility treatments. Sarhad Journal of Agriculture 31:37-44.

Seck A. (2017) Fertiliser subsidy and agricultural productivity in Senegal. The World Economy 40:1989-2006. DOI: https://doi.org/10.1111/twec.12487

Senaratne R., Liyanage N.D.L., Soper R.J. (1995) Nitrogen fixation of and N transfer from cowpea, mungbean and groundnut when intercropped with maize. Fertilizer Research 40:41-48. DOI: https://doi.org/10.1007/bf00749861

Seran T.H., Brintha I. (2010) Review on maize based intercropping. Journal of agronomy 9:135-145.

Settle W., Garba M.H. (2011) Sustainable crop production intensification in the Senegal and Niger River basins of francophone West Africa. International journal of agricultural sustainability 9:171-185. DOI: https://doi.org/10.3763/ijas.2010.0559

Shah Z., Shah S.H., Peoples M.B., Schwenke G.D., Herridge D.F. (2003) Crop residue and fertiliser N effects on nitrogen fixation and yields of legume–cereal rotations and soil organic fertility. Field Crops Research 83:1-11. DOI: http://dx.doi.org/10.1016/S0378-4290(03)00005-4.

Shahida B., Khan I.A. (2016) Impact of weed control techniques on intercropping of mungbean with maize under agro climate condition of Peshawar. Sarhad Journal of Agriculture 32:62-69. DOI: https://doi.org/10.17582/journal.sja/2016/32.2.62.69

Shepherd M.J., Lindsey L.E., Lindsey A.J. (2018) Soybean canopy cover measured with Canopeo compared with light interception. Agricultural & Environmental Letters 3:1-3. DOI: https://doi.org/10.2134/ael2018.06.0031.

Singh G., Sekhon H., Singh G., Brar J., Bains T., Shanmugasundaram S. (2011) Effect of plant density on the growth and yield of mungbean [*Vigna radiata* (L.) Wilczek] genotypes under different environments in India and Taiwan. International journal of agricultural research 6:573-583. DOI: https://doi.org/10.3923/ijar.2011.573.583

Tankari M., Traore F. (2017) Economic accounts for agriculture and farm income in Senegal, International Food Policy Research Institute (IFPRI).

The World Bank. (2018) Population growth (annual %). https://data.worldbank.org/indicator/SP.POP.GROW?locations=SN (accessed on 12 Septembre 2018).

Thilakarathna M.S., McElroy M.S., Chapagain T., Papadopoulos Y.A., Raizada M.N. (2016) Belowground nitrogen transfer from legumes to non-legumes under managed herbaceous cropping systems. A review. Agronomy for Sustainable Development 36:58. DOI: https://doi.org/10.1007/s13593-016-0396-4

Tounkara A., Clermont-Dauphin C., Affholder F., Ndiaye S., Masse D., Cournac L. (2020) Inorganic fertilizer use efficiency of millet crop increased with organic fertilizer application in rainfed agriculture on smallholdings in central Senegal. Agriculture, Ecosystems & Environment 294:106878. DOI: https://doi.org/10.1016/j.agee.2020.106878

Trail P., Abaye O., Thomason W.E., Thompson T.L., Gueye F., Diedhiou I., Diatta M.B., Faye A. (2016) Evaluating intercropping (living cover) and mulching (desiccated cover) practices for increasing millet yields in Senegal. Agronomy Journal. DOI: https://doi.org/10.2134/agronj2015.0422

Van den Broeck G., Van Hoyweghen K., Maertens M. (2018) Horticultural exports and food security in Senegal. Global food security 17:162-171. DOI: https://doi.org/10.1016/j.gfs.2017.12.002

Vanlauwe B., Hungria M., Kanampiu F., Giller K. (2019) The role of legumes in the sustainable intensification of African smallholder agriculture: Lessons learnt and challenges for the future. Agriculture, Ecosystems & Environment 284:106583. DOI: https://doi.org/10.1016/j.agee.2019.106583

Chapter 5 – Nitrogen fixation by mungbean genotypes in different soil textures

Abstract

Ensuring food and nutritional security in light of high climate variability and a rapidly growing population remains a challenge. Mungbean [*Vigna radiata* (L.) Wilczek] is a short duration and drought-tolerant legume crop capable of symbiotic atmospheric nitrogen fixation. Estimates of biological N_2 fixation by mungbean in different soil textures has not been extensively studied. We conducted this study to evaluate plant growth and N_2 fixation of five mungbean genotypes inoculated with *Bradyrhizobium* and grown in loamy sand and silt loam soils under glasshouse conditions. The percent of nitrogen derived from atmosphere (%Ndfa) by mungbean genotypes using the ^{15}N natural abundance method was lower in the silt loam soil than the loamy sand soil. As a result, mungbean took up more mineral N from the silt loam soil (235 mg plant^{-1}) than loamy sand soil (40 mg plant^{-1}). Mungbean also fixed more N when grown in the silt loam soil (67 mg plant^{-1}) than on loamy sand (16 mg plant^{-1}), demonstrating mungbean relied more on soil mineral N than symbiotically fixed N for its N nutrition. Among genotypes, IC 8972-1 had the highest biomass (7.85 g plant^{-1}), shoot N content (200 mg plant^{-1}), and soil N uptake (155 mg plant^{-1}) than other genotypes. The significant interaction between soil texture and genotypes for root dry matter and %Ndfa indicates the major role of legume root-nodule bacteria in symbiotic N_2 fixation. Correlations between dry matter and N-fixed, soil N uptake and $\delta^{15}N$ (‰), and shoot N content were significant, confirming that N_2 fixation in mungbean is affected by both genotype and soil properties. This study demonstrated that N_2 fixation by mungbean genotypes is influenced by soil properties.

Keywords: Mungbean, Nitrogen fixation, %Ndfa, Soil texture

Introduction

In symbiosis with rhizobia, legumes can fix atmospheric nitrogen and contribute to meeting nitrogen needs in agriculture. N_2 fixation plays an important role in increasing crop N-use efficiency and reducing N losses to the environment (Maseko et al., 2020). Biological fixation of atmospheric N_2 by legumes corresponds to its conversion by N_2-fixing bacteria called diazotrophs into plant-available ammonia (NH_3) using nitrogenase enzymes (Unkovich et al., 2008). This ability makes legume crops a viable option for providing N to the companion/subsequent crops and for developing more sustainable production systems (Peoples et al., 1995; Foyer et al., 2016; Diatta et al., 2019b). Annual estimates of N fixed by legumes in symbiosis with soil rhizobia were reported to be 21.5 Tg (Herridge et al., 2008) of which up to 30% is returned to soils (Reeves et al., 2016). Other reported benefits of including legumes into crop rotations are greater microbial and crop diversity, soil fertility, and reduction of pest incidence (Giller, 2001; Matusso et al., 2014; Franke et al., 2018; Diatta et al., 2019a; Vanlauwe et al., 2019; Singh et al., 2020). Legume crops are an important and economic source of protein, minerals, and vitamins in human diets and animal feed under smallholder agriculture (Graham and Vance, 2003; Tharanathan and Mahadevamma, 2003). To optimize legume crop potential for promoting productive and sustainable cropping systems, the contribution of legumes to agricultural systems need to be assessed to enable maximization of symbiotic N_2 fixation (Thilakarathna et al., 2016; Vanlauwe et al., 2019).

Mungbean is a short-duration legume crop widely grown in arid and semiarid environments of the tropics. It is cultivated on over 7 million ha and has recently experienced yield increases due to the development of varieties with short and synchronous maturity, higher yield, and greater disease-resistance (Nair et al., 2019). Potential yields of 2.5-3.0 Mg ha^{-1} have been reported in mungbean, but lower yields (0.5 Mg ha^{-1}) have been also observed, particularly in smallholder cropping systems (Pandey et al., 2018; Diatta et al., 2019a). Mungbean fits well into many cropping systems because of its short growth cycle and low water and N requirements (Chadha, 2001; Diatta et al., 2019a). In mungbean, fixed N ranged from 6 to 112 kg ha^{-1} (Shah et al., 2003; Ali et al., 2013a), allowing the crop to meet up to 75% of its N requirements from biological N_2 fixation (Shah et al., 2003). Dakora et al. (2015) reported that mungbean could fix up to 110 kg N ha^{-1}, while Zang et al. (2015) observed that 10% of fixed N can be transferred to companion and subsequent crops. Thus, it represents an opportunity to produce highly nutritious food under arid and semiarid conditions particularly for smallholder farmers (Keatinge et al., 2011). Limited production in regions other than South and Southeast Asia, Australia, and East Africa (Keatinge et al., 2011; Diatta et al., 2018) has resulted in inadequate research to understand the observed variation in N_2 fixation by mungbean and assess its contribution to cropping system (Herridge et al., 2008; Thilakarathna et al., 2016; Raji et al., 2019; Vanlauwe et al., 2019).

N_2-fixation capacity of legumes is influenced by several factors including inherent genetic potential and the presence of compatible and sufficient rhizobial communities in the soil (Franke et al., 2018). As a result, Herridge et al. (2005) recommended the selection of responsive soils and plants that are symbiotically competent and use of rhizobial strains present in the soil to increase nodulation and N_2 fixation by mungbean. Other parameters also affecting plant growth such as water deficit, nutrient availability particularly N and phosphorous, light and temperature, and insect-pests and disease incidence can influence the rates of fixed N (Diatta et al., 2019b; Nair et al., 2019; Vanlauwe et al., 2019; Singh et al., 2020). Furthermore, symbiotic performance of legumes can be affected by plant density, species, and agronomic practices (Makoi et al., 2009).

Soil texture is known to have a significant effect on *Rhizobium* survival, root development, crop growth, and biomass yield of mungbean which subsequently affect N_2 fixation yields

(Kirchhof and So, 1995; Singh et al., 2011; Diatta et al., 2018; Diatta et al., 2019b). Ahmad et al. (2015) demonstrated that a suitable soil can increase water and nutrient uptake by mungbean due to better root development. Other researchers have reported that beneficial effects include good aeration and drainage, soil water storage capacity, and nutrient retention (Travlos and Karamanos, 2006; Zhao et al., 2015; Ntukamazina et al., 2017). In addition to soil texture, N_2-fixing ability of mungbean has been demonstrated to vary by genotype (Delfin et al., 2008). Razzaque et al. (2016) showed that nodulation and biologically fixed N differed among 10 mungbean genotypes. Others have also reported variations in N_2 fixation rates due to inherent genotypic variability (Devi et al., 2010; Devi et al., 2013).

Most N fixation studies have focused on major crop legumes such as soybean, groundnut, cowpea, common bean, and chickpea. In contrast, estimates of biological N_2 fixation by mungbean are still lacking (Raji et al., 2019). A study conducted by Shah et al. (2003) in Pakistan revealed that 54 to 82% of mungbean N requirements can be met from 55 to 86 kg N ha^{-1} of fixed N. However, Hayat et al. (2008) reported lower values ranging from 19 and 47 kg N ha^{-1} and representing between 32% to 49% of mungbean total N nutrition. In the Philippines, George et al. (1995) reported that N fixed by mungbean ranged from 61 to 90 kg N ha^{-1} while Rosales et al. (1995) observed 21 to 85 kg N ha^{-1}. Variations in N_2 fixation estimates highlight the need to investigate these factors to better maximize N contribution to cropping systems. Of the limited research conducted on mungbean, most studies examined the effects of *Bradyrhizobium* inoculation, tillage, crop residues management, and mungbean-cereal sequences on N_2 fixation (Delfin et al., 2008; Hayat and Ali, 2010; Mohammad et al., 2010; Ali et al., 2013b). However, little research has focused on the combined effects of soil texture and genotype on N_2 fixation potential. The aim of this study was to assess plant dry matter production and N_2 fixation of mungbean genotypes grown under greenhouse conditions in silt loam and loamy sand soils using the ^{15}N natural abundance method.

Materials and methods

Soil description

Study soils were collected from Virginia Tech's Tidewater Agricultural Research and Extension Center (AREC) in Suffolk, VA (36°39′50.9″N latitude, 76°44′01.0″W longitude) and Kentland Farm in Blacksburg, VA (37°11′47.3″N latitude, 80°34′49.7″W longitude), respectively. The site in Suffolk has a Eunola loamy fine sand (Fine-loamy, siliceous, semiactive, thermic Aquic Hapludults) and had been under a corn (*Zea mays* L.) and cotton (*Gossypium hirsutum* L.) rotation, while the soil in Blacksburg was characterized by a continuous corn system and is a Guernsey silt loam (Fine, mixed, superactive, mesic Aquic Hapludalfs) (NRCS, 2019).

Soil sampling and analysis

Soils were collected by excavating to a depth of 20 cm from fields with no recent history of legumes in the crop management systems at those sites. After collection, composite soil samples were placed in plastic containers and air-dried in a dust-free glasshouse and then sieved to pass a 5 mm particle size diameter. Field capacity and soil pH, and plant available Ca, Mg, P, and K of soil samples were determined as described by Gupta and Larson (1979) and Maguire and Heckendorn (2011), respectively. The concentrations of (NH_4^+) and nitrate (NO_3^-) were measured using Lachat QuikChem AE flow-injection autoanalyzer and ion chromatography and were prepared as described by Bremner and Keeney (1966). Soil samples were analyzed by dry combustion using a vario MAX CNS Element Analyzer (Elementar Analysensysteme GmbH, Hanau, Germany) to determine total C and N. After determining physical and chemical properties (Table 1) of the two soil types, plastic pots (19 cm tall, 19 cm outside diameter, and 3785 cm^3

volume) were filled with 3.5 kg of each one of the two soils, which were collected in the field without mixing the different soil horizons. To prevent loss of water and the N-free Hoagland's solution used as fertilizer in this experiment, each plastic pot was lined with a polythene bag.

Table 1. Physical and chemical properties of the Eunola soil and Guernsey soil in the mungbean N_2 fixation study.

Soil properties †	Eunola soil	Guernsey soil
Soil texture	Loamy sand	Silt loam
Field capacity (%)	9	17
Soil pH	5.9	6.2
C (%)	0.98	0.93
N (%)	0.08	0.08
C/N	13	11
NO_3^- (mg kg^{-1})	1.52	2.67
NH_4^+ (mg kg^{-1})	0.32	0.25
P plant available (mg kg^{-1})	37	26
K plant available (mg kg^{-1})	63	61
Ca plant available (mg kg^{-1})	575	859
Mg plant available (mg kg^{-1})	72	167

† pH: soil (1:1 soil: deionized water mixture on a volumetric basis); Total carbon (C) and total nitrogen (N): vario MAX CNS Element Analyzer; Inorganic NO_3^- and NH_4^+: 2M KCl extraction; Plant available nutrients: soil (Mehlich 1 solution).

Experimental design and planting

Two factors were used in this greenhouse experiment. Mungbean genotypes were composed of one hybrid (Berken) (PI 662968, *Vigna radiata*) and 4 open-pollinated [8735 (PI 164442; *Vigna radiata* var. radiata), IC 8972-1 (PI 363217; *Vigna radiata* var. radiata), STB#122 (PI 425083; *Vigna radiata* var. radiata), and 223 (PI 473850; *Vigna radiata*)] (i.e., ‘genotypes’; 5

levels). The second factor (i.e., 'soil texture') had two levels: loamy sand and silt loam textures. Berken is a hybrid, medium-large seeded, and grown cultivar in the U.S. and was obtained from Oklahoma Foundation Seed Stocks (Stillwater, OK, USA). Open-pollinated mungbean seeds were obtained from the U.S. National Plant Germplasm System. Before sowing, mungbean seeds were inoculated with *Bradyrhizobium* inoculum (group I) at a rate of 10 g inoculant kg^{-1} seed. The seed inoculant contained less than 1% of active ingredients [*Bradyrhizobium* sp. (*Vigna*), *Bradyrhizobium japonicum, Rhizobium leguminosarum biovar phaseoli, Rhizobium leguminosarum biovar viceae*] by weight and 99% of inactive ingredients. Sorghum [*Sorghum bicolor* (L.)] and wheat (*Triticum aestivum*) were selected as the non-N_2 fixing reference plants. Seeds of sorghum were obtained from the Tidewater Agricultural Research and Extension Center (AREC) while those of wheat were provided by the wheat breeding group at Virginia Tech. Mungbean and non-legume species were each sown in two soil textures on May 31, 2019 at the Virginia Tech's greenhouse and maintained at 80% field capacity. Field capacity was determined at −0.33 bar water potential using pressure chambers in a 1500F2, 15 bar pressure plate extractors (Soil moisture equipment corp., Santa Barbara, CA). Temperature control systems in the glasshouse were thermostatically controlled keep the minimum daytime temperature at 29°C for 10 h and the minimum night-time temperature at 25°C for 14 h. The experimental pots were laid out in a randomized complete block design with factorial arrangement of factor-levels, resulting in 10 treatment combinations that were replicated six times each.

Plant sampling and processing

At the pod-filling stage (48 days after planting – DAP), mungbean was harvested and separated into shoots and roots while only shoots of reference plants were collected. Plant samples were oven-dried for 48 h at 60°C to constant weight and weighed separately to determine dry matter yield. Plants were then ground to <0.25 mm particle size and placed in 1.5 mL polyallomer tubes (Beckman Instruments, Inc., Fullerton, CA). Prior to shipping for ^{15}N isotopic analysis, finely milled samples were weighed to 3 mg using a Mettler Toledo UMX2 Automated Ultra-Micro Balance (Huntsville, AL) accurate to 0.001 mg, stored into 5x5 mm tin capsules, and placed in 96-well microtiter plates.

Determination of biological N_2 fixation

The ^{15}N natural abundance technique exploits naturally occurring differences in ^{15}N composition between plant-available N sources in the soil and that of atmospheric N_2 (Robinson, 2001; Unkovich et al., 2008). The ^{15}N natural abundance and total N of mungbean and reference plant samples were quantified using the Costech Elemental Analyzer (EA) interfaced to Finnigan MAT-252 isotope ratio mass spectrometer (Thermo Fisher Scientific, Waltham, MA). The ^{15}N abundance is the ‰ deviation of the relative abundance of the sample isotopes from the international standard ($atom\%^{15}N_{atmosphere} = 0.3667$) defined by International Atomic Energy Agency (IAEA). It is expressed using delta (δ) notation (Unkovich et al., 1994).

$$\delta N^{15}(‰) = \frac{atom\%^{15}N_{sample} - \ atom\%^{15}N_{atmosphere}}{atom\%^{15}N_{atmosphere}} \text{x } 1000$$

where $atom\%^{15}N_{sample}$ is the percentage of isotopic abundances ratios of sample ($^{15}N/\,^{14}N$) while $atom\%^{15}N_{atmosphere}$ is the percentage isotope ratio ($^{15}N/\,^{14}N$) in standard air.

The percent N derived from the atmosphere (%Ndfa) in mungbean was estimated as described by (Shearer and Kohl, 1986; Unkovich et al., 2008), as follows:

$$Ndfa(\%) = \frac{\delta^{15}N_{reference\ plant} - \ \delta^{15}N_{legume}}{\delta^{15}N_{reference\ plant} - \ \mathrm{B}} \text{x } 100$$

where $\delta^{15}N_{reference\ plant}$ is the ^{15}N natural abundance of non-N_2 fixing reference plant obtaining all its N from the soil. $\delta^{15}N_{legume}$ is the ^{15}N natural abundance of mungbean deriving all N from symbiotic N_2 fixation. The B value used for mungbean was $-2.50‰$ and is defined as $\delta^{15}N$ of mungbean shoots only dependent on symbiotic N_2 fixation for N nutrition (Shah et al., 2003; Unkovich et al., 2008). The proportion of N derived from atmosphere in mungbean was quantified using mean $\delta^{15}N_{reference\ plant}$ of reference plants. The total N content in mungbean shoots was determined by multiplying mungbean %N and shoot dry biomass weight. The amount of N-fixed was calculated as the product of the percentage of N_2 fixation derived from the atmosphere and the total N content of mungbean shoots (Unkovich et al., 2008). The amount of soil N uptake from soil was obtained by the difference between plant total N and N-fixed.

$\delta^{15}N$ values of reference plant species

To determine the proportion of N derived from the atmosphere (%Ndfa), $\delta^{15}N$ values from shoots of non-fixing legume plants (i.e., sorghum and wheat) were sampled, processed, and analyzed similarly to mungbean. The $\delta^{15}N$ of sorghum shoots in the loamy sand and the silt loam soils were 4.56‰ and 9.25‰, respectively (Table 2). Mean of $\delta^{15}N$ values for sorghum under different soil textures was 6.91‰. An average value of 7.07‰ was recorded for $\delta^{15}N$ in wheat from loamy soil (4.66‰) and silt loam (9.48‰) soils. The $\delta^{15}N$ values of reference plants were always lower in loamy sand compared to silt loam, suggesting that $\delta^{15}N$ values might be influenced by soil texture (Table 2). Differences in background $\delta^{15}N$ values between soil textures as a result of different soil mineral N have also reported by other authors (Mokgehle et al., 2014; Beyan et al., 2018; Raji et al., 2019).

Table 2. δ15N (‰) of reference plants used for estimating soil N uptake by mungbean genotypes in loamy sand and silt loam soils.

	Loamy sand	Silt loam
Reference plants	δ^{15}N values (‰)	
Sorghum *Sorghum bicolor* (L.)	4.56±0.64b†	9.25±0.23a
Wheat *Triticum aestivum*	4.66±0.63b	9.48±0.06a
Average	4.61±0.43b	9.37±0.12a

† Values (Mean ± SE) with dissimilar letters in a row are significantly different at $\alpha = 0.05$. Samples of non-fixing legumes were replicated six times.

Statistical and correlation analyses

Statistical analysis was performed on mungbean dry matter, shoot N concentration and content, δ^{15}N, %Ndfa, N-fixed, and soil N uptake using JMP Pro version 15 statistical software (SAS Institute Inc., Carey, NC). Analysis of variance (ANOVA) was used to test the effects of mungbean genotypes and soil texture on plant growth and symbiotic performance parameters. When treatment effects were significant at $\alpha = 0.05$, Fisher's protected LSD was used for mean separation. Correlation analyses were performed to ascertain the relationships between N fixed and mungbean dry weight as well as soil N uptake and shoot δ^{15}N and soil N uptake and Ndfa %.

Results

Dry matter yield of mungbean

There was a significant soil texture x genotype interaction for dry matter of mungbean roots but not for shoot and whole-plant dry matter (Table 3), indicating that genotypes had different root growth responses in the two soil textures. Analysis of root dry matter production showed that IC 8972-1 (1.4 g plant^{-1}) and Berken (1.43 g plant^{-1}) genotypes produced greater biomass than STB #122, 223, and 8735 genotypes in the loamy sand soil (Table 4). Similarly, genotypes 223 (2.78 g plant^{-1}) and STB #122 (2.59 g plant^{-1}) produced more root biomass in silt loam soil compared to other genotypes (Table 4).

There were significant differences ($P<0.05$) for plant growth (shoot and whole-plant dry matter) of mungbean grown in different soil textures (Table 3). Mungbean grown in silt loam soil produced significantly higher shoot (7.72 g plant^{-1}) biomass than plants in sandy loam soil (2.83 g plant^{-1}) (Table 5). As a result, whole-plant dry matter in silt loam soil (10 g plant^{-1}) was 151% higher than total biomass (4 g plant^{-1}) (Table 5). Genotype IC 8972-1 (6.04 g plant^{-1}) produced significantly greater shoot dry matter, which was not different from STB #122. The lowest shoot biomass was recorded for genotype 8735 (4.72 g plant^{-1}) (Table 5). Similar to shoot dry matter, significant ($P<0.05$) differences were also observed for total-plant dry matter yield between mungbean genotypes which followed the same pattern. The lowest biomass was produced by 8735 (6.11 g plant^{-1}), while biomass measured for genotype IC 8972-1 (7.85 g plant^{-1}) and STB #122 (7.37 g plant^{-1}) was greatest (Table 5).

δ^{15}N and %Ndfa values

The interaction of soil texture and genotypes was significant for %Ndfa, but not for δ^{15}N values (Table 3), indicating that %Ndfa of mungbean genotypes varied significantly under the two soil textures. Comparison of %Ndfa values of mungbean genotypes in the two soil textures revealed significant differences only in the sandy loam soil (Table 4). Genotype 223 derived more N from the atmosphere (42.9%) in the loamy sand soil which was not different from STB #122 (31.2%), the lowest values were recorded for 8735, IC 8972-1, and Berken (Fig. 2A). However, there were no significant differences ($P > 0.05$) among mungbean genotypes for %Ndfa values in silt loam soil (Table 4).

The mean of δ^{15}N values of mungbean grown in two soil textures were significantly different ($P < 0.05$) (Table 3). Plants grown in silt loam soil recorded mean of δ^{15}N values of 9.12‰ while mungbean genotypes in a loamy sand were 4.02‰ (Table 5). However, mean δ^{15}N values did not differ between mungbean genotypes (Table 5).

Shoot N content, amount of N-fixed and Soil N uptake

Shoot N content of mungbean differed ($P < 0.05$) between the two soil textures (Table 3). Mungbean plants in sandy loam soil recorded 432% lower N content in shoots compared to mungbean grown in silt loam (303.4 m plant^{-1}) (Table 5). The N content of mungbean shoots also significantly varied between the five genotypes. Genotype IC 8972-1, which had the highest whole-plant dry matter, recorded the highest N content (200 mg plant^{-1}), while 8735 exhibited the lowest N content of 160 mg plant^{-1} (Table 5). Overall, genotype IC 8972-1 always recorded the highest biomass and shoot N content while 8735 always recorded the lowest values. The similar pattern for whole-plant dry matter and N content might indicate that N content in mungbean genotypes might be influenced by dry biomass.

The amount of N-fixed by mungbean in silt loam soil was 67 mg plant^{-1} and was significantly higher ($P<0.05$) than plants grown in loamy sand soil which fixed 314% less N (Table 3). Similar to shoot N concentration and N content, mungbean plants in silt loam soils which produced the largest shoot biomass also fixed the highest amount of N. Despite significant differences in shoot dry mass between genotypes, the amount of N contribution by mungbean ranged insignificantly from 36.7 to 45.5 mg plant^{-1}, indicating the significant role of soil properties on the efficiency of N_2 fixation in mungbean (Table 5).

As the case with symbiotically fixed N, mungbean in silt loam soil derived more N from the soil than plants in loamy sand soil (Table 5). Genotypes in loamy sand soil obtained 40.8 mg plant^{-1} while, mungbean plants in silt loam soil had 235 mg plant^{-1} from the soil. A comparison of N-fixed and soil N uptake by soil texture revealed that mungbean took up 151% in loamy soil and 249% in silt loam more N from soil than from symbiotic N_2 fixation to meet their N requirements (Table 5). Higher soil N uptake in silt loam soil is explained by the relatively higher concentrations of nitrogen (59% more) compared to the loamy sand soil (Table 1). Overall, mungbean genotypes fixing more N symbiotically also took up more N from the soil. The mean of soil N uptake ranged from 123 to 155 mg plant^{-1} and significantly varied between mungbean genotypes. As shown in Table 3, genotype IC 8972-1 obtained 155 mg plant^{-1} of N the from the soil, followed by STB #122, Berken, 223, while 8735 took up the lowest amount of N (123 mg plant^{-1}) (Table 5).

Table 3. Two-way ANOVA of dry matter (DM) yield in shoot, root and whole plant, percent of nitrogen derived from atmosphere (%Ndfa), N content, concentration and N_2 fixation in shoot, and soil N uptake of mungbean genotypes in a loamy sand and silt loam soils.

	df	DM Shoot†	DM Root	DM Plant	$\delta^{15}N$	Ndfa	Shoot N conc.	Shoot N content	N-fixed	Soil N-uptake
		g plant^{-1}			‰	%		mg plant^{-1}		
Soil texture	1	***	***	***	***	**	***	***	***	***
Genotypes	4	***	*	***	ns	*	ns	**	ns	*
Soil texture x Genotypes‡	4	ns	*	ns	ns	**	ns	ns	ns	ns
Model	9									
Error	50									
Total	59									

† Mean values are significantly different at $p \leq 0.05$ (*), $p \leq 0.01$ (**), $p \leq 0.001$ (***), or ns = not significant.

‡ The interaction between soil texture and genotypes was significant for DM root and Ndfa and data is presented in Table 5.

Table 4. Dry matter root and %Ndfa values of mungbean genotypes in a loamy sand and silt loam soils.

	DM Root		%Ndfa	
	Loamy sand	Silt loam	Loamy sand	Silt loam
Genotypes	g plant^{-1}		%	
8735	0.83 ± 0.18b	1.96 ± 0.20c	23.61 ± 2.94b	22.23 ± 2.70a
IC 8972-1	1.4 ± 0.13a	2.23 ± 0.21bc	22.49 ± 3.50b	22.97 ± 1.22a
STB #122	1.1 ± 0.07ab	2.59 ± 0.13ab	31.23 ± 5.28ab	22.40 ± 2.02a
223	1.08 ± 0.10ab	2.78 ± 0.17a	42.85 ± 5.46a	20.45 ± 2.91a
Berken	1.43 ± 0.19a	2.05 ± 0.22bc	20.91 ± 3.88b	23.49 ± 2.35a

Values (Mean S.E.) with dissimilar letters in a column are significantly different at α = 0.05.

Table 5. Shoot and whole-plant dry matter yield, δ^{15}N, shoot N concentration and content, N-fixed, and soil N uptake of mungbean genotypes in a loamy sand and silt loam soils.

	DM Shoot	DM Plant	δ^{15}N	Shoot N conc.	Shoot N content	N-fixed	Soil N-uptake
	g plant^{-1}		‰	%	mg plant^{-1}		
Soil texture							
Loamy sand	2.83 ± 0.11b†	4.00 ± 0.15b	4.02 ± 0.05b	2.03 ± 0.07b	57.06 ± 3.0b	16.25 ± 1.5b	40.81 ± 2.6b
Silt loam	7.72 ± 0.17a	10.04 ± 0.21a	9.12 ± 0.08a	3.93 ± 0.04a	303.44 ± 7.3a	67.25 ± 3.2a	235 ± 6.7a
Genotypes							
8735	4.72 ± 0.69c	6.11 ± 0.87c	6.62 ± 0.76a	3.00 ± 0.27a	159.98 ± 32.6c	36.74 ± 8.6a	123.24 ± 25.0c
IC 8972-1	6.04 ± 0.78a	7.85 ± 0.92a	6.60 ± 0.75a	2.88 ± 0.32a	200.42 ± 41.5a	45.30 ± 9.4a	155.11 ± 32.5a
STB #122	5.53 ± 0.81ab	7.37 ± 1.03ab	6.53 ± 0.78a	3.00 ± 0.32a	191.64 ± 41.0ab	45.49 ± 8.5a	146.14 ± 33.3ab
223	4.92 ± 0.72c	6.84 ± 0.97b	6.50 ± 0.85a	3.10 ± 0.31a	173.99 ± 36.6bc	41.25 ± 6.7a	132.74 ± 31.7bc
Berken	5.18 ± 0.79bc	6.92 ± 0.90b	6.60 ± 0.74a	2.92 ± 0.29a	175.22 ± 37.4bc	40.70 ± 9.8a	134.52 ± 28.6abc

† Values (Mean ± SE) with dissimilar letters in a column are significantly different at $\alpha = 0.05$.

Correlation analysis

Correlation analyses were performed to evaluate if soil N uptake in the loamy sand and silt loam soils altered shoot dry matter, $\delta^{15}N$ (‰), %Ndfa, and shoot N content. The results in Fig. 1 show a significantly positive relationship between shoot dry matter and soil N uptake in the loamy sand (r = 0.71***) and silt loam soil (r = 0.76***). There was also a significantly positive association between $\delta^{15}N$ (‰) and soil N uptake in both soils (Fig. 2). As a result, we observed a significantly negative relationship between %Ndfa and soil N uptake by mungbean genotypes (Fig 3). To evaluate whether, increasing soil N uptake resulted in higher shoot N content, we measured the correlation coefficient and noted a significant relationship of r = 0.85*** and r = 0.90*** in the loamy sand (Fig 4A) and silt loam soil (Fig 4B), respectively. These results revealed that an increase in soil N uptake induced an increase in shoot dry matter, shoot N content, and $\delta^{15}N$ values, which lowered %Ndfa values (Figs. 1, 2, 3, and 4).

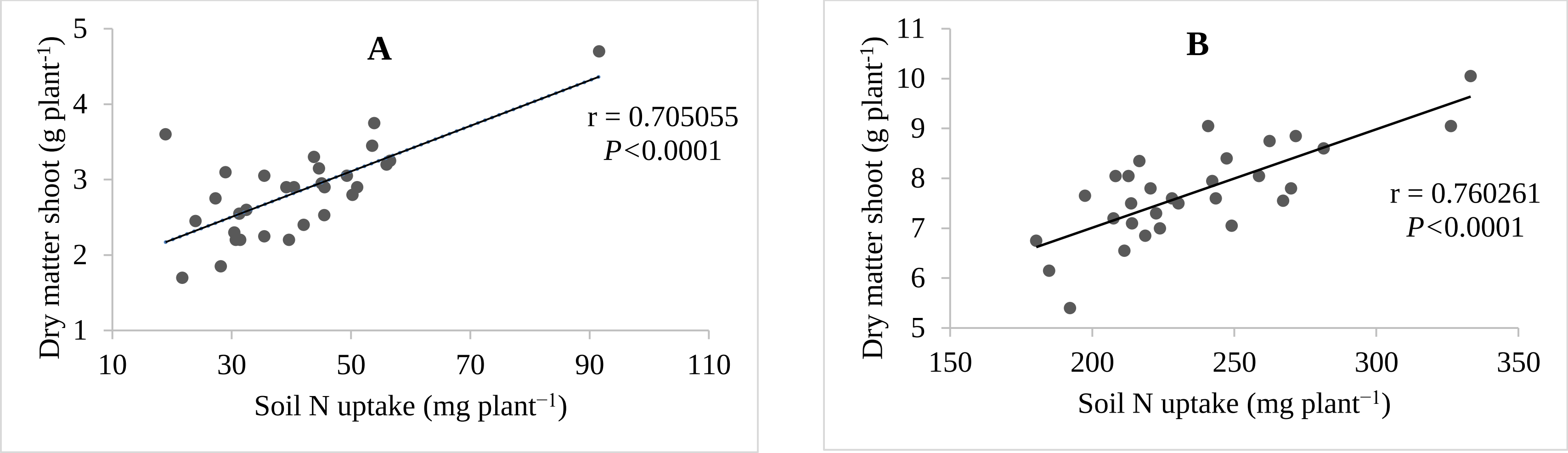

Figure 1. Relationship between shoot dry matter and soil N uptake of mungbean in loamy sand (A) and silt loam (B) soils.

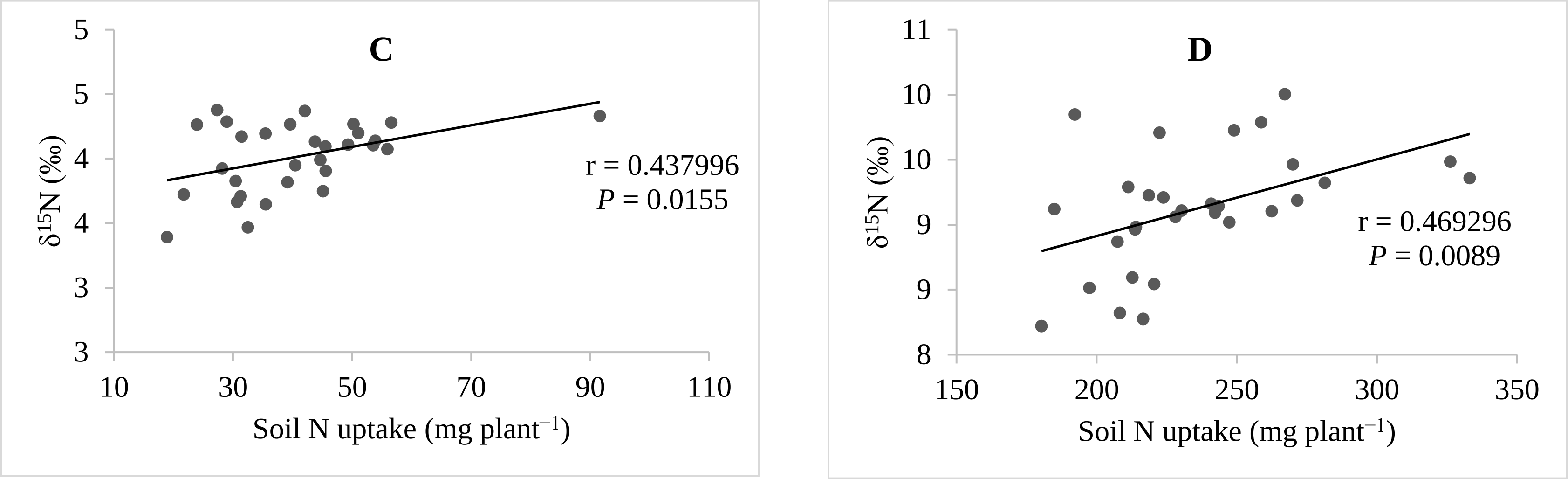

Figure 2. Relationship between δ^{15}N values and soil N uptake of mungbean in loamy sand (C) and silt loam (D) soils.

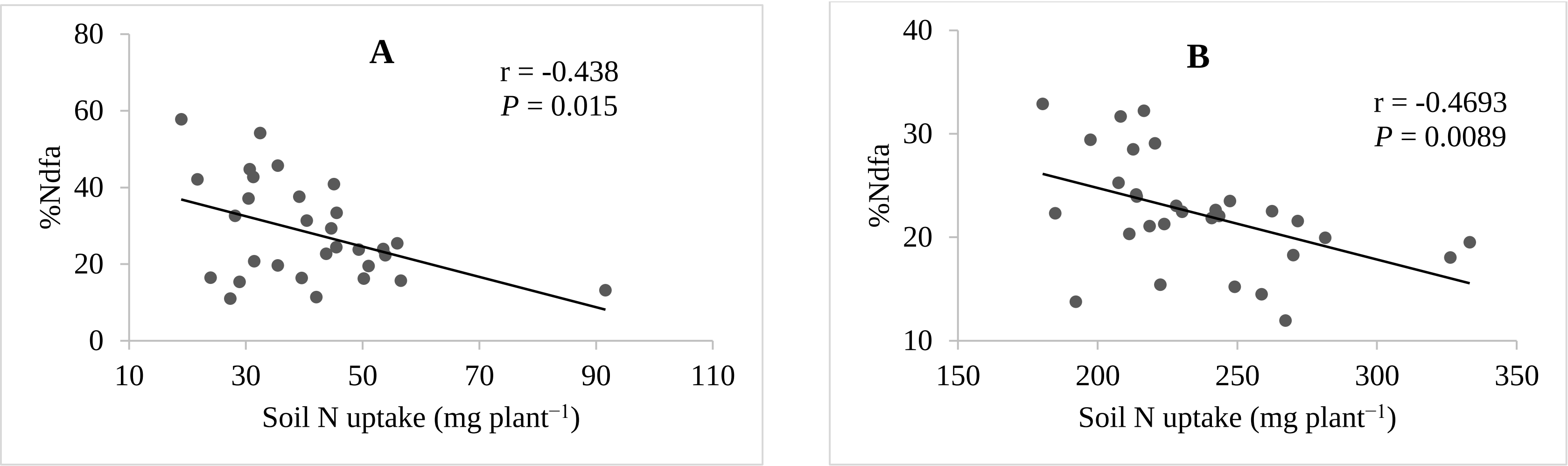

Figure 3. Relationship between %Ndfa and soil N uptake of mungbean in loamy sand (A) and silt loam (B) soils.

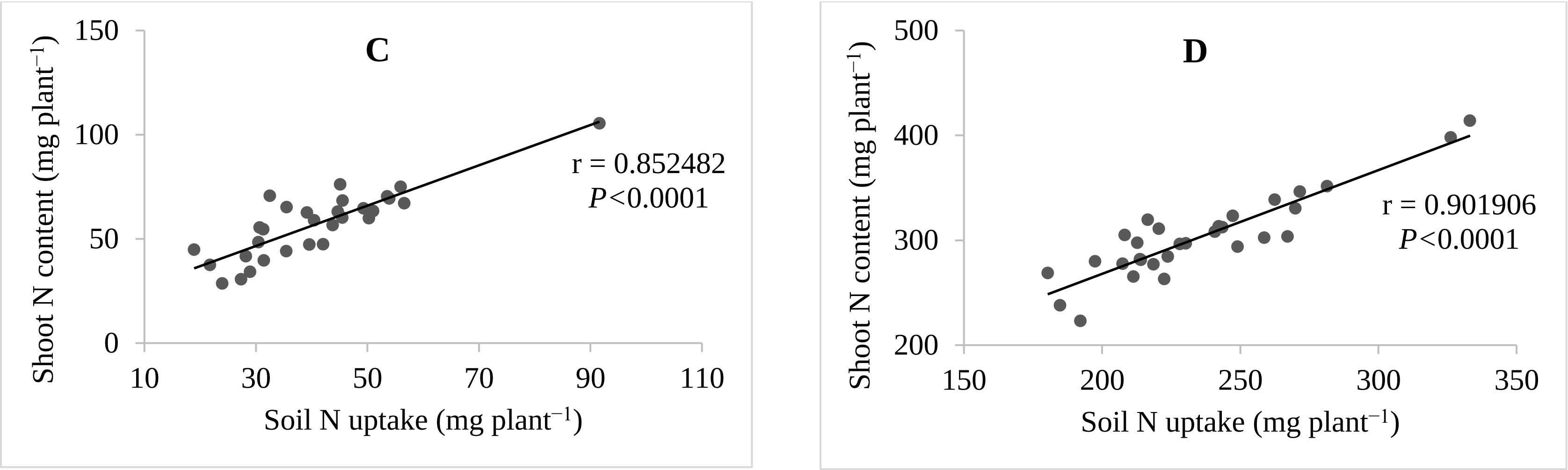

Figure 4. Relationship between shoot N content and soil N uptake of mungbean in loamy sand (C) and silt loam (D) soils.

Discussion

Analysis of the effects of soil texture on mungbean shoot and whole-plant dry matter and shoot N concentration and content revealed significant effects (Table 3). Similarly, $\delta^{15}N$ values, amount of N-fixed, and soil N uptake of mungbean varied between soil textures, demonstrating soil effects on N_2 fixation (Table 3). Mungbean plants grown in silt loam soil produced more biomass than mungbean grown in loamy sand which corresponded to 100% more dry matter yield than plants in the loamy sand soil (Table 5). Differences in biomass yields are probably due to larger concentrations of soil nutrients in the silt loam soil. Significant differences in mungbean biomass yields grown in different soil conditions have been also reported by Diatta et al. (2018).

Shoot N content of mungbean was 432% more in the silt loam soil than values in the loamy sand soil (Table 5). This result suggests that higher plant available soil N in the silt loam soil might have affected shoot N concentration and content. Shoot $\delta^{15}N$ values were 127% higher in the silt loam soil than values recorded in the loamy sand soil due to higher concentrations of plant available N. This increase resulted in 27% more N derived from atmosphere in loamy sand compared to silt loam soil (Table 4). Similar results were observed by Herridge et al. (2005) who found that lower availability of soil nitrate resulted in higher %Ndfa values in mungbean. The silt loam soil, despite having higher concentration of soil N, recorded the highest amounts of N_2 fixation (67.3 mg plant^{-1}) and soil N uptake (235 mg plant^{-1}). In contrast, Raji et al. (2019) found that higher concentration of N inhibits N_2 fixation in mungbean. Increase in N_2 fixation by mungbean in silt loam soil despite having higher soil N concentration could be attributed to N needs being greater than N supply (Salvagiotti et al., 2008).

Plant growth parameters, shoot N content, and soil N uptake significantly varied between genotypes (Table 3). A recent study (Diatta, unpublished data, 2019) documenting adaptation and performance of mungbean genotypes also reported significant difference for plant growth between 8735, IC 8972-1, STB #122, 223, and Berken genotypes. Similar results were observed on mungbean genotypes by Mbeyagala et al. (2016) in Uganda, Kumar and Sharma (2009) in India, Herridge et al. (2005) in Australia. Variations in plant growth between genotypes could be due attributed to genetic variation (Yimram et al., 2009; Rahim et al., 2010).

Though dry matter yields varied among genotypes, the amount of N fixed was similar, indicating that the amount of N fixed was more influenced by soil texture than genotype. In contrast, Herridge and Rose (2000) reported that higher biomass yield would result in increased N_2 fixation by legume crops. Kermah et al. (2018) assessed N contribution by cowpea, soybean and groundnut and indicated that higher biomass yields resulted in greater amounts of fixed N. In addition, Peoples et al. (2009) concluded that accumulated N in legumes could also affect amount of symbiotically fixed N. The review conducted by Dudeja and Duhan (2005) showed that differences in N_2 fixation among mungbean genotypes are also associated to the efficiency symbiosis with rizhobial strains. Soil N uptake differed between mungbean genotypes and ranged from 123 to 155 mg plant^{-1} for 8735 and IC 8972-1 genotypes, respectively. As for soil texture effects, genotypes with higher soil N uptake rates derived less N from atmospheric N_2. In general, mungbean genotypes took up on average 230% more N from the soil than from symbiosis, and yet fixed up to 45.5 mg plant^{-1}. This could indicate tolerance of mungbean-symbionts to soil mineral N. Similar findings were observed by Mokgehle et al. (2014) on groundnut and Mapope and Dakora (2016) on soybean in South Africa.

Mungbean genotypes derived different proportions of N from atmosphere when grown in different soil textures. This indicates the controlling effects of soil texture on N_2 fixation potential of mungbean genotypes (Beyan et al., 2018). On average, mungbean genotypes relied more on N from the atmosphere when grown on the loam sand soil than the silt loam soil. Increase of %Ndfa values in the loamy sand soil could be due to the relatively lower fertility status compared to the silt loam soil (Giller, 2001). Beyan et al. (2018) attributed increase in $\delta^{15}N$ values and subsequent decrease in %Ndfa between soybean genotypes to effective symbiosis with rhizobial populations in soils. Reported %Ndfa values from our study were consistent with the range of 15% and 90% %Ndfa reported by Peoples et al. (2009) and (Peoples et al., 1991), respectively. Shah et al. (2003) indicated from his study in Pakistan that mungbean could derive 100% of its N from N_2 fixation. A more recent study on rhizobial inoculation and P addition effects on mungbean reported mean %Ndfa values ranging from 17 to 50% in high input and low-input soils, respectively (Raji et al., 2019). These values indicate wide variation of mungbean dependence on N from atmosphere.

Generally, the mungbean genotypes taking up the greatest amounts of N also produced the highest dry matter biomass. We found a significantly positive correlation ($P<0.0001$) between soil N uptake and shoot dry matter (Fig. 1). Previous studies have also demonstrated a significantly positive correlation between soil N uptake and plant biomass in mungbean (Delfin et al., 2008). In both soils, mungbean genotypes met their N requirements more from soil N than symbiotically fixed N. There was a significant positive correlation between soil N uptake and $\delta^{15}N$ in the loamy sand (r = 0.44) and silt loam (r = 0.47) (Fig. 2). Mungbean grown in soil with relatively high levels of plant-available N also relied more on soil N uptake than N_2 fixation in field study in Ethiopia (Raji et al., 2019). However, several authors have indicated that limitations in accurately assessing below-ground of fixed N in roots and N inputs through root exudates and decayed root matter could underestimate the amounts of fixed N by legumes (Unkovich et al., 2008; Mapope and Dakora, 2016). We found that genotypes taking up the most N tended to proportionally derive less N from the atmosphere (Fig. 3). Similar results were reported by Mapope and Dakora (2016) when studying symbiotic fixation of soybean genotypes across farmers' fields in South Africa. The significant negative relationship in the loamy sand (r = -0.44) and silt loam (r = -0.47) between soil N uptake and %Ndfa as shown in Fig. 3 could help explain the important effect of soil N in N_2 fixation. A significantly positive relation was found for soil N uptake and shoot N content in both soils, indicating mungbean relied less on biological N_2 fixation for its N requirements than on soil N uptake (Fig. 4). Rao and Ali (2006) also reported that mungbean genotypes in the presence of more soil N enhanced amounts of N in plant biomass.

Conclusion

Estimation of N_2 fixation by mungbean in two soil textures using the ^{15}N the natural abundance technique revealed that plant growth and symbiotic fixation of N differed between genotypes. Plant growth parameters, N_2 fixation, and soil N uptake had significantly higher responses in the silt loam soil compared to loamy sand. These results indicate the role of soil properties in affecting plant development and subsequent N_2

fixation. Among genotypes, IC 8972-1 recorded the highest dry matter yield, shoot N content, and soil N-uptake, indicating that genetic constitution could also influence plant growth and performance of N_2 fixation in mungbean. We found that mungbean derived up to 42.9% of its N from the atmosphere and contributed up to 80.0 mg plant^{-1}. Significant correlations between dry matter and N-fixed, $\delta^{15}N$ (‰) and soil N uptake, %Ndfa and soil N uptake, shoot N content and soil N uptake indicate plant growth and soil properties could alter N_2 fixation. Thus, results from this study demonstrate that mungbean can contribute to N additions in agricultural systems if proper genotypes are grown in suitable soil conditions.

Acknowledgements

The authors are grateful to the School of Plant and Environmental Sciences (SPES) of Virginia Polytechnic Institute & State University for their support and technical assistance and the Virginia Tech's Tidewater Agricultural Research and Extension Center (AREC) for providing sorghum seeds.

References

Abaye A.O., Archibald T., Vaughan L., Thompson T., Thomason W.E., Mbaye D.F., Mamadou L., Abdoulaye S., Gueye F., Snyder G. (2018) Internationalizing the land grant mission: Lessons from Senegal.

Abaye O., Trail P., Gueye T., Gueye F., Mbaye D., Guisse B. (2015) Mungbean as an alternative high protein source food legume for Senegal, Spanish Association for Legumes (AEL), Madrid. pp. 85-86.

Agugo B., Oguike P., Kanu B. (2010) A preliminary field assessment of mungbean (*Vigna radiata* L. Wilczek) yield in the rain forest zone of southeastern Nigeria. American-Eurasian Journal of Agricultural and Environmental Science 8:752-757.

Ahmad S., Ali Khan A., Ali S., Ullah I., Imran M., Habibullah M. (2015) Impact of phoshporus levels on yield and yield attributes of mungbean cultivars under peshawar valley conditions.

Akaerue B., Onwuka G. (2005) The proximate composition, physical qualities, sensory attributes and microbial load of mungbean biscuits as affected by processing. Journal of Emerging Trends in Engineering and Applied Sciences 4:250-7.

Akaerue B., Onwuka G. (2010) Evaluation of the yield, protein content and functional properties of mungbean [*Vigna radiata* (L.) Wilczek] protein isolates as affected by processing. Pakistan Journal of Nutrition 9:728-735. DOI: https://doi.org/10.3923/pjn.2010.728.735

Akibode C.S. (2011) Trends in the production, trade, and consumption of food legume crops in Sub-Saharan Africa, Michigan State University. Agricultural, Food and Resource Economics.

Ali H., Khan E., Sajad M.A. (2013a) Phytoremediation of heavy metals-concepts and applications. Chemosphere 91:869-881.

Ali M., Gupta S. (2012) Carrying capacity of Indian agriculture: pulse crops. Current Science 102:874-881.

Ali S., Hasan A., Ijaz S., Ansar M. (2013b) Mungbean (*Vigna radiata*) yield and di-nitrogen fixation under minimum tillage at semi arid Pothwar, Pakistan. J Anim Plant Sci 23:198-202.

Ambachew S., Alamirew T., Melese A. (2014) Performance of mungbean under deficit irrigation application in the semi-arid highlands of Ethiopia. Agricultural water management 136:68-74. DOI: https://doi.org/10.1016/j.agwat.2014.01.012

Amin M., Karim M., Islam M., Aktar S., Hossain M. (2016) Effect of flooding on growth and yield of mungbean genotypes. Bangladesh Journal of Agricultural Research 41:151-162. DOI: https://doi.org/10.3329/bjar.v41i1.27680

Anjum T., Gupta K.S., Datta S. (2010) Mapping of mungbean yellow mosaic India virus (MYMIV) and powdery mildew resistant gene in black gram [*Vigna mungo* (L.) Hepper]. Electron J Plant Breed 1:1148-1152.

Anwar F., Latif S., Przybylski R., Sultana B., Ashraf M. (2007) Chemical composition and antioxidant activity of seeds of different cultivars of mungbean. Journal of food science 72:S503-S510. DOI: https://doi.org/10.1111/j.1750-3841.2007.00462.x.

Arsenault J.E., Hijmans R.J., Brown K.H. (2015) Improving nutrition security through agriculture: an analytical framework based on national food balance sheets to estimate nutritional adequacy of food supplies. Food Security 7:693-707. DOI: https://doi.org/10.1007/s12571-015-0452-y

Arvind K., Sucheta S., Sital J.S., Sarvjeet S. (2013) Effect of sulfur and nitrogen nutrition on storage protein quality in mungbean [*Vigna radiata* (L.) Wilczek] seeds. Indian Journal of Agricultural Biochemistry 26:86-91.

Auti S.G. (2012) Induced morphological and quantitative mutations in mungbean. Bioremediation, Biodiversity and Bioavailability 6:27-39.

Avav T., Ugese F. (2009) Studies on reproductive abscission and seed yield of mungbean (*Vigna radiata*) in sub-humid savanna of Nigeria. African Journal of Food, Agriculture, Nutrition and Development 9. DOI: https://doi.org/10.4314/ajfand.v9i8.48412

Awan F.K., Ashraf Zahid M., Yaqoob M. (2009) Weed management in mungbean (Vigna radiata (l.) R. wilczek) using different methods and row spacing. Pak. J. Weed Sci. Res 15:269-274.

Bado B., Bationo A., Cescas M. (2006) Assessment of cowpea and groundnut contributions to soil fertility and succeeding sorghum yields in the Guinean savannah zone of Burkina Faso (West Africa). Biology and Fertility of Soils 43:171-176. DOI: https://doi.org/10.1007/s00374-006-0076-7

Barrett C.B., Bevis L.E. (2015) The self-reinforcing feedback between low soil fertility and chronic poverty. Nature Geoscience 8:907-912. DOI: https://doi.org/10.1038/ngeo2591

Bationo A., Lompo F., Koala S. (1998) Research on nutrient flows and balances in West Africa: state-of-the-art. Agriculture, ecosystems & environment 71:19-35. DOI: https://doi.org/10.1016/s0167-8809(98)00129-7

Begum M., Begum M., Anwar M., Juraimi A. (2009) Optimizing seed rate for summer mungbean varieties. J. Agric. Soc. Sci 5:114-118.

Belane A.K., Dakora F.D. (2010) Symbiotic N 2 fixation in 30 field-grown cowpea (*Vigna unguiculata* L. Walp.) genotypes in the Upper West Region of Ghana measured using 15 N natural abundance. Biology and Fertility of Soils 46:191-198. DOI: https://doi.org/10.1007/s00374-009-0415-6

Beyan S.M., Wolde-meskel E., Dakora F.D. (2018) An assessment of plant growth and N 2 fixation in soybean genotypes grown in uninoculated soils collected from different locations in Ethiopia. Symbiosis:1-15. DOI: https://doi.org/10.1007/s13199-018-0540-9

Bhardwaj H.L., Rangappa M., Hamama A.A. (1999) Chickpea, faba bean, lupin, mungbean, and pigeonpea: potential new crops for the Mid-Atlantic Region of the United States. Perspectives on new crops and new uses:202.

Bibi Z., Gohar A., Sajid S., Shah Z., Ehtesham J. (2016) Response of brinjal (*Solanum melongena* L.) cultivars to nitrogen levels. Pure and Applied Biology 5:134-141. DOI: https://doi.org/10.19045/bspab.2016.50018

Binyamin R., Khan M.A., Khan N.A., Khan A.I. (2015) Application of SCAR markers linked with mungbean yellow mosaic virus disease-resistance gene in Pakistan mungbean germplasm. Genetics and Molecular Research 14:2825-2830. DOI: https://doi.org/10.4238/2015.march.31.13

Biriah N., Chemining'wa G., Olubayo F., Saha H. (2017) Effect of cropping system on soil moisture content, canopy temperature, growth and yield performance of maize and cowpea.

Boddey R.M., Peoples M.B., Palmer B., Dart P.J. (2000) Use of the 15N natural abundance technique to quantify biological nitrogen fixation by woody perennials. Nutrient Cycling in Agroecosystems 57:235-270.

Bogie N., Bayala R., Diedhiou I., Dick R., Ghezzehei T. (2019) Intercropping with two native woody shrubs improves water status and development of interplanted groundnut and pearl millet in the Sahel. Plant and soil 435:143-159. DOI: https://doi.org/10.1007/s11104-018-3882-4

Box G.E., Cox D.R. (1964) An analysis of transformations. Journal of the Royal Statistical Society: Series B (Methodological) 26:211-243.

Brooker R.W., Bennett A.E., Cong W.F., Daniell T.J., George T.S., Hallett P.D., Hawes C., Iannetta P.P., Jones H.G., Karley A.J. (2015) Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. New Phytologist 206:107-117. DOI: https://doi.org/10.1111/nph.13132

Brown M.E., Hintermann B., Higgins N. (2009) Markets, climate change, and food security in West Africa. Environmental science & technology 43:8016-8020. DOI: https://doi.org/10.1111/nph.13132

Cairns J.E., Hellin J., Sonder K., Araus J.L., MacRobert J.F., Thierfelder C., Prasanna B. (2013) Adapting maize production to climate change in sub-Saharan Africa. Food Security 5:345-360.

Cao D., Li H., Yi J., Zhang J., Che H., Cao J., Yang L., Zhu C., Jiang W. (2011) Antioxidant properties of the mung bean flavonoids on alleviating heat stress. PloS one 6:e21071. DOI: https://doi.org/10.1371/journal.pone.0021071

Carranca C., Torres M.O., Madeira M. (2015) Underestimated role of legume roots for soil N fertility. Agronomy for Sustainable Development 35:1095-1102. DOI: 10.1007/s13593-015-0297-y.

Chadha M. (2001) Mungbean (*Vigna radiata* L.), a choice crop for improvement of human and soil health in southern Africa, Combating Desertification with Plants, Springer. pp. 263-271.

Chikowo R., Mapfumo P., Nyamugafata P., Giller K. (2004a) Woody legume fallow productivity, biological N 2-fixation and residual benefits to two successive maize crops in Zimbabwe. Plant and Soil 262:303-315. DOI: https://doi.org/10.1023/b:plso.0000037053.05902.60

Chikowo R., Mapfumo P., Nyamugafata P., Giller K.E. (2004b) Maize productivity and mineral N dynamics following different soil fertility management practices on a depleted sandy soil in Zimbabwe. Agriculture, ecosystems & environment 102:119-131. DOI: https://doi.org/10.1016/j.agee.2003.08.009

Chitra U., Vimala V., Singh U., Geervani P. (1995) Variability in phytic acid content and protein digestibility of grain legumes. Plant Foods for Human Nutrition 47:163-172. DOI: https://doi.org/10.1007/bf01089266

Clay D., Chang J., Clay S., Ellsbury M., Carlson C., Malo D., Woodson D., De Sutter T. (1997) Field scale variability of nitrogen and δ15N in soil and plants. Communications in soil science and plant analysis 28:1513-1527. DOI: https://doi.org/10.1080/00103629709369893

Climate Research Unit of East Anglia. (2019) Average monthly temperature and rainfall for Senegal at locations (14.7,-16.46) and (13.74,-15.77) from 1990-2012. The World Bank Group, Climate Change Knowledge Portal. http://sdwebx.worldbank.org/climateportal/index.cfm?page=country_historical_climate&ThisRegion=Africa&ThisCCode=SEN (accessed 22 March 2016).

Connolly-Boutin L., Smit B. (2016) Climate change, food security, and livelihoods in sub-Saharan Africa. Regional Environmental Change 16:385-399. DOI: https://doi.org/10.1007/s10113-015-0761-x

Corbeels M., Cardinael R., Naudin K., Guibert H., Torquebiau E. (2019) The 4 per 1000 goal and soil carbon storage under agroforestry and conservation agriculture systems in sub-Saharan Africa. Soil and Tillage Research 188:16-26. DOI: https://doi.org/10.1016/j.still.2018.02.015

Dahiya P.K., Linnemann A.R., Van Boekel M.A.J.S., Khetarpaul N., Grewal R.B., Nout M.J.R. (2015) Mung bean: Technological and nutritional potential. Critical Reviews in Food Science and Nutrition 55:670-688. DOI: https://doi.org/10.1080/10408398.2012.671202

Dakora F.D., Belane A.K., Mohale K.C., Makhubedu T.I., Makhura P., Pule-Meulenberg F., Mapope N., Mogkelhe S.N., Gyogluu C., Phatlane G.P. (2015) Food grain legumes: their contribution to soil fertility, food security, and human nutrition/health in Africa. Biological nitrogen fixation:1063-1070. DOI: https://doi.org/10.1002/9781119053095.ch105

Daryanto S., Fu B., Zhao W., Wang S., Jacinthe P.-A., Wang L. (2020) Ecosystem service provision of grain legume and cereal intercropping in Africa. Agricultural Systems 178:102761. DOI: https://doi.org/10.1016/j.agsy.2019.102761

Delfin E.F., Paterno E.S., Torres° F.G., Santos P.J.A. (2008) Biomass, nitrogen uptake and fixed nitrogen partitioningin field grown mungbean (*Vigna radiata* L. Wilczek) inoculated with Bradyrhizobium. Philippine. Journal of Crop Science (PJCS) 33:24-33.

Devi M.J., Sinclair T.R., Beebe S.E., Rao I.M. (2013) Comparison of common bean (*Phaseolus vulgaris* L.) genotypes for nitrogen fixation tolerance to soil drying. Plant and Soil 364:29-37. DOI: https://doi.org/10.1007/s11104-012-1330-4

Devi M.J., Sinclair T.R., Vadez V. (2010) Genotypic variability among peanut (*Arachis hypogea* L.) in sensitivity of nitrogen fixation to soil drying. Plant and Soil 330:139-148. DOI: https://doi.org/10.1007/s11104-009-0185-9

Dey S.K., Chakrabarti B., Prasanna R., Mittal R., Singh S.D., Pathak H. (2016) Growth and biomass partitioning in mungbean with elevated carbon dioxide, phosphorus levels and cyanobacteria inoculation. Journal of Agrometeorology 18:7-12.

Dhayal B.L., Patel C.R., Mehta B.M. (2015) A study on constraints perceived by the farmers in adoption of moongbean production technology in Vadodara and Chhotaudaipur district of Gujarat. Agriculture Update 10:343-350. DOI: https://doi.org/10.15740/has/au/10.4/343-350

Dhole V.J., Reddy K.S. (2015) Genetic variation for phytic acid content in mungbean (*Vigna radiata* L. Wilczek). The Crop Journal 3:157-162. DOI: https://doi.org/10.1016/j.cj.2014.12.002

Diangar S., Fofana A., Diagne M., Yamoah C.F., Dick R.P. (2004) Pearl millet-based intercropping systems in the semiarid areas of Senegal. African Crop Science Journal 12:133-139. DOI: https://doi.org/10.4314/acsj.v12i2.27671

Diatta A., Abaye O., Thomason W., Lo M., Guèye F., Baldé A., Tine F., Vaughan L., Thompson T. (2019a) Effect of intercropping mungbean on millet yield in the Peanut basin, Senegal Innovations Agronomiques 74:69-81.

Diatta A., Thomason W.E., Abaye O. (2019b) Nitrogen fixation by mungbean genotypes in different soil textures, ASA, CSSA and SSSA International Annual Meetings (2019), ASA, CSSA, and SSSA.

Diatta A.A. (2016) Effects of biochar application on soil fertility and pearl millet (*Pennisetum glaucum* L.) yield, Virginia Tech.

Diatta A.A., Ndour N., Manga A., Sambou B., Faye C.S., Diatta L., Goudiaby A., Mbow C., Dieng S.D. (2016a) Ecosystem services of *Cordyla pinnata* (Lepr. ex A. Rich.) Milne-Redh. agroforestry parkland of Senegal's South Peanut Basin

International Journal of Biological and Chemical Sciences 10:2511-2525. DOI: https://doi.org/10.4314/ijbcs.v10i6.9

Diatta A.A., Ndour N., Manga A., Sambou B., Faye C.S., Diatta L., Mbow C. (2016b) Floristic composition and dynamics of *Cordyla pinnata* (Lepr. ex A. Rich.) Milne-Redh. agroforestry parkland of Senegal's South Peanut Basin International Journal of Biological and Chemical Sciences 10:1805-1822. DOI: https://doi.org/10.4314/ijbcs.v10i4.29

Diatta A.A., Thomason W.E., Abaye O., Vaughan L.J., Thompson T.L., Lo M., Chim B.K., Bateman S. (2018) Inoculation and soil texture effects on yield and yield components of mungbean. Journal of Agricultural Science (Toronto) 10:6-16. DOI: https://doi.org/10.5539/jas.v10n9p6

Dubey S.C., Birendra S. (2013) Integrated management of major diseases of mungbean by seed treatment and foliar application of insecticide, fungicides and bioagent. Crop Protection 47:55-60. DOI: https://doi.org/10.1016/j.cropro.2012.12.025

Dudeja S., Duhan J. (2005) Biological nitrogen fixation research in pulses with special reference to mungbean and urdbean. Indian Journal of Pulses Research 18:107.

Dwivedi A., Singh A., Naresh R., Kumar M., Kumar V., Bankoti P., Sharma D.K., Thaneshwar A.S., Singh O. (2016) Towards sustainable intensification of maize (Zea mays L.)+ legume intercropping systems; experiences; challenges and opportunities in India; a critical review. Journal of Pure and Applied Microbiology 10:725-741.

Elkowicz K., Sosulski F. (1982) Antinutritive factors in eleven legumes and their air-classified protein and starch fractions. Journal of Food Science 47:1301-1304. DOI: https://doi.org/10.1111/j.1365-2621.1982.tb07673.x

Erdle K., Mistele B., Schmidhalter U. (2011) Comparison of active and passive spectral sensors in discriminating biomass parameters and nitrogen status in wheat cultivars. Field Crops Research 124:74-84. DOI: https://doi.org/10.1016/j.fcr.2011.06.007

Fall A., Lo M. (2009) Etude de référence sur les céréales: mil, sorgho, maïs, et fonio au Sénégal. CORAF/WECARD, Sénégal.

FAOSTAT. (2019) Crops: production quantity. Available online: http://www.fao.org/faostat/en/#data/QC. (Accessed on 17 January 2019).

FAOSTAT. (2020) Crops: production quantity. Available online: http://www.fao.org/faostat/en/#data/QC. (Accessed on 19 February 2020).

Faye C., Faye M., Sambou H., Diatta A., Diatta L., Manga A., Konate K. (2019) Modélisation de la biomasse aérienne des parcs arborés à *Cordyla pinnata*: Keur Samba Guèye. Journal of Chemical, Biological and Physical Sciences 09:238-250. DOI: https://doi.org/10.24214/jcbps.d.9.3.23849

Foyer C.H., Lam H., Nguyen H.T., Siddique K.H.M., Varshney R.K., Colmer T.D., Cowling W., Bramley H., Mori T.A., Hodgson J.M., Cooper J.W., Miller A.J., Kunert K., Vorster J., Cullis C., Ozga J.A., Wahlqvist M.L., Liang Y., Shou H., Shi K., Yu J., Fodor N., Kaiser B.N., Wong F., Valliyodan B., Considine M.J. (2016) Neglecting legumes has compromised human health and sustainable food production. Nature Plants 2:16112. DOI: https://doi.org/10.1038/nplants.2016.112

Francis C.A., Flor C., Temple S.R. (1976) Adapting varieties for intercropping systems in the tropics. Multiple cropping 27:235-253. DOI: https://doi.org/10.2134/asaspecpub27.c12

Franke A., Van den Brand G., Vanlauwe B., Giller K. (2018) Sustainable intensification through rotations with grain legumes in Sub-Saharan Africa: A review. Agriculture, ecosystems & environment 261:172-185. DOI: https://doi.org/10.1016/j.agee.2017.09.029

Fu G., Shen Z.-X. (2016) Response of Alpine plants to nitrogen addition on the Tibetan Plateau: A Meta-analysis. Journal of Plant Growth Regulation 35:974-979. DOI: https://doi.org/10.1007/s00344-016-9595-0

Gamon J.A., Field C.B., Goulden M.L., Griffin K.L., Hartley A.E., Joel G., Penuelas J., Valentini R. (1995) Relationships between NDVI, canopy structure, and photosynthesis in three Californian vegetation types. Ecological Applications 5:28-41. DOI: https://doi.org/10.2307/1942049

Ganesan K., Xu B. (2017) A critical review on phytochemical profile and health promoting effects of mung bean (Vigna radiata). Food Science and Human Wellness. DOI: https://doi.org/10.1016/j.fshw.2017.11.002

Gastwirth J.L., Gel Y.R., Miao W. (2009) The impact of Levene's test of equality of variances on statistical theory and practice. Statistical Science:343-360. DOI: https://doi.org/10.1214/09-sts301

Gaudreau K., Gibson R.B. (2015) Sustainability assessment of the agricultural and energy systems of Senegal. Energies 8:3503-3528. DOI: https://doi.org/10.3390/en8053503

Gebru H. (2015) A review on the comparative advantages of intercropping to mono-cropping system. Journal of Biology, Agriculture and Healthcare 5:1-13.

Geng H., Pan H., Lu Y., Yang Y. (2012) Nymphal and adult performance of Apolygus lucorum (Hemiptera: Miridae) on a preferred host plant, mungbean Vigna radiata. Applied entomology and zoology 47:191-197.

George T., Ladha J.K., Garrity D.P., Torres R.O. (1995) Nitrogen dynamics of grain legume-weedy fallow-flooded rice sequences in the tropics. Agronomy journal 87:1-6. DOI: https://doi.org/10.2134/agronj1995.00021962008700010001x

Ghilotia Y., Meena R., Singh L. (2015) Pearlmillet and mungbean intercropping as influenced by various row ratios under custard apple orchard of Vindhyan region. The Bioscan 10:87-91.

Giller K., J Wilson K. (1991) Nitrogen fixation in tropical cropping systems.

Giller K.E. (2001) Nitrogen fixation in tropical cropping systems Cabi.

Gomez A.A., Gomez K.A. (1983) Multiple cropping in the humid tropics of Asia International development research centre.

Gong X., Ferdinand U., Dang K., Li J., Chen G., Luo Y., Yang P., Feng B. (2019) Boosting proso millet yield by altering canopy light distribution in proso millet/mung bean intercropping systems. The Crop Journal. DOI: https://doi.org/10.1016/j.cj.2019.09.009

Graham P.H., Vance C.P. (2003) Legumes: importance and constraints to greater use. Plant physiology 131:872-877. DOI: https://doi.org/10.1104/pp.017004

Grist N. (2014) Transformative adaptation in Africa's agriculture, Contribution Note for Africa Progress Panel meeting."Expert Consultation: an African Agenda for Green, Low Carbon Development", Geneva.

Gupta S.C. (1984) Programme d'amélioration du mil: développement des pratiques culturales pour les nouvelles variétés. In: Rapport annuel 1983-1984. ISRA, CNRA Bambey, 32 p.

Gupta Y. (1987) Anti-nutritional and toxic factors in food legumes: a review. Plant foods for human nutrition 37:201-228. DOI: https://doi.org/10.1007/bf01091786

Habibzadeh Y., Pirzad A., Zardashti M.R., Jalilian J., Eini O. (2013) Effects of arbuscular mycorrhizal fungi on seed and protein yield under water-deficit stress in mung bean. Agronomy Journal 105:79-84. DOI: https://doi.org/10.2134/agronj2012.0069

HanumanthaRao B., Nair R.M., Nayyar H. (2016) Salinity and high temperature tolerance in mungbean [*Vigna radiata* (L.) Wilczek] from a physiological perspective. Frontiers in Plant Science 7. DOI: https://doi.org/10.3389/fpls.2016.00957

Hawke D. (2001) Variability of δ15N in soil and plants at a New Zealand hill country site: correlations with soil chemistry and nutrient inputs. Soil Research 39:373-383. DOI: https://doi.org/10.1071/sr99094

Hayat R., Ali S. (2004) Potential of summer legumes to fix nitrogen and benefit wheat crop under rainfed condition. J. Agron 3:273-281. DOI: https://doi.org/10.3923/ja.2004.273.281.

Hayat R., Ali S. (2010) Nitrogen fixation of legumes and yield of wheat under legumes-wheat rotation in Pothwar. Pak J Bot 42:2317-2326.

Hayat R., Ali S., Ijaz S.S., Chatha T.H., Siddique M.T. (2008) Estimation of N2-fixation of mung bean and mash bean through xylem uriede technique under rainfed conditions. Pak J Bot 40:723-734.

Hemalatha S., Platel K., Srinivasan K. (2007) Influence of germination and fermentation on bioaccessibility of zinc and iron from food grains. European journal of clinical nutrition 61:342. DOI: https://doi.org/10.1038/sj.ejcn.1602524

Herridge D., Robertson M., Cocks B., Peoples M., Holland J., Heuke L. (2005) Low nodulation and nitrogen fixation of mungbean reduce biomass and grain yields. Australian Journal of Experimental Agriculture 45:269-277. DOI: https://doi.org/10.1071/ea03130

Herridge D., Rose I. (2000) Breeding for enhanced nitrogen fixation in crop legumes. Field Crops Research 65:229-248. DOI: https://doi.org/10.1007/978-94-009-5077-1

Herridge D.F., Peoples M.B., Boddey R.M. (2008) Global inputs of biological nitrogen fixation in agricultural systems. Plant and soil 311:1-18. DOI: https://doi.org/10.1007/s11104-008-9668-3

IMARC. (2018) International Market Analysis Research and Consulting. Global mung beans market driven by various health benefits and multiple uses in the food industry. https://www.imarcgroup.com/global-mung-beans-market (Accessed on April 18, 2018).

Imtiaz H., BurhanUddin M., Gulzar M.A. (2011) Evaluation of weaning foods formulated from germinated wheat and mungbean from Bangladesh. African Journal of Food Science 5:897-903. DOI: https://doi.org/10.5897/ajfs11.180

Juana J.S., Kahaka Z., Okurut F.N. (2013) Farmers' perceptions and adaptations to climate change in sub-Sahara Africa: A synthesis of empirical studies and implications for public policy in African agriculture. Journal of Agricultural Science 5:121. DOI: https://doi.org/10.5539/jas.v5n4p121

Kang Y.J., Kim S.K., Kim M.Y., Lestari P., Kim K.H., Ha B.-K., Jun T.H., Hwang W.J., Lee T., Lee J., Shim S., Yoon M.Y., Jang Y.E., Han K.S., Taeprayoon P., Yoon N., Somta P., Tanya P., Kim K.S., Gwag J.-G., Moon J.-K., Lee Y.-H., Park B.-S., Bombarely A., Doyle J.J., Jackson S.A., Schafleitner R., Srinives P., Varshney R.K., Lee S.-H. (2014) Genome sequence of mungbean and insights into evolution within Vigna species. Nature Communications 5:5443. DOI: https://doi.org/10.1038/ncomms6443

Kassa Y., Admasu D., Tigabe A., Abie A., Mamo D. (2018) Participatory on farm evaluation of improved mungbean technologies in the low land areas of North Shewa Zone Amhara Region, Ethiopia. Journal of Agricultural Extension and Rural Development 10:158-164. DOI: https://doi.org/10.5897/jaerd2018.0962

Kaur R., Bains T., Bindumadhava H., Nayyar H. (2015) Responses of mungbean (Vigna radiata L.) genotypes to heat stress: effects on reproductive biology, leaf function and yield traits. Scientia Horticulturae 197:527-541. DOI: https://doi.org/10.1016/j.scienta.2015.10.015

Keatinge J., Easdown W., Yang R., Chadha M., Shanmugasundaram S. (2011) Overcoming chronic malnutrition in a future warming world: the key importance of mungbean and vegetable soybean. Euphytica 180:129-141. DOI: https://doi.org/10.1007/s10681-011-0401-6

Kermah M., Franke A., Adjei-Nsiah S., Ahiabor B., Abaidoo R.C., Giller K. (2018) N2-fixation and N contribution by grain legumes under different soil fertility status and cropping systems in the Guinea savanna of northern Ghana. Agriculture, ecosystems & environment 261:201-210. DOI: https://doi.org/10.1016/j.agee.2017.08.028

Khan F., Ahmed Z., Muhammad A., Hassnain S. (2008) Response of mungbean genotypes to Rhizobium inoculum and varying levels of nitrogen fertilizer. Pakistan Journal of Agricultural Research 21:33-44.

Khattak A.B., Nizakat B., Aurangzeb. (2007) Quality assessment and consumers acceptability studies of newly evolved mungbean genotypes (*Vigna radiata* L.). American Journal of Food Technology 2:536-542. DOI: https://doi.org/10.3923/ajft.2007.536.542

Kim S.K., Nair R.M., Lee J., Lee S.-H. (2015) Genomic resources in mungbean for future breeding programs. Frontiers in plant science 6:626. DOI: https://doi.org/10.3389/fpls.2015.00626

Kirchhof G., So H. (1995) The effect of puddling intensity and compaction on soil properties, rice and mungbean growth: a mini-ricebed study. Management of clay soils for rainfed lowland rice-based cropping systems:51.

Klimek-Kopyra A., Zając T., Oleksy A., Kulig B. (2018) Biological and production responses of intercropped plants of pea, spring wheat, and linseed. Acta Agrobotanica 71. DOI: https://doi.org/10.5586/aa.1737

Kotir J.H. (2011) Climate change and variability in Sub-Saharan Africa: a review of current and future trends and impacts on agriculture and food security. Environment, Development and Sustainability 13:587-605. DOI: https://doi.org/10.1007/s10668-010-9278-0

Kouakou P.K., Muller B., Affholder F., Guisse A., Sultan B. (2015) Pearl millet yields and climate evolution across the last 20 years in central Senegal. A yield gap study.[P93].

Kumar A., Sharma K. (2009) Physiological responses and dry matter partitioning of summer mungbean (*Vigna radiata* L.) genotypes subjected to drought conditions. Journal of Agronomy and Crop science 195:270-277. DOI: https://doi.org/10.1111/j.1439-037x.2009.00373.x

Kumar Dahiya P., Nout M., A. van Boekel M., Khetarpaul N., Bala Grewal R., Linnemann A. (2014) Nutritional characteristics of mung bean foods. British Food Journal 116:1031-1046. DOI: https://doi.org/10.1108/bfj-11-2012-0280

Kumar R., Singh R. (2008) Improvement in mungbean: present scenario and future challenges. National Journal of Plant Improvement 10:69-74.

Kumar S., Kumar R. (2014) Genetic improvement in mungbean [*Vigna radiata* (L). Wilzeck] for yield, nutrition and resistance to stresses-a review. International Journal of Tropical Agriculture 32:683-687. DOI: https://doi.org/10.1111/j.1439-0523.2012.01964.x

Laio F. (2004) Cramer–von Mises and Anderson-Darling goodness of fit tests for extreme value distributions with unknown parameters. Water Resources Research 40. DOI: https://doi.org/10.1029/2004wr003204

Lal R., Singh B.R., Mwaseba D.L., Kraybill D., Hansen D.O., Eik L.O. (2015) Sustainable intensification to advance food security and enhance climate resilience in Africa. Springer International Publishing Switzerland, Heidelberg. doi 10:978-3. DOI: https://doi.org/10.1007/978-3-319-09360-4

Lal S. (1985) A review of insect pests of mungbean and their control in India. International Journal of Pest Management 31:105-114. DOI: https://doi.org/10.1080/09670878509370960

Lalinia A.A., Hoseini N.M., Galostian M., Bahabadi S.E., Khameneh M.M. (2012) Echophysiological impact of water stress on growth and development of mungbean. International Journal of Agronomy and Plant Production 3:599-607.

Lambrides C., Godwin I. (2007) Mungbean, Pulses, sugar and tuber crops, Springer. pp. 69-90.

Li Y., Ran W., Zhang R., Sun S., Xu G. (2009) Facilitated legume nodulation, phosphate uptake and nitrogen transfer by arbuscular inoculation in an upland rice and mung bean intercropping system. Plant and Soil 315:285-296. DOI: https://doi.org/10.1007/s11104-008-9751-9

Lithourgidis A., Vlachostergios D., Dordas C., Damalas C. (2011) Dry matter yield, nitrogen content, and competition in pea–cereal intercropping systems. European Journal of agronomy 34:287-294. DOI: https://doi.org/10.1016/j.eja.2011.02.007

Lloyd S.J., Kovats R.S., Chalabi Z. (2011) Climate change, crop yields, and undernutrition: development of a model to quantify the impact of climate scenarios on child undernutrition. Environmental health perspectives 119:1817. DOI: https://doi.org/10.1289/ehp.1003311

Lu Y., Wu K., Wyckhuys K., Guo Y. (2009) Potential of mungbean, *Vigna radiatus* as a trap crop for managing *Apolygus lucorum* (Hemiptera: Miridae) on Bt cotton. Crop Protection 28:77-81. DOI: https://doi.org/10.1016/j.cropro.2008.08.018

Magrini M.-B., Anton M., Cholez C., Corre-Hellou G., Duc G., Jeuffroy M.-H., Meynard J.-M., Pelzer E., Voisin A.-S., Walrand S. (2016) Why are grain-legumes rarely present in cropping systems despite their environmental and nutritional benefits? Analyzing lock-in in the French agrifood system. Ecological Economics 126:152-162. DOI: https://doi.org/10.1016/j.ecolecon.2016.03.024.

Makoi J.H., Chimphango S.B., Dakora F.D. (2009) Effect of legume plant density and mixed culture on symbiotic N 2 fixation in five cowpea (*Vigna unguiculata* L. Walp.) genotypes in South Africa. Symbiosis 48:57-67. DOI: https://doi.org/10.1007/bf03179985

Maman N., Dicko M., Abdou G., Kouyate Z., Wortmann C. (2017) Pearl millet and cowpea intercrop response to applied nutrients in West Africa. Agronomy Journal 109:2333-2342. DOI: https://doi.org/10.2134/agronj2017.03.0139

Mapope N., Dakora F.D. (2016) N2 fixation, carbon accumulation, and plant water relations in soybean (*Glycine max* L. Merrill) varieties sampled from farmers' fields in South Africa, measured using 15N and 13C natural abundance. Agriculture, Ecosystems & Environment 221:174-186. DOI: https://doi.org/10.1016/j.agee.2016.01.023

Maseko S.T., Maredi M.P., Mathews C., Dakora F.D. (2020) Harnessing ecosystem services from biological nitrogen fixation, The Role of Ecosystem Services in Sustainable Food Systems, Elsevier. pp. 73-94.

Matusso J., Mugwe J., Mucheru-Muna M. (2014) Potential role of cereal-legume intercropping systems in integrated soil fertility management in smallholder farming systems of sub-Saharan Africa. Journal of Agriculture and Environmental Management 3:162-174.

Mbaye M., Kane A., Gueye M., Bassene C., Ba N., Diop D., Sylla S., Noba K. (2014) Optimal sowing date and density of cowpea [*Vigna unguiculata* (L.) Walp.] in an intercropping system with millet [*Pennisetum glaucum* (L.) R. Br.]. Journal of Applied Biosciences 76:6305-6315.

Mbeyagala E., Amayo R., Obuo J. (2016) Adaptation of introduced mungbean genotypes in Uganda. African Crop Science Journal 24:155-166. DOI: https://doi.org/10.4314/acsj.v24i2.4

Mbeyagala E., Kwikiriza N., Amayo R., Omadi J., Okwang D., Obuo J. (2017) Participatory selection of mungbean genotypes in Uganda. African Crop Science Journal 25:253-262. DOI: https://doi.org/10.4314/acsj.v25i2.9

Mbow C., Mertz O., Diouf A., Rasmussen K., Reenberg A. (2008) The history of environmental change and adaptation in eastern Saloum–Senegal—Driving forces and perceptions. Global and Planetary Change 64:210-221. DOI: https://doi.org/10.1016/j.gloplacha.2008.09.008

Mead R., Willey R. (1980) The concept of a ‘land equivalent ratio’and advantages in yields from intercropping. Experimental Agriculture 16:217-228. DOI: https://doi.org/10.1017/s0014479700010978

Mertz O., Mbow C., Reenberg A., Diouf A. (2009) Farmers’ perceptions of climate change and agricultural adaptation strategies in rural Sahel. Environmental management 43:804-816. DOI: https://doi.org/10.1007/s00267-008-9197-0

Mian M.A.K., Hossain J. (2014) Nitrogen level and physiological basis of yield of mungbean at varying plant population in High Ganges River Flood Plain Soil of Bangladesh. Pakistan Journal of Biological Sciences 17:925-930. DOI: https://doi.org/10.3923/pjbs.2014.925.930

Mogotsi K. (2006) Vigna radiata (L.) R. Wilczek.[Internet] Record from Protabase. Brink, M. & Belay, G.(Editors). PROTA (Plant Resources of Tropical Africa/Ressources végétales de l’Afrique tropicale), Wageningen, Netherlands.

Mohammad W., Shehzadi S., Shah S.M., Shah Z. (2010) Effect of tillage and crop residues management on mungbean (*Vigna radiata* (L.) Wilczek) crop yield, nitrogen fixation and water use efficiency in rain fed areas. Pak. J. Bot 42:1781-1789.

Mohammed I., Olufajo O., Singh B., Oluwasemire K., Chiezey U. (2008) Productivity of millet/cowpea intercrop as affected by cowpea genotype and row arrangement. World Journal of Agricultural Sciences 4.

Mohan S., Sheeba A., Murugan E., Ibrahim S. (2014) Screening of mungbean germplasm for resistance to Mungbean Yellow Mosaic Virus under natural condition. Indian Journal of Science and Technology 7:891-896. DOI: https://doi.org/10.15406/apar.2017.07.00276

Mokgehle S.N., Dakora F.D., Mathews C. (2014) Variation in N2 fixation and N contribution by 25 groundnut (Arachis hypogaea L.) varieties grown in different agro-ecologies, measured using 15N natural abundance. Agriculture, ecosystems & environment 195:161-172. DOI: https://doi.org/10.1016/j.agee.2014.05.014

Molla M., Solaiman A., Jahiruddin M., Mridha M., Khanam D. (2011) Influence of different doses of phosphorus in the presence of arbuscular mycorrhiza and *Rhizobium* on the growth and yield of mungbean. Bulletin of the Institute of Tropical Agriculture, Kyushu University 34:49-67.

Morton F., Smith R., Poehlman J.M. (1982) The mungbean. Mayaguez, Puerto Rico, Department of Agronomy and Soils, University of Puerto Rico.

Moswetsi G., Fanadzo M., Ncube B. (2017) Cropping systems and agronomic management practices in smallholder farms in South Africa: Constraints, challenges and opportunities. Journal of Agronomy 16:51-64. DOI: https://doi.org/10.3923/ja.2017.51.64

Mubarak A.E. (2005) Nutritional composition and antinutritional factors of mung bean seeds (*Phaseolus aureus*) as affected by some home traditional processes. Food Chemistry 89:489-495. DOI: https://doi.org/10.1016/j.foodchem.2004.01.007

Munawwar M.H., Asghar A., Malik S.R. (2014) Identification of resistance in mungbean and mashbean germplasm against mungbean yellow mosaic virus. Pakistan Journal of Agricultural Research 27:129-135.

Nadarajan N., Chaturvedi S. (2010) Genetic options for enhancing productivity of major pulses–retrospect, issues and strategies. Journal of Food legumes 23:1-8.

Nair R., Schafleitner R., Kenyon L., Srinivasan R., Easdown W., Ebert A., Hanson P. (2012) Genetic improvement of mungbean. SABRAO Journal of Breeding and Genetics 44:177-190.

Nair R.M., Pandey A.K., War A.R., Hanumantharao B., Shwe T., Alam A., Pratap A., Malik S.R., Karimi R., Mbeyagala E.K. (2019) Biotic and abiotic constraints in mungbean production—Progress in genetic improvement. Frontiers in plant science 10. DOI: https://doi.org/10.3389/fpls.2019.01340

Nair R.M., Thavarajah P., Giri R.R., Ledesma D., Yang R.-Y., Hanson P., Easdown W., Hughes J.d.A. (2015) Mineral and phenolic concentrations of mungbean [*Vigna radiata* (L.) R. Wilczek var. radiata] grown in semi-arid tropical India. Journal of Food Composition and Analysis 39:23-32. DOI: https://doi.org/10.1016/j.jfca.2014.10.009

Nair R.M., Yang R.Y., Easdown W.J., Thavarajah D., Thavarajah P., Hughes J.d.A., Keatinge J. (2013) Biofortification of mungbean (*Vigna radiata*) as a whole food to enhance human health. Journal of the Science of Food and Agriculture 93:1805-1813. DOI: https://doi.org/10.1002/jsfa.6110

Naresh K., Bairwa R., Yadav R., Singh S., Rakesh S. (2017) Evaluation of yield attributes and yield on pearl millet (Pennisetum glaucum) and mungbean (Vigna radiata L.) intercropping system under arid western plain zone in India. Annals of Agri Bio Research 22:188-191.

Naresh R.K., Purushottam, Singh S.P., Ashish D., Vineet K. (2013) Effects of water stress on physiological processes and yield attributes of different mungbean (L.) varieties. African Journal of Biochemistry Research 7:55-62.

Naylor R.L., Falcon W.P., Goodman R.M., Jahn M.M., Sengooba T., Tefera H., Nelson R.J. (2004) Biotechnology in the developing world: a case for increased investments in orphan crops. Food Policy 29:15-44. DOI: https://doi.org/10.1016/j.foodpol.2004.01.002

Ncube B., Twomlow S.J., Van Wijk M.T., Dimes J.P., Giller K.E. (2007) Productivity and residual benefits of grain legumes to sorghum under semi-arid conditions in southwestern Zimbabwe. Plant and Soil 299:1-15. DOI: https://doi.org/10.1007/s11104-007-9330-5

Ngwuta A., Okoro A., Agugo B., Odiyi A., Eke K., Ogoke I. (2010) Variations in some morphological and yield characteristics of mungbean (*Vigna radiata* (L.) Wilczek) cultivars introduced into the rain-forest agroecology of Southeastern Nigeria. International Journal of Agriculture and Rural Development 13. DOI: https://doi.org/10.4314/ijard.v13i2.67392

Niang I., Ruppel O., Abdrabo M., Essel A., Lennard C., Padgham J., Urquhart P. (2014) Africa, climate change 2014: impacts, adaptation and vulnerability—Contributions of the Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. 1199–1265.

Nicou R. (1977) Le travail du sol dans les terres exondées du Sénégal motivations-contraintes, ISRA.

NRCS. (2019) Natural Resource Conservation Service. Web Soil Survey. Available online: http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm (accessed on 24 February 2020).

Ntare B.R. (1990) Intercropping morphologically different cowpeas with pearl millet in a short season environment in the Sahel. Experimental Agriculture 26:41-47. DOI: https://doi.org/10.1017/s0014479700015386

Ntukamazina N., Onwonga R.N., Sommer R., Mukankusi C.M., Mburu J., Rubyogo J.C. (2017) Effect of excessive and minimal soil moisture stress on agronomic performance of bush and climbing bean (*Phaseolus vulgaris* L.). Cogent Food & Agriculture 3:1373414. DOI: https://doi.org/10.1080/23311932.2017.1373414

Odeny D.A. (2007) The potential of pigeonpea (*Cajanus cajan* (L.) Millsp.) in Africa, Natural resources forum, Wiley Online Library. pp. 297-305.

Ogallo L. (1984) Variation and change in climate in sub-Saharan Africa, Advancing agricultural production in Africa: proceedings of CAB's First Scientific Conference, Arusha, Tanzania, 12-18 February 1984/edited by DL Hawksworth, Farnham Royal, Slough,[England]: Commonwealth Agricultural Bureaux, c1984.

Ogindo H., Walker S. (2005) Comparison of measured changes in seasonal soil water content by rainfed maize-bean intercrop and component cropping systems in a semi-arid region of southern Africa. Physics and Chemistry of the Earth, Parts A/B/C 30:799-808.

Ojehomon O. (1968) Flowering, fruit production and abscission in cowpea, *Vigna unguiculata* (L.) Walp. Journal of the West African Science Association.

Ojiem J.O., Vanlauwe B., de Ridder N., Giller K.E. (2007) Niche-based assessment of contributions of legumes to the nitrogen economy of Western Kenya smallholder farms. Plant and soil 292:119-135. DOI: https://doi.org/10.1007/s11104-007-9207-7

Okweche S.I., Avav T.-R. (2013) Yield evaluation of some cultivars of mungbean (*Vigna radiata* (L.) Wilczek) in southern giunea savanna location of Nigeria. International Journal of Plant, Animal and Environmental Sciences 3:85-88.

Oo H.H., Araki T., Kubota F. (2005) Effects of drought and flooding stresses on growth and photosynthetic activity of mungbean, *Vigna radiata* (L.) Wilczek, cultivars.

Osborne J. (2010) Improving your data transformations: Applying the Box-Cox transformation. Practical Assessment, Research, and Evaluation 15:12.

Oseni T.O. (2010) Evaluation of sorghum-cowpea intercrop productivity in savanna agro-ecology using competition indices. Journal of Agricultural Science 2:229. DOI: https://doi.org/10.5539/jas.v2n3p229

Pandey A.K., Burlakoti R.R., Kenyon L., Nair R.M. (2018) Perspectives and challenges for sustainable management of fungal diseases of mungbean [*Vigna radiata* (L.) R. Wilczek var. radiata]: A Review. Frontiers in Environmental Science 6:53. DOI: https://doi.org/10.3389/fenvs.2018.00053

Pataczek L., Zahir Z.A., Ahmad M., Rani S., Nair R., Schafleitner R., Cadisch G., Hilger T. (2018) Beans with benefits—the role of mungbean (*Vigna radiata*) in a changing environment. American Journal of Plant Sciences 9:1577. DOI: https://doi.org/10.4236/ajps.2018.97115

Patel V.D., Mahatma L. (2016) Epidemiology of mungbean yellow mosaic virus (MYMV) disease in mungbean in south Gujarat. Journal of Agrometeorology 18:140-141.

Patrignani A., Ochsner T.E. (2015) Canopeo: A powerful new tool for measuring fractional green canopy cover. Agronomy Journal 107:2312-2320. DOI: https://doi.org/10.2134/agronj15.0150

Paul T., Mozumder N., Sayed M., Akhtaruzzaman M., Akhtaruzzaman M.S.M. (2011) Proximate compositions, minerals contents and determination of protease activity from green gram (*Vigna radiata* L. Wilczek). Bangladesh Res. J 5:207-213.

Peoples M., Bergersen F., Turner G. (1991) Use of the natural enrichment of 15 N in plant available soil N for the measurement of symbiotic N 2 fixation, Stable isotopes in plant nutrition, soil fertility and environmental studies.

Peoples M., Brockwell J., Herridge D., Rochester I., Alves B., Urquiaga S., Boddey R., Dakora F., Bhattarai S., Maskey S. (2009) The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. Symbiosis 48:1-17. DOI: https://doi.org/10.1007/bf03179980

Peoples M., Herridge D., Ladha J. (1995) Biological nitrogen fixation: an efficient source of nitrogen for sustainable agricultural production?, Management of Biological Nitrogen Fixation for the Development of More Productive and Sustainable Agricultural Systems, Springer. pp. 3-28.

Peoples M.B., Herridge D.F. (1990) Nitrogen fixation by legumes in tropical and subtropical agriculture. Advances in agronomy 44:155-223. DOI: https://doi.org/10.1016/s0065-2113(08)60822-6

Phoomthaisong J., Toomsan B., Limpinuntana V., Cadisch G., Patanothai A. (2003) Attributes affecting residual benefits of N 2-fixing mungbean and groundnut cultivars. Biology and fertility of soils 39:16-24. DOI: https://doi.org/10.1007/s00374-003-0676-4

Puranik V., Mishra V., Singh N., Rai G. (2011) Studies on development of protein rich germinated green gram pickle and its preservation by using class one preservatives. Am J Food Technol 6:742-752. DOI: https://doi.org/10.3923/ajft.2011.742.752

Rachaputi R.C., Chauhan Y., Douglas C., Martin W., Krosch S., Agius P., King K. (2015) Physiological basis of yield variation in response to row spacing and plant density of mungbean grown in subtropical environments. Field Crops Research 183:14-22. DOI: https://doi.org/10.1016/j.fcr.2015.07.013

Rahim M., Mia A., Mahmud F., Zeba N., Afrin K. (2010) Genetic variability, character association and genetic divergence in mungbean ('*Vigna radiata*'L. Wilczek). Plant Omics 3:1. DOI: https://doi.org/10.18805/ijare.a-4929

Raina S.K., Venkadasamy G., Mahesh K., Singh A.K., Jagadish R., Minhas P.S. (2016) Genetic variation in physiological responses of mungbeans (*Vigna radiata* (L.) Wilczek) to drought. Acta Physiologiae Plantarum 38:263. DOI: https://doi.org/10.1007/s11738-016-2280-x

Raji S.G., Tzanakakis V., Dörsch P. (2019) *Bradyrhizobial* inoculation and P application effects on haricot and mung beans in the Ethiopian Rift Valley. Plant and Soil 442:271-284. DOI: https://doi.org/10.1007/s11104-019-04170-2

Ram K., Meena R. (2015) Evaluation of pearl millet and mungbean intercropping systems in arid region of Rajasthan (India). Bangladesh Journal of Botany 43:367-370.

Ramanujam S. (1981) Biometrical basis for yield improvement in mungbean, Procedings 1st International Mung bean Symposium. pp. 210.

Ramírez Villegas J., Thornton P.K. (2015) Climate change impacts on African crop production.

Rao C., Ali M. (2006) Response and nutrient uptake of urdbean and mungbean genotypes to optimum nutrient supply on nutrient deficient sandy loam soil. Indian Journal of Pulses Research 19:259-262.

Rao N., Lawson E.T., Raditloaneng W.N., Solomon D., Angula M.N. (2019) Gendered vulnerabilities to climate change: insights from the semi-arid regions of Africa and Asia. Climate and Development 11:14-26. DOI: https://doi.org/10.1080/17565529.2017.1372266

Rao S.C., Northup B.K. (2009) Capabilities of four novel warm-season legumes in the southern Great Plains: Biomass and forage quality. Crop science 49:1096-1102. DOI: https://doi.org/10.2135/cropsci2008.08.0499

Rashid M., Kausar R., Alvi S., Sajjad M.R. (2015) Assessment of runoff and sediment losses under different slope gradients and crop covers in semi-arid watersheds. Soil & Environment 34.

Razzaque M., Haque M., Karim M. (2017) Effect of nitrogen on growth and yield on mungbean in low nutrient soil. Bangladesh Journal of Agricultural Research 42:77-85.

Razzaque M.A., Haque M.M., Karim M.A., Solaiman A.R.M. (2016) Nitrogen fixating ability of mungbean genotypes under different levels of nitrogen application. Bangladesh Journal of Agricultural Research 41:163-171. DOI: https://doi.org/10.3329/bjar.v41i1.27681

Reddy K., Visser P., Buckner P. (1992) Pearl millet and cowpea yields in sole and intercrop systems, and their after-effects on soil and crop productivity. Field Crops Research 28:315-326. DOI: https://doi.org/10.1016/0378-4290(92)90017-4

Reeves T., Thomas G., Ramsay G. (2016) Save and grow in practice: maize, rice, wheat--a guide to sustainable cereal production. UN Food and Agriculture Organization, Rome. DOI: https://doi.org/10.1007/s12571-016-0585-7

Robinson D. (2001) δ15N as an integrator of the nitrogen cycle. Trends in Ecology & Evolution 16:153-162. DOI: https://doi.org/10.1016/s0169-5347(00)02098-x

Rochester I., Peoples M., Constable G., Gault R. (1998) Faba beans and other legumes add nitrogen to irrigated cotton cropping systems. Australian Journal of Experimental Agriculture 38:253-260. DOI: https://doi.org/10.1071/ea97132

Rosales C., Rivera F., Hautea R., Del Rosario E. (1998) Field evaluation of N 2 fixation by mung bean in the Philippines, and residual effects on maize.

Rosales C., Rivera F., Hautia R., Del Rosario E. (1995) Nitrogen fixation by mung bean (*Vigna radiata* L.) under field conditions in the Philippines as quantified by 15N isotope dilution, Philippine Nuclear Research Inst.

Roudier P., Sultan B., Quirion P., Berg A. (2011) The impact of future climate change on West African crop yields: What does the recent literature say? Global Environmental Change 21:1073-1083. DOI: https://doi.org/10.1016/j.gloenvcha.2011.04.007

Roy S., Barman M., Puste A., Gunri S., Jana K. (2016) Growth, yield, water use efficiency and competitive functions of intercropping system of maize (*Zea mays* L.) and mungbean (*Vigna radiata* L.) as influenced by irrigation. SAARC Journal of Agriculture 13:94-107. DOI: https://doi.org/10.3329/sja.v13i2.26571

Sabbagh E., Lakzayi M. (2016) Influence of intercropping on weed control, soil fertility and forage quality. International Journal of Agriculture and Biosciences 5:285-290.

Safdar A., Khan M.A., Zeshan M.A., Amer H., Haider M.S. (2015) Characterization of conducive environmental conditions for mungbean yellow mosaic virus disease incidence on mungbean germplasm. Pakistan Journal of Phytopathology 27:27-30.

Saha H. (2017) Effect of cropping system on soil moisture content, canopy temperature, growth and yield performance of maize and cowpea.

Sakai H., Naito K., Takahashi Y., Sato T., Yamamoto T., Muto I., Itoh T., Tomooka N. (2015) The Vigna Genome Server,‘Vig GS’: A genomic knowledge base of the genus Vigna based on high-quality, annotated genome sequence of the Azuki Bean, Vigna angularis (Willd.) Ohwi & Ohashi. Plant and Cell Physiology 57:e2-e2. DOI: https://doi.org/10.1093/pcp/pcv189

Saleem R., Ahmad Z.I., Anees M.A., Razzaq A., Saleem A. (2015) Productivity and land use efficiency of maize mungbean intercropping under different fertility treatments. Sarhad Journal of Agriculture 31:37-44.

Salvagiotti F., Cassman K.G., Specht J.E., Walters D.T., Weiss A., Dobermann A. (2008) Nitrogen uptake, fixation and response to fertilizer N in soybeans: A review. Field Crops Research 108:1-13. DOI: https://doi.org/10.1016/j.fcr.2008.03.001

Samal S., Rao K., Poonia S., Kumar R., Mishra J., Prakash V., Mondal S., Dwivedi S., Bhatt B., Naik S.K. (2017) Evaluation of long-term conservation agriculture and crop intensification in rice-wheat rotation of Indo-Gangetic Plains of South Asia: Carbon dynamics and productivity. European Journal of Agronomy 90:198-208. DOI: https://doi.org/10.1016/j.eja.2017.08.006

Sangakkara U., Frehner M., Nösberger J. (2001) Influence of soil moisture and fertilizer potassium on the vegetative growth of mungbean (*Vigna radiata* L. Wilczek) and cowpea (*Vigna unguiculata* L. Walp). Journal of Agronomy and Crop Science 186:73-81. DOI: https://doi.org/10.1046/j.1439-037x.2001.00433.x

Sanginga N., Dashiell K., Okogun J., Thottappilly G. (1997) Nitrogen fixation and N contribution by promiscuous nodulating soybeans in the southern Guinea savanna of Nigeria. Plant and Soil 195:257-266.

Seck A. (2017) Fertiliser subsidy and agricultural productivity in Senegal. The World Economy 40:1989-2006. DOI: https://doi.org/10.1111/twec.12487

Senaratne R., Liyanage N.D.L., Soper R.J. (1995) Nitrogen fixation of and N transfer from cowpea, mungbean and groundnut when intercropped with maize. Fertilizer Research 40:41-48. DOI: https://doi.org/10.1007/bf00749861

Seran T.H., Brintha I. (2010) Review on maize based intercropping. Journal of agronomy 9:135-145.

Settle W., Garba M.H. (2011) Sustainable crop production intensification in the Senegal and Niger River basins of francophone West Africa. International journal of agricultural sustainability 9:171-185. DOI: https://doi.org/10.3763/ijas.2010.0559

Shah Z., Shah S.H., Peoples M.B., Schwenke G.D., Herridge D.F. (2003) Crop residue and fertiliser N effects on nitrogen fixation and yields of legume–cereal rotations and soil organic fertility. Field Crops Research 83:1-11. DOI: http://dx.doi.org/10.1016/S0378-4290(03)00005-4.

Shaheen S., Harun N., Khan F., Hussain R.A., Ramzan S., Rani S., Khalid Z., Ahmad M., Zafar M. (2012) Comparative nutritional analysis between *Vigna radiata* and *Vigna mungo* of Pakistan. African Journal of Biotechnology 11:6694-6702. DOI: https://doi.org/10.5897/ajb11.3496

Shahida B., Khan I.A. (2016) Impact of weed control techniques on intercropping of mungbean with maize under agro climate condition of Peshawar. Sarhad Journal of Agriculture 32:62-69. DOI: https://doi.org/10.17582/journal.sja/2016/32.2.62.69

Shaker-Koohi S., Nasrollahzadeh S., Raei Y. (2014) Evaluation of chlorophyll value, protein content and yield of sorghum (*Sorghum bicolor* L.)/mungbean (*Vigna radiate* L.) intercropping. International Journal of Biosciences (IJB) 4:136-143. DOI: https://doi.org/10.12692/ijb/4.8.136-143

Shanmugasundaram S., Keatinge J., Hughes J.d.A. (2010) The mungbean transformation: Diversifying crops, defeating malnutrition. Proven Successes in Agricultural Development:381.

Shearer G., Kohl D.H. (1986) N2-fixation in field settings: estimations based on natural 15N abundance. Functional Plant Biology 13:699-756. DOI: https://doi.org/10.1071/pp9860699

Shepherd M.J., Lindsey L.E., Lindsey A.J. (2018) Soybean canopy cover measured with Canopeo compared with light interception. Agricultural & Environmental Letters 3:1-3. DOI: https://doi.org/10.2134/ael2018.06.0031.

Sherasia P., Garg M.R., Bhanderi B. (2017) Pulses and their by-products as animal feed Food and Agriculture Organization of the United Nations (FAO).

Shishaye H.A. (2015) The Negative impacts of climate change in Sub-Saharan Africa and their mitigation measures. DOI: https://doi.org/10.9734/bjast/2015/17665

Singh D., Mathimaran N., Boller T., Kahmen A. (2020) Deep-rooted pigeon pea promotes the water relations and survival of shallow-rooted finger millet during drought—Despite strong competitive interactions at ambient water availability. PloS one 15:e0228993. DOI: https://doi.org/10.1371/journal.pone.0228993

Singh G., Sekhon H., Singh G., Brar J., Bains T., Shanmugasundaram S. (2011) Effect of plant density on the growth and yield of mungbean [*Vigna radiata* (L.) Wilczek] genotypes under different environments in India and Taiwan. International journal of agricultural research 6:573-583. DOI: https://doi.org/10.3923/ijar.2011.573.583

Smartt J. (1984) Gene pools in grain legumes. Economic Botany 38:24-35. DOI: https://doi.org/10.1007/bf02904413

Smith A., Snapp S., Dimes J., Gwenambira C., Chikowo R. (2016) Doubled-up legume rotations improve soil fertility and maintain productivity under variable conditions in maize-based cropping systems in Malawi. Agricultural Systems 145:139-149. DOI: https://doi.org/10.1016/j.agsy.2016.03.008

Snapp S.S., Cox C.M., Peter B.G. (2019) Multipurpose legumes for smallholders in sub-Saharan Africa: Identification of promising ‘scale out’options. Global Food Security 23:22-32. DOI: https://doi.org/10.1016/j.gfs.2019.03.002

Song H. (2005) Effects of VAM on host plant in the condition of drought stress and its mechanisms. Electronic Journal of Biology 1:44-48.

Stefanović S., Pfeil B.E., Palmer J.D., Doyle J.J. (2009) Relationships among phaseoloid legumes based on sequences from eight chloroplast regions. Systematic Botany 34:115-128. DOI: https://doi.org/10.1600/036364409787602221

Sugandh S., Sharma V.K., Harsh K., Shahi V.K. (2015) Screening of mungbean [*Vigna radiata* (L.) Wilczek] genotypes for resistance to mungbean yellow mosaic virus (MYMV). Environment and Ecology 33:855-859. DOI: https://doi.org/10.15406/apar.2017.07.00276

Sunil K., Gokulakrishnan B.J., Prakash M. (2015) Effect of drought stress on seed yield and bio-physical characters in mungbean (*Vigna radiata* L.) Wilczek. International Journal of Tropical Agriculture 33:853-864.

Swaminathan R., Singh K., Nepalia V. (2012) Insect pests of green gram *Vigna radiata* (L.) Wilczek and their management, Agricultural Science, InTech.

Tadele Z. (2017) Raising crop productivity in Africa through intensification. Agronomy 7:22. DOI: https://doi.org/10.3390/agronomy7010022

Tajini F., Suriyakup P., Jansa J., Drevon J.-J. (2011) Assessing hydroaeroponic culture for the tripartite symbiosis of mungbean (*Vigna radiata* L.) with arbuscular mycorrhizal fungi and rhizobia. African Journal of Biotechnology 10:7409-7415.

Tang D., Dong Y., Ren H., Li L., He C. (2014) A review of phytochemistry, metabolite changes, and medicinal uses of the common food mung bean and its sprouts (*Vigna radiata*). Chemistry Central Journal 8:4. DOI: https://doi.org/10.1186/1752-153x-8-4

Tankari M., Traore F. (2017) Economic accounts for agriculture and farm income in Senegal, International Food Policy Research Institute (IFPRI).

Tariq S., Ali S., Ijaz S.S. (2007) Improving nitrogen fixation capacity and yield of mungbean and mashbean by phosphorous management in Pothowar. Sarhad Journal of Agriculture 23:1027.

Terdoo F., Feola G. (2016) The vulnerability of rice value chains in Sub-Saharan Africa: a review. Climate 4:47. DOI: https://doi.org/10.3390/cli4030047

Tharanathan R., Mahadevamma S. (2003) Grain legumes - a boon to human nutrition. Trends in Food Science & Technology 14:507-518. DOI: https://doi.org/10.1016/j.tifs.2003.07.002

The World Bank. (2018) Population growth (annual %). https://data.worldbank.org/indicator/SP.POP.GROW?locations=SN (accessed on 12 Septembre 2018).

Thilakarathna M.S., McElroy M.S., Chapagain T., Papadopoulos Y.A., Raizada M.N. (2016) Belowground nitrogen transfer from legumes to non-legumes under managed herbaceous cropping systems. A review. Agronomy for Sustainable Development 36:58. DOI: https://doi.org/10.1007/s13593-016-0396-4

Tirado M., Hunnes D., Cohen M., Lartey A. (2015) Climate change and nutrition in Africa. Journal of Hunger & Environmental Nutrition 10:22-46.

Toomsan B., Cadisch G., Srichantawong M., Thongsodsaeng C., Giller K., Limpinuntana V. (2000) Biological N2 fixation and residual N benefit of pre-rice leguminous crops and green manures. NJAS-Wageningen Journal of Life Sciences 48:19-29. DOI: https://doi.org/10.1016/s1573-5214(00)80002-0

Tounkara A., Clermont-Dauphin C., Affholder F., Ndiaye S., Masse D., Cournac L. (2020) Inorganic fertilizer use efficiency of millet crop increased with organic fertilizer application in rainfed agriculture on smallholdings in central Senegal. Agriculture, Ecosystems & Environment 294:106878. DOI: https://doi.org/10.1016/j.agee.2020.106878

Trail P., Abaye O., Thomason W.E., Thompson T.L., Gueye F., Diedhiou I., Diatta M.B., Faye A. (2016) Evaluating intercropping (living cover) and mulching (desiccated cover) practices for increasing millet yields in Senegal. Agronomy Journal. DOI: https://doi.org/10.2134/agronj2015.0422

Travlos I., Karamanos A. (2006) Effects of soil texture on vegetative growth of tropical legume marama bean (*Tylosema esculentum*). Journal of Agronomy 5:609-12. DOI: https://doi.org/10.3923/ja.2006.609.612

Tuba A., Gupta K.S., Subhojit D. (2010) Mapping of Mungbean Yellow Mosaic India Virus (MYMIV) and powdery mildew resistant gene in black gram [*Vigna mungo* (L.) Hepper]. Electronic Journal of Plant Breeding 1:1148-1152.

Ullah M.A., Hussain N., Schmeisky H., Muhammad R. (2016) Enhancing soil fertility through intercropping, inoculation and fertilizer. Pakistan Journal of Scientific and Industrial Research, Series B: Biological Sciences 59:1-5.

Umair A., Ali S., Hayat R., Ansar M., Tareen M.J. (2011) Evaluation of seed priming in mung bean (*Vigna radiata*) for yield, nodulation and biological nitrogen fixation under rainfed conditions. African Journal of Biotechnology 10:18122-18129. DOI: https://doi.org/10.5897/ajb11.1385

UNDP. (2007) United Nations Development Programme. Fighting climate change: human solidarity in a divided world Springer.

Unkovich M., Herridge D., Peoples M., Cadisch G., Boddey B., Giller K., Alves B., Chalk P. (2008) Measuring plant-associated nitrogen fixation in agricultural systems Australian Centre for International Agricultural Research (ACIAR).

Unkovich M.J., Pate J.S., Sanford P., Armstrong E.L. (1994) Potential precision of the δ15N natural abundance method in field estimates of nitrogen fixation by crop and pasture legumes in south-west Australia. Australian Journal of Agricultural Research 45:119-132. DOI: https://doi.org/10.1007/s11104-012-1330-4

USDA. (2010) United States Department of Agriculture. National Nutrient Database. Agricultural Research Service, Nutrient Data Laboratory. http://www.nal.usda.gov/fnic/foodcomp/search/.

Van den Broeck G., Van Hoyweghen K., Maertens M. (2018) Horticultural exports and food security in Senegal. Global food security 17:162-171. DOI: https://doi.org/10.1016/j.gfs.2017.12.002

Van K., Kang Y., Han K., Lee Y., Gwag J., Moon J., Lee S. (2013) Genome-wide SNP discovery in mungbean by Illumina HiSeq. TAG Theoretical and Applied Genetics 126:2017-2027. DOI: https://doi.org/10.1007/s00122-013-2114-9

Vanlauwe B., Hungria M., Kanampiu F., Giller K. (2019) The role of legumes in the sustainable intensification of African smallholder agriculture: Lessons learnt and challenges for the future. Agriculture, Ecosystems & Environment 284:106583. DOI: https://doi.org/10.1016/j.agee.2019.106583

Vashro T.N. (2017) The effect of mung bean on improving dietary diversity in women and children in Senegal, Virginia Tech.

Vashro T.N., Farris A., Kraak V.I., Hulver M.W., Gueye F., Abaye A.O. (2018) Effects of mung bean consumption on dietary diversity of women and children in Senegal. Journal of Nutritional Ecology and Food Research 5:40-46. DOI: https://doi.org/10.1166/jnef.2018.1181

Vesterager J.M., Nielsen N.E., Høgh-Jensen H. (2008) Effects of cropping history and phosphorus source on yield and nitrogen fixation in sole and intercropped cowpea–maize systems. Nutrient Cycling in Agroecosystems 80:61-73. DOI: https://doi.org/10.1007/s10705-007-9121-7

Wang Q., Bao W.-F., Yang F., Xu B., Yang Y.-Z. (2017) The specific host plant DNA detection suggests a potential migration of Apolygus lucorum from cotton to mungbean fields. PloS one 12:e0177789.

Waniale A., Wanyera N., Talwana H. (2014) Morphological and agronomic traits variations for mungbean variety selection and improvement in Uganda. African Crop Science Journal 22:123-136.

Yakubu H., Kwari J., Ngala A. (2010) N 2 Fixation by grain legume varieties as affected by *Rhizobia i*noculation in the sandy loam soil of Sudano-Sahelian Zone of North Eastern Nigeria. Nigerian Journal of Basic and Applied Sciences 18. DOI: https://doi.org/10.4314/njbas.v18i2.64325

Yimram T., Somta P., Srinives P. (2009) Genetic variation in cultivated mungbean germplasm and its implication in breeding for high yield. Field crops research 112:260-266. DOI: https://doi.org/10.1016/j.fcr.2009.03.013

Yin Z., Guo W., Xiao H., Liang J., Hao X., Dong N., Leng T., Wang Y., Wang Q., Yin F. (2018) Nitrogen, phosphorus, and potassium fertilization to achieve expected yield and improve yield components of mung bean. PloS one 13:e0206285.

Zang H., Yang X., Feng X., Qian X., Hu Y., Ren C., Zeng Z. (2015) Rhizodeposition of nitrogen and carbon by mungbean (*Vigna radiata* L.) and its contribution to intercropped oats (*Avena nuda* L.). PloS one 10:e0121132. DOI: https://doi.org/10.1371/journal.pone.0121132

Zewdie A. (2014) Impacts of climate change on food security: a literature review in Sub Saharan Africa. Journal of Earth Science & Climatic Change 2014. DOI: https://doi.org/10.4172/2157-7617.1000225

Zhao C., Jia L., Wang Y., Wang M., McGiffen Jr M. (2015) Effects of different soil texture on peanut growth and development. Communications in Soil Science and Plant Analysis 46:2249-2257. DOI: https://doi.org/10.1080/00103624.2015.1059845

Zhongxiao G., Lianxue Z., Minghai W. (2012) Study on early identification method of drought tolerance of mungbean cultivars. Journal of Northwest Agriculture and Forestry University.