

Research Application Summary

Impact of degraded acidic soils on nitrogen fixation, and yields of soybean on smallholder farms

Kollie, W.

Faculty of Agriculture, Uganda Martyrs University (UMU), P.O. Box P 5498, Kampala, Uganda

Corresponding author: kolliewilliam@gmail.com; kollie.william@stud.umu.ac.ug

Abstract

Soybean is an ideal crop for improving nutrition, food security and plays an important function in the natural ecosystem and agriculture. In Uganda, the crop is produced in the Northern and Eastern regions by smallholder farmers in degraded acidic soils. Degraded acidic soils remain a major constraint to soybean production with farmers' yields below global production average. In spite of its economic importance, little investment has been made to research on soybean in degraded acidic soils in Uganda. Maksoy 1N, Maksoy 3N, Maksoy 4N, Maksoy 5N etc. are some of the improved soybean varieties that are currently being cultivated across farmers' fields in Uganda. This paper reviews the current state of soybean production in Sub Saharan Africa; highlights the soil fertility trends and the effects on soybean yields in the region, addresses the importance of lime to degraded acidic soils, biological nitrogen fixation (BNF) as influenced by rhizobial inoculants, and climatic requirement. Past and current studies showed that soybean grown in degraded acidic soils under different lime regimes had varied growth and yield. However, there were no clear trends on maximum soybean yield under different lime regimes in degraded acidic soils.

Key words: Degraded acidic soils, lime levels, nitrogen fixation, Rhizobial inoculants, Soybean yield, Uganda

Résumé

Le soja est une culture idéale pour améliorer la nutrition, la sécurité alimentaire et joue un rôle important dans l'écosystème naturel et l'agriculture. En Ouganda, la culture est produite dans les régions du nord et de l'est par de petits exploitants agricoles dans des sols acides dégradés. Les sols acides dégradés restent une contrainte majeure à la production de soja, les rendements des agriculteurs étant inférieurs à la moyenne de production mondiale. Malgré son importance économique, peu d'investissements ont été faits pour la recherche sur le soja dans les sols acides dégradés en Ouganda. Maksoy 1N, Maksoy 3N, Maksoy 4N, Maksoy 5N, etc. sont quelques-unes des variétés de soja améliorées qui sont actuellement cultivées dans les champs des agriculteurs en Ouganda. Cet article passe en revue l'état actuel de la production de soja en Afrique subsaharienne ; met en évidence les tendances de la fertilité des sols et les effets sur les rendements de soja dans la région, aborde l'importance de la chaux pour les sols acides dégradés, la fixation biologique de l'azote influencée par les inoculants rhizobiens et les exigences climatiques. Des études passées et actuelles ont montré que le soja cultivé dans des sols acides dégradés sous différents régimes de chaux avait une croissance et un rendement variés. Cependant, il n'y avait pas de tendances claires sur le rendement maximal du soja sous différents régimes de chaux dans les sols acides dégradés.

Mots clés: Sols acides dégradés, taux de chaux, fixation de l'azote, inoculants rhizobiens, rendement du soja, Ouganda

Introduction

Soybean (*Glycine max* (L.) Merrill) is the world's leading source of oil and protein and is an economically important crop which is believed to have been first introduced in Uganda in 1908 (Tukamuhabwa, 2016). Trials started in the late 1930s at Bukalasa and Serere, and by 1940 promising varieties were multiplied for distribution to farmers (Tukamuhabwa, 2016). The crop is being hailed as a poor man's meat and crop of the future (Tukamuhabwa, 2010) and provides the cheapest source of plant protein known to man in terms of accessibility especially in developing countries (Idrisa *et al.*, 2010). It can be processed into animal feed and its seed contains oil which can be used for cooking, making margarine and other industrial uses such as bio-fuel (Mathu *et al.*, 2010). Estrada (2004) found soybean uses in South Africa to be 56% for livestock feed, 12% for oil, 23% for food relief, and 9% as textured soybean protein products. Similar importance was reported by SNV (2011) in Uganda. Cultivation of the crop is rapidly gaining popularity in Africa following high demand from the expanding livestock feed industry (which consumes about 70 - 80% of soybean produced per year) and its use to restore soil nitrogen in symbiosis with rhizobium makes it a very good colonizer of low-N soils (Mahasi *et al.*, 2011).

However, degraded acidic soils remain one of the most limiting factors in nitrogen fixation by legume-rhizobia symbiosis (Van Zwieten *et al.*, 2015). Soil with pH < 5.0 limits soybean nodulation due to toxicity effects of Al and Fe ions causing poor nodules formation and functioning (Nisa *et al.*, 2012). The crop requires high nutrients, with P and K being the most crucial for optimal production (Sikka *et al.*, 2012). Degraded acidic soils reduce organic matter breakdown, nutrient cycling by microorganisms, reduce uptake of nutrients by plant roots and causes inhibition of root growth (Fageria *et al.*, 2013). The soils are often deficient in phosphorus (P), magnesium (Mg), calcium (Ca), molybdenum (Mo), and potassium (K) with a high concentration of iron (Fe), aluminium (Al), hydrogen (H), copper (Cu) and manganese (Mn) ions (Keino *et al.*, 2015).

Globally, acid soil is a key problem contributing towards reduced agricultural productivity (Van and Smith, 2014). Nkonya *et al.* (2008) reported that land affected by degradation in Uganda ranges from 20% in flat and vegetation-covered areas to 90% in the eastern and southwestern highlands. In Sub-Saharan Africa (SSA). Degraded acidic soils occupy 29% of the total area, which is associated with reduced fertility levels (Muindi *et al.*, 2016), and nutrient depletion is a major aspect of soil degradation (Vanlauwe *et al.*, 2012). In Eastern Uganda (Tororo, Iganga, Kamuli and Soroti Districts), the soils are degraded and are extremely acidic with a pH < 4.5 and have low organic matter, and low nutrient status of nitrogen content, phosphorus availability, exchangeable potassium, and varied trace elements from different land uses (Gachimbi and Maitima, 2004). Continuous cropping using incorrect fertilizer types, leaching of basic cations (Ca^{2+} , K^+ , Mg^{2+} ,) due to rainfall thus replacing them with acidic cations (Al^{3+} , H^+) have intensified the chemical degradation of cultivable soils resulting in reduced capacity to produce crops sustainably (Kisinyo *et al.*, 2014). At low soil pH, soybean nodulation and biological nitrogen fixation (BNF) is limited and this has been attributed to the low P level at pH < 5.5 due to its sorption by Al and Fe (Kisinyo *et al.*, 2014).

Soybeans are grown in different agro ecological regions across Sub Saharan Africa (SSA). In Uganda for instance, the crop is grown in the Northern and Eastern regions where resource limited farmers are engaged in production in degraded acidic soils. Despite the numerous benefits of the crop, the grain yield per unit area is low in smallholders' farms across Uganda averaging 2-3.5 t ha⁻¹ (Tukamuhabwa *et al.*, 2006) as compared to in the United States of America (82 t ha⁻¹) followed by Brazil (65 t ha⁻¹), Argentina (40 t ha⁻¹) and China (12 t ha⁻¹) (FAO, 2013). This could be attributed to the knowledge gaps that still exist about the state of soil fertility in the region. It could also be that research programs have not placed emphasis on soil fertility management such as liming or that, these soils might have probably reached the last stages of weathering with limited nutrient replenishment (Glatzel *et al.*, 2014) caused by continuous nutrient mining with minimal nutrient replenishment via crop harvests, soil erosion, leaching during heavy rainfall and soil acidity markedly influencing soil degradation (Verde *et al.*, 2013). Besides, many small-scale farmers across Africa depend on such soils for their livelihood. Therefore, the problem of degraded acidic soils needs to be given much attention. This is important so that some leguminous crops like soybean can successfully be grown in such soils.

Soil fertility trends in Sub Saharan Africa (SSA)

Soil health remains a vital component for agriculture production and holds a solidified future for the rural poor across Sub Saharan Africa (SSA). However, the soils are unhealthy, largely due to years of crop nutrient-mining and limited organic or inorganic resupply (Jones, 2013). Soil erosion by water and wind, depletion of soil nutrients, salinity, water logging, acidification and deforestation are the major agents of soil degradation in the region (Ibrahim, 2015). These soils in their current states are not able to provide adequate nutrition for the region's population, with 236.5 million people undernourished and an increase of 60 million expected in 10 years (FAO, 2017). Apart from widespread low levels of N and P across the highly weathered soils in SSA, deficiency of other essential nutrients, low organic matter, and soil acidity also contribute to low crop yields (Kihara *et al.*, 2017). About 65% of the agricultural soils in SSA are degraded due to poor management practices, which induce decline in soil biological, chemical and physical quality and reduced capacity of the soil to support crop production and provide other ecosystem services (Oldeman *et al.*, 1991, Zingore *et al.*, 2015). Annual nutrient depletion in the year 2000 was estimated to have reached 38 kg ha⁻¹ (i.e., 26 kg N, 3 kg P, 9 kg K (FAO and ITPS, 2015), leaving soils with serious fertility constraints. Such degraded soils reduce annual agricultural productivity by nearly 3% (Zingore *et al.*, 2015), costing the SSA region about USD 68 billion annually. The degradation has stagnated or even reduced yields levels of legume crops at a time when the region's population is rapidly rising (Obalum *et al.*, 2012). Meeting the growing demand for food while supporting 70% of the households in the region depending directly or indirectly on agriculture will be a big problem if the current trends of degraded acidic soils continue (FAO, 2002).

There have been review articles covering soil fertility approaches for SSA; however, those reviews are almost exclusively biophysical in nature (Buresh *et al.*, 1997; Donovan and Casey, 1998; Bationo *et al.*, 2006; Conway, 2012). Long-term solutions, such as approaches that build organic matter (OM) and organic nutrient pools in addition to inorganic fertilizer applications will be an essential component to achieving sustainable soil fertility in SSA (Vanlauwe *et al.*, 2010, 2014, 2015) with lime and inoculants being effective amendments for improving soil fertility, increasing microbial activity, and generally improving crop yield (Nekesa *et al.*, 2011; Badole *et al.*, 2015).

Liming Materials

Lime in a broad sense is any material containing calcium (Ca) or magnesium (Mg) that tends to neutralize soil acidity thereby making soluble nutrients insoluble for plant uptake. Liming materials include CaCO_3 , $\text{CaMg}(\text{CaCO}_3)_2$, $\text{Ca}(\text{OH})_2$, CaO and others, which vary according to their degree of fineness and neutralizing capacity (TSO, 2010). Addition of lime to degraded acidic soils supplies Ca^{2+} and Mg^{2+} ions and displaces H^+ , Fe^{2+} , Al^{3+} , Mn^{4+} and Cu^{2+} ions from the soil adsorption site thus resulting in an increase in the soil pH (Andric *et al.*, 2012). Indirect effects of lime include the increased availability of P, Mo and B, and more favorable conditions for microbial mediated reactions such as nitrogen fixation and nitrification, and in some cases improved soil structure (Nekesa *et al.*, 2005). For instance, application of lime significantly increased root and shoot yields in degraded acidic soils in Nigeria (Anetor and Akinrinde, 2006) and grain yields of soybean in Brazil (Kassel *et al.*, 2000; Caires *et al.*, 2008). Similarly, in Croatia Andric *et al.* (2012) reported increased soybean yield by 44 % as a result of lime application in degraded acidic soil. Moreover, Nekesa *et al.* (2011) in Western Kenya also found positive response of soybean grain yield to lime application either alone or when combined with P fertilizer.

Current state of soybean production in Sub Saharan Africa

Average soybean yield in SSA has stagnated at 1.1 t ha^{-1} in the last four decades, in contrast to the world average of 2.4 t ha^{-1} (Woomer *et al.*, 2012). The low soybean yields in SSA may be accounted for largely by poor-performing varieties, lack of sustained rhizobial inoculants use, and fertilizer application as influenced by soil degradation (Woomer *et al.*, 2012).

In SSA, South Africa was the largest soybean producer in 2016, followed by Nigeria, Zambia, and Uganda (Rusike *et al.*, 2013). In 2016/2017, South Africa (2290 kg ha^{-1}) and Zambia (1940 kg ha^{-1}) had the highest average yields followed by Nigeria (960 kg ha^{-1}) and Uganda (600 kg ha^{-1}). Average yields in South Africa, Nigeria, Zambia, and Uganda during 2012 to 2016 are presented in Table 1.

Table 1. Average yields (kg ha^{-1}) in leading soybean producing countries in Sub-Saharan Africa during 2012/2017

Country	2012/2013	2013/2014	2014/2015	2015/2016	2016/2017
South Africa	1300	1620	1450	1480	2290
Nigeria	1000	1000	1000	960	960
Zambia	1200	1200	1560	2020	1940
Uganda	630	650	600	600	600

Data Source: Index Mundi, 2017 (<http://www.indexmundi.com>)

Tanyima (2015) reported that despite government's efforts to increase soybean production in Uganda through breeding high yielding and rust resistant varieties, soybean production was still very low compared to in other African soybean producing countries such as South Africa and Nigeria and far low compared to in developed countries such as the United States of America and Brazil. Commercial soybean varieties released and cultivated in Uganda are Maksoy 1N and Namsoy 4M (2004), Maksoy 2N (2008), Maksoy 3N (2010), Maksoy 4N and Maksoy 5N (2013).

However, production still faces several socio-economic and technical challenges, such as low soil fertility, low quality seeds and poor access to good seeds, inadequate finance for acquiring improved technologies, poor traditional methods of farming, poor marketing system and poor road system (SNV, 2011). Besides, these varieties are yet to be studied in degraded acidic soils with the proper use of biological inoculants as a way of developing protocol (s) for determining maximum soybean yield under different lime levels.

Biological nitrogen fixation in soybean

According to Horben *et al.* (2011), nitrogen is a critical limiting element for plant growth and production. Korir *et al.* (2017) suggested that nitrogen as an essential element for plant growth and development is a key issue for enhancing crop productivity as most studies indicated that nitrogen fertilizers contribute to resolving the challenge the world is facing in feeding the human population.

The bacteria known as *Bradyrhizobium japonicum* have a nitrogenase enzyme which is capable of converting atmospheric nitrogen into amino acids and protein through ammonia (Ali and Kemal, 2011). This process begins by the attachment of the rhizobia to the flavanoids produced by the root cells; the bacteria then attach themselves to the extensions of the epidermal cells known as the root hairs (Thuita *et al.*, 2012). This is followed by a firmer attachment of the bacteria to the root surface. The host legume then senses the chemicals produced by the bacteria known as the nod factors (Thuita *et al.*, 2012). This causes the colonized root hairs to curl and form a tubular structure known as the infection thread (Salavati *et al.*, 2012b). When the bacteria reach the root itself, they stimulate cortical cell divisions that lead to the formation of a nodule in which chemical process that is BNF takes place (Wagner, 2012). Although the process involves a large number of chemical reactions, it can be summarized by the following equation; $N_2 + 8 H_2 + 16 ATP \rightarrow 2NH_3 + 2H_2 + 16 ADP + 16 Pi$. The equation indicates that one molecule of nitrogen gas combines with eight molecules of hydrogen also known as protons to form two molecules of ammonia and two molecules of hydrogen gas. The 16 molecules of ATP (= Adenosine Triphosphate, an energy storing molecule) represent the energy required for the biological nitrogen fixation to take place (Wagner, 2012).

Because the usually acidic, saline, and low organic matter of SSA soils, the average soybean yield is usually well below the world average (Thuita *et al.*, 2012). A report by Mohammadi *et al.* (2012), showed that soil nutrient status has a tremendous influence on symbiosis, as well as independent growth and survival of both partners, and therefore fixation tends to decrease with legume age, mainly because of the concomitant increase in soil N. It was further stated by Graham and Vance (2000) that more than 1.5g ha⁻¹ of acid soils limit agriculture production worldwide and as much as 25% of the earth's croplands are impacted by problems associated with soil acidity.

Rhizobial inoculants. The *rhizobium-legume* symbiosis plays an important role in agriculture because it offers the ability to convert atmospheric molecular nitrogen into forms usable by plants (Rebah *et al.*, 2007). This has led to the adoption of commercial *rhizobial* inoculants to help in enhancing the process of biological nitrogen fixation and also in land remediation (Mohammadi *et al.*, 2012). Soybean has been known for its good nitrogen fixing ability and is capable of fixing up to 80% of its nitrogen requirements when it is well nodulated (Thuita *et al.*, 2012). Studies indicated that legumes have specific requirements for rhizobia (e.g. soybean, chickpea) and thus need inoculation (Thuita *et al.*, 2012).

Climatic requirement. Soybean grows well in the tropical, subtropical and temperate climates (Singh and Chauhan, 2010). One of the important challenges facing crop physiologists and agronomists is to understand and overcome the major abiotic stresses in agriculture which reduce crop productivity and yield (Habibpor *et al.*, 2011). Interest in crop response to environmental stresses has increased greatly in recent years because of severe losses that result from drought, heat, low P, acidity, and salinity (Jogaiah *et al.*, 2013). Rienke and Joke (2005) described soybean as being typically a short day plant, physiologically adapted to temperate climatic conditions. Minimum temperature at which it develops is 10 °C, the optimum being 22 °C and the maximum about 40 °C. The seeds germinate well at temperatures between 15 °C and 40 °C, but the optimum is about 30 °C (Rienke and Joke, 2005).

Conclusion

Soil degradation is one of the most important constraint to soybean production in Sub-Saharan Africa. Low levels of nutrients availability are the primary fertility constraints. Soils across Uganda are becoming increasingly degraded thus hindering the productivity of most annual crops. Numerous studies in Uganda and across SSA have shown the potential of improving soil fertility with legumes through the use of lime and rhizobial inoculants. Results from those studies have however failed to clearly show maximum soybean yield in degraded acidic soils with the proper use of biological inoculants under different lime regimes. Therefore, research is underway to develop protocol (s) for determining maximum soybean yield for three local commercial soybean varieties with the use of rhizobial inoculants under different lime levels in degraded acidic soils in Eastern and Northern Uganda.

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