



# Role of Legumes in Soil Carbon Sequestration

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Sandeep Kumar, Ram Swaroop Meena, Rattan Lal,  
Gulab Singh Yadav, Tarik Mitran, Babu Lal Meena,  
Mohan Lal Dotaniya, and Ayman EL-Sabagh

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S. Kumar

Department of Agronomy, CCS Haryana Agricultural University, Hisar, Haryana, India

R. S. Meena (✉)

Department of Agronomy, Institute of Agricultural Sciences (BHU), Varanasi, UP, India

R. Lal

Carbon Management and Sequestration Center, SENR/FAES, The Ohio State University, Columbus, OH, USA

G. S. Yadav

Division of Crop Production, ICAR Research Complex for NEH Region, Lembucherra, India

T. Mitran

School of Environment and Natural Resources, The Ohio State University, Columbus, OH, USA

B. L. Meena

ICAR – Central Soil Salinity Research Institute, Karnal, India

M. L. Dotaniya

ICAR – Indian Institute of Soil Science, Bhopal, India

A. EL-Sabagh

Department of Agronomy, Faculty of Agriculture, Kafrelshekh University, Kafr El-Shaikh, Egypt

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## Abstract

The soil organic carbon (SOC) pool is the key indicator of soil health and quality which in turn plays a vital role to soil sustainability. The continuous uses of unsustainable agricultural approaches have depleted most of the SOC pool of global agricultural lands. Promoting cultivation of leguminous crops, grasses, shrubs, and trees offers multiple advantages, e.g., augmenting crop and soil productivity and adapting to climate change by increasing resilience of agroecosystems. As per model-based prediction by World Bank, the cumulative soil carbon (C) sequestration of pulses in Asia and Africa is expected to be 33.0 and 35.12 Mg ha<sup>-1</sup>, respectively, by 2030. Legumes have the potential to reduce the CO<sub>2</sub> emitted during the manufacturing of chemical nitrogenous fertilizers through their biological nitrogen fixation (BNF) capacity. Therefore, the main advantage of using legumes is to ensure that the BNF which in turn reduces the amount of nitrogen (N) fertilizer required for the succeeding crop. A meta-analysis study suggested that the legumes have the capacity to store 30% higher soil organic carbon (SOC) when compared to other species; this is because of their N-fixing ability. The leguminous vegetation improves soil health and soil C content as per the nature of the specific crop. The C sequestration potential and the amount of organic C returned by leguminous species to soil depend largely on specific legume species, growth behavior, root morphology and physiology, leaf morphology, climatic conditions, structure and aggregation, prevailing cropping system, and agronomic interventions during crop growth period. The aboveground plant biomass (e.g., plant leaves, branches, stem, foliage, fruits, wood, litter-fall) and the belowground plant biomass (e.g., dead roots, carbonaceous substances from root exudates, rhizospheric deposition, and legume-promoted microbial biomass C) directly contribute to the SOC pool.

## Keywords

Legumes · Soil C sequestration · Soil quality · Soil microbes · Climate change

## Abbreviations

ANPP	Aboveground net primary productivity
C	Carbon
DM	Dry matter
DW	Dry weight
GT	Giga tone
SMBC	Soil microbial biomass carbon
SOC	Soil organic carbon
SOM	Soil organic matter
WSOC	Water-soluble organic carbon

## 4.1 Introduction

The challenges of the soil organic carbon (SOC) sequestration and preservation are manifold, and some are caused by human-induced factors such as low adoption rates of sustainable soil management practices (FAO and ITPS 2015). After carbon (C) enters the soil in the form of organic material from soil fauna and flora, it may persist in the soil for decades, centuries, or even millennia. The soil organic matter (SOM) has a direct linear relation with SOC, as SOM contains about 58% organic C (Kumar et al. 2006). The SOC is the biggest C pool in the terrestrial biosphere and is more than double of the atmospheric C and the biotic pools combined (Jobbagy and Jackson 2000; Liang et al. 2016).

Legume-based cover cropping is one of the important options for soil C sequestration in agriculture and plays a critical role to mitigate climate change (Lal 2015; Meena et al. 2015c). Leguminous cover crops supply organic C to the soil by decomposing their residues. Continued crop production potentials of soils are directly related to their SOC contents (Lal 1998; Mann et al. 2002). Within limits, crop productivity is positively related to the SOC content (Doran 2002) because of improvement in soil physical, chemical, and biological properties and consequently crop yields (Franzluebbers 2002). The soil physical characteristics influenced by SOC are those associated with soil aggregation and aggregate stability (Six et al. 2002). The management of legumes residues determines the soil aggregation and thus influences the soil C sequestration (Franzluebbers 2002). Six et al. (2002) advocated that sun hemp (*Crotalaria juncea*) crop have a highly dense and extensive root system which accounts in the formation of macroaggregates. The retention of legumes residue promotes soil macroaggregation and SOC storage (Kushwaha et al. 2001). Naturally, the legumes fix greater amount of nitrogen (N) through the process of biological nitrogen fixation (BNF) which, in turn, contributes to C sequestration with an average rate of  $0.88 \text{ Mg ha}^{-1} \text{ year}^{-1}$  (Diekow et al. 2005), greater than the grasses ( $0.71 \text{ Mg ha}^{-1} \text{ year}^{-1}$ ) (Martin et al. 2012). The capability of alfalfa (*Medicago sativa*) to formation of stable soil aggregates is much higher (Six et al. 2002). SOC enhances the stability of soil aggregates and structure because SOM remains physically protected in the core of soil aggregates. The stability of soil aggregation decides the soil water contents, gaseous exchange between soil and atmosphere, soil microbial communities, and nutrient cycling (Sexstone et al. 1985). The soil structure is comprised of primary soil particles, macro- and microaggregates acting as physical units of aggregates. The turnover of legumes residue in soil is the base of soil aggregation, which ensures the availability of C to the soil microbial community as a source of metabolic energy, leading to improvement in soil biological diversity and stimulating biodegradation of harmful soil contaminants (Grego and Lagomarsino 2008). This is closely associated with the increased soil aggregation and consequently reduced decomposition of organic C by soil microbes (Conceicao et al. 2013).

The crop diversity with legumes, higher is amount and value of the crop residues being incorporated into the soil, which is available for soil microbes as feed or a

source of energy. Accordingly, the activities of microbial communities are augmented, which in turn promote the formation of macroaggregation, where SOM remain safe to microbial attack and the subsequent decomposition and can accrue (Tiemann et al. 2015; Yadav et al. 2017). For example, in mega-aggregates the concentration of soil C increased up to 33% in soils under diverse planting with legumes as compared to the soil under monocropping of corn (Tiemann et al. 2015).

Legume-based cropping systems can increase biomass input and extend the biomass residence time in soil by reducing the mineralization rate (Meena 2013). Biomass production can also be increased by legume-based bicultural system, a mixture of legume with nonlegume species. The magnitude of soil C sequestration varies among different leguminous cover crops depending exclusively on total biomass production, decomposition rates, and conversion of liable C to soil recalcitrant C (McLauchlan and Hobbie 2004; Lal 2004a, b; Benbi and Brar 2009). Accumulation of SOC is a long-term biotic process influenced by abiotic factors (Jarenyama et al. 2000; Lal 2004a, b). Thus, it is an important to optimize the management skills through legume-based cultivation practices (Curtin et al. 2000). The objective of this chapter is to deliberate the rate and magnitude of the soil C sequestration potential of legumes. By changing the land-use pattern following a sustainable way through introducing leguminous crops, shrubs, and tree species in the existing system, the annual C sequestration rate could be increased by 20–75 g C m<sup>-2</sup>, and soil organic C may reach a new equilibrium in the interior, several years onward (Liu et al. 2013). Legumes are an imperative component of ecological sustainability and nutritional security and a valuable source of food proteins. This chapter will be helpful to researchers and policy makers to know the role of legumes in the alarming issues of climate change (Meena et al. 2017a) and food and nutritional security, especially after the Paris Agreement of December 2015, which appeals for action to store and increase the sink capacity of SOC pool for soil sustainability and world food security.

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## 4.2 Soil C Sequestration Through Legumes

The intensive cultivation without the inclusion of legumes may result in the common problem of reduced SOC pool (Jarenyama et al. 2000; Lal 2010). The purpose to tap the C sequestration potential of soil and the cultivation of plants belonging to Papilionaceae family needs to be endorsed in the agricultural system (FAO and ITPS 2015). The population explosion and economical emergencies, especially in the developing world, the significance of advanced legume-based approaches, and their impacts on soil and ecological dimensions need to be considered more now than in the past (Reeves 1997; Jarenyama et al. 2000). More importantly, care should be taken while selecting the appropriate legume crops in farming practice. Some approaches can accelerate the economic production but still are C exhaustive in nature and, so, increase the CO<sub>2</sub> emission from soil into the atmosphere (Chan 2008). Likewise, Chaer et al. (2011) confirmed that the apparent profits of growing

perennial legumes toward capturing atmospheric CO<sub>2</sub> and gathering it into the soil additionally their capability to offer a strong sink to store the CO<sub>2</sub> in their biomass.

Although the actual quantity of soil C sequestration in the different horizons highly varies with the soil management or legume-based farming practices along with the climatic conditions, soil properties, and the native C level of that sites (Whitbread et al. 2000), the C capturing capacity of soil can be enhanced and improved via legume-based farming practices and perhaps those that restored soil fertility and health. Promoting legume cultivation offers multiple advantages: augmenting crop and soil productivity (Meena et al. 2015b), adapting to climate change resilience, sequestering atmospheric C, and dropping of concentration of greenhouse gases (GHGs) emission from the atmosphere (Curtin et al. 2000; FAO and ITPS 2015). Legume crops residue is one of the main sources of C in agricultural soils and produces a considerable amount of residues which in turn favor the accumulation of humus and in consequent soil's C pool upon incorporation into the soil (Hajduk et al. 2015; Dhakal et al. 2016). Unlike cereals and other crops, the cultivation of legumes substantially enlarges the soil C sequestration over the other nonlegume crops because of their ability for larger belowground biomass production and leaf-shedding ability (Ganeshamurthy 2009; Abberton 2010). The increased SOC content in the legume-based rotation had also been confirmed in several scientific studies (Podleoeny 2005; Rochester 2011; Rutkowska and Pikua 2013; Hajduk et al. 2015). The legume-based farming practices are improved via adopting an ecologically sustained strategy with high diversity, mixed farming, and a sensible crop rotation (Ram and Meena 2014). While enclosing legume, in leguminous tree-based agroforestry systems, and adding of legume shrubs into the silvopastoral system are found to be good concerning sustainable soil C sequestration (Curtin et al. 2000; Chan 2008).

It is also important whether the forage legume is annual or perennial in growth habit. The potential effects of forage legumes seem to be higher with perennial legume species (Young et al. 2009). These are associated with two things, firstly, the potential of legumes for higher C inputs because of their ability to efficiently utilize rainfall and their extended growing period (Peoples and Baldock 2001) and, secondly, decreased C losses from organic compounds over annual legumes as perennial legumes help in maintaining lower water contents in soil, thus, reducing the soil microbial activities, associated decomposition, and consequently the release of organic C through microbial respiration (Young et al. 2009). Several scientific reports suggested that raising of perennial species of legumes such as alfalfa, tamarind (*Desmanthus virgatus*), and purple bean (*Macroptilium atropurpureum*) enhanced an abundance of SOC pool as compared to the SOC returned by the annual crop (Whitbread et al. 2000; Young et al. 2009).

Besides the nature and growth habits of legume crops, the nutrient management in legumes and associated pasture are a key factor in the direction of building SOC pool which directly affects the plant biomass production and consequently the contribution of plants in SOC accumulation (Chan et al. 2011). Once the ways of C

sequestration are recognized, the adoptions of proper agronomic practices are crucial to preserve and improve the SOC pool (Lal 2009). Thus, any crop management intervention that increases crop production and the retention of crop root and shoots residues response to lessen C losses from soil directly or indirectly and increase soil C sequestration (Hoyle et al. 2011). Williams and Donald (1957) observed that the augmenting C sequestration in the soil is directly correlated to the plant biomass production and hereafter to soil fertility. The enhancing soil fertility is probably the utmost actual approach for increasing the C sink capacity of the soil (Abberton 2010; Verma et al. 2015). The soil C dynamics rest on the balance between C inputs (crop residues and other organic substances) and outputs (CO<sub>2</sub> evaluation from SOC decomposition) (Wang 2015). The amount of C to be stored in soil also varies based on the total quantity and quality of residues being added in the soil. This suitably explains the reasons of dissimilarities in C sequestration among different crop rotations (Wamisho 2013). Apart from producing a large amount of aboveground plant biomass, the increase in belowground plant biomass, i.e., plant roots, also has a greater significance in C sequestration (Gregorich et al. 2001; Kundu et al. 2007; Kane 2015).

According to Adeboye et al. (2006), the starter dose of 20 kg N ha<sup>-1</sup> in three legume plants, i.e., soybean (*Glycine max*), cowpea (*Vigna unguiculata*), and cavalcade centro (*Centrosema pascuorum*), enhances the organic C buildup in the soil. It is reported that BNF is responsible for a vigorous plant growth which in turn assimilated more CO<sub>2</sub> from the atmosphere through the process of photosynthesis. The assimilated C in plants returns to the soil upon their incorporation and subsequent decomposition. Lange et al. (2015) stated that the increase in the total N content and SOC was interrelated; the decreased root biomass production by legumes produced the negative effect of SOC. Conversely, they advocated most pronounced effects of the legume on soil C sequestration in the topmost 5 cm soil, but not in top 30 cm soil when considering as a whole. Although crop species have a vital role in retaining amount and quality of SOC reserves apart from the diversity of crop residue (Mandal et al. 2007). The total quantity of crop residues being added to the soil system is considerably higher in soils under legume cultivation after cereal crops than in uncultivated fallow soils (Sombrero and de Benito 2010). The residues of perennial legumes are considered as good in quality and produced in large quantity, which are more effective in supplying a considerable amount of soil C for the long term (World Bank 2012). Gregorich et al. (2001) concluded that the quality of residues had an imperative role in the direction of maintaining or increasing soil C in agroecosystem (Dhakal et al. 2016). They also advocated that the soil under legume-based system have a tendency to be more preservative of residue C inputs, mostly from roots and their exudates than that of soils from monoculture. Apart from the amount of C inputs, the C sequestration efficiency (i.e., conversation rate of C inputs) also decides the contribution of incorporated organic C inputs into the soils (Liang et al. 2016).

### 4.3 Legume Improves Carbon in Soils

The rate of organic C production and sequestration by the legumes or their mixtures with grasses is correlated with soil texture which is reported higher in heavy soils than light soils (McLauchlan 2006; Gawel 2011). Kong et al. (2009) laboratory experiments evidenced the inverse correlations between clay content and the decomposition rate of SOC. The beneficial effects of growing legume plants in silty soils already rich in organic matter sequester more C compared to the growing of cereals such as oats (Hajduk et al. 2015). In the same direction, Gami et al. (2009) also confirmed the synergistic relationship between silt + clay soil and soil C sequestration. In contrast, legume cultivation in sandy-textured soils did not have a significant effect on soil C storage after crop harvesting ( $7.39 \text{ g C kg}^{-1}$  dry matter), as compared to the initial organic content ( $7.76 \text{ g C kg}^{-1}$  dry matter) (Hajduk et al. 2015). Wang et al. (2010) in an experiment on fine sandy (Dadhich et al. 2014) and gravelly loamy soils with six winter and summer cover crops observed that the C sequestration capability of faba bean (*Vicia faba*) was the maximum which added  $597 \text{ g C m}^{-2}$ , whereas white clover (*Trifolium repens*) accumulated the lowest quantity of C ( $149 \text{ g m}^{-2}$ ). Among summer crops, the maximum amount of C ( $481 \text{ g m}^{-2}$ ) was returned by sun hemp into the gravelly loamy soil, whereas the lowest amount was added by castor bean (*Ricinus communis*) with a value of  $102 \text{ g m}^{-2}$  at  $30 \text{ }^\circ\text{C}$ . At the end of the completion of one cycle of summer and winter cover crops, the soil C pool increased by 39.1 and 13.8% in fine sandy and gravelly loamy soil, respectively, over the respective soils. A long-term study conducted by Rutkowska and Pikula (2013) reported that on loamy- and sandy-textured soils, the crop rotation with legumes/cover crops is the principal factor toward stabilizing the SOC pool.

### 4.4 Leguminous Cover Cropping Enhances C Pool

Cover crops are referred to as the growing of crops like legumes aimed toward protection and improvement of soil in between the periods of regular crop production (Nair et al. 2015). The growing of legumes as cover crop in rotation improves soil structure and quality by accelerating organic C storage in soil strata through production of large biomass (World Bank 2012; Nair et al. 2015). Alternating their extensive well-developed deep and shallow root systems helps in improving SOC pool and prevents soil erosion (Nair et al. 2015). Santos et al. (2011) from an experiment of over 17 years concluded that the forage-based rotation of alfalfa and rye grass (*Lolium perenne*) sequesters SOC considerably more over cover crop-based rotation with cereal crops. They established that the roots of forage-based or cover-based rotation had more predominant role in the direction of building SOC pool and residues. Nair et al. (2015) and Ram and Meena (2014) advocated that legume-based cover crop accumulated more C into the soil over the grass-based cover crop rotation with nonlegume crops. The adoption of velvet beans (*Mucuna pruriens*) as

cover crop resulted in a higher yield of dry matter by 11.9 Mg ha<sup>-1</sup> annually in shoot residues, which was significantly higher than the dry matter produced by the conventionally unfertilized monoculture of maize (*Zea mays*). The replacement of reed meadows field by alfalfa because of the higher demand of forage for live pool resulted in increased SOC levels (Zhang et al. 2009).

#### 4.5 Legumes Crops in Rotation Improve C Pool

The selection of legume crops for cultivation in the rotation decides the amount of C being sequestered into the soil (Abdurahman et al. 1998). Crop rotation can improve biomass production and eventually the soil C sequestration, principally the rotations of legumes with nonlegumes, and SOC can be enriched by the use of appropriate crop rotations (Lal 2010). Legume-based cropping systems and SOC sequestration capacity are presented in Table 4.1.

The C sequestration potential and the amount of organic C being added into the soil strata by the leguminous crop greatly vary with the selection of appropriate legume. The growth habit, canopy structure, quantity and quality of residues left on the soil surface, root physiology and pattern, number of leaves being produced, climatic stimuli, soil aggregation, existing cropping system, and agronomic interventions during the crop cycle improve SOC pool (Chan and Heenan 1996; Gregorich et al. 2001; World Bank 2012; Nair et al. 2015). This is because of the higher conversation efficiency from residue C to soil C by legumes in rotation over the monoculture cereal crops such as wheat (*Triticum aestivum*) (Campbell et al. 1999). The legume-based rotations are more efficient in converting biomass to SOC in comparison to the grass-based rotation. Inclusion of legumes in rotation has the potential of guaranteeing the in situ availability of N which in turn plays a vital role in generating higher biomass C. It also promotes the release of C via root exudation into the rhizospheric zone (Hajduk et al. 2015). The N fixed by the root nodules of legumes also accelerates the C sequestration potential of succeeding crops in the rotation, more likely because of the improved microbial activities and biomass production by successive crop (Nair et al. 2015). The N provided by the legumes enhances the N utilization efficiency and produces more root biomass and, thus, leads to C inputs in soil (Conceicao et al. 2013; Meena et al. 2013).

**Table 4.1** Carbon sequestration in different soybean-based cropping systems

Crops rotation	C/N ratio	Rate of C sequestration (Mg ha <sup>-1</sup> C per year)
Soybean-corn	11:70	0.68
Soybean-soybean	11:74	0.69
Soybean-sunflower	11:77	0.57
Soybean-oilseed radish	11:75	0.54
Soybean-sun hemp	11:63	0.79

Data source: Junior et al. (2016)

Scientific studies also reported improved organic C status under the rotation of forage legumes with grain crops after several years of cropping compared with that of a monoculture of grain crop (Campbell and Zentner 1993; Gregorich et al. 2001). In the same direction, Campbell et al. (1999) reported that the wheat-lentil (*Lens culinaris*) rotation sequestered more C pool compared with that of C sequestered by wheat crop alone in monoculture. Venkatesh et al. (2013) and Meena et al. (2015b) reported increased SOC pool due to the addition of pulse in upland maize-based system and most importantly in top 0–20 cm soil layer. Rochester (2011) also reported that the higher C sequestration takes place in the subsoil rather than that of surface soil (up to 30 cm). In soil, fresh plant residue, roots, living microbes, and macrofauna account <15% of the total SOC pool, whereas stable humus, partially decomposed plant residues, and indecomposable organic C, i.e., charcoal, represent the balance (Hoyle et al. 2011; Jensen et al. 2012). The distribution of the soil C pool relied on the soil deepness. The passive C fractions dominate in subsurface soil horizons over the active C pool, whereas in the surface soil, the active C has more storage over passive C pool (Venkatesh et al. 2013). Blair and Crocker (2000) scrutinized the effects of different rotations including legumes and uncultivated fallow in a long-term experiment and stated that introduction of legumes in rotation promoted the buildup of liable C reserve in the soil profile more than those with the continuous wheat and a long-uncultivated fallow period.

The soil C reserve had reported 130–134 Mg ha<sup>-1</sup> in top 70 cm soil when maize was grown in rotation with alfalfa which was considerably greater than the maize under monoculture, as it stored only 109–115 Mg ha<sup>-1</sup> C in soil (Jensen et al. 2012). On the contrary, in the absence of appropriate crop rotation, plant biomass production and associated SOC decrease because of a higher incidence of biotic factors, i.e., weeds, insects, and diseases (Wang et al. 2010). Besides this, increase in cropping intensity or frequency by cultivating bare fallow land in the crop rotation is an alternative way toward enhancing biomass production and consequently the soil C sequestration (Wang et al. 2010). In subhumid to arid climates, the cotton (*Gossypium* spp.)-legume system performed better with respect to soil C sequestration than the other cropping systems, while C sequestration under the rotation of sorghum (*Sorghum bicolor*)-legume was better in semiarid regions, but in dry areas, the same rotation failed to sequester soil C (Chaudhury et al. 2016; Ram and Meena 2014).

The introduction of soybean in rotation returns higher organic C in soil than that added by cowpea (*Vigna unguiculata*) because soybean produced a 35% higher stover biomass than the cowpea (Akinnifesi et al. 2007). The higher C inputs through plant roots and crop residues may lead to greater organic C under soybean rotation. Pigeon pea (*Cajanus cajan*) also produced the greater amount of dry leaves (3.0 Mg ha<sup>-1</sup>), which was about twice that of the dry leaves returned by the cowpea (1.14 Mg ha<sup>-1</sup>) (Abdurahman et al. 1998). Newaj and Yadav (1994) also found higher SOC under the pulse-based cropping system, but the highest improvement was noticed in rotation involving pigeon pea because of its long growing duration. The SOC content was found to be increased by 10.7% over the initial content under the legume-based system (Newaj and Yadav 1994). The inclusion of cowpea and green gram (*Vignaradiata*) in maize-wheat cropping system after wheat harvest

increased SOC by 6.3% due to their leguminous biomass (Singh and Sandhu 1980; Meena 2013). In the same way, the average amount of total C input under pigeon pea-wheat (49.04 Mg C ha<sup>-1</sup>) and maize-wheat-green gram (48.68 Mg C ha<sup>-1</sup>) system was higher as compared to that without legume inclusion in existing maize-wheat system (37.06 Mg C ha<sup>-1</sup>) (Venkatesh et al. 2013). This significant improvement in total SOC under maize-wheat-green gram and pigeon pea-wheat was 11 and 10% over the existing conventional maize-wheat system, respectively. The monocropping of cotton in black soils failed to sequester the organic C in soil, but when it was rotated with pigeon pea, the sequestration of organic and inorganic C increased by 0.75 and 1.12%, respectively (Chaudhury et al. 2016). In Asia, the inclusion of the green gram as a grain legume in the existing short fallow of rice (*Oryza sativa*)-wheat system after wheat harvest produced a total dry matter of 4.5 tons ha<sup>-1</sup> and increased soil C (Yaqub et al. 2010; Meena et al. 2015a, b, c). According to Hajduk et al. (2015), pea (*Pisum sativum*) sequesters and deposits more C into the soil column compared to lupin (*Lupinus albus*) (7.58 vs. 7.23 g C kg<sup>-1</sup> dry matter) which had a small effect on C storage in soil. This was closely associated with the narrowing of lupin leaves as it assimilates less photosynthate.

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## 4.6 Green Manuring with Legumes

The critical determinants of soil C pool are the total quantity of organic matter input into the soil from plant residues and the duration for which they remain in soil that varies with their decomposition rate (Paustian et al. 1995). In general, farmers left the soil bare or fallow between the two crops in the predominant cropping system like after wheat harvest in rice-wheat cropping system in the Indo-Gangetic plains of Southern Asia (Kane 2015; Curtin et al. 2000). It means no biomass is produced in 3–4 months of the year on that land meaning that of considerably lower C inputs into the soil. Hence, it is difficult to balance the C losses that occur during the year. The introduction of legumes as green manure between two existing crops in the cropping system ensures a good biomass production which in turn offsets C losses and confirms net gain of C in the soil (Tiemann et al. 2015). In green manuring, accumulated standing biomass is directly incorporated into the soil system (Zentner et al. 1996). Biederbeck et al. (1996) stated that green manuring with annual legumes in place of partial fallow may add dry matter to the tune of 3 Mg ha<sup>-1</sup>. Furthermore, they have reported that rotation in which legumes was involved added 49% higher stubble C, 133% higher stubble N, and about 60% extra SOC below 30 cm of soil. Likewise, the introducing vetch (*Vicia sativa*) along with soybean as a winter green manure crop in rotations before the maize crop increased the SOC sequestration by about 10 Mg C ha<sup>-1</sup> after 13 years of experimentations (Sisti et al. 2004). The rate of crop residue decomposition varies negatively with its C/N ratio and lignin content as lignin is resistant to microbial degradation (Silver and Miya 2001; Dhakal et al. 2016). In the same way, Curtin et al. (2000) advocated that replacement of partial fallow with legume green manuring had a little impact (~25%) on soil C storage because green manuring crops have narrow C/N ratio (12–13: 1) and low in lignin content; this is why they decompose quickly (Zentner et al. 1996; Curtin et al.

2000). The growing of sun hemp as green manure improved the SOC pool by 0.92% but reduced soil inorganic carbon (SIC) by 0.64% (Chaudhury et al. 2016). The advantages of sun hemp in capturing atmospheric C and subsequent storing in soil may be credited to a lower C/N ratio (23: 1) of its residue, which helps in enhancing the N availability, required for hasty residue conversion into particulate C fraction of C pool (Junior et al. 2016). Legume-based green manuring contributes to GHGs emission reduction in two ways, *first*, by converting plant C into SOC and, *second*, by reducing the requirement of nitrogenous fertilizers consequently in lowering of N<sub>2</sub>O emissions (Biederbeck et al. 1996; Curtin et al. 2000; Nair et al. 2015).

## 4.7 Legume-Based Pasture Development

In several parts of the world, the mixed pastures based on ryegrass (*Lolium multiflorum*) and clovers (*Trifolium* spp.) are grown extensively, but still scientific studies on the effects of pasture mixture on soil C sequestration are very rare (Daly et al. 1996; Chan et al. 2011). The mixture of legume species with pasture increases the production of below- and aboveground biomass which in turn ensures a higher soil C pool (World Bank 2012; FAO 2016). The evidence from many research experiments in different climatic conditions and regions confirmed the SOC acquisition ability of legume-based pastures (Wright et al. 2004; Chan et al. 2011). Arrouays et al. (2001) reported that the growing of legume mixture replacing grass leys resulted increase 10 Mg C ha<sup>-1</sup> into the soil at the end of 20 years of study period. Yang and Kay (2001) reported significantly greater mean SOC reserve under continuous alfalfa in top 40 cm soil in comparison to the continuous corn. Mortensen et al. (2004) also quantified the similar legume effects of yellow-flowering alfalfa (*Medicago sativa*) on building SOC pool when inter-seeded with grasses in range lands and stated that the mean rate of SOC deposition in upper 1.0 m soil layer was 1.56, 0.65, and 0.33 Mg C ha<sup>-1</sup> per year after 4, 14, and 36 years of inclusion of alfalfa, respectively. In contrast, alfalfa would be expected to have more capability than the clover to enhance the C accumulation in >30 cm soil depth because of its extensive deep root system (Peoples and Baldock 2001). The rotation of wheat-sweet clover (*Melilotus officinalis*) accelerated the SOC contents at different soil depths and also had the highest size of SOC (Liu et al. 2003a, b). Liu et al. (2003a) advocated that adoption of improved crop rotation can upsurge the organic C pool and improve quality and structure of black soils, thus, capture higher atmospheric CO<sub>2</sub> and consequently mitigate the greenhouse effects. The introduction of perennial legume peanut (*Arachis pintoi*) in pastures increased C sequestration potential by 7.8 Mg ha<sup>-1</sup> every year in top 1.0 m soil profile over the growing of pure grass, regardless of legume's contribution with only 20% of the total root biomass (Fisher et al. 1994). Further, the C balance should be favorably changed by enhancing the chemical complexity, quantity, and quality of carbonic substance being added in soil to compensate the C losses from microbial attack or decomposition (Kane 2015; Yadav et al. 2017). It is supposed that carbonic compounds in the legume green manure crops are resistant enough to microbial

decomposition and may also enhance the diversity and complexity of soil C for its long-term stabilization (Wickings et al. 2012).

## 4.8 Leguminous Oilseeds Improve Soil C Pool

The soils under two important oilseed crops, i.e., soybean and groundnut (*Arachis hypogaea*), are believed to be the important sites in the global C cycle (Bhattacharyya et al. 2009). Most of the scientific studies proved the positive response of oilseed legumes in the way of soil C sequestration (Aziz et al. 2014). In subtropical regions' soybean-wheat cropping system, the C contribution from harvestable aboveground biomass of soybean was observed to be 22% higher than wheat, which resulted in 18% of annual total C being assimilated more than wheat (Kundu et al. 2001; Meena et al. 2015a, b, c). The long-term experiments are one of the effective pathways to track the effects of continuous soybean monocropping as well as the crop residue retention on soil surface change in SOC levels (Leigh and Johnston 1994). In the same direction, the results of a long-term (30 years) experiment revealed that under rainfed soybean-wheat system, the SOC level increased because of the greater C returned by the system than that of the quantity needed to sustain SOM content (Kundu et al. 2007). They found that soybean and wheat annually produced 3.54 and 3.32 Mgha<sup>-1</sup> aboveground biomass, respectively, and the average share of both the crops in harvestable aboveground biomass was 29 and 24%, respectively. In soybean, about 13% of gross biomass (below- and aboveground plant) was alone contributed by root exudates and rhizospheric deposition (Kemper et al. 1998), even though, in most of the crops, these values ranged from 5 to 20% (Kundu et al. 2007). Kundu et al. (1997) also reported that the soybean returned belowground root biomass to the soil which was 31% of the aboveground biomass. The contribution of different parts of soybean like root nodules, roots, and leaves in the gross C returned by the crop to the soil was 32, 34, and 38%, respectively. In soybean, rhizospheric deposition of C was the main contributor in total C inputs. The winter and summer cover crops are the foremost choice to improve the C turnover through advancement in soybean cultivation (Amado and Bayer 2008). A multi-locational trials in different agroecological zones are reported that the increased total organic C under soybean-wheat system was up by 46% over the cereal-based rotation of corn-black oat (*Avena strigosa*) (Amad et al. 2006), although the rotations generated almost equal quantity of crop residues, most likely because of the quick breakdown of soybean residues which thereafter accelerated the dry matter production capacity of wheat in sequence (Weber and Mielniczuk 2009). Bhattacharyya et al. (2009) also found higher trends of C pool returned into the soil from roots and rhizospheric deposition of soybean with a value of 620 and 362 kg C ha<sup>-1</sup> year<sup>-1</sup> in irrigated and rainfed conditions, respectively (Meena et al. 2017b).

A 15-year experiment with corn-soybean cropping system registered the highest productivity and returned huge crop residues to the soil system in comparison to the monocropping of either corn or soybean (Drinkwater et al. 1998). Further, Drinkwater et al. (1998) advocated that the application of crop residue of having a narrow C/N ratio to improve soil fertility in the corn-soybean system has the

potential to increase the soil C sequestration by 13–30 Tg year<sup>-1</sup>, which is equal to 1–2% of projected C emissions from fossil fuel combustions. Based on the assumption of 50% residue retention, the global cumulative C sequestration for soybean varies from 0.5 MT to 0.7MT by 2030. Junior et al. (2016) found the increased total C content when pigeon pea, sun hemp, and soybean were grown as a sequential crop after corn. Among these, soybean/corn rotation and soybean monocropping sequestered the significantly greater amount of C in soil followed by the sun hemp. The soybean monocropping increased soil C in soil as particulate C fraction over the monocropping of corn. It was because of the lower C and N balance of soybean residues than that of corn, which in turn, contributed to the rapid C addition into the soil system as a medium particulate fraction. In this study, the mean C deposition rate in soil under these crop sequences was 0.63 Mg C ha<sup>-1</sup> annually, which was lower than that observed (0.85 Mg C ha<sup>-1</sup> annually) by Sa and Lal (2009) and much higher (0.35 Mg C ha<sup>-1</sup> annually) than that reported by Bayer et al. (2006). The incorporation of surface litter and aboveground biomass of groundnut into the soil caused considerable variation in SOC, which quickly shrank once by coming in contact with favorable temperature and soil moisture for their breakdown (Capriel 1991). Ghosh et al. (2006) in their 6-year experiment stated that the total annual C input was comparatively more under groundnut-based [0.24 ( $r = 0.80$ ,  $P \leq 0.01$ )] crop rotation than that of fallow-based [0.36 ( $r = 0.80$ ,  $P \leq 0.01$ )] system; moreover, the rate of C loss was also higher. Among the groundnut-based system, the gross annual C production to some extent was higher in groundnut-mustard (*Brassica nigra*) rotation over the groundnut-wheat, groundnut-sunflower (*Helianthus annuus*), groundnut-chickpea (*Cicer arietinum*), and groundnut-groundnut system, even though the contribution of rhizospheric deposition (Meena et al. 2017b) and root biomass in total C inputs in soil was higher under the groundnut-wheat system.

#### 4.9 Leguminous Shrubs Enhance the Soil C Pool

The conversion of pasture and forest to cropland has been responsible for 59 and 24% loss of stored soil C globally (He et al. 2011; Guan et al. 2016). The impacts of the shrub encroachment on the change in SOC pool are in direct or indirect control of several biotic (shrub types) and abiotic (soil texture and climate) factors (Kulmatiski and Beard 2013). Since the last decade, an increase in dominance and abundance of legume shrubs has been reported in the world's grasslands (Kulmatiski and Beard 2013). The replacement of grasslands by shrub-intruded grasslands can be responsible for some ecological consequences, like altering biodiversity, the pattern of SOC, and the local C balance (Jackson et al. 2002). The gain or loss in net C in soil stratum heavily depends on the type of shrub in the encroachment of either grassed species or legume closely associated with their aboveground net primary production (ANPP). Li et al. (2016) reported that the rate of increase in SOC contents was higher in leguminous shrub-based grassland than that of nonlegume shrubs with an effect of 0.32 and 0.15%, respectively. Legume-based shrub planting exhibits the amazing capacity of countering atmospheric CO<sub>2</sub> via soil C sequestration and, thus, plays a counter role in the global C cycle (Liu et al. 2010). The

proliferation of woody leguminous shrub can influence the C pool at regional or global level. In this context, the SOC pool could improve, if legume shrubs are more productive over herbaceous plants (Wheeler et al. 2007).

Guan et al. (2016) evaluated the effect of bush clover (*Lespedeza davurica*), milk vetch (*Astragalus adsurgens*), and alfalfa on the gross amount of SOC returned in upper 2 m soil layer over 7 years. Their report revealed that the level of SOC significantly increased in soil under legume crops/shrubs whereas decreased to some extent under the fallow uncultivated soil in top 2 m soil profile at the end of 7 years of the experiment. This increment in SOC concentration in soil under cultivation of bush clover, milk vetch, and alfalfa was 19.9, 14.6, and 24.1 Mg C ha<sup>-1</sup>, respectively, and reduced in bare soil by 4.2 Mg C ha<sup>-1</sup>. The increased SOC content in deeper soil layer under bush clover, milk vetch, and alfalfa might be due to improved turnover and proliferation of finer roots deeper in soil or might be due to the downward movement of soluble C from upper to lower soil strata with water after heavy irrigation or rainfall (Guan et al. 2016). The projected, root biomass C in milk vetch 20 Mg C ha<sup>-1</sup> was observed more than the aboveground biomass C production of 15 Mg C ha<sup>-1</sup> in 7 years of study (Fan et al. 2015). Similarly, in bush clover, the root biomass C production was 15 Mg C ha<sup>-1</sup> (32 Mg ha<sup>-1</sup> root biomass) having an aboveground biomass production of 42 Mg ha<sup>-1</sup> (Guan et al. 2016). The higher SOC deposition in top 30 cm soil by bush clover was attributable to the greater turnover of legume residues, litter, carboxylic acids, and other carbonic substances along with root proliferation in the surface layer (Zhou et al. 2006). The litter-fall and its decay are crucial for the formation of organic matter, mineralization, and terrestrial C sequestration (Zhou et al. 2012). The decomposition of deposited litter on soil surface depends on various factors like quality of litter precipitation, solar radiation, soil water content, biological activities, etc. (Austin and Vivanco 2006). The litter of leguminous shrubs, i.e., bladder senna (*Colutea arborescens*) and tree medic (*Medicago strasseri*), is low in lignin content which are prone to quick degradation of organic C (Alegre et al. 2004).

Su et al. (2005) stated that planting of littleleaf pea shrub (*Caragana microphylla*) substantially improved the soil C status in upper 0–5 and 5–20 cm soil layers in sand dunes of semiarid regions. Liu et al. (2013) reported increase in 21.84, 30.0, and 39.09% C content under littleleaf pea shrub at the age of 5, 21, and 34 years, respectively, compared to the grassland ecosystem in top 20 cm soil stratum. The result might be linked with the inclusion of organic layer and preplanting disturbance (Laganiere et al. 2010). The ANPP of the young shrub is less, and the total amount of C returned in soil is not adequate to offset the C pool (Liu et al. 2013). With the advancement in age of the plant, the ANPP proportionally increases along with newly changed microclimate and greater C protection which stimulate the gathering of C in the soil stratum (Six et al. 2002). The legume shrubs colutea (*Colutea cilicica*) and bladder senna (*Colutea arborescens*) produced the organic C with a value of 0.69 Mg and 0.66 Mg ha<sup>-1</sup> year<sup>-1</sup>, respectively, in a semiarid climate (Alegre et al. 2004). Another shrub legume tree medic (*Medicago arborea*) generated 1.75 Mg organic C ha<sup>-1</sup> annually (Alegre et al. 2004), presented in Table 4.2.

**Table 4.2** SOC increase through different legumes

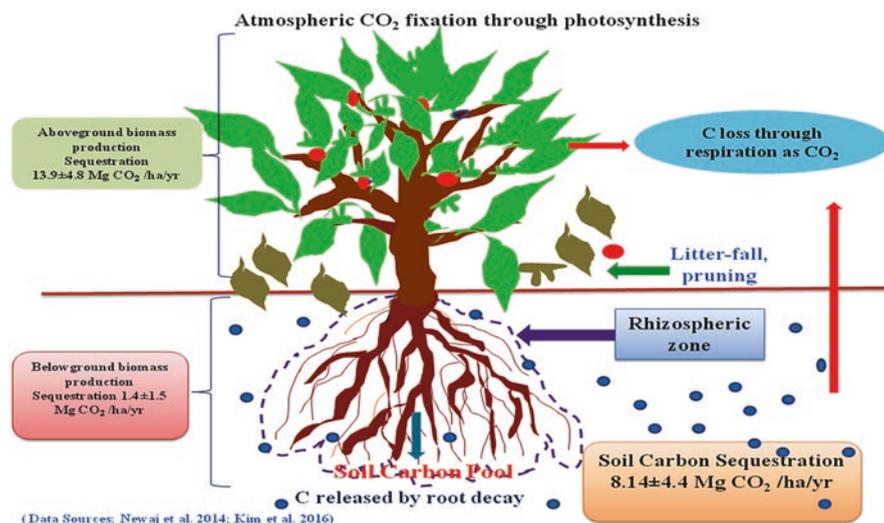
Legumes	Soil depth (cm)	SOC increase (Mg ha <sup>-1</sup> )	References
<i>Colutea cilicica</i>		0.69	Alegre et al. (2004)
<i>Colutea arborescens</i>		0.66	Alegre et al. (2004)
<i>Medicago arborea</i>		1.75	Alegre et al. (2004)
<i>Lespedeza davurica</i>	200	19.9	Guan et al. (2016)
<i>Astragalus adsurgens</i>	200	14.6	Guan et al. (2016)
<i>Medicago sativa</i>	200	24.1	Guan et al. (2016)
<i>Vicia sativa</i>		10.0	Sisti et al. (2004)
<i>Medicago sativa</i>	100	0.33–1.56	Mortensen et al. (2004)
<i>Arachis pintoi</i>	100	7.8	Fisher et al. (1994)

Soil texture seems to be key factor influencing the SOC buildup under shrub encroachment (Li et al. 2016). The results of the structural equation model (SEM) also showed that the soil texture had the greater potential to change the rate of SOC turnover over time accounted for the shrub encroachment (Six et al. 2000). As of a fact, shrubs are made up of a larger amount of ANPP in coarse-textured soils than that of fine-textured soils with same cover (Liang et al. 1989). It means, if shrubs are included within the grassland system in the sandy-/coarse-textured soils, they will exhibit a greater capacity of biomass production, SOC increment, and, thus, C sequestration. As of another fact, the bulk capacity of coarse-textured soils have a tendency to be high, so a positive correlation was present between the soil bulk density and the change in mean percent SOC content. Wheeler et al. (2007) stated that the inclusion of C<sub>3</sub> legume shrubs into the grassland predominated by the C<sub>4</sub> species resulted in an increase in the SOC level by about 23% in coarse-textured soils than the clay loam soils under similar environmental conditions. The soil N content also significantly contributed in regulating the effect of shrub encroachment in building of SOC pool (Kirkby et al. 2013). It is supposed that an amount of 1 g N is capable of storing 7–13 g of C as per the global meta-analysis (Johnson and Curtis 2001; Yang et al. 2011). Shrub encroachment apparently stimulates the soil N accumulation and consequently secures their role in accumulating SOC contents (Jackson et al. 2002). The increased returns of roots of along with the root exudation greatly decide the accumulation of C in plant and consequently in the SOC contents (Sun et al. 2001; Shahzad et al. 2015). The minor roots share about 33% of annual ANPP and that directly affect the C dynamics and sequestration (Zhou et al. 2012).

#### 4.10 Legume Trees Improve Soil C Pool

Along with the food, feed, fiber, fuel, and fodder, legume trees are also important to enhance the soil fertility and soil C sequestration presented in Fig. 4.1.

The soil under the agricultural system is supposed to be an excellent source of C sink (Albrecht and Kandji 2003; Ibrahim et al. 2010; Abberton 2010). The soils



**Fig. 4.1** C sequestration mechanism of leguminous trees

**Table 4.3** SOC increase through different legume tree species

Trees	Soil depth (cm)	SOC increase ( $\text{Mg ha}^{-1}$ )	References
<i>Leucaena leucocephala</i>	0–10	8.34	Onim et al. (1990)
<i>Cajanus cajan</i>	0–30	0.73	Onim et al. (1990)
<i>Acacia auriculiformis</i>	0–10	3.41	Dreschel et al. (1991)
<i>Cassia siamea</i>	0–10	5.20	Dreschel et al. 1991
<i>Sesbania sesban</i>	0–30	3.10	Onim et al. (1990)
<i>Crotalaria grahamiana</i>	0–20	1.69	Impala (2001)

under tree plantation have greater potential to maintain a higher concentration of SOC pool in their profile, as presented in Table 4.3.

The tree-based land-use systems could be sustainable in many ways to capture and accumulate the atmospheric  $\text{CO}_2$  because of their high C capturing capacity, cost-effectiveness, and accompanying soil benefits (Dhruw et al. 2009; Wani and Qaisar 2014). Based on the information collected from various sites, the SOC pool in global soils ranged from 6.9 to 302  $\text{Mg ha}^{-1}$  (Nair et al. 2009). In spite of huge variation in these values, the difference between various systems, soil, and ecological provenances, the tree plantation have a significant place in enhancing soil C sequestration. So, the sink capacity of a soil can be improved by introducing the legume trees in the system (Albrecht and Kandji 2003). For a reason that the legume trees have high potentiality to establish and survive under the harsh conditions, also they have the capacity to generate high biomass C (Macedo et al. 2006, 2008;

Meena et al. 2015b). It is anticipated that after some time of establishment, the biomass produced by legume trees will be amalgamated into the soil.

The multipurpose legume trees have greater potential to accrue the huge amount of aboveground biomass and to convert it toward organic C through regular foliage pruning to use as green manure or to feed animals, qualitative and quantitative leaf litter-fall, and root exudation and depositions in the rhizosphere (Kumar et al. 2001; Bertin et al. 2003; Becker et al. 2016). The litter-fall pruned plant parts and biomass of dead trees accumulate on the soil surface which is recycled efficiently to direct contribution to SOC deposition (Ibrahim et al. 2010). Fornara et al. (2009) identified that finer root particles having a diameter of less than 2 mm enhance total annual primary productivity and significantly contribute toward the terrestrial ecosystem and global C pools. In the tree species, the root densities are low in upper 30 cm of soil depth, and root nodules are noticed very rarely. Even the root nodulation increases below 4 m depth of soil (Virginia et al. 1986). In general, it was found that the C constitutes nearly about 50% of the dry weight of branches and 30% of plant foliage parts. The belowground plant parts such as living and dead root biomass, other plant parts, soil microbes, and C deposited in soil strata share about 66% (2/3rd) of total C sequestration (Pinho et al. 2012). These added materials are an important substrate for the diverse microbial population and their activities (Bertin et al. 2003). Beside these complex processes, the contribution of legume trees in enhancing soil C sequestration is an interesting and needful subject of discussion at current to lower down the atmospheric CO<sub>2</sub> (Bertin et al. 2003).

The leguminous trees store the C in their woody biomass, deeper in soil and instable soil. The soil C flux in 0–25 cm upper soil profile could be ascribed SOC redistribution in the course of cultivation practices (Kaongaa and Smith 2009). The lower subsurface soil horizons (25–200 cm) accumulated 75% of C flux most likely owing to the soil C density, leaching of SOC from upper horizons to lower one with rainwater, deep-rooted behavior of legume trees and associated an additional root C turnover, SOM deposition through cultivation practices and increased resistance of SOM fluxes to microbial breakdown deeper in soil because of unfavorable physico-chemical environments for microbial functionaries that restricts decomposition (Sanchez 1995; Kaongaa and Smith 2009). The deep-rooted leguminous trees store the C in their woody biomass, deeper in soil and stable soil aggregates and enhance the potential of subsoil as C sink by promoting plant growth (Rosenstock et al. 2014).

The need of promoting the legume tree plantation for sustainable intensification of the ecological system and soil C dynamics is of increasing interests (Abberton 2010). Under legume tree plantation, the soil C sequestration is linked with the total biomass production and consequently the soil fertility. The soil fertility is one of the chief ways for enhancing the sink capacity of the soil C (Abberton 2010; Verma et al. 2015), although as earlier discussed the quantity of C accumulated as ANPP and the potential of soil to capture and store the C highly depends on the type, age, and population density of the tree, climatic parameters, soil texture and aggregation, agronomic intervention, and so on (Ibrahim et al. 2010). The capacity of an ecosystem to capture the atmospheric CO<sub>2</sub> is also regulated by soil biological

activities and the C use efficiency (Becker et al. 2016). The climatic parameters like relative humidity and temperature greatly influenced the soil microbial activities and associated organic matter decomposition and, thus, the soil C sequestration (Pinho et al. 2012).

Numerous studies have shown that the plantation of the leguminous tree accumulates a large amount of C in their biomass as well as soil system (Pregitzer and Euskirchen, 2004; Macedo et al. 2006). The legume tree species also have an imperative role toward increasing C concentration in soils of dryland (Nair et al. 2015). The acacia (*Acacia nilotica*) and prosopis (*Prosopis* sp.) plantations reported to increase C pool by 2 Mg ha<sup>-1</sup> in soils of subtropical regions (Geesin et al. 2000). The inclusion of leguminous tree species senegal (*Faidherbia albida*) and gliricidia (*Gliricidia sepium*) increases the soil C pool in the agricultural system of semiarid regions (Kalinda et al. 2015; Kaonga and Coleman 2008). Balieiro et al. (2008) reported the beneficial effects of incorporation of leguminous tree guachapele (*Pseudosamanea guachapele*) with nonlegume trees eucalyptus (*Eucalyptus globulus*) on the soil C accumulation. They evaluated that the soil under pure plantation of guachapele and eucalyptus derived 27 and 19% SOC from tree species, whereas this value increased up to 40% when both these were mixed. This difference in SOC accumulation in legume and nonlegume trees might be associated with the quantity of litter being produced.

The Calliandra (*Calliandra calothyrsus*) a small leguminous tree or large shrub when used as live fence sequestered 2 Mg C m<sup>-2</sup> of live fence (3–4 Mg dry matter m<sup>-2</sup>) at the age of 10 months, which epitomize C equal to 20 Mg ha<sup>-1</sup> in an average fence width of 1 m. Likewise, the live fence of 4 years gliricidia produced a gross annual C up to 35 and 50 Mg ha<sup>-1</sup> (7 and 9.5 Mg m<sup>-2</sup> total biomass) when pruned at 4- and 6-month intervals, respectively. Kang et al. (1999) also stated that gliricidia and subabul (*Leucaena leucocephala*) added 15% more SOC equivalent to 2 Mg C ha<sup>-1</sup> under 12-year hedgerow intercropping than that added by the sole crops in Alfisol. Under the hedgerow intercropping system, subabul increased the SOC content in 0–15 cm soil depth by 1.23 and 0.94% in hedgerow and alleys, respectively, over the continuous cropping after 5 years (Kang 1997). Lasco and Suson (1999) in their experiment reported that the subabul added on an average 16 Mg C ha<sup>-1</sup> during 6 years. They have reported increases in ANPP from 4 Mg in first year to 64 Mg in sixth year, while about 25% of the aboveground biomass C was estimated in woody debris. The increase in annual SOC deposition in top 15 cm soil stratum by the legume tree subabul substantially improved by 0.08, 0.26, and 0.76 Mg C ha<sup>-1</sup> at the age of 14, 20, and 38 years of planting, respectively, over the grass pasture in tropical regions (Radrizzani et al. 2011). The introduction of subabul, cassia tree (*Senna siamea*) and pasture grass specie (*Imperata cylindrica*) were found to be more efficient in enhancing the SOC content in upper 20 cm soil (Gaiser et al. 2012), whereas legume tree guava (*Inga edulis* sp.) returned 12% more organic C (0.23 Mg C ha<sup>-1</sup>) into the soil profile after 5 years of the hedgerow intercropping (Alegre and Rao 1996). But Rhoades et al. (1998) stated guava returned 20 Mg ha<sup>-1</sup> additional C in upper 15 cm furrow slice than that of open pasture. Another 10 m height flowering leguminous tree

coral bean (*Erythrina bertroana*) recorded the same trend of 30 and 55 Mg C ha<sup>-1</sup> annually, respectively, in the same research. de Jong et al. (1995) also reported the C sequestration potential of live fence trees of 24–36 Mg C ha<sup>-1</sup> in 25–30-year cycle. However, there is a need to consider the entire C cycle of the trees for the better assessment of C sequestration potential of the system (Albrecht and Kandji 2003).

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#### 4.11 Legume Root Biomass Role in Soil Carbon Sequestration

Unless legume crops were harvested, all underground biomass turnover was present for being assimilated into the SOM (Nair et al. 2015). The underground plant portion and root production directly contribute into the soil system and by itself have greatest potential to incorporate directly into the SOM pool (Sanderman et al. 2010; Sainju 2016). Several scientific studies had reported the correlations between plant root extension and the distribution of SOC within soil depth. The SOC contributed by plant root system remains present in the soil for a longer time in comparison to the aboveground residues associated with slow decomposition of roots in soil (Kuziyako and Domanski 2000; Rasse et al. 2005; Blagodatskaya et al. 2014). Legume-based crop rotation accounts to soil C sequestration because of increased rate of SOC accumulations at different soil depths as per the rooting habit of different species (Nair et al. 2015). The crop rotation with deep-rooted legumes builds the C pool deeper in soil via rhizospheric deposition, and root biomass extended deep in the soil. Gregorich et al. (2001) and Meena et al. (2017b) compared the legume-based rotation (maize-oat-alfalfa-alfalfa) with monoculture maize in over 35 years under fertilized and non-fertilized conditions. They concluded that the C sequestration in legume-maize rotation was 20 Mg ha<sup>-1</sup> higher as compared to the monoculture of maize at the end of experiment. And more importantly, they stated that SOC in legume-based rotation below plow layer (top 15 cm layer) appeared to be in a biologically resistant form (e.g., more aromatic C content), signifying the role of deep-rooted legumes toward enhancing long-term C sequestration in deeper soil. Similarly, under legume-based rotation, the size of C<sub>3</sub>-C pool beneath the plow layer was 40% higher over the monoculture.

The increased atmospheric CO<sub>2</sub> possibly induces the legumes root biomass production which in due course leads C returns to the soil. This is associated with the greater root turnover along with exudation of numerous carbonic substances which in turn contribute to greater soil C. The C sequestration through the root exudates and release of organic compounds from plant root during plant growth cycle and also the slaughtering of minor roots and their hairs by root elongation is well documented (Kemper et al. 1998; Rasse et al. 2005; Kumar et al. 2006). Legume roots exhibit the property to synthesize, store, and release various types of compounds (Kumar et al. 2006). The term “rhizo-deposition” is used to describe the release of carbonic substances from the plant roots as root exudates (Kuziyako and Domanski 2000). These secreted organic substances comprehend water-soluble and complex

compounds like mucilage, root border cells, simple and complex sugars, vitamins, organic acids, amino acids, phenolics, polypeptides, polysaccharides, extracellular enzymes, and other secondary plant metabolites. These compounds accumulate in the rhizospheric zone of plant roots (Paul and Clark 1996).

The transfer of photosynthates in the form of organic compounds in the direction of root's surrounding areas through roots occurs by the mechanism of root exudation, respiration, lysis, and root death (Kemper et al. 1998). The mechanisms of root death can be categorized into three states: (i) *apoptotic death* (occurring of C re-translocation to other plant-growing regions), (ii) *non-apoptotic death* (severage of principal roots – roots excised, rests metabolically energetic, and gradually exhausts inner soluble C pool); and (iii) *non-apoptotic death* (mechanically injured roots – metabolic activities terminate instantly and whole C contents go into the soil system) (Kumar et al. 2006). The all soluble C substance existing in the root may enter into the rhizospheric zones; on the other hand, the root exudates are still dominated by solutes having lower molecular weights in the cytoplasm present within the cell membrane (Kuzyakov et al. 2001). The repetitive discharge of carbonic substances from plant roots is further categorized into two classes: *first*, exudates which are discharged with a particular intention which is strongly regulated by the plant and, *second*, exudates which are lost on account of passive diffusion over which plants have limited or no control. The roots also liberate the CO<sub>2</sub> into the soil ecosystem as a result of carbohydrate respiration. The C in soluble form is discharged by non-metabolically active plant roots which are termed as “lysis,” whereas metabolically active plant roots account for CO<sub>2</sub> respiration and exudation (Rasse et al. 2005).

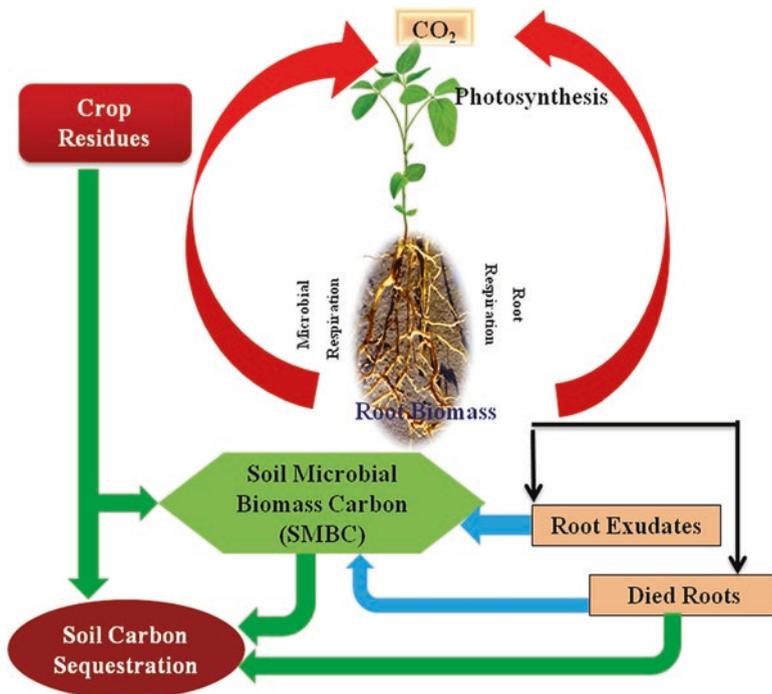
The rhizospheric depositions also have a great role in sequestering of the C. The root-derived exudate accelerates the working capacity of soil micro-/macroflora and fauna by providing the C as a source of energy (Paul and Clark 1996). The C released in rhizospheric zones assist proliferation of the growth and dynamics of microbial populations in the surface rhizosphere, endorhizosphere, and outside of the roots, i.e., ectorhizosphere. As soon as the releases of the C substance in the rhizosphere provinces occur, the soil bacteria attack and consume the substrate and proliferate quickly regarding growth, activity, and number which upon death contribute to SOC pool (Kumar et al. 2006). Blagodatskaya et al. (2014) also confirmed the higher microbial diversity and profusion along with rapid growth inside the rhizospheric environment of legumes when compared to the fallow soil. Now clearly, this was because of the abundant C availability released by the roots in the rhizosphere. The phenolic compounds secreted by the legume roots are supposed to be involved in the genetic triggering of the legume-*Rhizobium* association (Nair et al. 2015). The root-derived chemical promotes the growth and development of plant-fungal symbiotic association and provides the powerful signals that change the mycorrhizal association with the host plants. The dense root system of certain legumes and improved microbial functionaries can encourage the soil aggregation (Bronick and Lal 2005). Plant root system alters the soil structure using their physiology, biochemistry, and functions. The size and number of root nodules per plant also

significantly account toward the SOC pools. Root nodules support the bacteroids inhabiting in the rhizosphere. Henceforth, these supposed that the legume cultivation is a potential way to increase soil C sequestration. (Libault 2014).

#### 4.12 Legumes Improve Soil Microbial Biomass C (SMBC)

The soil under legume cultivation behaves in a similar pattern as to that of an organically managed field; this is also the reason behind the increased organic C content and associated soil microbial activities under legumes cultivation presented in Fig. 4.2.

Many researchers reported the increased N availability and metabolic activities of microbes and below- and aboveground biomass production in the legume-based system (Robinson et al. 1996; Adeboye et al. 2006; Diepeningen et al. 2006). Soil microbial biomass carbon (SMBC) comprises of 2–5% of total soil C (Smith and Paul 1990). The biological activities and subsequent SMBC in soil system under legume crops presented a higher C than nonleguminous crop. This was supported by the increased amount of biomass C, diversity of added plant residue, and biomass ninhydrin under legume cultivation over nonleguminous (Robinson et al. 1996;). Crop rotation with legumes significantly altered the status of both water-soluble organic carbon (WSOC) and SMBC (Adeboye et al. 2006; Ganeshamurthy 2009).



**Fig. 4.2** Soil microbial biomass carbon and sequestration through legumes

They found that crop rotation may not always affect the total SMBC but may affect physiologically distinct sub-component of microbial biomass. Similarly, the soybean rotation returned the greater SMBC and WSOC, whereas the fallow rotation produced the least values of these parameters. These SMBC and WSOC were linearly correlated with SOC and soil pH but not with the total N content (Moore et al. 2000). The crop rotation of maize-wheat-green gram and pigeon pea-wheat significantly improved the SMBC by 10 and 15% over the existing conventional maize-wheat system (Venkatesh et al. 2013). Adeboye et al. (2006) in their study found that any rotation with legume has a higher proportion of organic C as compared to the fallow rotation. This might be due to the low C/N ratio or high quality of residues of legumes returned into the soil which is more favorable for growth and survival of soil microbial populations and hereafter greater biomass C as a proportion of SOC.

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### 4.13 Conclusion and Future Perspective

Legumes are an imperative component of ecological sustainability and nutritional security and a valuable source of food proteins. Most of the global soils have become depleted in SOC pool over the years under intensive agriculture while a strong link between nutritional security and the C pool in terrestrial ecosystems, notably the SOC pool. Legume-based cropping systems crops are some of the key components to significant improvement in SOC pool in stressed soils. Legumes have positive effects on soil processes such as benefiting agroecosystem, agricultural productivity, soil conservation, soil biology, SOC and N pool, soil chemical and physical properties, BNF, nitrous oxide (N<sub>2</sub>O) emission, and nitrate (NO<sub>3</sub><sup>-</sup>) leaching by reducing the need for chemical fertilizers. The SOC pool, its amount, and depth-distribution improve along with involvement of legumes in the systems as a component of soil quality and a source of numerous ecosystem services. This will be helpful to researchers and policy makers to form decisions on the alarming issues of climate change and food and nutritional security, especially after the Paris Agreement of December 2015, which appeals for action to store and increase the sink capacity of SOC pool for soil sustainability and world food security.

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