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Grain legume impacts on soil biological processes in sub-Saharan Africa

Newton Z. Lupwayi[1]*, Ann C. Kennedy[2] and Rowland M. Chirwa[3]

[1]Agriculture & Agri-Food Canada, Lethbridge Research Centre, 5403-1 Avenue South, P.O. Box 3000, Lethbridge, AB, T1J 4B1, Canada
[2]USDA-ARS, 217 Johnson Hall, Washington State Univ., Pullman, WA 99164-6421.
[3]CIAT Regional Bean Program, Chitedze Agricultural Research Station, P.O. Box 158, Lilongwe, Malawi.

Grain legumes occupy about 20 million hectares in Africa. The major crops are cowpea (*Vigna unguiculata* L.), which is grown on about 11 million hectares mostly in West Africa, and common bean (*Phaseolus vulgaris* L.), grown on about 5 million hectares mostly in eastern and southern Africa. These grain legumes have impacted soil organisms, including nitrogen fixers, mycorrhizae, fauna, and the processes that they perform. The legume-*Rhizobium* symbiosis results in dinitrogen (N_2) fixation that adds plant-available nitrogen to the soil system. Some of the fixed N_2 is recycled when legume crop residues decompose for the benefit of non-legume crops grown with or after grain legumes. This N recycled by grain legumes is minimal because most of the N in these legumes is in the grain that is removed from the farm at harvest. Non-legume crops grown in rotation with legumes may also benefit from endophytic rhizobia. Mycorrhizal associations that improve plant nutrient and water uptake also benefit from the legume in a cropping system. Besides breaking pest cycles, grain legume crops also reduce disease infestation of non-legume crops by enhancing biological pest control through increased microbial diversity and activity. Legumes may contribute to greenhouse gas (nitrous oxide and carbon dioxide) emissions during nitrification and denitrification of fixed N_2. However, because less fertilizer N is used in legume-based cropping systems, overall greenhouse gas emissions are usually less than those in fertilized monoculture cereals. Through their effects on soil biology, legume crops also improve soil structure by enhancing the formation and maintenance of soil aggregates. Therefore, grain legumes in Sub-Saharan Africa have positive effects on agriculture by adding and recycling biologically fixed N_2, enhancing nutrient uptake, reducing greenhouse gas emissions, and improving soil structure and breaking non-legume crop pest cycles.

Key words: Pulse crops**,** soil biology, soil health, tropical soils.

INTRODUCTION

Soil microorganisms mediate many agriculturally beneficial processes that include N_2 fixation, recycling of nutrients like N, P and S, formation and maintenance of soil structure, biological control of plant and animal pests, and degradation of agro-chemicals and pollutants. Therefore, soil management systems that foster the development of healthy, diverse microbial communities are more likely to be sustainable than those that do not. Soil microorganisms are also good early indicators of changes in soil health.

Grain legumes, excluding oilseed crops soya bean (*Glycine max* L.) and groundnut (*Arachis hypogaea* L.), occupy about 20 million hectares in Africa (FAO, 2009). The major crops are cowpea (*Vigna unguiculata* L.), which is grown on about 11 million hectares mostly in west Africa, and common bean (*Phaseolus vulgaris* L.), grown on about 5 million hectares mostly in eastern and southern Africa (Figure 1). Yields of these crops are low, averaging 742 and 594 kg ha^{-1} for cowpea and common

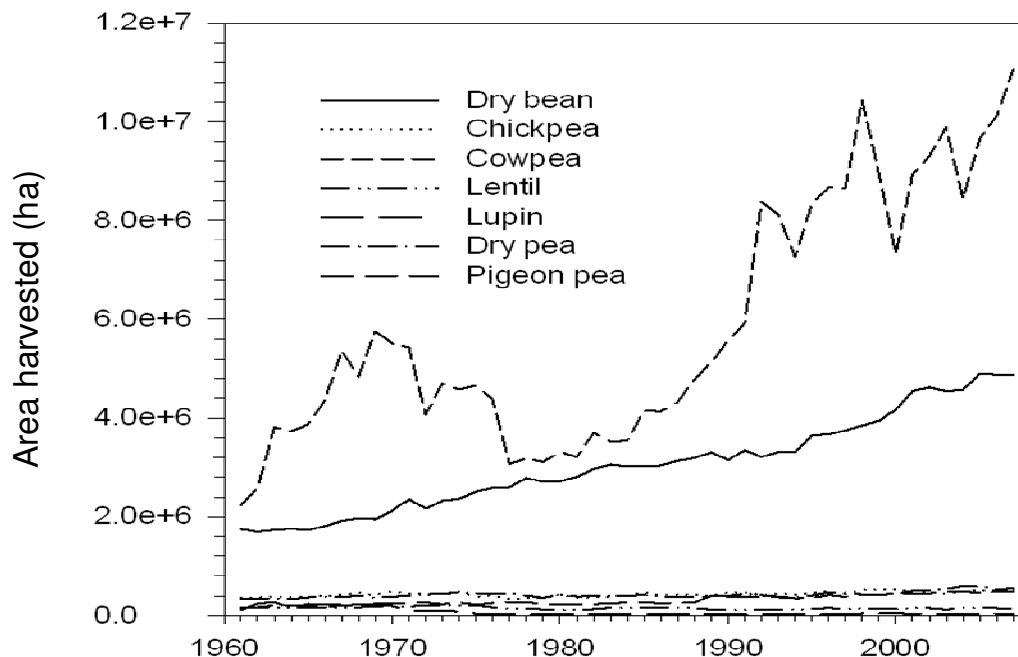*Corresponding author. E-mail: newton.lupwayi@agr.gc.ca. Tel: 403-317-3315.

Figure 1. Area (hectares) of grain legumes harvested in Africa from 1961 to 2007 (drawn using data from FAO Stat, 2009).
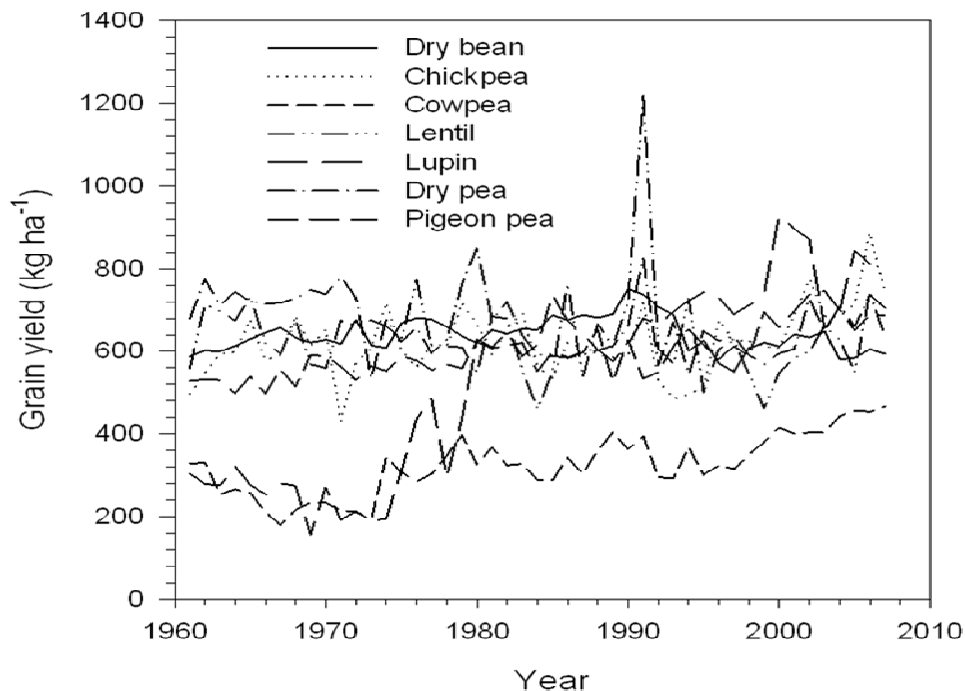

Figure 2. Yields of grain legumes in Africa from 1961 to 2007 (drawn using data from FAO Stat, 2009).

bean, respectively (Figure 2). Growing these legumes impacts soil organisms and the various beneficial processes that they mediate. For example, Yusuf et al. (2009) in Nigeria observed that soil microbial biomass C (MBC) and N (MBN) increased by about 30 and 200%, respectively, when maize (*Zea mays L.*) was rotated with cowpea compared to monoculture maize (Table 1). Such effects on soil biology occur in the spermosphere (the soil

Table 1. Soil microbial biomass C (MBC) and N (MBN) in maize plots in monoculture or in rotation with cowpea in Nigeria (Modified from Yusuf et al., 2009).

Preceding crop	MBC (mg kg^{-1} soil)	MBN (mg kg^{-1} soil)
Maize	253b	10.6b
Fallow	250b	11.9b
Cowpea variety 1	327a	31.4a
Cowpea variety 2	335a	30.8a

zone surrounding, and influenced by, seeds), rhizosphere (the soil zone surrounding, and influenced by, roots), and detritusphere (the soil zone surrounding, and influenced by, decomposing crop residues), and they impact biological processes in the soil. Examples of the impact of grain legumes on these biological processes in Sub-Saharan Africa (SSA) are presented in this paper. Where information from SSA is not available, results from other parts of the world are used to illustrate some points.

NITROGEN FIXATION

One of the most widely studied beneficial plant-microbe interactions is the symbiotic relationship between legumes and *Rhizobium* spp. (The terms *Rhizobium* or rhizobia are used collectively for the genera *Rhizobium, Bradyrhizobium, Sinorhizobium, Mesorhizobium, Allorhizobium,* and *Azorhizobium*, unless specified otherwise). Interactions between rhizobia and legume roots result in formation of root nodules, in which rhizobia use energy from the host plant to transform (fix) atmospheric N_2 into plant-available forms of nitrogen.

The amount of N_2 fixed by a legume crop varies widely because it depends on the legume genotype, *rhizobium* strain and the soil environment. Ojiem et al. (2007), working with various legume crops for grain, green manure and fodder, showed that the legume crops demonstrated greater N_2 fixation potential under medium rainfall than under high or low rainfall in western Kenya. Similarly, the legume biomass production (3.0 to 14.8 t ha^{-1}) was highest under medium rainfall compared to high rainfall (2.5 to 8.4 t ha^{-1}) or low rainfall (2.5 to 4.9 t ha^{-1}). Ojiem et al. (2007) also observed declining N_2 fixation with declining soil fertility status, e.g., a 44% decrease in N_2 fixed by grain legumes under low fertility relative to that fixed under high fertility. Results from agronomic studies on maize-bean intercropping systems and their influence on N_2 fixation in Malawi showed that applying P fertilizer consistently increased N_2 fixation and grain yield (Snapp et al., 1998). For example, 30% of bean plant N was derived from N_2 fixation when no P was applied and 60% when 30 kg P ha^{-1} was applied.

Since most grain legumes in SSA are intercropped with cereals, there is competition for water and nutrients in the root zone. Quoting various sources, Giller et al. (1997) summarized the amounts of N_2 fixed by grain legumes in SSA as ranging from 11 to 201 kg N_2 ha^{-1} for sole-cropped cowpea, 9 to 125 kg N_2 ha^{-1} for intercropped cowpea, 2 to 58 kg N_2 ha^{-1} for sole-cropped common bean, and 0 to 71 kg N_2 ha^{-1} for intercropped common bean. Assuming an average N_2 fixation of 45 kg N_2 ha^{-1} for cowpea and 30 kg N_2 ha^{-1} for common bean, and multiplying these amounts by their respective hectares (Figure 1), it is estimated that about 500 and 150 million kg N_2 were fixed by cowpea and common bean, respectively, in SSA in 2007. Including other grain legumes, a total of about 720 million kg N_2 were fixed in SSA in 2007, representing 14% of the global estimate of 5000 million kg N_2 fixed by grain legumes excluding soya bean (Herridge et al., 2008).

The ability of legumes to fix N_2 allows farmers to grow them with minimal inputs of N fertilizer. Non-legume crops grown in association or in rotation with them usually have reduced fertilizer N requirement ("Nitrogen Cycling"), which has both economic and environmental benefits.

NITROGEN CYCLING

Some of the N_2 fixed by legumes is recycled, mostly during decomposition of above-ground and below-ground crop residues. Nitrogen cycling is mediated by soil (micro) organisms, and the rate and pattern of N release from crop residues is regulated by soil microbial activity, residue quality and soil environment. Environmental conditions like soil moisture and temperature affect N mineralization by influencing soil microbial activity (Vigil and Kissel, 1995; Agehara and Warncke, 2005). Mineralization of N is usually positively correlated with residue N concentration and negatively correlated with C/N, lignin/N and polyphenol/N ratios (Lupwayi and Haque, 1999).

Most of the N in grain legumes is contained in the high-protein grain and is removed from the farm at harvest. Even in bushy, creeping legumes like cowpea, which have more residues than less bushy legumes, at least 50% of their N is contained in the grain (Table 2). This removal of N through grain at harvest means that little N is returned to the soil with crop residues, e.g., 23 to 26 kg N ha^{-1} in residues of four cowpea varieties in Ghana

Table 2. Nitrogen distribution in cowpea plants at harvest in Ghana (Adapted from Adjei-Nsiah et al., 2008).

Cowpea variety	Grain N (kg ha^{-1})	Straw N (kg ha^{-1})	Grain N harvested (%)
Variety 1	30	26	54
Variety 2	35	24	59
Variety 3	26	26	50
Variety 4	26	23	53

Table 3. Mycorrhizal colonization of monoculture millet and millet rotated with cowpea in Niger (Bagayoko et al., 2000).

Preceding crop	Roots infected (%)	
	45 days after planting	95 days after planting
Millet	27b	48b
Cowpea	48a	64a

(Adjei-Nsiah et al., 2008), and results in crop residues that have high C/N, lignin/N and polyphenol/N ratios and therefore decompose slowly (Paustian et al., 1992). Consequently, the limited N contained in these residues is released slowly or even immobilized by the decomposing microflora. Giller et al. (1997), quoting several sources, reported that only 12 to 24% of cowpea shoot residue N was recovered in the first subsequent crop. Adjei-Nsiah et al. (2008) observed a net N contribution of 8 to 11 kg N ha^{-1} from the 23 to 26 kg N ha^{-1} added through cowpea residues. However, the N contribution by decomposing legume roots is usually not added to these estimates because sampling roots is labour-intensive. Similarly, estimates of N uptake by subsequent crops does not usually include root N due to root sampling difficulties. Even when legume crop residues result in short-term N immobilization, they benefit long-term soil nutrient status by increasing soil organic matter when used in crop rotations. Soil organic matter improves soil physical structure that may reduce soil erosion and increase water and nutrient retention. Grain legumes also increase biological diversity in ecosystems (Sharma et al., 2005).

Nitrogen "sparing" is another way in which legume crops contribute N to intercropped or rotation crops. Since part of their N requirement is met by N$_2$ fixation, legumes utilize less of the available soil N than cereals, thereby "sparing" or "conserving" inorganic N for the intercrop or following crop (Chalk et al., 1993; Herridge et al., 1995). However, N sparing is not universal because legumes sometimes take up as much or even more soil inorganic N than comparable non-legume crops (Chu et al., 2004). Some grain legume crops such as pigeon pea (*Cajanas cajan* (L.) Millsp.) have strong deep roots.

These legumes not only contribute to improving the soil physical structure by breaking the soil hardpan to improve soil water and air flow, but also mine plant nutrients from deep layers of the soil that other crops cannot reach. The nutrients are deposited in the soil surface layers as the crop residues decompose, contributing to nutrient cycling. In Malawi, the inclusion of pigeon pea in rotation increased the total N concentration in the top soil to approximately 100 µg g^{-1} soil, compared with 25 µg g^{-1} soil in cropping systems with no grain legume included in the rotation or intercrop (Likoswe, 1994).

NUTRIENT UPTAKE

Mycorrhizae

Mycorrhizae are nonpathogenic fungi that form symbiotic associations with plant roots, including those of grain legume crops. The beneficial relationship between the two organisms can increase the uptake of nutrients and water in plants, and can increase N$_2$ fixation in legumes by improving host nutrition (Xavier and Germida, 2002). Hamel (2004) reviewed the impact of mycorrhizae on crop N and P nutrition. Mycorrhizal associations have the greatest impact on plant growth in stressed environments, phosphorus deficient soils, eroded sites, and acidic or reclaimed lands. Crop rotations, especially those with legumes, can increase root colonization by mycorrhizae. In Niger, Bagayoko et al. (2000) observed 27% colonization of pearl millet (*Pennisetum glaucum* L.) roots (45 days after planting) by mycorrhizae when millet was grown in monoculture, and 48% colonization when millet followed cowpea in rotation (Table 3). One of the reasons that legume residues increase mycorrhizal colonization in other crops is that they offer an alternative food source for soil fauna that would otherwise graze on mycorrhizae (Borie et al., 2002).

Endophytic Rhizobia

Roots of non-legume crops grown in rotation with legumes

contain endophytic rhizobia. When barley (*Hordeum vulgare* L.), wheat (*Triticum aestivum* L.) and canola (*Brassica rapa* L.) were each grown in monoculture or in rotation with field pea (*Pisum sativum* L.) in northern Alberta, populations of endophytic rhizobia up to 7,244 cells g^{-1} root DM were observed in pea-based rotations, but less than 10 cells g^{-1} root DM were observed in monoculture (Lupwayi et al., 2004). These endophytic rhizobia and other bacteria have been found to increase yields of non-legume crops such as rice and maize (Biswas et al., 2000; Chaintreuil et al., 2000; Riggs et al., 2001). In a potted soil experiment in Senegal, Chaintreuil (2000) reported significant response of wild rice (*Oryza breviligulata* A. Chev. & Roehr) growth and grain yield to inoculation with *Bradyrhizobium* spp. There is no conclusive evidence that the benefits of endophytic rhizobia involve symbiotic N_2 fixation (James, 2000; Yanni et al., 2001).

These bacteria increase yields by stimulating plant growth, increasing disease resistance, or improving the plant's ability to withstand environmental stresses like drought. The rhizobia act as plant growth-promoting rhizobacteria (PGPR) that have been shown to expand the root architecture of the crop, enabling those plants to accumulate more N, P, K, Ca, Mg, Na, Zn and Mo than control plants (Yanni et al., 2001). Therefore, rhizobia contribute to the rotational benefits of legumes in cropping systems in more ways than just fixing N_2. Even in legumes, seed treatment with rhizobia has been shown to reduce disease incidence. In field experiments in southern Alberta, treatment of pea and lentil (*Lens culinaris* Medik.) seed with *Rhizobium leguminosarum* bv. v*iciae* reduced the incidence of damping-off, a disease caused by soil-borne pathogens *Pythium* spp. (Huang and Erickson, 2007). However, the relative roles of crop protection and crop nutrition in the effects of rhizobia (as PGPR) on non-legume crops require clarification.

GREENHOUSE GAS EMISSION

Legumes contribute to N_2O emissions because the atmospheric N_2 fixed by the legume during *Rhizobium* symbiosis is nitrified and denitrified like fertilizer nitrogen. Also, rhizobia in root nodules are capable of denitrification as well as N_2 fixation. While high rates of denitrification by *Rhizobium* species have been shown in laboratory studies, losses of nitrogen occurring in the field due to denitrification by these species are inconsistent or not well documented (O'Hara and Daniel, 1985). Therefore, the ecological implications of denitrification by rhizobia are not well understood.

Greenhouse gases (mainly CO_2 and N_2O) are produced during microbial utilization of organic compounds in the spermosphere, rhizosphere and detritusphere. Nitrous oxide emissions, in particular, occur during nitrification (in well aerated soil) or denitrifica-

tion (in poorly aerated soil) of soil N from inorganic or organic sources. Huang et al. (2004) and Toma and Hatano (2007) found that both N_2O and CO_2 emissions were negatively correlated with the C/N ratio of crop residues, that is, pulse crop residues may produce more N_2O and CO_2 than cereal residues if the pulse residue C/N ratio is narrower than that of cereal residue. However, since legume crops are grown with little or no fertilizer N, emissions of N_2O are expected to be less in a legume crop than in a fertilized cereal crop. This was the case in a Canadian study when emissions were compared between legume (receiving 0 or 5 kg ha^{-1} fertilizer N yr^{-1}) and non-legume (receiving 0 to 190 kg N ha^{-1} yr^{-1}) crops (Helgason et al., 2005). Gregorich et al. (2005) found similar results (legume-based systems vs. fertilized annual crops) in eastern Canada and northeastern USA. In addition, the reduced use of fertilizer N in legume-based cropping systems means less burning of fossil fuel (CO_2 emission) in manufacturing, transporting and applying fertilizer N (Jensen and Hauggard-Nielsen, 2003).

In Saskatchewan, Zentner et al. (2001) reported 24% less total energy requirement in a lentil-wheat rotation compared with a wheat-wheat system because N_2 fixed by lentil reduced fertilizer N requirements for subsequent wheat crops. Therefore, it can be concluded that the contribution of legumes to greenhouse gas emissions is usually more than offset by reduced emissions from less fertilizer manufactured, transported and applied, and increased soil carbon sequestration. However, without similar field results from SSA, where less fertilizer is used compared to developed countries, it is not known whether such offsets occur. In a controlled-environment, simulated-rainfall study of soils collected from farmers' fields in Senegal, soils collected from groundnut fields emitted less NO and N_2O than soils collected from sorghum (*Sorghum vulgare* L.) fields (Dick et al., 2006), but the difference was not statistically significant.

BIOLOGICAL PEST CONTROL

Growing the same crop continuously on the same piece of land fosters build-up of pests (pathogens, insects and weeds) to which the crop is susceptible. Rotating crops with non-host crops interrupts the pest cycle. For cereals, rotations with legumes are particularly attractive because the legumes are likely to contribute N to the soil/plant system as well as interrupt pathogen cycles. In Ethiopia, a faba bean (*Vicia faba* L.)-wheat-wheat rotation reduced the severity of wheat take-all (*Gaeumannomyces herpotrichoides*) disease compared with wheat monoculture (Asefa et al., 2002). In South Africa, the incidence of wheat-crown-rot fungus (*Fusarium pseudograminearum*) and disease were lower in forage-legume-based rotations than in monoculture wheat (Lamprecht et al., 2006).

Disease reduction is variable with common bean and cowpea in rotation. In Uganda, rotation of potato (*Solanum tuberosum* L.) with common bean had no effect on the incidence of potato bacterial wilt (*Ralstonia solanacearum*) (Lemaga et al., 2001). In Niger, plant-parasitic nematodes were 70% more abundant in pearl millet (*P. glaucum* L.) rotated with cowpea than in monoculture millet at one site, but the difference was not significant at two other sites (Bagayoko et al., 2000). Although the trend was reversed in sorghum (*Sorghum bicolour* L.)-groundnut rotations, the differences were not significant. This means that the pest control benefits of legumes do not always occur, and opposite effects can occur. However, the increased microbial diversity and activity in legume spermosphere, rhizosphere or detritusphere usually promotes biological pest control (Janvier et al., 2007).

SOIL AGGREGATE FORMATION AND MAINTENANCE

Through their effects on soil biology, legume crops also improve soil structure by enhancing the formation and maintenance of soil aggregates. Good soil physical structure reduces soil erosion, protects soil organic C from microbial breakdown, and increases water infiltration and air circulation. Research in Australia (Chan and Heenan, 1991) has shown the following order of crops in maintaining soil structure: lupin (*Lupinus angustifolius* L.) > lentil > canola > pea > linseed (*Linum usitatissimum* L.) > barley. In Nigeria, Obi (1999) observed the following order of legume and grass cover crops in cumulative water infiltration in a degraded soil: legumes (*Stylosanthes gracilis* L. and *Pueraria phaseoloides* L.) > grasses (*Panicum maximum* L.*, Pennisetum polystachion* L.*, Cynodon plectostachion* L.*,* and *Axonopus compressus* L.) > bare soil. The order of soil organic C contents was similar, and the differences were related to soil structure. Therefore, the forage legumes had greater restorative effects of the soil than grasses and bare soil. We were unable to find examples on grain legumes in SSA, but it is probable that they have similar effects.

CONCLUSION

The soil is in flux from the time the grain legume seed is planted and continues to change until after the crop is harvested. The altered soil biology has mostly beneficial effects to agriculture by adding and recycling biologically fixed N_2, enhancing nutrient uptake, reducing greenhouse gas emissions through reduced N fertilizer use, breaking crop pest cycles, and improving soil structure. Most studies on the contribution of pulse crops to the N economy of the following crop are conducted in only one subsequent crop. Multi-year studies are required to show whether net N immobilization (if it occurs) in the first year of residue decomposition reverses to net N mineralization

in later years as the C/N ratio narrows. The role of N rhizodeposition in contribution of N to subsequent crops needs further study because usually only contributions from above-ground legume residues are quantified. The increased microbial diversity and activity when legume crops are grown can mitigate disease through enhanced biological pest control. However, some of these effects have not been demonstrated unequivocally, or at all, in SSA, and there is need to investigate these gaps. Examples of the rotational benefits of common beans, although grown widely in eastern and southern Africa, are particularly lacking. Also lacking for SSA is information on the impact of growing grain legumes on greenhouse gas emissions.

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