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Soils under Plastic and Grass Cover: Effects on Soil Aggregation and Nutrient Cycling in Brazilian Coffee Growing

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Abstract

Coffee is one of the most traditional and economically important agricultural commodities in tropical countries, especially in Brazil, the world´s greatest producer. Typically, site preparation for planting coffee stands includes deep furrowing, which allows for better mitigation of soil physical and chemical limitations and thus stronger and deeper root development. However, the practice of deep tillage prior to planting coffee seedlings strongly disrupts soil aggregates and thus affects negatively soil physical quality. Thus, after these deep tillage operations, some management practices must be employed to improve soil aggregation and thus enhance the sustainability of coffee production. In this chapter, we review evidence of improved soil aggregation in planting furrows promoted by application of gypsum and grass biomass residues, favoring a better organization of the soil porous space for coffee roots. Other innovative techniques are also discussed, such as the use of organo-mineral fertilizers associated with plastic mulching in soil aggregation.

Keywords: soil management, plant nutrition, plastic mulch, perennial crops, organic fertilizers

Introduction

Coffee (Coffea sp.) beans are the world’s second largest agricultural commodity [27], and since 1850 Brazil is the leader in its production and export [7,31]. The southeastern region of Brazil, and especially the States of Minas Gerais, São Paulo and Espírito Santo, marked by a warm humid climate, accounts for ca. 84% of the national coffee production [18]. However, agriculture in this region is subject to recurrent and severe dry spells, accompanied by intense heat, strong insolation and low relative humidity. As coffee production is mainly rainfed, such dry spells and unexpectedly long dry seasons have a major potential to affected crop productivity and bean quality, which demands innovative actions to promote an efficient use of soil water. The most widely used of such techniques are soil conditioners for deeper rooting, and mulching, which reduces evaporation losses and soil surface temperatures. In addition, tillage practices are employed simultaneous to “construction of fertility” (i.e., liming and fertilization of the chiefly acidic and nutrient-leached soils) in the planting furrows [13-15, 44-47].

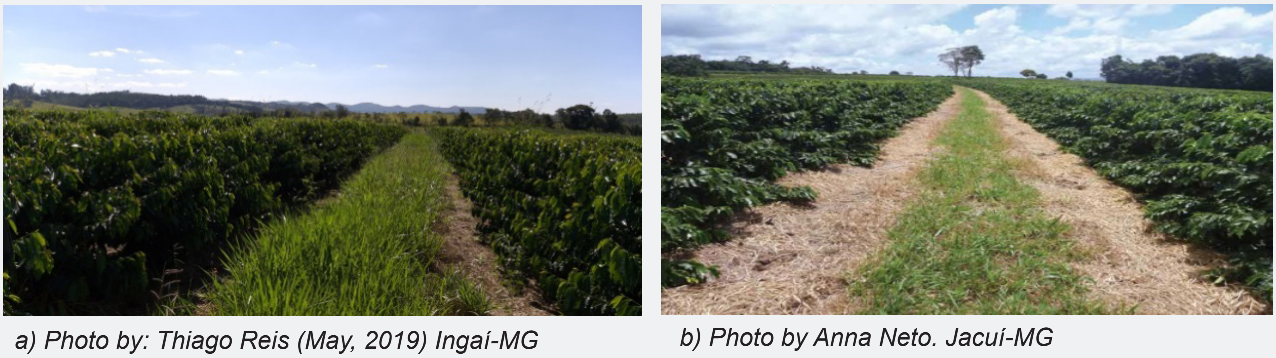
Other approaches are becoming increasingly popular among the most specialized coffee growers, such as cover crops between coffee rows, which protect soils from raindrop impacts, increase soil biodiversity, provide more organic inputs and increase root colonization, with positive effects on aggregation and nutrient cycling [38]. For instance, intercropping between coffee trees and signalgrass (Urochloa or Brachiaria sp.) can increase soil organic carbon stocks, thus removing CO_2, a greenhouse gas, from the atmosphere [53]. In such management systems, decomposition of the high organic matter inputs favor soil aggregation [50-53] and faunal activity, promoting formation of biopores, which enhance coffee root growth and mitigate compaction-related problems [26]. Coffee crops are among the most nutrient-demanding in tropical agriculture, and most Brazilian soils are marked by strong acidity and very low levels of phosphorous and base cations in all horizons and layers. Therefore, in addition to routine liming and fertilization made in surficial layers, it is often necessary to provide some chemical amendments in deeper (> 20cm depth) layers. A commonly used option is phosphogypsum, i.e. gypsum produced as a by-product of phosphate fertilizer production, which in most crops is applied on the soil surface as a physical conditioner. Phosphogypsum is highly mobile throughout the soil profile, moving downward as an ionic pair and then releasing Ca^{2+} and sulfate (SO_4^{-2}), which also decreases Al3+ activity by its binding with SO_4^{2} [16]. The enhancement of soil fertility in the subsurface layers allows greater root development [15, 49], favoring uptake and nutrient cycling, especially of N, Mg2+and K+ [40]. More specifically in coffee stands, phosphogypsum can be disposed on surface of the soil and then covered with a mixture of soil and signalgrass residues from the inter-rows, resulting in even deeper rooting and more organic matter inputs [40, 44] that will further enhance aggregation.

Some farmers, encouraged by researchers and entrepreneurs, are using alternative fertilizer sources which allegedly bear lower environmental impacts and lower costs. Organo-mineral fertilizers are produced by mixing conventional, mineral fertilizers with natural or composted organic materials locally available, formulated in proportions and applied in amounts comparable to those in comon mineral fertilizations [23]. On-site studies performed in coffee crops showed the superior efficacy of associated deep furrowing, organo-mineral fertilization and plastic mulching in soil aggregation [55]. Plastic mulching, by covering the soil surface, reduces evaporation and resulted in higher soil moisture contents, that improved plant growth [8]. Better vegetation development leads to higher soil organic matter contents, which is a very important factor affecting aggregate stability and water holding capacity. Because of the formation of stronger aggregates, soil macroporosity becomes higher and water availability for plant roots is improved [60]. This chapter describes in detail the characteristics of these management techniques and their effects on soil aggregation indicators.

Planting Grass in Coffee Farming Systems

Coffee is a perennial plant with a size varying from shrubs to small trees, which are able to colonize greater soil volumes for much longer time lapses than annual crops. The fine roots are mostly responsible for nutrient absorption, and typically occur to a depth of 40cm [36]. However, even in mature stands which received the recommended amounts of fertilizers, the most mobile nutrients in the soil, namely N, K, S and B, often leach below the deepest absorbent roots. Thus, as a means to enhance uptake and cycling of these nutrients, it is desirable to alternate rows of coffee tress with inter-rows covered with perennial plants with deep root systems, such as grasses.

Signalgrass, better known in Brazil as brachiaria (Urochloa sp.), is a grass native from Africa that has adapted very well to Brazilian tropical areas, especially in the central savanna region (the Cerrados), where most soils are marked by strong acidity and very low soil fertility [17,42]. Although considered an invasive plant for most agricultural crops, brachiaria is widely planted as forage and offers a high potential for soil cover between rows of coffee trees (Figure 1), due to aspects such as: a) high adaptability to soil and climate conditions; b) size and growth habits appropriated to use in consortiums with coffee trees; c) perennial life cycle and easy propagation; d) high rusticity, low-cost maintenance associated and resistance to mechanization and other stresses [42]. Brachiaria-covered inter-rows do not interfere with mechanized coffee harvesting, and for other operations, brachiaria can be easily controlled with herbicides, although recovering in few weeks if rains occur.



a) Photo by: Thiago Reis (May, 2019) Ingaí-MG

b) Photo by Anna Neto. Jacuí-MG

Figure 1: Intercropping between coffee tree and brachiaria - before (A) and after (B) of the cutting operation.

Therefore, brachiaria grasses (Urochloa sp) are a species of choice for soil cover and straw incorporation into the soil, due to high dry mass production and high C:N ratios [37]. In coffee trees and brachiaria grass consortia (Figure 1), all plant residues are cycled and eventually used for coffee nutrition, especially those beneath the coffee canopy [30]. The amount and regularity of crop residue addition is more important than the time between release and nutrient demand by the coffee trees. The increase in organic

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matter content over the years due to this addition of crop residues brings many benefits to the soil and coffee. In low fertility soils, increased soil organic matter contents in brachiaria-associated coffee crop also have a side benefit of increased cation exchange capacity, since such soils only have pH-dependent charges associated with humus, then indirectly increasing soil nutrients [59].

The presence of organic residues covering the soil in inter-rows reduces weed growth and prevents soil temperatures from exceeding 33°C, which can potentially result in localized root death [29,39]. In hot days, if such cover is absent, temperatures can exceed 45°C. In soils more exposed to the sun, plant growth is negatively affected by soil temperature and also by the high evaporation, reaching 1.5mm of water day-1. In regard to the soil biological community, growth of brachiaria roots results in beneficial associations with soil microorganisms, such as mycorrhizal fungi, which can strongly increase uptake of phosphates sorbed by soil clay minerals. In a ten-year non-fertilized brachiaria grass stand, soil Mehlich-I phosphorus was 45% higher under tussocks than between tussocks [21]. Brachiaria roots are more efficient than those of coffee trees in extracting inorganic phosphorus from soils, and part of that P will become available gradually with straw decomposition and mineralization near the canopies. Based on the average brachiaria productivity of 15Mg ha^{-1} yr-1 [17] and an approximate 30% coverage of total area in consortia with coffee trees, it can be estimated 3 plant cuts per year with 5Mg ha^{-1} in each harvest. Considering the average nutrient contents in brachiaria residues, cutting and disposing these biomass on the soil surface would eventually release ca. 75 kg N, 20.6 kg P_2O_5, 193kg K_2O, 24.5kg CaO, 20.8kg MgO, 3.5kg S-SO_4, 90g B, 55g Cu, 1,002g Fe, 475g Mn and 400g Zn per hectare [29]. The mineralization process depends on water availability, temperature and microorganism activity, and some nutrients like N and P are only partially released in the first 3 years [41], but in any case there is a considerable stimulation of the nutrient cycle in such consortia.

Despite the many advantages presented by growing brachiaria grasses between coffee rows, there may be some disadvantages, especially if this cover crop incorrectly managed. Severe water stress can result in strong competition for water and nutrients between the different plants, which would result in even stronger decreases in coffee bean yield [2]. The implementation of coffee crops requires good planning, since the stands must be productive for at least 13 years (10 crops), although in some cases a productive lifespan can reach 50 years. In order to maximize profit and environmental sustainability in coffee-brachiaria consortia, a careful management is required to ensure that the cover crop does not outcompete coffee trees. However, if well managed, coffee-brachiaria consortia are win-win alternatives to reduce erosion, lower soil temperature and evaporation, increase water infiltration and soil organic matter contents.

Soil Aggregation: Effects of Plastic Mulching and Organo-Mineral Fertilizers in Coffee Stands

Due to the increasing scarcity of water resources, a more sustainable agriculture requires management practices that increase soil water use efficiency [28,32]. In this regard, mulching the soil surface with plastic films has been used for various crops, including coffee stands [22,56]. The main objective of plastic mulching is to reduce evaporation and temperature oscillation of the soil surface [22,34,56,62]. However, there are other indirect benefits, such as soil protection against rain drop impacts [28]. In this regard, recent studies have shown that plastic mulching, when associated with the use of organo-mineral fertilization, can strongly favor the formation of more stable aggregates [55].

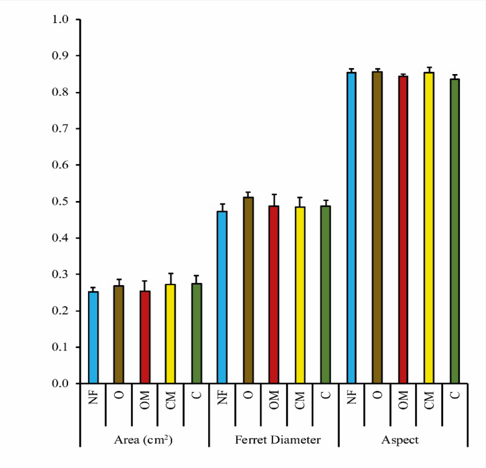

Figure 2: Mean values for morphometric variables area, ferret diameter and aspect. NF: native forest, O: Organomineral, OM: Organomineral + cover plastic, CM: Chemical + cover plastic, C: Chemical. Source: adapted from Souza et al., in is [55].

In studies carried out by Souza et al., in [55] it was verified that in only six months after the opening of the planting grooves, the aggregates of an Argisol under different management with organominerals and plastic cover showed morphological characteristics (area, ferret diameter and aspect) similar to those observed in this soil under native forest conditions (Figure 2). The results of this work demonstrated that after the tillage soil, the fertilization of the planting furrows with organomineral fertilizers, can contribute to a rapid reorganization of the soil structure. This is because the organomineral causes an increase in the organic matter content, greater biological activity and, consequently, a greater flow of energy and matter to the system [20]. In this way, the smaller structures present in the soil, after their revolving, in an environment with organic matter input, are able to reorganize in larger and complex structures, giving rise to new macroaggregates of the soil [58].

Some authors believe that the formation of microaggregates within macroaggregates is a key process involved in the physical protection of organic carbon in soils (e.g.,in [5]). Microaggregates are also an important reserve of macro- and micronutrients in cultivated soils, due to their greater resistance to disaggregation and high stability, preventing or reducing nutrient losses due to degradation processes of the soil physical structure [10]. The stability of aggregates formed after intensive site preparation in coffee production systems is very important for carbon sequestration, resistance to erosion and overall soil quality. In coffee stands, higher b/a indexes , which is found from the linearization of the soil dispersion curves [55], were observed for crops treated with organo-mineral and mineral fertilizers (Figure 3, in [55]). When the fertilization in the planting furrows was carried out without the plastic mulching, the stability of the newly formed aggregates decreased significantly.

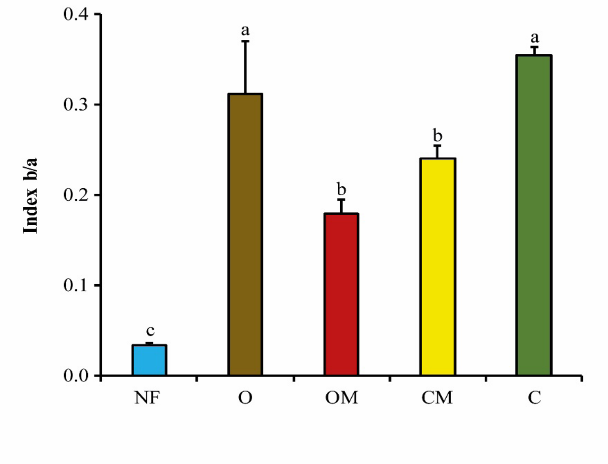

Figure 3: Mean values of the b/a index as affected by coffee management:
NF: native forest, O: Organomineral, OM: Organomineral + cover plastic, CM: Chemical + cover plastic, C: Chemical. Means followed by same letter do not differ by the Scott-Knott 5% test. Source: adapted from Souza et al., is [55].

Barbosa, in [9] studied early coffee development (< 2 yrs) after planting in furrows 60 cm deep and noted that the combination of organo-mineral fertilizers and plastic mulching contributed to stronger growth in height and stem diameter, and increased number of leaves. In addition, more fine roots and a better root system distribution was noted in soils under plastic mulching to a depth of 45cm. The results suggest that coffee plants growing in those conditions have potentially a more efficient water use, which may be critical in the study area near Lavras, Minas Gerais, where water deficits can be greater than 400mm in some years.

Ultrasonic Energy and Morphology as Tools for Evaluating Aggregation Soil under Management with Gypsum and Brachiaria

The use of cover crops, by increasing the amount of organic inputs, increases soil organic matter retention but also soil microbial activity, both indirectly increasing soil aggregate stability [35]. Rossi et al., in [43] observed that brachiaria growing on Oxisols provides ca. 6 Mg ha^{-1} of dry matter, which is later humified into soil organic matter. The quality of plant materials from cover crops between rows of coffee trees also has a strong influence on soil aggregation [58]. Due to their greater recalcitrance, the residues of brachiaria grasses remain for a considerable time on the soil surface [3]. In fact, brachiaria straw has a long half-life on the soil surface, thus providing physical protection against the impact of raindrops, reducing mechanical stress exerted by agricultural machines, and helping preserve soil moisture [59]. Also, perennial grasses present a dense, fasciculate root system that is frequently renewed since fine roots are short-lived [59]. Organic compounds derived from decomposition of grassy residues comprise recalcitrant cementing substances, which do not readily decompose [1]. The combination of all these features

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favors soil microbial activity and the production of aggregate-forming organic compounds [12]. Furthermore, the release of exudates in the rhizosphere of the fine roots, associated to decay of dead fine roots, also promote the formation and stabilization of soil aggregates [52, 53].

Therefore, it is expected that coffee cultivation in consortium with cover crops between the rows is more beneficial to soil aggregation in comparison to monocultural coffee stands, especially those keeping inter-rows bare. Silva et al., in [51] studied macroaggregate morphology in soils of brachiaria-covered inter-rows of coffee stands grown on an Inceptisol and noted a significant increase in aggregate dimensions (area and Ferret diameter), which resulted in better structural quality and increased porosity. Furthermore, periodic cuttings of brachiaria leaves grown on inter-rows, and the resulting grass residues can be subsequently distributed on the planting row, under or near the coffee plants [44,53]. Thus, since the grass residues are distributed on both rows and inter-rows, its decomposition can promote positive effects on aggregation of the whole stand area.

In the State of Minas Gerais, a large area under savannic vegetation (known as Cerrado) is marked by a dry season typically comprising 3-5 months, which can result in more severe water stress that jeopardize coffee bean productivity. Thus, in addition to the brachiaria-covered inter-rows, some farmers developed a novel management system employing mechanical practices and soil conditioners, more specifically phosphogypsum [44,49]. In this system, terraces on contour lines are built as a mechanical practice for soil and water conservation. Soil is prepared by deep (until 60cm depth) cultivation with subsoiler and plough for the planting rows, followed by application of lime and fertilizers, and also high amounts (7 and 28Mgha^{-1}) of phosphogypsum on the soil surface [44,53]. This set of practices allows for a pronounced downward movement of gypsum, which becomes a source of calcium for deeper roots and thus favors greater soil exploration also for water, which is critical during the winter and summer dry spells [15,46,49,51]. Aggregation is also affected: adding 7 Mg ha-1 of gypsum significantly decreased the percent of mid-sized aggregates (1 to 0.105mm), which was ascribed to an increase in soil organic carbon at a depth of 0.15m [53].

Recent data using novel assessment techniques for aggregation study also have shown potential to the study of coffee-brachiaria consortia. Andrade (2018) studied soil aggregation in 8-yrs-old coffee-brachiaria consortia testing different doses of gypsum (0; 14; 28; 56 Mgha^{-1}) and brachiaria on the inter-row, using ultrasound as technique for aggregate disruption. In the management systems with gypsum and brachiaria, but not in the conventional system, the disintegration constant K1 was greater than the dispersion constant K_2 up to 0.45m depth (Figure 4). According to Field and Minasny, in [24], there is hierarchy between the fractions of aggregates when K1 is greater than K2. In other words, these results showed the existence of aggregate hierarchy in the soil under management with gypsum and brachiaria until a depth of 0.45m [25]. The concept of hierarchy of soil aggregates has been put forward by Tisdall and Oades, in [57] and is the most accepted [6] as the one that best describes the interactions between aggregates and soil organic matter [54]. According to the assumptions of this theory, aggregates, in each size scale, are formed by different cementing agents [54,63].

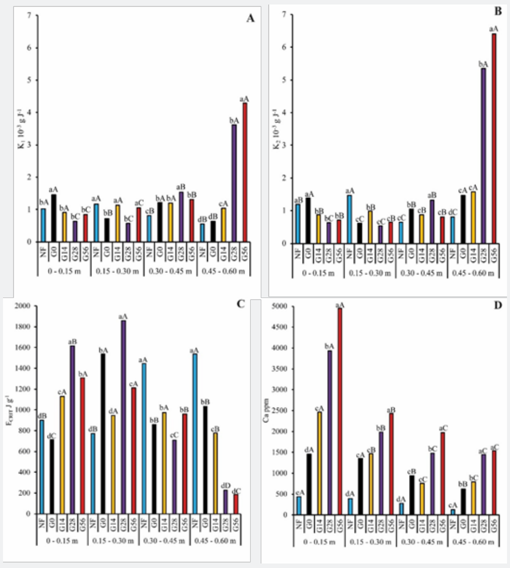

Figure 4: Effect of gypsum dosage in aggregation indicators for soils under coffee-brachiaria consortia. A) K1-breakdown constant; B) K2 dispersion constant; C) Ecrit-critical energy; D) Ca – total (X-ray fluorescence) calcium. * Means followed by the same capital letter do not differ by the Scott-Knott (p<0.05) among depths within the same treatment. Means followed by the same lower-case letter do not differ by the Scott-Knott (p<0.05) among treatments, for the same depth. Numbers following the letter G refer to gypsum dose (0,7,14,28 and 56Mg ha-1). Source: adapted from Andrade, is [4].

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However, in superficial layers, the values of K2 decreased with very high doses of gypsum [4]. The critical energy up to 30 cm deep was also higher at high dosages of gypsum, where the presence of more stable microaggregates was observed, requiring more than 1000J g-1 to start their dispersion. These results confirm those observed by Silva et al., in [53] and suggest that Ca^{2+} released from gypsum dissolution acted in the formation of high stability clay-Ca-organic matter complexes [19] forming microaggregates that need greater critical energy to start your dispersal.

Another positive aspect is that management systems with gypsum and brachiaria employ deep tillage (soil preparation with furrow to 0.60 m of depth), aiming physical conditioning for root system development [13,15,44]. Although soil tillage causes the disruption of soil aggregates, works by Silva et al., in [53] and Andrade, in [4] have shown that subsequent management practices such as fertilization of planting furrows associated gypsum application and brachiaria biomass input was able to promote the formation of new aggregates, with morphological characteristics and stability favorable to a better soil porous space organization [50,51]. An interesting side effect of this novel conservationist management system in relation to conventional systems is carbon sequestration. Figure 5 shows that soil organic carbon (SOC) contents have increased in subsurface: the 40-60cm and 80-100cm depth layers presented respectively 21% and 7.4% more SOC under the conservationist than in the conventional system.

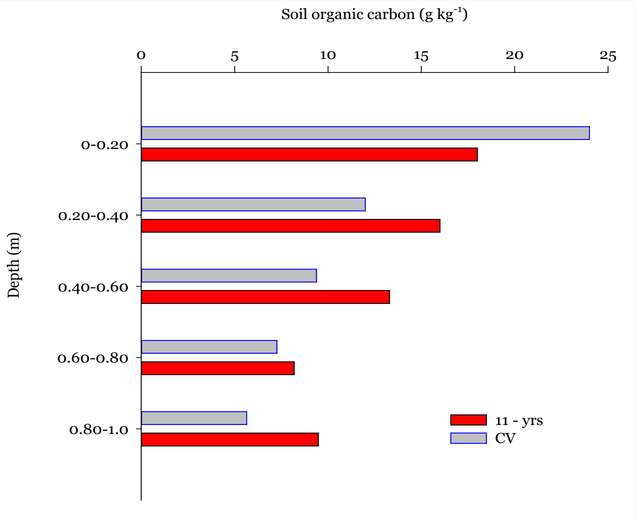

Figure 5: Mean soil organic carbon concentration in an Oxisol under conventional (CV) and conservationist management system coffee crops (11- yrs).

This greater carbon sequestration can be mostly due to deeper root development as a typical effect of deep cultivation and gypsum [15,49]. Several authors suggest that SOC receives a disproportional contribution from the root system, since roots are less exposed to climate and in direct contact with soil particles. This not only results in occlusion of coarse residues within aggregates, but also allows organic decomposition byproducts to be readily absorbed onto soil colloids, forming clay-organic complexes less likely to be decomposed, and finally, microbial activity decreases in depth [11,33]. Even for annual crops, the contribution of the root system can be up to 1.8 times greater than aboveground biomass [61]. Since organic decomposition rates are typically slower than in the soil surface, this represents a more stable C pool that offers many benefits such as improved aggregation, water retention and biological activity. However, positive effects can also occur in surface soils. Silva et al., in [53] noted that 7 Mg ha^{-1} of gypsum promoted a significant SOC at the top 15cm in a clay Oxisol, 2 years after planting of the coffee trees. In addition, the periodical cuttings of brachiaria leaves growing on inter-rows provide more organic inputs to the soil surface and consequently contributed to the increase of SOC [53].

Final remarks

In this chapter, we review evidence of improved soil aggregation in planting furrows promoted by application of gypsum and grass biomass residues, favoring a better organization of the soil porous space for coffee roots. In addition, we demonstrated that the intercropping between coffee tree and brachiaria can increase the soil organic carbon stocks, reducing the emission of greenhouse gases into the atmosphere.

Other innovative techniques were also discussed, such as the use of organo-mineral fertilizers associated with plastic mulching in soil aggregation. The results of this work showed the superior efficacy of associated deep furrowing, organo-mineral fertilization and plastic mulching in the formation of more stable aggregates.

Acknowledgments

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Conflict of Interest

The authors declare no conflict of interest.

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