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Soil Organic Matter as Affected by Green Manure at Brazilian Conditions

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ABSTRACT

The use of green manure has been associated with increasing soil organic matter (SOM), which is an essential component of high-quality agricultural soils, especially in tropical environments such as Brazil. The aim of this review was to present evidence of the effectiveness that green manures use has on the improvement of Brazilian SOM stocks. The contribution of soil aggregation to SOM stabilization, the importance of returning high amounts of plant residues to the soil, and the effectiveness of including N-fixing legumes in the cropping systems are all summarized. Soil aggregation is highly dependent on the continual addition of crop residues to the soil, and creates favorable conditions for SOM accumulation. SOM build-up is directly correlated to the amount of crop residues added to the soil and it is closely dependent on the duration, in the long-term, of this soil residue input. Moreover, the quality of these crop residues is of major importance, considering not only the high content of C directly added to the soil by the green manures, but also their N content, which is a determinant in the growth of subsequent crops, resulting in increased amounts of residue-derived C returned to the soil. The inclusion of green manures in cropping systems, especially legume species, in association with appropriate soil management practices, is a feasible and sustainable way to increase long-term SOM stocks in Brazilian tropical conditions.

Keywords: biological nitrogen fixation, cover crops, organic carbon, sustainability, tropical soils
Abbreviations: C, carbon; **CEC**, cation exchange capacity; **CO_2**, carbon dioxide; **ha**, hectare; **Mg**, megagram; **N**, nitrogen; **N_2**, molecular nitrogen; **NT**, no till; **SOC**, soil organic carbon; **SOM**, soil organic matter

CONTENTS

INTRODUCTION

Green manuring is an ancient practice used by Greek, Roman and Chinese societies. More than 3,000 years ago, Greeks used to cultivate lentils, fava beans and other legumes for food purposes, with benefits to subsequent crops. In China (1.200 BC) and in Macedon and Thessaly (400 BC), however, cultivation of legumes was used intentionally for soil improvement purposes, i.e. as green manures (Amabile and Carvalho 2006). Recently, it has been assumed that the main benefits of green manures on the improvement of soil quality are associated with the increase in soil organic matter (SOM) levels, nutrient availability and cation exchange capacity (CEC), organic acid formation, reduction of Al^{3+} levels, and the recycling and mobilization of nutrients from deeper soil layers. For the recovery of degraded soils in tropical environments, the addition and balance of SOM are of fundamental importance, since the improvement of soil physical conditions can be reached and maintained only via biological activity such as root action, macro and microbiological activity, and organic material decomposition (Alves 2006).

SOM is an essential component of high-quality agricultural soils in tropical environments because it affects many soil processes, such as microbial activity, nutrient release, and soil fertility buildup (Balota *et al.* 2004; Causarano *et al.* 2008). In this context, the inclusion of green manures, especially legume species, in association with other practices such as mineral N fertilization and no-till (NT), are key strategies of soil management (Bayer *et al.* 2003; Diekow *et al.* 2005a; Lal 2006; Vieira *et al.* 2007; Zotarelli *et al.* 2007). Although both legume species cropping and mineral N fertilization can promote an increase in soil organic carbon (SOC) stocks, Zanatta *et al.* (2007) observed that, per unit of increase in C added through residues, legume cover crop inclusion was more efficient in accumulating SOC than was increasing biomass production through mineral N fertilization. This is attributed to the C-related costs associated with the production and use of mineral N as fertilizer (Zanatta *et al.* 2007) and to increased decomposition of the native SOM when fertilizer is added (Kuzyakov *et al.* 2000; Khan *et al.* 2007).

There are several reasons to attribute the effectiveness of green manures (as cover crops in rotational cropping systems or as intercrops) in accumulating organic matter in the soil. The addition of aboveground residues and roots in

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high input cropping systems can: 1) promote the formation and stabilization of soil aggregates (Wendling *et al.* 2005; Salton *et al.* 2008; Martins *et al.* 2009), which in turn enhance the physical protection of SOM from oxidization (Six *et al.* 1999); 2) add high amounts of C-rich plant biomass to the soil, at rates that surpasses the decomposition rate (Vieira *et al.* 2009); and 3) convert atmospheric N_2 to organic-N forms through nitrogen biological fixation (NBF), improving total plant biomass production in sequential crops and, subsequently, C additions to the soil (Sisti *et al.* 2004; Zanatta *et al.* 2007; Vieira *et al.* 2009; Boddey *et al.* 2010).

Brazilian cultivated soils can potentially act as an important sink of C in a worldwide context, mitigating greenhouse gas emissions in tropical conditions (Leite *et al.* 2009). This is particularly due to the large extension of agricultural lands in Brazil and the adoption of NT practices - which is currently in the order of 25.5 million ha (FEBRAPDP 2007) – associated with cropping systems with high residue inputs, in rotational schemes including cover crops (Amado *et al.* 2001).

Therefore, in this review we discuss some aspects related to the effects of green manures on changes in SOM contents, based on available literature, with an emphasis on Brazilian conditions. Topics related to the contribution of soil aggregation on SOM stabilization, the importance of returning high amounts of plant residues to the soil, and the effectiveness of including N-fixing legumes in the cropping systems for high quality residue production, are summarized in order to emphasize the importance and potential of green manure on SOM accumulation in tropical agroecosystems.

THE ROLE OF GREEN MANURES ON SOIL AGGREGATION AND SOM CONTENTS

Soil aggregation plays an important role on the physical protection of SOM (Six *et al.* 1999). The relationship between increasing SOC stabilization in cropping systems with high annual input, increasing soil macro-aggregation, and stabilization of SOC in micro-aggregates contained within macro-aggregates, was described by Kong *et al.* (2005). According to Vieira *et al.* (2009), the physical protection of SOM within micro and macro-aggregates has been considered by many authors to be one of the main mechanisms of SOM stabilization in NT soils from tropical and temperate regions. Some estimates (Conceição *et al.* 2007) suggest that up to 30% of the total SOM accumulation in NT soils was due to the physical protection of SOM into soil aggregates in southern and mid-western Brazilian regions.

The relationship between soil aggregation, SOM and cover crops used as green manures has been the subject of several studies. Aspects related to mineral fractions, soil fauna/microorganisms, root action, inorganic agents, and environmental aspects have been pointed out as key factors in the formation and stability of soil aggregates (Salton *et al.* 2008). The role of roots in soil aggregate formation has shown to be of relevant importance, especially for grasses. The activity of grass root systems associated with NT contributes to the formation of stable soil aggregates (Pinheiro *et al.* 2004).

In general, grasses tend to show a more efficient and prolonged effect on soil aggregation. Silva *et al.* (1998) observed stronger effects of *Brachiaria* sp. on soil aggregation compared to legume cover crops. In the Southeast of Brazil, Wendling *et al.* (2005) also reported higher soil aggregation and SOC content in soils cultivated with *Cynodon* sp. According to the these authors, the effect on soil aggregation is caused by the release of organic exudates by grass roots, the compression of unitary soil particles, and water removal, which in turn favors the cohesion of soil particles. Salton *et al.* (2008) found that, for the mid-west Brazilian region, higher stable soil aggregate formation was reached only in soil management systems that included permanent grass-based pastures, or in rotational systems including grasses and grain crops. They also found that macro-aggregate stability is correlated to the SOC, which was also reported by Wendling *et al.* (2005). Martins *et al.* (2009) observed, for the Southeast Brazilian region, that maize monocropping provided the highest water-stability of soil aggregates due to the greater activity of roots releasing mucilage and greater physical protection by crop residues. This crop sequence also provided the highest content of SOC.

Legumes may also contribute significantly to increasing soil aggregation and consequently, the SOC stocks. The use of legumes adds photosynthesized C and biologically-fixed N to the soil, improving its structure and contributing to the formation and maintenance of soil aggregates (Albuquerque *et al.* 2005). Boddey *et al.* (2010) found positive effects of legume cover crops on the SOC stocks for Southern Brazilian conditions. The authors stated, based on their findings and on results found by Chen *et al.* (2008), that legumes probably promote a larger microbial population in the rhizosphere than cereal crops. If arbuscular mycorrhizal associations with roots are favored by legumes, this may also increase SOC as it has been suggested that arbuscular mycorrhizae facilitate the binding of aggregates and otherwise promote soil C accumulation in undisturbed soils (Rillig and Mummey 2006). Zotarelli *et al.* (2007) found that the combination of NT and green manures, including legumes, in the soil management system promoted the stabilization of aggregate-associated C. Long-term management practices that increase residue-C levels returned to the soil will result in increased aggregate stability, increased aggregate-associated SOC levels, and long-term C sequestration (Kong *et al.* 2005). These authors concluded that preferential C sequestration in the micro-aggregate-within-small macro-aggregate fraction seems to be a principal mechanism and ideal indicator of long-term soil C sequestration in agro-ecosystems.

INPUT OF BIOMASS-DERIVED C BY GREEN MANURES AND SOC

Conversion of native tropical forests to agricultural systems tends to disturb the soil's physical structure and decrease the input of plant biomass, leading to a reduction in the SOM stocks (Leite *et al.* 2004). In this scenario, the use of cropping systems with high potential for residue production is of major importance (Lovato *et al.* 2004; Bayer *et al.* 2006; Costa *et al.* 2008; Vezzani and Mielniczuk 2009). However, there are differences in the rates of SOM decomposition among disturbed and undisturbed soils, and soils under reduced tillage or NT systems tend to present a smaller requirement for C input (Bayer *et al.* 2006). Therefore, the use of a NT system can be considered a strong ally of green manure-based cropping systems, which return considerable amounts of high-quality crop residues to the soil.

Vieira *et al.* (2009) proposed a useful conceptual relationship between SOC stocks and annual C addition in cropping systems, showing the importance of high and continuous addition of residue-derived C by the crops, which correlates positively with the maintenance and increase of SOM stocks. The authors have found that the SOC stocks were significantly correlated (R^2 = 0.86, $P < 0.001$) with the mean annual C input provided by green manures in rotation or intercropped with maize.

In general, the highest C addition to the soil occurs in systems involving cover crops (Amado *et al.* 2001) and differences in the amount of C returned to the soil as crop residues are specially governed by the presence of N-fixing leguminous species. These authors found that in a cover crop/maize-based system, the main differences in C additions depended basically on the cover crop species used, and that C addition by maize residues amongst the treatments was not significant. On the other hand, results have shown that maize crop was the major C contributor in most management systems involving cover crops, being responsible for up to 73% of the total addition of C in some treatments (Zanatta *et al.* 2007). Regarding the contribution of

Table 1 Amount of total N sequestered in Brazilian agricultural soils for various management practices involving green manures.

Soil N sequestration	Depth (cm)	Region	Reference
+ 0.07 Mg ha^{-1} year^{-1}	0-20	Santa Maria (RS)	Conceição *et al.* 2005
+ 0.06 Mg ha^{-1} year^{-1}		Eldorado do Sul (RS)	
+ 0.05 Mg ha^{-1} year^{-1}	0-107.5	Eldorado do Sul (RS)	Diekow *et al.* 2005b
+ 0.04 Mg ha^{-1} year^{-1}			
+ 0.14 Mg ha^{-1} year^{-1}	0-40	Londrina (PR)	Franchini *et al.* 2005
+ 0.13 Mg ha^{-1} year^{-1}	0-100	Passo Fundo (RS)	Sisti *et al.* 2004
+ 0.03 Mg ha^{-1} year^{-1}	0.17.5	Eldorado do Sul (RS)	Lovato *et al.* 2004
+ 0.22 Mg ha^{-1} year^{-1}	0-20	Chapecó (SC)	Bayer *et al.* 2003
+ 0.16 Mg ha^{-1} year^{-1}	0-20	Santa Maria (RS)	Amado *et al.* 2001

cover crops on the addition of C, Zanatta *et al.* (2007) ranked the species in the order of oat < vetch < oat + vetch/ cowpea, indicating that the potential of multiple-cover crop systems to add C to the soil may be greater when compared to single-cover crop systems. They found also that application of inorganic N to the maize had no effect on the increase in C added by the cover crops.

In Southern Brazil, Diekow *et al.* (2005a) found that, in a 17-year-experiment, bare soil and the oat/maize sequence without mineral N fertilizer lead to losses of 18 and 13%, respectively, in the SOC contents. Although the soil was managed under NT, the low residue input of these cropping systems was unable to counterbalance the organic matter mineralization output. However, legume-based cropping systems (lablab + maize and pigeonpea + maize) significantly increased soil C and N stocks over 17 years, probably due to their higher annual aboveground plant biomass production. Similar results were found by Costa *et al.* (2008), where cropping systems including vetch as legume green manure in succession to maize resulted in higher soil C inputs compared to an oat/maize succession. The authors noted that mineral N fertilization was not used in the treatments and therefore, the differences in C inputs were due to the effect of green manures' N addition on maize growth and residue production.

Based on the relationship between SOC stocks and C input, Vieira *et al.* (2009) determined, for the Southern Brazilian conditions, that the annual C input requirement to maintain the original SOC stock is 4.05 Mg ha^{-1}, which is very close to the value of 3.9 Mg ha^{-1} found by Bayer *et al.* (2006) for NT soil in an neighboring experiment, but which is almost half of the minimum requirement of 8.8 Mg ha^{-1} for the same soil under conventional tillage. On the other hand, Nicolosso *et al.* (2008) reported an annual soil C-addition requirement of 4.5 Mg ha^{-1} for a crop-livestock system including soybean and maize in Southern Brazil, which corresponds to 11 Mg ha^{-1} of plant biomass (stems and roots). Most results available for Brazilian conditions refer to experiments located in the Southern region. Central and Northern Brazilian regions exhibit higher mean temperatures and a bimodal rainfall pattern, which can enhance the SOM decomposition and therefore, require higher amounts of soil residue-C inputs to maintain the stocks of SOM, as reported by Nascimento *et al.* (2005).

LEGUME-BASED SYSTEMS' EFFECTS ON SOIL N INPUT AND INCREASED BIOMASS PRODUCTION

Cropping systems that include N-fixing legumes as green manures return high-quality residues to the soil. Moreover, results obtained by Kong *et al.* (2005) suggest that residue quality is directly linked to the amount of SOC sequestered in cropping systems. Continuous additions of significant amounts of high quality crop residues result in higher plant biomass production by subsequent crops and SOC stocks are enhanced (Amado *et al.* 2001; Lovato *et al.* 2004; Sisti *et al.* 2004; Conceição *et al.* 2005; Diekow *et al.* 2005b; Amado *et al.* 2006; Franchini *et al.* 2007; Zanatta *et al.* 2007; Costa *et al.* 2008; Vieira *et al.* 2009). Diekow *et al.* (2005b) observed that the high residue input of intercropped pigeon pea plants and the biological N fixation, which benefitted the subsequent maize plant biomass input, were the most likely explanation for the higher C stocks in this legume-based cropping system. Similar trends were observed in the results of total soil N stock. Soil N stocks can also be maintained or even significantly improved in systems managed with green manures as cover crops, as summarized in **Table 1**.

Amado *et al.* (2001) stated that the differences in SOC stocks were related to the amounts of plant biomass returned to the soil, which in turn was influenced by the nitrogen biologically fixed by legumes. Lovato *et al.* (2004) observed that legume cover crops contributed up to 50% of C addition to the soil. According to Conceição *et al.* (2005), 26% of N added via plant residues remains stored in the soil and therefore, the combined use of legumes and NT is an effective practice to restore soil N stocks.

Data reported by several authors (Lovato *et al.* 2004; Sisti *et al.* 2004; Diekow *et al.* 2005b; Amado *et al.* 2006) showed that the use of legume species increased the C and N additions to the soil, resulting in a higher plant biomass production by the maize in succession, which was attributed to the fixed-N supply to this crop. Based on these results, one could expect that the N mineral fertilization in maize would result in the same efficiency for N addition to the soil, consequently influencing SOC stocks. Indeed, for many cropping systems, mineral fertilization with N is a key factor that controls biomass production and thus may influence SOC storage patterns (Zanatta *et al.* 2007). On the other hand, Lovato *et al.* (2004) showed that when mineral N was applied to maize on an oat/maize cropping system at an average rate of 139 kg ha^{-1} year^{-1}, biomass production increased by 92% over the treatment without N. However, in a vetch/ maize system, biomass production increased only 38% with the same level of N fertilization, clearly indicating that the legume winter cover crop may supply most of the N required by the maize.

According to Conceição *et al.* (2005), the input of biologically fixed nitrogen provided by legumes and in association with NT practices is a more efficient strategy to recover soil N stocks than the use of mineral N fertilization, which is reinforced by Boddey *et al.* (2010). Conceição *et al.* (2005) based this statement on the higher (26%) amount of N stored in the soils under legume-based cropping systems, compared to cereal-based successions, both with mineral N fertilization. Besides, the positive effect of fertilization with mineral N on soil C balance does not necessarily result in atmospheric C mitigation because the benefits of increasing SOC stocks may be counterbalanced or surpassed by the C-equivalent costs related to the applied N-based fertilizers (Zanatta *et al.* 2007).

GREEN MANURES AND POTENTIAL SOIL C SEQUESTRATION AT BRAZILIAN CONDITIONS

As mentioned earlier, most research results reported here refer to Southern Brazilian conditions, where long term experiments have been carried out. In that region, temperature and rainfall patterns do not represent the conditions of the whole country. In the Northern Brazilian regions, as a consequence of higher temperatures and the bimodal rainfall pattern, the SOM decomposition is accelerated and there is

Table 2 Amount of TOC sequestered in Brazilian agricultural soils for various management practices involving green manures.

Soil C sequestration	Depth (cm)	Region	Reference
+ 0.52 Mg ha^{-1} year^{-1}	0-17.5	Eldorado do Sul (RS)	Vieira *et al.* 2009
+ 1.02 Mg ha^{-1} year^{-1}	0-100	Cruz Alta (RS)	Boddey *et al.* 2010
+ 1.13 Mg ha^{-1} year^{-1}		Santo Ângelo (RS)	
+ 0.32 Mg ha^{-1} year^{-1}	0-30	Eldorado do Sul (RS)	Zanatta *et al.* 2007
+ 0.35 Mg ha^{-1} year^{-1}	0-10	Goiânia (GO)	Metay *et al.* 2007
+ 0.38 Mg ha^{-1} year^{-1}	0-20	Eldorado do Sul (RS)	Amado *et al.* 2006
+ 0.59 Mg ha^{-1} year^{-1}		Santa Maria (RS)	
+ 0.62 Mg ha^{-1} year^{-1}	0-20	Santa Maria (RS)	Conceição *et al.* 2005
+ 0.40 Mg ha^{-1} year^{-1}		Eldorado do Sul (RS)	
+ 0.88 Mg ha^{-1} year^{-1}	0-17.5	Eldorado do Sul (RS)	Diekow *et al.* 2005a
+ 1.01 Mg ha^{-1} year^{-1}	0-107.5	Eldorado do Sul (RS)	Diekow *et al.* 2005b
+ 1.42 Mg ha^{-1} year^{-1}			
+ 1.17 Mg ha^{-1} year^{-1}	0-40	Londrina (PR)	Franchini *et al.* 2005
+ 0.82 Mg ha^{-1} year^{-1}	0-100	Passo Fundo (RS)	Sisti *et al.* 2004
+ 0.92 Mg ha^{-1} year^{-1}			
+ 0.56 Mg ha^{-1} year^{-1}	0.17.5	Eldorado do Sul (RS)	Lovato *et al.* 2004
+ 2.23 Mg ha^{-1} year^{-1}	0-20	Chapecó (SC)	Bayer *et al.* 2003
+ 0.67 Mg ha^{-1} year^{-1}	0-20	Santa Maria (RS)	Amado *et al.* 2001

a need for higher amounts of residue addition to the soil, in order to maintain SOC stocks. In the tropical conditions of Mexico, Astier *et al.* (2006) did not find significant effects of legume green manures on SOC concentrations during a short-term (2 years) experiment. Similarly, in the North-eastern Brazilian region, Nascimento *et al.* (2005) reported that leguminous green manures maintained SOC concentrations over a 3-year experiment.

Despite these results, Amado *et al.* (2001) stated that if sustainable management systems are used, it is possible to recover SOM stocks even in soils subjected to fast microbial decomposition and with low clay contents, where the physical protection is reduced. Vieira *et al.* (2009) emphasizes, supported by data from Six *et al.* (1999) and Zotarelli *et al.* (2007), that the physical protection of SOM in micro and macro-aggregates has been considered one of the main mechanisms of SOM stabilization in NT soils from temperate and even tropical regions. Metay *et al.* (2007) found in 5-year experiment carried out at Central Brazilian Savannah, that the use of winter cover crops in association with NT practices in a dryland rice production system result in significant increases (0.35 Mg ha^{-1} year^{-1}) in the SOC stocks. In the Southeast region of Brazil, Wendling *et al.* (2005) observed a positive effect of the perennial pasture grass *Cynodon* sp. on the formation and stabilization of soil aggregates, which in turn correlated positively with SOC contents.

For the Southern Brazilian region, several studies have shown the efficiency of legumes' inclusion in cropping systems with regards to the improvement in SOC stocks, as shown in **Table 2**. This data displays a high diversity of results, ranging from an annual loss of 0.5 Mg C ha^{-1} year^{-1} (13 years) in an oat-maize succession system under conventional tillage (Lovato *et al.* 2004), to an increase of 2.23 Mg C ha^{-1} year^{-1} (5 years) in a maize + mucuna (*Stizolobium cinereum*) intercrop under NT (Bayer *et al.* 2003).

Even for field experiments carried out for longer periods, data has shown the effectiveness of green manures associated with sustainable soil management practices on the progressive increase of SOC stocks (Zanatta *et al.* 2007 [18 years]; Costa *et al.* 2008 [18 years]; Vieira *et al.* 2009 [19 years] and Boddey *et al.* 2010 [26 years]). Diekow *et al.* (2005b) found a linear C and N accumulation pattern with time, for silt-size and mainly sand-size soil fractions. The authors concluded that contrary to soil clay fraction, both sand and silt-size fractions do not have a finite capacity to store C and N, and that these fractions will be the only where further increases of total soil organic C stock will take place when the clay-size fraction becomes saturated.

Most research studies have considered the influence of green manures on the top soil layers. However, the permanent use of cover crops in the long-term may result also in changes in the SOC stocks in deeper layers (Amado *et al.* 2001). Sisti *et al.* (2004) stated that if sampling were restricted only to 20 or 30 cm depths (the maximum depth affected by the disc ploughing under CT), the gain in C and N stocks would be grossly underestimated. The authors have found higher SOC and N stocks at deeper layers in NT compared to conventional tillage in cropping rotations involving legumes as green manure. According to Diekow *et al.* (2005a), although the major effects of soil management are found in the 0-17.5 cm layer, up to 24% of the overall C losses and up to 63% of the gains in the whole 0-107.5 cm layer occurred below the 17.5 cm depth, reinforcing the importance of subsoil as a C source or sink. The authors have found that the average C sequestration rate of legume-based cropping systems (N fertilized treatments) was 0.83 Mg C ha^{-1} year^{-1} in the top 0-17.5 cm layer and 1.42 Mg C ha^{-1} year^{-1} in the whole 0–107.5 cm layer. Boddey *et al.* (2010) support these findings, reinforcing that there is a linear relationship between soil C accumulation to 30 cm with that to 100 cm. These authors suggested, based on their study, that on average the soil C stock until the depth of 100 cm was 97% greater than the stock estimated until a depth of 30 cm only.

CONCLUDING REMARKS

Several studies have shown the importance of soil aggregation for the physical protection of SOM. Soil aggregation is governed, to a large extent, by regular addition of crop residues to the soil. Therefore, the use of cover crops as green manures plays an important role in physically conditioning the soil to stock high amounts of organic matter. SOM build-up is directly correlated to the amount of crop residues added to the soil and it is closely dependent on the duration, in the long-term, of this residue input. Moreover, the quality of these crop residues is of major importance, considering not only the high content of C directly added to the soil by the green manures, but also considering that soil N content is a determinant in the growth of subsequent crops, eventually resulting in increased amounts of residue-derived C returning to the soil. From the data presented here, it is possible to conclude that the inclusion of green manures in cropping systems, especially legume species, in association with appropriate soil management practices, is a feasible and sustainable way to increase long-term SOM stocks under tropical Brazilian conditions.

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