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CHAPTER IX

Enhancing the role of legumes: potential and obstacles

Abstract

Legumes have a potentially significant role to play in enhancing soil carbon sequestration. They can also have considerable additional benefits beyond their importance regarding nitrogen fixation and high protein feeds. These include positive impacts on biodiversity and soil quality. There is a great need for a strong focus on developing the role of legumes and their contribution to both the sustainable intensification of production and the livelihoods of smallholder farmers in many parts of the world.

POTENTIAL OF LEGUMES TO ENHANCE CARBON SEQUESTRATION AND DELIVER CO-BENEFITS

Legumes and carbon sequestration

For a number of years, the potential importance of legumes in many agro-ecosystems, but also the limited extent to which this potential has been realized, has been recognized. Legumes do not just contribute in terms of food, feed and fertility, but are also important as fuelwood and with respect to carbon (C) sequestration. In this chapter we focus on the extent to which legumes can contribute to enhanced C sequestration and the delivery of co-benefits including greater biodiversity and reduced greenhouse gas (GHG) emissions. We also consider briefly the main reasons why legumes are currently underutilized and the prospects for a greater role in the future.

Enhancing C sequestration in the soil is linked to increased biomass and hence to soil fertility. Raising fertility is possibly the most effective way of rapidly increasing C sink capacity. Clearly, one way of doing this is through increased addition of nitrogenous fertilizers. However, caution in the widespread use of nitrogenous fertilizers as an approach to increased productivity is appropriate for a number of reasons, including the potential for other emissions. By contrast, the role of legumes in supplying nitrogen (N) through fixation is being increasingly seen as important and more beneficial in terms of overall GHG balance than had once been thought. The introduction of legumes and their greater utilization as part of a pasture improvement process are therefore likely to be worthy of serious consideration in many circumstances.

Herridge, Peoples and Boddey (2008) used data on yields and areas of legumes and cereals from FAO (FAOSTAT) to generate global estimates of legume-fixed N per year. These were calculated as 29.5 Tg for pulses and 18.5 Tg for oilseeds. There are no available statistics with respect to the areas and yields of forage, fodder and green manure legumes on a global basis. This is a major gap in our knowledge and thus estimates with respect to these crops have much greater uncertainty attached. Nonetheless, Herridge, Peoples and Boddey (2008) give broad calculations of 12–25 Tg N fixed per year from pasture and fodder legumes. Tropical legumes fix as much N as temperate ones, e.g. 575 kg/ha/year for a pure stand of *Leucaena leucocephala,* and there is greater C storage in legume-based tropical pastures than grass only.

Lynch *et al.* (2005), using simulation and spreadsheet analysis, considered changes in soil C sequestration in responses to alterations in grazing, fertilization and seeding of grasses and legumes. They showed that some treatments, e.g. seeding of grasses and legumes combined with continuous grazing, could result in increased soil organic carbon (SOC) of pastures but that this did not translate into improved net returns. Zhang *et al*. (2009) showed that conversion of reed meadows to alfalfa fields, in response to increased demand for forage for livestock systems in China, could result in increased levels of SOC. Fornara, Tilman and Hobbie (2009) showed that the presence of legumes and non-leguminous forbs and in particular their greater fine root decomposition led to enhanced root N release and increased net soil N mineralization compared with grass only swards. The authors stated that fine roots (less than 2 mm diameter) constitute a large fraction of annual primary productivity in many terrestrial ecosystems and have a significant influence on N and C cycling. Cadisch *et al.* (1998) emphasized the role of legumes in building up soil organic matter (SOM) and considered that the importance of this in tropical soils may be as great as N supply. Again, persistence was highlighted as the key to realizing the benefits from legume stands.

Biodiversity

A major potential co-benefit of an increased use of legumes is enhanced biodiversity. Fornara, Tilman and Hobbie (2009) studied the long-term effects of plant functional diversity (functional composition) on N limited grassland with fixation as the main N source. Net soil accumulation of C and N to 1 m was measured on agriculturally degraded soil in Minnesota over 12 years. High diversity perennial grassland species showed 500–600 percent more soil C and N than monocultures. Greater root biomass accumulation was seen in these mixtures, especially from C4 grass and legume mixtures. Steinbess *et al.* (2008) studied a biodiversity gradient from one to 60 species in four functional groups. C storage significantly increased with sown species richness in all depth segments. De Deyn *et al.* (2009) studied the impact of mixtures composed of plant species from different functional groups. They noted in particular that soil C and N pools were enhanced by the presence and biomass of white clover and birdsfoot trefoil. Steinbess *et al.* (2008) showed that C sequestration in soils of temperate grassland may be positively affected by plant diversity at least in the short term. This effect was probably independent of the greater root biomass observed with more diversity but the proportion of legumes was not itself particularly correlated with changes in SOC content over a two-year period.

Soil quality

There is also evidence that plant species differ in their visible effects on soil structure (Drury *et al.,* 1991) and anecdotal reports have long supported a positive role for legumes in this respect. More detailed investigations of the process of soil structuring have been carried out on white clover (Mytton, Cresswell and Colbourn, 1993; Holtham, Matthews and Scholefield, 2007) and red clover (Papadopoulos, Mooney and Bird, 2006). It has been reported that the changes in soil structuring brought about by white clover resulted in improvements in water percolation rate (i.e. the soil became more freely drained), and in the extraction by plants of nutrients from the soil. Holtham, Matthews and Scholefield (2007) also reported evidence of local structuring of soil around white clover roots and greater drainage of water through soil cores under white clover than under perennial ryegrass monocultures. Similar benefits in terms of soil structure were noted for soil cores under red clover monocultures by Papadopoulos, Mooney and Bird (2006), although the effects were transient and were reversed when a cereal crop was sown the following year. Improved soil structure reduces the risk of soil compaction and water runoff, increases the soil's biological activity, and facilitates seedling establishment and root penetration. However, it appears likely that legume-driven improvements in soil structure and drainage also directly result in increased leaching of both fixed and applied nitrate in legume monocultures (Holtham, Matthews and Scholefield, 2007).

Reduction in greenhouse gas emissions

Legumes are also likely to have a role to play in reducing GHG emissions from ruminant systems. An approach to reducing methane emissions of current interest and supported by some initial evidence is the use of tannin-containing forages and breeding of forage species with enhanced tannin content. Forage legumes such as *Lotus corniculatus* (birdsfoot trefoil) and *L. uliginosus* (greater trefoil) possess secondary metabolites known as condensed tannins (CTs) in their leaves. CTs are flavonoid polymers that complex with soluble proteins and render them insoluble in the rumen, yet release them under the acidic conditions found in the small intestine, reducing bloat and increasing amino acid absorption. They are not present on the leaves of white or red clover but are present in the inflorescences. Methane production values were lower in housed sheep fed on red clover and birdsfoot trefoil than on a ryegrass/white clover pasture (Ramirez-Restrepo and Barry, 2005). Gregorich *et al.* (2005) found that emissions of nitrous oxide from soils increased linearly with the amount of mineral nitrogen fertilizer applied and because systems containing legumes produce lower annual nitrous oxide emissions, alfalfa and other legume crops should be considered differently when deriving national inventories of GHG from agriculture. Rochette *et al. (*2004) measured nitrous oxide emissions from soils with alfalfa and soybean cropping, looking at soil surface emissions in comparison with perennial grass. Low nitrous oxide emissions were seen under grass and soil mineral N was up to ten times greater under legumes but soil mineral N pools were not closely related to nitrous oxide emissions. Comparable emissions were seen under timothy (*Phleum pratense*) as under legumes.

Productive temperate grasslands typically require significant inputs in the form of fertilizer, particular nitrogen, phosphorus and potassium. Wood and Cowie (2004) carried out a review on studies of GHG emissions from fertilizer production. Nitrogen fertilizer manufacture brings with it significant GHG emissions from the Haber-Bosch process of synthesizing ammonia and from nitric acid production. Synthesis of ammonia, the primary input for most nitrogen fertilizers, is extremely energy-demanding, with natural gas the primary energy source. Nitric acid is used in the manufacturing of ammonium nitrate, calcium nitrate and potassium nitrate. The oxidation of ammonia to give nitric oxide also produces a tail gas of nitrous oxide, nitric oxide and nitrogen dioxide. Nitric acid production is the largest industrial source of nitrous oxide, although clearly this is also used for purposes other than fertilizer manufacture. Estimates of nitrous oxide emissions from nitric acid manufacture are very variable: 550–5 890 CO_2eq/kg nitric acid. Urea accounts for almost 50 percent of world nitrogen fertilizer production and is synthesized from ammonia and CO_2 at high pressure to produce ammonium carbonate, which is then dehydrated by heating to give urea and water.

Jarvis, Wilkins and Pain (1996), in a systems synthesis study of dairy farms, found that the use of white clover, especially at relatively low clover contents, was an effective approach to reducing nitrogenous losses. Sixty-six percent of the support energy for grassland management on a dairy farm came from fertilizer production and this could be more than halved by the use of white clover. However, there was a cost to production and losses per livestock unit did not differ markedly from those under some alternative management systems. This points to the need for maintaining the productivity of white clover (or other forage legumes) and persistence in mixed swards and this has been a long-term objective of many breeding programmes (reviewed in Abberton and Marshall, 2005).

FACTORS LIMITING LEGUME USE AND POTENTIAL FOR IMPROVEMENT

Legumes in smallholder systems

‘t Mannetje (1997, 2007) reviewed the prospects for legume-based pastures in the tropics. Many important forage legume genera originated in tropical America, e.g. *Stylosanthes, Arachis* and *Leucaena.* Germplasm collections of these species have been made and new cultivars developed, although uptake by farmers appears to be limited (Jank, do Valle and Carvalho, 2005). Ncube *et al.* (2009) studied semi-arid smallholder farming systems in sub-Saharan Africa, in particular southwestern Zimbabwe. They grouped farmers in three categories: better, medium and poorly resourced. Those farmers in the “better resource” category used animal manure and some fertilizer on cereals. In the “medium resource” some manure was used but no fertilizer. Those farmers in the “poorly resourced category” used no inputs. All farmers produced less than 300 kg/ha/season of legumes. The authors stated that “lack of seed was cited as the main reason for poor legume production”.

Bloem, Trytsman and Smith (2009) showed that in South Africa less than 10 percent of grain crops planted annually are legumes. This is despite the fact that maize yields following or intercropped with legumes were comparable with those from crops that gained from added fertilizer (54 kg/ha at planting and 54 kg/ha as top dressing). Monocropping of maize is common in this region and the acidic soils undergo leaching because of high rainfall, but fertilizer inputs are limited. The authors focused on the need for provision of inoculation and the dissemination of inoculant techniques to realize more of the potential from maize/legume intercropping or rotations. They considered that there were “six pillars” necessary for enhancing the role of legumes and appropriate use of inoculants: awareness and communication; local institution building; training of trainers; farmer-to-farmer extension; on farm experimentation; and partnerships.

Pule-Meulenberg and Dakora (2009) focused on grain and tree legumes in Botswana. They showed that the extent to which crops were deriving N from fixation was very variable and can be very high. Many of these species showed a significant moisture limitation. The authors stressed the important role of shrub and tree legumes, e.g. different *Acacia* spp. and *Dichrostachys cinerea.*

Mtambanengwe and Mapfumo (2009) investigated the challenges associated with increasing the use of legumes. They found that there had been successful testing of technologies but that the “rate of adoption has not significantly contributed to rural livelihoods”. Land allocated to legumes was too small to make a significant impact and, where intercropping was carried out, a strong focus was maintained on maize yields, which were often very low. The authors studied the reasons for the adoption or non-adoption of various legumes and these can be summarized as follows:

- Bambara nut (*Vigna subterranea*): poor seed availability, significant labour requirement at maturity;
- Cowpea (*Vigna unguiculata*): poor seed availability, losses to pests;
- Groundnut (*Arachis hypogaea*): poor seed availability, lack of markets, significant labour requirement;
- Soybean (*Glycine max*): lack of appropriate rhizobia, heavy crop losses, poor seed availability until recently;
- Common bean (*Phaseolus vulgaris*): this was the most favoured legume studied with good seed availability (local dealers, supermarkets) but seed can be of poor quality leading to poor yields;
- Sunhemp (*Crotalaria juncea*): lack of awareness, poor seed availability.

Lack of awareness was also a major issue with indigenous legumes. Naab, Chimphango and Dakora (2009) assessed N fixation in cowpea in the Upper West Region of Ghana using the ^{15}N natural abundance method. They showed that the symbiosis is efficient and the major need in terms of increasing yield was therefore to optimize plant density. Tauro *et al.* (2009) investigated the potential of indigenous legumes in Zimbabwe. Smallholders were commonly being affected by poor germination of legumes and consequently poor stands. There were very considerable mismatches in the areas of (introduced) legumes and cereals. The authors identified 36 different indigenous legume species mainly in the genera *Crotalaria, Indigofera* and *Tephrosia* that will grow on nutrient-depleted soils. They investigated germination, emergence in the field and biomass under smallholder farm conditions and identified issues of low germination and seed hardness in some cases. Nezomba *et al.* (2009) carried out a more detailed study of indigenous legumes/fallows (indifallows) in terms of C mineralization and these authors stressed the importance of phosphorus availability.

Routes to improvement

In a major recent review, Peoples *et al.* (2009) stated, as an average global value, that for every tonne of dry matter produced by *crop* legumes, N fixation on a whole plant basis is approximately 30–40 kg of N. Major issues limiting uptake of legumes were described by these authors as lack of persistence and stress tolerance, including stresses on the legume-rhizobia symbiosis, particularly temperature, N, phosphorus and water. Nodulation efficiency and the supply of seed of adapted varieties with appropriate inoculant where necessary are further important factors.

Ceccarelli and Grando (2007) stated that participatory approaches to breeding are particularly suited to environments of lower (yield) potential or where farmers have less ability to modify environments (and thereby increase potential). They give the ability for the farmers to choose in their own environments varieties suited to local needs and conditions. Selection in the target environment is decentralized and may be more efficient. Such approaches have been taken up by the Consultative Group on International Agricultural Research (CGIAR) centres, for example, in collaboration with the International Centre for Agricultural Research in the Dry Areas (ICARDA) and regional/national centres.

Vanlauwe and Giller (2006) highlighted the loss of land productivity and higher labour requirements that could arise through the use of green manures and found that weed suppression was an important element where their use had succeeded.

In the context of maintaining N fertility, Nichols *et al.* (2007) have called for greater efforts to improve annual tropical legumes to complement species such as lablab (*Lablab purpureus* L.) and cowpea (*Vigna unguiculata* L.). Historically, well-adapted tropical legumes for cropped soils have been unavailable and were perceived as unnecessary for maintaining grain yield and because animal production was not as profitable as grain production (Pengelly and Conway, 2000). However, this is likely to change because of increasing agricultural commodity prices and demand for N fertilizer inputs. In general, the significance of seed availability is very clear. Clearly, a major challenge is the production and effective dissemination of good-quality seed. Recent initiatives such as the Alliance for a Green Revolution in Africa (AGRA) have recognized this and established the Programme for Africa's Seed System (PASS), which addresses these issues. The critical need to enhance the soil resource base has been recognized by the establishment of the Soil Fertility Consortium for Southern Africa (SOFESCA) (Mtambanengwe and Mapfumo, 2009).

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