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John Tenywa
Makerere University

Erasmus Otabbong
Swedish University of Agricultural Sciences

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Development of Common Bean (*Phaseolus Vulgaris* L.) Production Under Low Soil Phosphorus and Drought in Sub-Saharan Africa: A Review

Namugwanya Margaret[1,2], John Stephen Tenywa[1], Erasmus Otabbong[3], Drake N. Mubiru[4] & Twaha Ali Basamba[1]

[1] Department of Agricultural Production, Makerere University, Kampala, Uganda

[2] Department of Agriculture, Kyambogo University, Kampala, Uganda

[3] Department of Soil and Environment, Swedish University of Agricultural Sciences, Ornskoldsvik, Sweden

[4] National Research Laboratories-Kawanda, Kampala, Uganda

Correspondence: Namugwanya Margaret, Department of Agricultural Production, Makerere University P. O. Box 7062, Kampala, Uganda; Department of Agriculture, Kyambogo University, Uganda, P. O. Box 1 Kyambogo, Uganda. Tel: 256-783-619-021. E-mail: namugwanya@yahoo.com

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Abstract

Owing to its nutritional value, especially proteins, carbohydrates, vitamins and micronutrients, common bean (*Phaseolus Vulgaris* L.) has been recognised as a crop that could ensure food security mostly, in Sub-Saharan Africa, where its productivity is low. Its low productivity is attributed to a milliard of constraints, of which low plant-available phosphorus (P) and limited moisture in soil are among the major limiting factors. Synergistic effects of the two factors are accentuated in Sub-Saharan African region. This paper discloses the importance of the synergistic effects of plant-available P and moisture in soils on common bean production. It has been observed that studies investigating impacts of interactions of low P levels and moisture deficit conditions in soils are yet to be conducted. Identification of traits that contribute to high performance under low P availability and moisture deficit in the same genotypes remains a major research and development challenge. However, engineering new genotypes alone may not alleviate the problem of ensuring improvement of high bean yields. Root architecture and root exploration of the soil that enable the plant to access the two soil resources, traditional methods that preserve good status of organic matter in soils and moisture and soil preparation techniques are equally important. This, calls for holistic investigations that include soil plant-available P and moisture, common bean genotypes and their root systems, and agronomic measures to facilitate a comprehensive evaluation of impacts of deficiencies in soils on common bean yields. This paper explores and synthesizes existing research and development of common bean grown in soils deficient in plant-available P and moisture, aiming at designing future research to enhance common bean productivity.

Keywords: developing countries, food security, nutritional value, plant-available phosphorus, soil moisture, synergistic effects

1. Introduction

Common bean (*Phaseolus Vulgaris* L.) is a food-secure and nutritious crop, especially in Sub-Saharan Africa (SSA). It plays a big dietary role; supplying proteins, carbohydrates, essential elements and vitamins to both rural and urban households. It is estimated that the crop meets more than 50% of dietary protein requirements of households in SSA (Broughton et al., 2003; Wortman, Kirkby, Eledu, & Allen, 2004). The annual *per capita* consumption of common bean is higher among low-income people (Table 1) who cannot afford to buy nutritious food stuff, such as meats and fish (Beebe, Rao, Blair, & Acosta-Gallegos, 2013; Broughton et al., 2003). Additionally, its consumption also varies by region. For instance, in eastern Africa, the *per capita* consumption of 50 to 60 kg year^{-1} in Rwanda, Kenya and Uganda is considerably higher than in Latin America where *per capita* consumption is 4 and 17 kg year^{-1} in Colombia and Brazil, respectively (Beebe et al., 2013; Broughton et al., 2003). In addition to its subsistence value, common bean is an important commercial crop contributing significant incomes to the majority of the rural peasants in SSA (Wortman et al., 2004).

Table 1. Bean *per capita* consumption in Latin America and Africa(Broughton et al. (2003)

Region/Country	***Per capita* consumption (%)**
	Latin America
Mexico	16.0
Honduras	13.0
Colombia	4.3
Costa Rica	11.0
El Salvador	13.5
Ecuador	6.0
Brazil	17.2
	Africa
Western Kenya (Kissi)	66.0
Rwanda	48.0
Eastern Uganda (Mbale)	58.0

Despite its importance, common bean production potential has not been realised, particularly, in the resource-constrained SSA. Globally, common bean is cultivated on about 28 million ha, producing on average, approximately 715 kg year^{-1} ha^{-1} (Broughton et al., 2003). The worldwide average yield increased approximately, from 600 kg in 1996 to more than 750 kg ha^{-1} in 2008. That change shows an increasing trend in production even though the increase is not significant in the resource-poor regions where the average yields are still below 600 kg ha$^{-1.}$ (Akibode & Maredia, 2011). Hillocks, Madata, Chirwa, Minja, and Msolla (2006) observed an average yield of improved common bean varieties in Tanzania of 500 kg ha^{-1} in areas with unreliable rainfall. Similarly, Akibode and Maredia (2011) reported average yields in Uganda, Kenya, Angola, Malawi and Democratic Republic of Congo of 500, 490, 280, 490 and 540 kg ha^{-1}, respectively. All those values were far below the potential yield of 1500-3000 kg ha^{-1} under required bean production conditions (Hillocks et al., 2006).

The low level of production in SSA has been attributed partly to low levels of soil plant-available P and drought stress, caused by climate change variability (Beebe et al., 2011; Beebe et al., 2013; Wortman et al., 2004). Significant research and development efforts have always focused on overcoming the limitations of these production constraints, however, most of the efforts (Acosta-Díaz, Acosta-Gallegos, Trejo-López, Padilla-Ramírez, & Amador-Ramírez, 2009; Beebe et al., 2006; Cichy, Blair, Mendoza, Snapp, & Kelly, 2009; Cichy, Snapp, & Blair, 2009; Manjeru, Madaanzi, Makeredza, Nciiza, & Sithole, 2007; Miller, Ochoa, Nielsen, Beck, & Lynch, 2003) address individual abiotic stress factors, with limited regard for the possible interactive effects under field conditions. The objective of this paper is, therefore, to scan and discuss existing research results and development information on common bean production, with attention being given to soil P deficiencies under drought conditions.

2. Review Rationale

Recent reviews (Beebe et al., 2013; Buruchara et al., 2011; Hillocks et al., 2006; Porch et al., 2013) emphasized constraints that included deficiencies of plant-available P and moisture in soils, and pests and diseases that attack common beans.

Hillocks et al. (2006) emphasized development of bean improvement programmes in Tanzania since 1959 to which the international programmes contributed development strategies used to obtain high yielding bean varieties that could resist drought, pests and disease attacks. However, the review did not guide on ways to achieve those research goals in a simultaneous presence of low levels of P and moisture in soils; the major problems facing common bean producing areas in SSA.

Reviewing seed breeding and seed delivery strategies for Pan-African Bean Research Alliance (PABRA), Buruchara et al. (2011) pointed out that a number of genotypes with multiple responses were released for resistance to pests and diseases and low soil fertility. It was, however, noted from the same review that new research was progressing without testing recommendations made in research that has been published.

Beebe et al. (2013) extended focus on efforts required to improve common bean tolerance for drought;

particularly, the genetic diversity and physiological mechanisms by which they overcome drought stress. Although that review recommended matching drought resistance traits and mechanisms to specific environments in respect to patterns of drought, it did not clearly indicate the relationship between drought and plant-available P and how interactions of the two constraints would affect crop production.

Porch et al. (2013) provided knowledge gaps and research strategies in relation to response of common bean to climate change, *Phaseolus* species resources and their conservation status; the use of wild relatives and closely related species in breeding efforts. That review directs research in generation of valuable resources and tools embracing characterized germplasm resulting from wild relatives. It also generated genotypic information on wild accessions, structured populations, advanced populations with wild relative introgressions, and associated quantitative root traits for drought and heat resistance in common bean crop.

The reviews, except the one published by Buruchara et al. (2011), contextualised common bean production in relation to single stress factors, yet the aggregate effect of low levels of plant-available P and moisture deficit in soils remains to be determined. It is, therefore, imperative that another review is done to re-direct research in the presence of interactive soil P deficiency and moisture deficit that have wildly affected agricultural production.

3. Plant-available Soil P in Common Bean Producing Areas in SSA

In resource-poor farming of SSA, P is one of the most deficient nutrients for cultivation of common bean (Beebe et al., 2011; Cichy, Blair, et al., 2009). Soils are considered deficient in P if the soil plant-available P contents are less than 40 mg kg^{-1} P determined by Bray-1 method (Mourice & Tryphone, 2012). Characteristically, the soils are deficient in P after being subjected to prolonged degradation by erosion and repeated removal in crop harvest without replacement of the removed P (Henao & Baanante, 2006). Those soils are acidic and possess high P-fixing capacities (Nziguheba, 2007). Based on soil analytical data, 65 to 80% of the bean producing areas in SSA are deficient in plant-available P (Broughton et al., 2003; Lunze et al., 2007; Wortman et al., 2004) reducing common bean yield by over 60% (Acosta-Díaz et al., 2009). Roy, Misra, Lesschen, and Smaling (2003) reported a negative nutrient balance of P ranging from 2.3 kg ha^{-1} in 1983 to 3.0 kg ha^{-1} in 2000 on cultivated land of SSA. Similarly, Henao and Baanante (2006) reported 9.2 kg P ha^{-1} year^{-1} loss in East African cultivated soils. Most of that P loss was caused by erosion. Nziguheba (2007) reported P depletion of 6.6 kg ha^{-1} yr^{-1} in Rwanda, Ethiopia and Kenya was accounted for by P removed in crops and erosion.

Of the tropical soils, 43 % are acid-weathered and if arranged in increasing order of weathering they are Andisols < Ultisols < Oxisols (FAO, 2004) and possess capacities to fix P in the range of 70 to 90 % of P applied as inorganic fertilizers (Sanchez & Salinas, 1981). Because common bean requires P to enhance energy for its metabolic activities, the crop possesses high requirements for P and is, hence sensitive to low plant-available P in soils (Boutraa, 2009). According to Kimani, Buruchara, and Lubanga (2006), P deficiency accounts for common bean yield loss of 253 kg ha^{-1} yr^{-1} in East Africa. That crop loss is equivalent to a monetary loss of $303.6.

In order to address P deficiency for common bean and inability of smallholder farmers to afford P fertilisers, the International Center for Tropical Agriculture (CIAT) has spearheaded breeding programmes in which a number of bean genotypes were screened for ability to thrive in P-deficient soils (Beebe et al., 2013; Lunze et al., 2007). These genotypes are widely designated as low P tolerant bean materials and the CIAT-breed genotypes include: MCM5001/K131, MCM 2001/NABE 3, AND932-A-1, AFR709-1, AFR708, AFR703-1, Nm126806-2A, FOT44-1, T842-6-9, AND1055-1, NR12634-13C-1, BZ12894-C-1, DRK137-1 and ARA8-B-1, among others.

Recent studies indicated that those materials may yield between 880 and 1352 kg ha^{-1} on soils deficient in plant-available P. Those are significant yields compared to 750 kg ha^{-1} of the local common bean genotype grown on P-deficient soils (Lunze et al., 2007). However, the genetic potential of the new common bean materials have not been tested in drought prone environments and under farmers' P deficiency conditions in SSA. It is not clear how these materials would perform under drought conditions, given that with climate change effects, drought spells can be experienced even within the would be normal rainy seasons (Mubiru, Agona, & Komutunga, 2009). Besides, the mechanism by which those new genotypes are able to thrive in P-deficient soils is, yet to be investigated. For example, whether the genotypes develop deep and massive root systems capable of exploring and extracting P and moisture from the deep soil layers needs to be explored.

3.1 Response to P deficiency

Common bean has evolved a number of mechanisms for surviving under low levels of soil P. The main mechanisms for tolerance are ascribed to mechanisms that contribute to high P acquisition efficiency and/or P utilisation efficiency (Atemkeng, Remans, Michiels, Tagne, & Ngonkeu, 2011; Cichy, Snapp, et al., 2009). Common bean genotypes employ different mechanisms to access soil P some of which are described herein:

3.1.1 Mechanisms for P Acquisition

Tolerance to low soil P availability is associated with increased P acquisition efficiency, which is achieved by development of root architecture capable of foraging the nutrient (Beebe et al., 2006; Cichy, Snapp, et al., 2009; Miller et al., 2003). Phosphorus acquisition efficiency is the ability of a plant to mobilise and absorb more P from the fertile soil layers (Atemkeng et al., 2011). Plant root architecture regulates the capacity of soil explored by roots, thereby playing a central role in P acquisition. Since P content and availability are more in top than in subsoil, root architectural traits that allow the exploration and use of P from surface layers govern P acquisition (Beebe et al., 2006; Liao et al., 2004; Miller et al., 2003). The P-efficient common bean genotypes which increase the below-ground biomass are able to acquire P in P-deficiency conditions (Liao et al., 2004; Namayanja, Semoka, Buruchara, Nchimbi, & Waswa, 2014).

The importance of root architectural traits in P acquisition has been investigated (Beebe et al., 2006; Cichy, Blair, et al., 2009; Liao et al., 2004; Miller et al., 2003). Miller et al. (2003) reported that greater production of adventitious roots in common beans helps in P acquisition by improving plant foraging in the most P rich soil environment, while Beebe et al. (2006) noted that basal root development and specific root length are responsible for efficient P acquisition. In their separate studies, Liao et al. (2004) and Cichy, Blair, et al. (2009) observed that the shallower the basal root angle, and the greater total root length and root length of basal roots in the top 3 cm area, the greater the P uptake in the P limiting environment. These traits enable low P tolerant genotypes to exploit the topsoil layers where soil P availability is more than in the subsoil layers. Thus, the difference in these root traits elucidates the differences among common bean genotypes in P acquisition efficiency.

Common bean also responds to low P availability by formation of an association with mycorrhizal fungi in their root system (Richardson et al., 2011; Shenoy & Kalagudi, 2005). These mycorrhizal fungi colonise the root system connecting the crop and soils; improving the efficiency with which the root system draws P from the soil (Birhane, Sterck, Fetene, Bongers, & Kuyper, 2012). The external hyphae permits the roots to tap large capacities of soil (Birhane et al., 2012) thereby absorbing P from non-labile sources and conveying it to the plant in exchange for organic elements released in soil by roots (Richardson et al., 2011; Shenoy & Kalagudi, 2005). Through this relationship, roots absorb P which would otherwise be inaccessible to them from P deficient soils (Shenoy & Kalagudi, 2005).

Further, in soils containing low levels of plant-available P, the uptake of P by plants can be increased through excretion of carboxylate and phosphatases by roots. Carboxylate solubilizes P by chelating Al, Fe and Ca from the insoluble Al-P, Fe-P and Ca-P, respectively, thereby rendering P soluble(Lambers, Cramer, Pearse, & Veneklass, 2006). Atemkeng et al. (2011) observed that P tolerant genotypes produced more P solubilising organic acids (citrate, oxalate and tartrate) in the roots than the non-P-tolerant common bean genotypes. These organic acids combine with metal cations Fe, Al, and Ca that bind phosphate and so solubilise the respective P compounds in the soil bound by these ions by ligand substitute (Lambers et al., 2006). More so, root exudation of acid phosphatase is believed to free bound P from the soil and has been shown to hydrolyse organic P in the rhizosphere into plant-available P for uptake (Lambers et al., 2006; Richardson et al., 2011; Song, 2005). This increases the availability of P in cluster roots resulting in increased root surface area for P uptake (Lambers, Bishop, Hopper, Laliberte, & Zu´n˜iga-Feest, 2012).

3.1.2 P utilisation Efficiency

Common bean plants also respond to low P availability through efficient use of absorbed P to produce biomass (Boutraa, 2009; Liao et al., 2004) . This is related to the capacity of the plant to accumulate dry matter despite the inadequacy of soil P for plant growth. Distribution of more biomass to roots than shoots is related to P use efficiency of P-tolerant common bean plants under low P levels. Crops develop an excellent ability to change the acquired P into plant biomass and yield, which is related to reduced P requirement in plant tissues (Cichy, Blair, et al., 2009). In separate studies, Boutraa (2009) and Namayanja et al. (2014) observed that more P-efficient common bean genotypes had greater root biomass and higher root: shoot ratio than the less efficient genotypes. Furthermore, low P-tolerant genotypes are able to produce more pods and seeds than non-P-tolerant genotypes (Boutraa, 2009, Atemkeng et al., 2011). However, whether all these phenomena can equally remain the same under moisture deficit soils requires empirical investigations.

4. Drought Occurrence in Common Bean Production Areas

Drought is an increasingly acute problem in SSA and is expected to worsen due to widespread climate change (Beebe et al., 2013; UNESCO, 2007). It is expected that some productive agricultural areas will be marginalised and will become unproductive (Boko et al., 2007). Sub-Saharan Africa is faced with high incidences of drought events; between 1970 and 2004, over ten drought incidents were reported in many countries. Uganda alone, registered nine incidences during the same period (UNESCO, 2007).

The frequent occurrence of drought periods is a critical constraint to common bean production in SSA (Beebe et al., 2013; Emam, Shekoofa, Salehi, & Jalali, 2010). It is estimated that more than 40% of bean growing areas of SSA are affected by drought at any stage of its growth (Beebe et al., 2013; Broughton et al., 2003). On average, rainfall recorded in those areas was <400 mm, during the three months following the main sowing dates for beans, which was less than the optimum rainfall of 400 mm (Broughton et al., 2003). Similarly, drought has been reported to be widespread in the bean growing areas in eastern and southern Africa, leading to bean yields less than 400 kg ha^{-1} year^{-1} (Beebe et al., 2011; Beebe et al., 2013) which is smaller than the optimum production of 1,500 kg ha^{-1} year^{-1} realised in less drought-constrained areas in eastern Africa (Hillocks et al., 2006).

In SSA, about 3,741,000 ha is sown with common beans and about 1,496,400 ha of that acreage was affected by drought (Broughton et al., 2003; Wortman et al., 2004). This has resulted to yield loss of 265 kg ha^{-1} yr^{-1} (Kimani et al., 2006) equivalent to annual loss of $318. In the same region, an estimated 682,000 ha in semi-arid area sown with common bean and 1140 kg ha^{-1} year^{-1} is lost due to drought (Beebe et al., 2013), translating into monetary loss of $1368 year^{-1}. Furthermore, it has been observed in SSA that <300, 300-375, 375-450 and > 400 mm of rainfall resulted in losses of 1000, 600, 400 and 0 kg of common bean per season ha^{-1}, respectively (Wortman et al., 2004).

This problem could have far reaching consequences on food security and household incomes in SSA where irrigation is not practiced. This is partly due to the economical implication on a crop like common bean which is produced by resource-poor farmers (Beebe et al., 2013; Broughton et al., 2003). It should also be borne in mind that most of the producing areas, especially in Uganda, Rwanda and Burundi are located on sloping land difficult to irrigate. According to Beebe et al. (2013), improvement of drought tolerance is a sustainable option that has demonstrated increased bean productivity by 31%. In that respect, several genotypes have been developed and several studies have been conducted to assess their levels of resistance to drought. Thus,

a) Lizana et al. (2006) examined the effects of drought on grain yield and photosynthesis of two common bean genotypes. They observed that the effects of drought on photosynthesis and yield depended on the genotype which was determined by the genotypes' stability to drought conditions

b) Manjeru et al. (2007) focused on effects of water stress at different growth stages on yield components and grain yield of common bean. In that study, it was reported that drought reduced grain yield by 700 kg ha^{-1}, however, the level of impact varied with the genotypes.

c) Acosta-Díaz et al. (2009) investigated the traits in dry bean genotypes adapted to drought stress in Mexico. In that study, some genotypes escaped from drought through reduced number of days to physiological maturity. However, genotypes showed varying degrees of physiological mechanisms to withstand dehydration and the stomata were effective in controlling water loss by decreasing stomata conductance and assimilation rate.

d) Porch, Ramirez, Santana, and Harmsen (2009) evaluated response of common bean to drought in Juana Diaz, Puerto Rico. In that study, some genotypes (SEA 5, G 21212, SEN 21, A 686 and SER 21) produced same yields under both stress and reduced stress conditions. The stable performance in those materials was ascribed to possession of deep tap roots that accessed soil moisture at deep soil layers. Those materials were recommended to serve as sources of drought tolerance for breeding, and genetic analysis.

e) Gebeyehu, Wiese, and Schubert (2010) investigated the effects of drought on two common bean genotypes; BrSP- a drought susceptible and SEA 15- a drought resistant. In their study, they reported that drought stress reduced the yield of the genotypes by 53 and 30 %, respectively.

Overall, drought severely lowers biomass production, yield components and grain yield. However, all the above studies were conducted under controlled irrigation conditions whereby, drought was manipulated in terms of severity and timing. Porch et al. (2009) induced drought stress at flowering stage up to harvest, Manjeru et al. (2007), Lizana et al. (2006) and Acosta-Díaz et al. (2009) applied drought at given intervals, while Emam et al. (2010) and Gebeyehu et al. (2010) carried out a greenhouse experiment in which experimental units were maintained at different moisture levels. All those controlled conditions did not reflect the actual situation under rain-fed conditions where rainfall is usually uncertain and key nutrients, such as P, are sub-optimal.

4.1 Mechanisms for Drought Resistance

Drought resistance in bean plants is attributed to a number of mechanisms, one of which is the ability of the plant to avoid tissue dehydration, while preserving comparatively high tissue water potential (Beebe et al., 2013). That behaviour is partly attributed to architectural root traits such as improved root length, density and rooting depth that maximize the available soil moisture for uptake by the crop (Beebe et al., 2013; Chaves, Maroco, & Pereira, 2003). Therefore, making soil soft enough to allow deep root exploration can enhance moisture acquisition by root system.

Increased rooting depth of root systems has been closely associated with plant adaption to soil moisture deficit (Frahm et al., 2004). One of the strategies by which deep root systems avail plants with soil moisture is by hydraulic distribution (Sun, Meng, Zhang, & Wan, 2014; Whitmore & Whalley, 2009). Sun et al. (2014) observed that during a dry season, deep rooting systems increased shallow soil moisture content through hydraulic lift, especially at night, thus improved yield. However, this strategy has not got any attention in breeding of common bean.

Plants also respond to soil moisture deficit through avoidance mechanisms by formation of associations between plant roots and fungi, especially mycorrhizal fungi (Quilambo, 2003; Song, 2005). The mycorrhizal fungi adhere to soil particles and outspread hyphae that penetrate smaller soil pore spaces thereby permitting mycorrhizal plant to access water that is not available to non-mycorrhizal plants (Beltrano & Ronco, 2008). Studies (Beltrano & Ronco, 2008; Kaya, Higgs, Kirnak, & Tas, 2003) demonstrate that mycorrhizal symbiotic association improves resistance to soil moisture deficit through increased water uptake; increasing yield under soil moisture deficit. Beltrano and Ronco (2008) reported improved water uptake, increased relative water content and higher dry matter weight in mycorrhizal inoculated wheat plants than non-mycorrhizal plants. Similarly, Song (2005) stated enhanced drought resistance in maize and alfalfa inoculated with mycorrhizal fungi. A study conducted by Kaya et al. (2003) observed that inoculation of mycorrhizal fungi improved water use efficiency in watermelon which consequently increased fruit yield.

One of the mycorrhizalstrategies involved include the increased soil-to-root contact in dry soils by the fungi hyphae; the fungi improve exploration of bound water by increased access to soil below permanent wilting potential (Birhane et al., 2012). However, according to Beltrano and Ronco (2008), the strategies involved with this mechanism are contentious, therefore, cannot be generalised, thus needs more attention and studies cited were conducted in controlled experiments. Extrapolation to field conditions of results obtained under controlled conditions has been hampered. There is vast information in literature about positive benefits of mycorrhizae, but that information is yet to be verified in fields. More so, the applicability of this mechanism in common bean is yet to be explored.

Drought resistance can also be achieved in plants through escape mechanism; the ability of a plant to complete its life cycle before harsh soil moisture deficits occur (Beebe et al., 2013). This mechanism involves rapid phonological development of early flowering and early maturity; and remobilization of photosynthates to the grain (Beebe et al., 2013; Chaves et al., 2003). The mechanism has been reported in common bean in Mexico by Acosta-Díaz et al. (2009). In their study, they observed that common bean genotypes that escaped from the effects of soil moisture deficit displayed earlier developments in reaction to the stress. However, the applicability of this mechanism to synergistic effects of low levels of P and moisture deficit in soils is not well demonstrated in common beans.

5. Plant-available P and Moisture Constraint

Deficiency in intrinsic P available for plants (Wortman et al., 2004) coupled with soil moisture deficit (Beebe et al., 2013; Miller et al., 2003) constitute major limitations of common bean production in SSA. With advent to climatic change prediction, the problem deepens (Beebe et al., 2013; Boko et al., 2007), warranting interest to investigate synergistic effects of the two factors. Although improved low P tolerant and drought resistant genotypes have been investigated, implementation of the results is yet to be popularised. This is crucial in marginal agro-ecological zones where a combination of P and moisture stress is severe. However, since inclusion of multiple stresses during selection makes the process complex and masks valuable genetic variability in drought resistance, it is better to study the response of such genotype to the combined stresses with advanced lines as advocated by Beebe et al. (2013). Therefore, it is essential to identify genotypes from the existing ones, with combined traits that leverage better utilisation of the scarce soil resources.

Studies have shown that some genotypes can perform well in both low P and moisture deficit (Beebe, Rao, Cajiao, & Grajales, 2008; Cichy, Snapp, et al., 2009; Porch et al., 2009). Beebe et al. (2008) revealed that drought selected genotypes; NCB 226, SER 118 and G 21212 were resistant to both constraints. Cichy, Snapp, et al. (2009) also observed that some indeterminate lines were achieved well under combined stressed conditions and Porch et al. (2009) observed further that G 21212 genotype was resistant to both low soil P availability and moisture deficit. However, in the same study, the latter authors reported that BAT 477, a resistant genotype to both constraints did not perform well under the interactive stressing conditions. This calls for more studies to elucidate that divergence. Moreover, most of the studies we surveyed were carried out in Latin America, not in Sub-Saharan African farming conditions.

5.1 Synergistic Effect of P Levels and Moisture Status in the Soil

Soil moisture has a long-term effect on P uptake and build-up by plants. Soil moisture deficit determines plant-available P in the soil and diffusion rates from the soil matrix to the absorbing root surface (Farooq, Wahid, Kobayashi, Fujita, & Basra, 2009). Since P transportation into the rhisosphere requires water, soil moisture deficit lowers P availability, acquisition by the roots and utilisation efficiency due to reduced mobility of $P0_{4,}^{3-}$ reduced transpiration rates and membrane permeability leading to depreciated root-absorbing potential of the crop (Farooq et al., 2009; Lambers et al., 2006). Therefore, increased soil moisture, especially at the topsoil improves P availability and acquisition efficiency. Sun et al. (2014) noted that presence of water in topsoil eased P availability and acquisition by the topsoil roots due to better fine root activities and ion mobility and diffusion on roots, and stretched root survival.

Nevertheless, drought resistance that has been reported in common bean was partly caused by availability of P in the soil. That uptake of P leads to faster development of roots that facilitates extraction of available soil moisture at the early stage of crop growth well before the commencement of soil moisture deficit is triggered by terminal drought (Chaves et al., 2003). Studies have indicated that application of P-fertilizers promotes drought tolerance. Thus, Garg, Burman, and Kathju (2004); Jones, Jacobsen, and Wraith (2005) and Jin et al. (2006) reported that application of P-fertilizers, at the time dry spells occurred for moth bean (*Vigna aconitifolia*), barley (*Hordeum vulgare*) and soybean (*Glycine max*), respectively, accelerated root development with subsequent access to soil moisture that enhanced early grain maturation before the beginning of terminal drought. Therefore, adequate levels of available P in the soil leads to early reproduction, allowing the plant escape the effect of soil moisture deficit

Our survey reveals the importance of the synergistic effects of plant-available P and moisture in soils on common bean production. Nevertheless, it should be noted that studies investigating impacts of interactions of low P levels and moisture deficit conditions in soils are yet to be conducted.

5.2 Mechanisms to Cope up with Low Levels of Plant-Available P and Soil Moisture

Root architecture has been associated with plant acquisition of P and moisture in soils (Ho, Rosas, Brown, & Lynch, 2005; Suriyagoda, Ryan, Renton, & Lambers, 2010). Architectural root traits have been explored in bean breeding programs to address tolerance to low soil P availability as well as drought resistance. However, response of architectural root traits to combined influences of low levels of P and moisture deficit in soils has received less attention in common bean, yet this mechanism is as important as application of P-fertilizers in common bean fields.

An abundant and shallow root system is advantageous to low soil P availability which is divergent to a deep root system for adaption to moisture deficit (Ho et al., 2005). Studies have showed that some common bean can perform well in both low P deficient and moisture deficit in soils (Beebe et al., 2008; Cichy, Snapp, et al., 2009). Beebe et al. (2008) observed that selection for drought also enhanced yield in P restricted conditions, while Cichy, Snapp, et al. (2009) noticed that some determinate lines performed well in P-limited areas with low amounts of rainfall. This is an indication of the importance of interaction between P and moisture availabilities in soils. However, the above studies emphasised shoot and yield traits more than those of roots, yet the interaction of architectural root traits for low P and moisture deficit in soils in the same genotypes is crucial for adaption to the combined conditions.

Studies have shown that a number of plants have profuse branching patterns of root systems in both top and deep layers of the soil, that allow for efficient absorption of P and moisture, respectively. Suriyagoda et al. (2010) reported that some Australian native perennial legumes developed correspondingly high magnitudes of roots in both top and subsoils soil layers at low P levels under soil moisture deficit. A study carried out by Morino, Obrador, Cubera, and Dupraz (2005) in Mediterranean shrubs also observed that some plant species had fine root systems in different soil layers, vesting them to explore topsoil P and deep moisture. This opportunity has not been fully explored in common bean genotypes that are grown in the relatively less dry areas of the tropics.

A study conducted by Ho et al. (2005) on root architectural trade-offs for P acquisition and moisture reported that BAT 477 had both a shallow root system linked to acclimatisation to low P and a deep root system for utilization of soil moisture deficit. This implies that such genotypes have the capacity to acquire both P from the topsoil and limited soil moisture from deep layers. However, this is the only information known to us which is limited, thererfore, cannot be based on to draw conclusive confirmation of the performance of common bean in agro-ecological zones characterised by low levels of P and moisture deficit in the soil.

Furthermore, plant roots form associations with mycorrhizal fungi that broadens the root absorption area, thereby improving P and moisture absorption by the plant (Quilambo, 2003; Song, 2005). Studies have indicated that mycorrhizal association with plant roots improves P availability (Birhane et al., 2012) and moisture status (Beltrano & Ronco, 2008). The fungi and the plant roots symbiotically share benefits; while the fungi get soluble organic compounds excreted by roots, the fungi in turn supply soil P and moisture to the plant. One of the strategies related to mycorrhizal mechanism is the direct uptake and transfer of P and moisture from inaccessible spaces by the fungi under low levels of P and moisture deficit in soils (Shen et al., 2011). In mycorrhizal plants, the improved absorbing surface created by the hyphae enhances the ability of plants to take up P and moisture from soils with low levels of P and moisture, respectively. That the hyphae has the capacity to reach very tiny soil pores that retain P and moisture as the soils dries, hence more widespread exploitation of the soils (Birhane et al., 2012; Shen et al., 2011).

5.3 Management of Plant-Available P and Moisture

Improved genetic resources alone are not the only option to be sought of in order to address low levels of plant-available P and moisture deficit in soils. Agronomic practices such as application of P-fertilizers and irrigation can reduce the losses caused by low levels of plant-available P and moisture deficit in soils, respectively. However, farmers in resource-constrained SSA cannot afford to buy commercial P-fertilizers and irrigating their farms (Beebe et al., 2011) on top of concerns about the environmental problems as a result of such intensive agriculture. Therefore, this calls for development and promotion of cheap and environmentally sound P-fertilizer sources such as organic materials to offset the effects of low levels of P in the soil. Application of organic materials to common bean production does not only serve as a source of P, it also enhances root mycorrhizal infestation potential in the soil by supplying mycorrhizae with carbon in exchange for P (Bukola, Fagbola, & Osonubi, 2012; Quilambo, 2003), thus increased efficiency of mycorrhizal association. Further, there is need to improve on water management and develop and promote cheap-accessible irrigation technologies for resource poor farmers. According to Lotze-Campen (2011), a number of low-cost ‘rainwater harvesting’ technologies have been advanced in many poor countries. However, such technologies are yet to be popularized.

Application of management practices such as use of organic manure; proper crop residues management and crop rotation can also serve as source of soil organic P, while mulch and minimum tillage preserve and conserve soil moisture during the dry season and periodic drought. Minimum ploughing only in the seedbed rows may be optimum and deep ploughing needs should be avoided because it may promote erosion. These practices also ensure minimum disturbance to the spores and improve the colonisation potential of mycorrhizal fungi.

6. Way forward and Conclusion

Despite the success of regional breeding programmes, a number of challenges in common bean production have persisted in SSA. Identification of crop traits and mechanisms that contribute to high performance under combined low levels of plant-available P and moisture deficit remains a major research and development challenge. Therefore, a number of measures can be emphasised to boost production under the combined stresses, which include the following:

6.1 Development of Bean Genotypes with Improved Root Traits

Since several specific architectural root traits that improve bean productivity under low levels of plant-available P and moisture in soils have been identified, there is need to improve these traits for the synergetic effects. Breeders should integrate phenotypes composed of massive and deep root architecture capable of exploring and extracting P and moisture from different soil layers that increase performance in target agro-ecosystems with combined constraints. Moreover, the evaluation exercise of the developed genotypes should be done on-farm to represent actual field conditions.

6.2 Enhancement of Mycorrhizal Associations

Meanwhile, mycorrhizal associations increase the ability of a plant to cope with soil P deficiency and moisture deficit caused by drought, plant mycorrhizal inoculation with suitable fungi is an area that needs attention. To deal with such constraints, local and cheap inoculants should be developed for poor resource farm production. Besides, use of soil fertility management practices such as application of organic manure is believed to stimulate the populations and activities of the mycorrhiza. Therefore, improvement of soil organic matter by using organic materials serves as a source of P and at the same time supply mycorrhizae with carbon in exchange for P. This calls for development of cheap, accessible and environmentally friendly fertilizers from organic materials for low income earners. The use of mycorrhizal infested plants could also reduce the quantity of fertilizers needed for plant growth.

6.3 Development of Integrated Crop Management Systems

Water conservation and soil management practices such as the use of organic manure to enhance soil organic matter; mulch to preserve moisture; crop residue management; crop rotations and minimum tillage that conserve soil moisture during the dry season and periodic drought should be emphasised. Deep ploughing is detrimental, therefore, it should be avoided since it may promote erosion. Minimum ploughing only in the seedbed rows may be optimum. These practices also ensure minimum disturbance to the spores and improve the colonisation potential of mycorrhizal fungi. Cheap and environmentally friendly fertilizers should be produced and cheap irrigation technologies should be developed.

6.4 Conclusion

The significance of increased common bean genotypes with ability to take up soil P and moisture is crucial in rain-fed agriculture in bean growing areas which are becoming drier due to climate change and as P is becoming more unavailable and expensive in SSA. Our survey reveals the importance of the synergistic effects of low levels of P and moisture deficit in the soils on common bean production. Nevertheless, it should be noted that studies investigating impacts of interactions of low P levels and moisture deficit conditions in soils are yet to be conducted. Therefore, there is need for holistic investigations that include soil plant-available P and moisture, common bean genotypes and their root systems, and agronomic measures to facilitate a comprehensive evaluation of impacts of deficiencies in soils on common bean yields.

While referring to combined effects of plant-available P deficiency and moisture deficit, consideration should be borne in mind about the root architecture and root exploration of the soil that enables the plant to access the two soil resources. Addressing the negative effects caused by soil P and moisture deficiencies by engineering new genotypes alone may not alleviate the problem of ensuring enhancement of high bean yields. The traditional methods that preserve good status of organic matter in soils and moisture and soil preparation techniques seem to be important as well and, hence should be considered in the strategies.

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