Chapter 3

Green Manures and Crop Residues as Source of Nutrients in Tropical Environment

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Additional information is available at the end of the chapter

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Abstract

Tropical areas have prevalence of soils with low fertility, which makes the management of soil fertility a necessary practice to maintain a farming system economically and environmentally sustainable. The purpose of this chapter is to demonstrate the importance of green manure and the use of crop residues as management for soil fertility. We highlight the potential of these practices to increase/sustain productivity by providing nutrients. First, we made a short review on the main factors influencing the decomposition and mineralization processes. Subsequently, we discuss green manure techniques, presenting the main green manures, criteria for choosing, managements, potential for nutrient accumulation, and advantages and disadvantages of this practice. Finally, we use some examples to demonstrate the potential nutrient supply of crop residues from the main crops grown in the tropics. The difficulties and limitations involved are also discussed.

Keywords: cover crops, legumes, biological nitrogen fixation, fresh organic matter, mineralization

1. Introduction

The global demand for food will grow considerably in the coming years due to the increasing global population that is supposed to reach 9 billion people by 2050. The agriculture practiced in the tropics has key importance on food supply for much of the current global population and may become even more important for future generations.

The soils in most of these tropical environments have high acidity and aluminum toxicity, and are rich in oxides and poor in nutrients. Therefore, the use of lime and fertilizers accounts for a large part of the agricultural production cost. Thus, to increase the environmental and economical sustainability of these environments, it is important to make rational use of fertilizers and find viable alternatives to maintain a good physical, chemical, and biological soil characteristics.

We highlight the use of green manures and crop residues as practices that can help maintain or increase the productivity capacity of the soils, since they act as conditioners of the physical, chemical, and biological characteristics. Since the ancient Greeks, Romans, and Chinese, the humanity wisely used fresh organic matter as green manures in order to maintain the land productivity, and even today, this practice has been used with the same purpose. Meanwhile, crop residues were "a problem" for many years in agriculture. The removal and/or burning of residues were common practiced used in order to accelerate its degradation in conventional tillage. The expansion of no-till system, from the 1970s, presented several benefits by conserving and managing residues of annual crops, especially at medium and long term. The cultivation of perennial crops also presented major recent changes, such as management of weeds between plants, not using fire in renewing and especially the use of processed residues.

In this chapter, we present some of the benefits of management of green manure and crop residues, mainly the nutrient supply potential for crops of economic interest. Initially, we discuss the factors that most influence the fresh organic matter decomposition and nutrient mineralization in tropical areas. Subsequently, we discuss the concept of green manure, its management, the amount of nutrients potentially accumulated and their advantages and disadvantages. In the last part, we present examples from the main crops grown in the tropics. Regarding the annual crops, we focused on legumes with greater economic impact, since they are the first crops to be planted in rotation or succession managements. Regarding perennial crops, we present the contribution of the main crop residues and the processing of sugarcane, coffee, and eucalyptus.

2. Main factors influencing the decomposition of crop residues and green manures in tropical environments

The decomposition of crop residues or green manures in the soil is a complex process, which is the result of the interaction between different factors (biotic and abiotic) specific of each environment. However, the main abiotic factors that drive this process are related to their influence on soil organisms, since the decomposition is essentially a biological process [1].

Initially, the decomposition consists in the physical fragmentation process of the organic residues into smaller particles, which is a process performed by components of the soil macro-, meso-, and microfauna. Physical fragmentation of residues provides an increase in surface area, facilitating microbial colonization and subsequent hydrolysis by microbial extracellular enzymes. Thus, complex polymers are degraded into monomeric compounds and ions, which can be absorbed by microbial cells or plants.

The factors that can affect the direction and magnitude of the decomposition process are the nutrient content and biochemical composition of the crop residues or green manure added to the soil, the nature and abundance of the present microbial communities, Soil moisture, temperature, aeration, pH, the carbon/nutrient ratios of the soil organic matter (SOM) [2, 3], and the presence or absence of inhibitor substances.

In this part, we discuss the main factors involved in decomposition and its peculiarities in tropical environments.

2.1. C/N, C/P, and C/S ratios in crop residues and green manures

The use of green manures and crop residues provides various conditioning effects to the soil; however, the main objectives of this practice in low-fertile tropical soils are increasing soil cation exchange capacity (CEC) and provide nutrients for the plants. Thus, the nutrient contents present in these plants (mainly N, P, and S) are one of the first characteristics to be observed.

However, N, P, and S contents in the residue do not necessarily mean that they will be released synchronously with the plant needs during the decomposition process. After the decomposition, monomeric compounds and ions can be absorbed by microorganisms present in the soil, which use them as energy supply or metabolic precursors. After these requirements are satisfied, excess ions may be released into the soil solution and be available for the plants.

2.2. Mineralization and immobilization

Extracellular enzymes released by the fauna and soil microorganisms during the decomposition release part of the P, S and N initially linked to organic compounds in the fresh organic matter (crop residues or green manures). Extracellular phosphatases are responsible for the mineralization of P in organic compounds (C–O–P links) to phosphate ions, HPO_4^{2-}, and $H_2PO_4^-$ (prevalent in tropical soils). Sulfatases are responsible for breaking estersulphates (C–O–S links) to SO_4^{2-} ions, and urease converts urea into NH_4^+.

After organic compounds fragmentation, amino acids containing C–N and C–S bonds, amino sugars, and nucleic acids are absorbed by microorganisms to attend their energy, C, N and S demand. Then, intracellular hydrolases convert C-N and C-S bonds into NH_4^+ and SO_4^{2-} for subsequent internal use. Mineralization is the sequence of reactions that converts the nutrient from organic to inorganic form, resulting from microbial decomposition [4]. However, in practice, mineralization is when nutrients are released in the soil solution during the decomposition process. Thus, we say that nutrients were immobilized in microbial biomass and are unavailable for absorption by the plants when the N and S are mineralized into the microbial cell and/or when the NH_4^+, SO_4^{2-} and $H_2PO_4^-$ ions from soil solution are carried to microbial cytoplasm and subsequently used as precursors for synthesis of other compounds.

The microbial cell demand for energy, nutrients, and C does not occur at the same proportion and is different for each microbial community. The C/N ratio of bacteria range between 4 and 5, while for fungal, it is about 15. But, since fungal biomass is often twofold larger than bacterial in most soils, it is assumed that the C/N ratio of the total biomass of the soil is approximately 8 [5].

Each microbial community in the soil has a different C/N, C/P, and C/S demand, as well as C utilization efficiency. Thus, an average C/N, C/P and C/S are also assumed to the fresh organic matter (crop residues or green manures), from which the nutrient mineralization or immobilization will be defined. The average C/N in plant residues is 20–30, when the C/N > 30, the N is immobilized in the microbial biomass and when the C/N < 20, the N mineralization is favored. The average C/P in the plant matter is approximately 200–300. When C/P>300, P immobilization is greater than mineralization, the opposite occurring when C/P<200. The average C/S in plant residues is 200, with C/S>200 promoting greater S immobilization and C/S<200 favoring S mineralization.

The C/N, C/P, and C/S of the crop residues and green manures added to the soil must be known, since they present major influence on the mineralization/immobilization processes. Legumes have higher levels of N in their tissues compared to non-legume species, due to the biological nitrogen (N_2) fixation (BNF). Studies have shown the effectiveness of the use of these species as green manures to meet N plant demands [6, 7]. However, this is not the case for P demand, which is barely attended by use of such cover crops [8–10].

The immobilization and mineralization process does not depend only on the C/N, C/P, and C/S in the residues, since they are also greatly influenced by these ratios in the SOM compounds. Organic compounds from decomposed residues interact with the SOM during the decomposition process. SOM decomposition may increase when organic residues are added to the soil. A theory for this fact is that the soil microorganisms degrade easily degradable organic compounds present in SOM to acquire energy, C or N (and possibly other nutrients) co-metabolically with the residues added to the soil [11–13]. This effect is known as "priming effect" [14] and can be positive when it accelerates SOM decomposition or negative when it slows down SOM decomposition. Therefore, N, P and S contents in the residues and SOM are important, as well as the availability of these nutrients in the soil solution, which influences mineralization and immobilization processes, being an important tool in the management of residue decomposition.

However, the decomposition of residues and SOM would release other nutrients like Ca, Mg, K and trace elements, which are subjected to the same principles of the mineralization and immobilization explained above. K is a very abundant element in plant tissues, however it is not part of biomolecules, being released very easily and at high rates [15]. Studies have shown that legumes used as green manures have been effective in supplying K for plants [6, 7]. Besides N, they also show higher levels of K due to their branched and deep root systems, allowing nutrient cycling [16].

Tropical soils are generally acid and with low natural fertility, presenting restrictions to the crops because their high Al^{3+} availability in the soil solution and the low P availability for plants, due to the formation of irreversible Tropical soils are generally acid and with low natural fertility, presenting restrictions to the crops because their high Al^{3+} content and low P availability for plants, especially due to the formation of irreversible bindings with Fe and Al oxyhydroxides. In this context, the high production of organic acids by the decomposition of residues and green manures causes a competition for P adsorption sites on the soil, promoting a greater P availability in the soil solution [17]. This process occurs due to: *i*) H^+ and Al^{3+} sorption on the surface of the organic material; *ii*) Al^{3+} complexation with organic acids; *iii*) competition with phosphate by binding sites, decreasing P adsorption. Moreover, in tropical environments, the P organic forms from residues are essential for P availability to plants [18]

2.3. Other factors influencing the decomposition

2.3.1. Biochemical composition of green manures and crop residues

Biochemical composition influences plant residue decomposition and microbial communities in the soil. Plant residues consist basically of the same components, but the proportions can vary between species, plants of the same species, organs of the same plant, and crop conditions [19].

Green manure residues quality is dependent on the species used (N_2-fixing species have usually lower C/N compared with non-legume species), nutrient content and the age of the crop used as green manure, which affect the size, fiber content, lignin content and C/N ratio [20].

In general, the compounds present in the plant cell cytoplasm and walls are waxes and pigments (1%), amino acids, nucleotides and sugars (5%), starch (2–20%), proteins (5–7%), hemicellulose (15–20%) celulose (4–50%), lignin (8–20%) and secondary compounds (2–30%) [21]. Most of these components are present in the primary and secondary cell walls of plant cells. The primary wall is formed basically by cellulose and hemicellulose. After the primary wall growth cease, the secondary walls begin to form, which has the lignin as the main component and gives resistance to the cell wall [22]. Phenolic compounds are secondary metabolites such as polyphenol and lignin, which have no direct function in the plant growth and development [22]. Additionally, non-structural carbohydrates, such as free sugars, starch, and arabinose, may affect the decomposition of materials in the soil [23].

Some studies report that soluble carbohydrate materials are readily decomposed, as well as the components rich in N, establishing the initial decomposition rate of the crop residue [23–25].

The decomposition of some organic compounds of wild pine trees (*Pinus sylvestris*), for example, can be explained through a system comprising two phases [26]. In phase 1, nutrients found in higher concentrations such as N, P and S favor the mass loss of non-lignified organic compounds. In general, organic compounds from simple structures (labile) tend to be used more efficiently compared to those more complex (polymerized) or associated with other compounds (e.g., lignin–cellulose) [27–29]. In phase 2, lignin content increases during residue decomposition [30, 31], remaining most of the more lignified material. Plant degradation is determined by the reduction of the lignin concentration, which is negatively affected by high N concentrations and positively affected by high cellulose concentrations.

The negative influence of high N concentrations on lignin degradation may be due to the ligninolytics enzymes suppression at high levels of NH_4^+ and N organic compounds of low molecular weight. This repression can be explained by: *i*) the N can change the decomposing microorganisms competition, including those able to degrade lignin [32]; *ii*) high NH_4^+ levels reduce the production of ligninolytics enzymes [33, 34]; *iii*) the amino compounds condensate with polyphenols, forming toxic compounds or inhibitors [35, 36].

On the other hand, the positive effect of lignin degradation by high cellulose content occurs because lignin has very stable bonds, which require energy to break. Thus, a co-metabolism with more labile (easy degraded) compounds is necessary and positively influences the residue decomposition [37]. The SOM also influences this process by providing nutrients and more labile compounds, which can supply the most immediate forms of energy to the microorganisms, enabling them to degrade some recalcitrant compounds of the residues, which direct affect the energy supply to the microorganisms along the decomposition.

Consequently, the values of some biochemical fractions of the residues can serve as decomposition rate indicators. The fractions commonly used are the water-soluble extractives and extractives soluble in neutral organic solvents, which are secondary components and are not part of the cell structure. The holocellulose fraction, which consists of cellulose and hemicellulose, is constituent of structural components as well as the lignin fraction. Thus, the proportion of these fractions in crop residues and green manures, as well as the C/N, lignin/N and polyphenols/N, directly affect the decomposition of crop residues [38, 39]. This information can help managing the residues in order to synchronize nutrients release to plants.

2.3.2. Temperature and humidity

Temperature and humidity are factors that directly affect the microbial activity, more precisely the microbial enzyme complex [40, 41]. Temperature and humidity are factors that directly affect the microbial activity, more precisely the microbial enzyme complex [40, 41]. Residue decomposition rate correlates positively with temperature and water availability within a broad range [42].The enzymatic activity increases with an increase temperature or humidity up to a plateau, from which temperature and humidity can limit decomposition. Thus, the weather strongly affects the residue decomposition rate [43].

Moist tropical soils, which have Moist tropical soils, which have high average temperature and humidity throughout the year, have faster decomposition rates than temperate soils. Thus, in the tropical environments, the temperature and humidity present less restriction to decomposition, which depends primarily on the quality of the residues and the SOM [44].

It has been shown that chemically complex litterfall have stronger responses to temperature compared to less chemically complex litterfall [45]. Moisture is essential for the reactions that occur in the soil, and water is required for all hydrolytic reactions, affecting the extracellular enzymes activity and the diffusion coefficients [46]. Soil water content of 60% of its total porous space is assumed to be the optimum for the decomposition rate of aerobic soil microorganisms [47].

Natural cycles of wetting and drying in the soil are important modulators of decomposition rates [48]. Some agricultural practices can assist water management in order to achieve higher rates of decomposition, such as: (*i*) irrigation; (*ii*) drainage furrows installation in the field to remove excess water; (*iii*) maintenance of residues on the soil surface to increase water infiltration and decrease evaporation and *iv*) synchronization of residue incorporation with the rainy season based on historical and forecast rainfall [49].

Excess moisture can also cause anaerobic conditions that will negatively influence plant residues decomposition rates. Anaerobic environments are not favorable to fungi and actinomycetes, and only some bacteria are able to perform anaerobic digestion, decreasing decomposition rates.

2.3.3. Microbial communities in the soil

Different organisms work in the residues within the soil. The soil microbial community is diverse and shows an uneven distribution along the soil profile and throughout the microenvironments [50].

There is a change in the biochemical composition of the residues during the decomposition process, what drives a microbial succession. Simpler compounds are used as a growth substrate for a large number of microorganisms that have short life-span, which are called r-strategists or copiotrophs. In the later, degradation stages occur the metabolism of more complex compounds, in which some microorganisms break components more slowly and are called oligotrophic or k-strategists [4].

Among the r-strategist and k-strategist microorganisms there are autotrophic and heterotrophic bacteria, fungi, and actinomycetes. Moreover, studies have reported that the presence of N influences the microbial community diversity during decomposition.

Changes in the microbial community are reported to happen within150 days of incubation of eucalyptus residues due to changes in the residue biochemical composition [51]. Moreover, these same authors found that, with the application of N, the change in the microbial community occurred within the 25 days of incubation, remaining constant to the end of the experiment, suggesting that the chemical differences of residues can be minimized when the C/N of the residues are closer to the C/N of the soil microorganisms [52, 53].

High bacteria and low fungi biomasses were observed for 8 years in soils with eucalyptus receiving applications of N [54]. Moreover, an increase in the Gram+/Gram-bacteria ratio was observed in an experiment with incubation of residues (leaves) of *P. massoniana* and *M. macclurei* in coniferous forest soils [55]. A study of *Pinus sylvestris* L. forests grown for 50 years in northern Sweden, report that, during two decades with nitrogen fertilization, there were reductions in the ectomycorrhizal fungi community, showing that the effects of N go beyond simple enzymatic removal of fungi and may comprise factors that are still unclear regarding the decrease in residue decomposition with presence of N [52].

Another important factor during residue decomposition is the soil pH, which directly affects the type, density, and activity of bacteria, fungi, and actinomycetes. The residue decomposition rate is higher in soils with neutral pH than in more acidic soils such as tropical soils. However, liming acidic soils promotes accelerated decomposition of the residues.

The construction and maintenance of microbial diversity in the soil favor higher rates of decomposition [49]. Some agronomic practices are recommended for this purpose, such as: (*i*) regular application of organic residues or the use of biochemically complex green manures associated with those biochemically simple and easy decomposing, which supports the greater diversity of microbial communities in the soil; (*ii*) maintenance of soil cover, which promotes energy (via root exudates) for free-living and symbiotic microorganisms and produces extracellular enzymes in addition to the enzymes released by plant roots [56].

3. Green manures

Green manure can be defined as the practice of plant cultivation until the flowering stage or until the incomplete development of seeds, with subsequent cutting and/or incorporation of its biomass into soil [57, 58]. The basic purpose of this technique is to improve chemical, physical, and biological soil characteristics in order to increase or stabilize the production of one or more crops in an area [57, 58]. Famers usually use legumes as green manure because of the high biomass yield, biological nitrogen fixation (BNF), and cycling of nutrients from deeper soil layers [57, 58].

After Green Revolution, the practice has gained importance, especially in organic production systems [58]. However, the species used as green manure are not restricted to these systems. They are also used, for example, to control soil degradation in minimum tillage, no-till (NT) and in integrative systems [58–60]. In some situations, these species are called "cover crops," since the main purpose may be to conserve the soil. Species from the Poaceae family are the most common used cover crops [58]. A better soil cover and diversification of species in an area may also be used to suppress the development of weeds and also the emergence of pests and diseases [58, 61]. From an environmental stand point, the use of these plants can be a form of sequestering CO_2 from the atmosphere [58]. This practice can also improve the use of mineral fertilizers, especially for those nutrients more susceptible to losses by leaching or sorption [58].

The main species used as green manure, their benefits, limitations, and managements are discussed in the following topics. More information, you can find in the references [58, 62, 63].

3.1. Plants used as green manure

Tropical environments allow the cultivation of a wide variety of green manure species, with plants from the families Fabaceae, Brassicaceae, Asteraceae, and Poaceae, among others. Some of the main species used in tropical environments, their characteristics of dry matter yield, amount of fixed nitrogen, and mineral composition of macronutrient and micronutrients is presented in **Table 1**.

Common name	Specific name	Dry matter	Fixed N	N	P	K	Ca	Mg	S	B	Cu	Mn	Zn
Preferred sowing in spring–summer (September to March)													
		t/ha	kg/ha	g/kg of dry matter						mg/kg of dry matter			
Brachiaria	*Brachiaria decumbens*	4–20	–	12–20	0.8–3.0	12–25	2–6	1.5–4.0	0.8–2.5	10–25	4–12	40–250	20–50
Sunnhep	*Crotalaria breviflora*	3–5	67	32.9	1.4	28.4	9.1	2.5	–	–	17	81	31
Sunnhep	*Crotalaria juncea*	10–17.6	150–450	11.3–44.0	0.9–3.7	5.7–33.7	3.3–23.1	2.5–8.0	1.2–2.7	15–25	5.5–14	23–179	16–44
Sunnhep	*Crotalaria paulina*	5.4–15	100–170	12.4–14.8	0.9–1.1	4.2–9.5	6.3–8.0	2.4–4.1	0.8–3.6	17	5,0	34	17
Sunnhep	*Crotalaria spectabilis*	4–14.9	60–120	19.7–33.0	0.7–2.5	7.9–17.8	4.3–18.5	3.7–5.0	1.5–1.6	34–41	8–9.3	53–126	23–30
Jack bean	*Canavalia ensiformis*	3.4–8	49–v190	22.2–33.9	1.2–5.7	11.1–56.2	16.4–25.8	2.4–6.3	1.1–2.0	24–33	9–17	15.7–106	13–62
Canavalia	*Canavalia brasiliensis*	3–6.5	142–173	22.7–27.1	1.1–1.5	15.8–18.1	2.0–15.9	1.6–2.1	–	25–28	4–24	17–35	12–18
Sunflower	*Helianthus annuus*	2–12	–	10.2–18.0	1.5–2.4	24.0–27.8	15.5	6.2	–	–	18	96	31
Pigeonpea	*Cajanus cajan*	8–15.6	37–280	13.2–33.5	0.9–2.5	4.7–28.4	5.7–17.9	1.9–4.9	1.9–2.1	22–25	5–12	26–99	15–66
Labe-labe	*Dolichos lab lab*	5–11	66–180	13.6–50.0	1.3–11.5	5.3–27.7	11.6–16.5	2.7–6.6	1.1–3.5	26	5–10	48–143	16–33
Leucaena	*Leucaena leucocephala*	5.5–16	400–600	31.8–44.3	1.7–2.8	10.0–19.4	6.9–8.6	5.0–5.6	–	–	–	–	–
Millet	*Pennisetum glaucum*	8–15	–	3.4–34.0	2.0–4.0	17.0–35.0	2.5–8.0	1.5–5.0	1.5–3.0	7–35	5–16	27–101	24–98
Dwarf velvet bean	*Mucuna deeringiana*	2–4	50–100	27.5–35.2	1.6–5.3	15.7–48.4	19.4–23.7	4.6–6.5	2.6–2.9	35	9–27.6	179–358	61–85
Velvet bean	*Mucuna nívea*	5–8	120–210	15.6–26.5	1.5–5.7	10.0–15.5	11.0	2.7	–	–	16	183	28
Velvet bean	*Mucuna aterrina*	6–13	120–210	19.7–30.8	1.1–6.1	7.8–20.5	8.7–12.8	2.7–3.5	1.2–2.8	27	15–26	133–174	10–29
Soybean	*Glycine max*	2–4	60–180	13.5–40.0	2.1–2.5	10.8–17.6	10.0–20.0	4.0–6.0	2.0–2.5	21–55	10–30	20–100	20–50
Perennial soybean	*Neonotonia wightii*	4–6	40–100	24.4–28.5	1.7–3.0	22.4–24.5	9.9	3.5	–	–	8	102	32
Forage sorghum	*Sorghum bicolor*	10–20	–	5.0–11.0	1.0–3.0	14.0–22.0	3.0–4.0	2.5–5.0	0.1–0.2	4–20	4–20	10–190	14–50
Preferred sowing in autumn–winter (April to August)													
White oat	*Avena sativa*	2.5–7.0	–	8.1	0.6	24.0	2.4	1.7	1.5–4.0	5–20	6	138	9
Black oat	*Avena strigosa*	2.5–11	–	7.0–16.8	1.0–4.2	10.8–30.8	2.5–3.6	1.7–2.0	–	21–22	5–7	41–102	11–22
Ryegrass	*Lollium multiflorum*	2–6	–	11.6–13.4	0.7–1.0	21.2–26.0	4.1–4.4	2.2	–	–	9	214	23
Rye	*Secale cereale*	2–8	–	5.8–12.2	0.8–2.9	7.5–14.5	1.8	1.4	1.5–5.0	5–20	5–25	14–150	15–70
Grasspea	*Lathyrus sativus*	2–6	80	22.0–32.5	1.0–2.6	29.0–30.0	3.9–7.9	1.9–4.3	–	–	11–29	52–70	11–22
Pea	*Psium sativum*	2.5–7	60–90	20.9–28.9	1.2–2.0	15.0–21.7	7.0–8.5	2.0–3.2	–	–	22	102	8
Vetch	*Vicia sativa*	2–10	90–180	2.0–46	1.3–3.8	21.0–25.6	8.6–10.5	2.7	–	–	9–24	69–87	22–30
Forage turnip	*Raphanus sativus*	2–9	–	9.2–29.6	1.8–3.3	20.2–49.0	10.0–21.5	2.3–9.5	4.5–5.2	22–23	8–15	18–84	14–49
Lupine	*Lupinus albus*	2–5	128–268	12.2–19.7	0.9–2.9	10.0–26.6	4.6–5.9	3.9	–	–	12	330	57
Triticale	*Triticosecale wittmack*	2–8	–	13.7	1.1	25	3.8	2.7	–	–	12	53	19

Source: Wutke E.B., Trani P.E., Ambrosano E.J., Drugowich M.I. Adubação verde no Estado de São Paulo. Campinas: Coordenadoria de Assistência Técnica Integral-CATI; 2009. 89 p.

Table 1. Dry matter yield, amount of fixed nitrogen, and mineral composition of macro- and micronutrients in the shoot of species frequently used as green manure and cover crops in Southeastern Brazil.

The first thing to consider in the process of choosing a green manure is the purpose of the farmer in using it. When the farmer objective is nutrient supply, plants with high biomass production and capable of associating with N-fixing bacteria can be suggested (**Table 1**). Among these plants are species from the genus *Crotalaria*, *Canavalia*, *Cajanus*, *Leucaena*, and *Acacia*. We recommend inoculation of seeds with *Rhizobium* in order to increase the symbiosis efficiency and consequently the biological nitrogen fixation. On the other hand, when the farmer objective is erosion control, species with higher C/N ratio, fasciculate root system, greater biomass production and lower shoot/root ratio can be suggested, such as some species of genus *Pennisetum* and Brachiaria. (**Table 1**).

Another important point to consider for choosing the correct green manures is the phytosanitary aspect. Some species can control plant pathogens, such as species from the *Crotalaria* genus, which are effective in controlling certain nematode species that cause root-knot [58]. However, others are hosts of pathogen species and pests of commercial crops. An example of this problem is the cultivation of common beans (*Phaseolus vulgaris*) in succession or rotation with jack beans (*Canavalia ensiformis*). This green manure hosts the whitefly (*Bemisia tabaci*), an insect that transmits the bean golden mosaic virus [57]. Therefore, the use of species from different phylogenetic groups is recommended. Moreover, the use of species from different families is convenient, since they have different patterns of nutrient accumulation and root architecture, enabling the exploitation of different soil layers.

Many green manure species are better adapted to the climatic conditions of spring and summer while others to the autumn and winter (**Table 1**). Sunnhep (*Crotalaria* sp.) and pigeonpea (*Cajanus cajan*), for example, have greater biomass and nutrient accumulation when grown between the spring and summer due to their water requirements, photoperiod, and/or thermoperiod [63]. In general, sunnhep and pigeonpea plants require short days to flowering, so they have low biomass production when sown in late summer [63]. These plants should be selected for pre-cultivation management of commercial crop. Other species are more versatile, like the millet (*Pennisetum glaucum*), canavalia (*Canavalia brasiliensis*), and jack bean (*Canavalia ensiformis*) [62], which have little or no sensitivity to photoperiod and good drought tolerance [63]. Such species may have satisfactory dry matter yield in semi-arid conditions; however, they have to be sown, preferably, when there is still moisture in the soil for germination, such as the period after the summer harvest [63]. On the other hand, the genres *Avena*, *Lollium*, *Lathyrus*, and *Vicia* have to be cultivated preferably between the autumn and winter, and some of them are better adapted to subtropical conditions.

Therefore, the success in using the green manures technic depends on its adaptability to the region soil, climate conditions, cultivation system, and on their phytosanitary aspects. Experiments determining which species have greater biomass and nutrient accumulation are recommended when some of this information is unavailable.

3.2. Management of green manures in tropical conditions

Green manure plants can be used in minimum tillage, no-till or in systems with plowing and harrowing. These plants can be managed as soil cover in fallow, intercropping with perennial crops or in rotation or succession plans with annual crops. In general, when the plants reach the reproductive stage, when approximately 50% of the flowers are opened, a cut must be carried out with or without the plant matter incorporation into the soil. Some species might have longer cycles, but have to be cut before the seeds become viable. The black oat (*Avena strigosa*), for example, should be cut when grain maturation reaches the milky grain stage [63]. Cutting these plants before this stage allows a regrowth, and after this stage the grains may become viable [63]. Both cases may result in economic losses due to competition between the black oat plants and the main crop [63].

The toppling of plants in conservation systems can be obtained using mechanical or manual mowing, a roll-knife or herbicides for desiccation [62]. In conventional systems, set of harrows are commonly used to incorporate the green manure into the soil or a rotary hoe is used in some cases [62].

Figure 1. Coffee seedlings with pigeonpea tipped over between planting lines. Photos by Lucas de Ávila-Silva.

Plants from the Fabaceae family with C/N ratio around 20 (Table 2) are rapidly decomposed in tropical conditions. Therefore, the commercial crop planting in rotation/succession to this type of plant should be performed few days (less than two weeks) after the green manure tipping over and/or incorporation, since much of the N is mineralized in the first 60 days [58]. Adopting species with higher C/N rates, around or above 40, such as species from the Poaceae family, enable to wait longer to the commercial crop planting. A 2-week interval between the grass cutting and the commercial crop planting is recommended, because of the low availability of N and possible allelopathic effects. Regarding the interim crops (**Figure 1**), the use of green manure species with climber habits should be avoided, since they may use commercial species as tutors. A solution to this problem is the use of more than one green manure species, a technique known as cocktail, using species with climbing and erect growth habit, so that the latter will serve as tutor for the first. It is also important an adequate inter-line plant density, in order to avoid competition for growth resources between the green manure and the commercial crop.

A study carried out in Brazil evaluated different green manures in rotation with maize under two managements, minimum or conventional tillage [64]. The green manures used were as follows: *Crotalaria juncea*, *Canavalia ensiformes*, *Rafhanus sativus*, mixed species (cocktail) with *Crotalaria juncea*, *Canavalia ensiformes* and *Rafhanus sativus*, and weeds (control) [64]. The green manures treatments had maize yield higher than the control with weeds, with average of 2.8 t/ha of peeled green ears [64]. Another study, in the same region, evaluated the effect of N topdressing absence, pre-cultivation of *C. juncea* and topdressing with ammonium sulfate or urea on maize yield produced for silage [65]. The use of *C. juncea* incorporated 12 days before the maize planting resulted in a yield increase of 14 t/ha compared with the control treatment without nitrogen topdressing [65]. However, the treatment with green manure did not surpass the treatments with ammonium sulfate or urea topdressing, which increased silage productivity by 33 and 27 t/ha compared to the control without topdressing, respectively [65].

Therefore, in order to maintain a competitive agricultural system, the green manure practice must be managed together with chemical fertilizers. Amado et al., for example, proposed to consider the green manure contribution to define the nitrogen fertilizer dose, which is especially important in no-till and integrative systems. These authors considered the following criteria for setting the dose: the soil organic matter content; the commercial crop expected yield; and the previous cover crop (green manure) residue nature and amount [66].The previous cover crop contribution was considered in three situations: legumes, grasses in monocrop, and consortia (cocktails) [66].They considered that the higher the green manure dry matter yield, higher the N supply to the commercial crop in succession to legumes [66]. The contribution of grasses for the N supply was estimated to be very small or non-existent compared with uncultivated areas and may even reduce the availability of N due to its short term immobilization [66]. Regarding the consortia system (cocktails), the contribution is estimated according to the percentage of legume biomass in total biomass of green manure. In some conditions, fertilizer savings can reach up to 80 kg/ha of N [66].

An example of the green manure potential intercropped with perennials plants is a study with soursop (*Annona muricata*) in southeastern Brazil, in which the author evaluated three green manures species (*Gliricidia sepium*, *Crotalaria juncea*, and *Cajanus cajan*) [67]. The greater amount of biologically fixed nitrogen was found with *G. sepium* (80% of the accumulated N) and with *C. juncea* (64.5% of the accumulated N). During the 2 years of experiment, the *C. juncea* added to the soil, in two cuts, about 149.5 kg/ha of N, from which 96.5 kg/ha came from biological nitrogen fixation (BNF) [67]. The *G. sepium*, managed with three annual pruning, added 113–160 kg/ha of N, with 90–128 kg/ha derived from BNF. Variations in natural ^{15}N amounts indicated that green manure with *C. juncea* and *G. sepium* contributed to N supply for the soursop, transferring about 22.5 and 40% of the fixed N, respectively [67]. They conclude that the use of these two green manure legumes contribute as organic fertilizer, supplying nutrients, mainly N [67].

The use of fresh organic matter from green manures brings more than just nutrients, affecting physical-chemical and biological characteristics of the soil. Pegoraro et al. [68] showed the effect of the use of green manure (*Acacia mangium*) grown after the *Eucalyptus* cut in short rotation system (6–7 years of growth). The authors noted that the use of a legume in succession enabled the increased in stocks of total C and N, C and N in humic substances and in microorganisms compared to crops without the legume succession [68]. Vegetable residues with lower C/N ratio accelerate the recycling of residues from commercial crops (ex.: *Eucalyptus*), which reduces the microbial attack on soil organic matter (SOM) and increases the levels of stabilized organic matter [68].

The effect on the soil organic matter supply makes the green manure a promising practice for recovery degraded areas and help to restore the A horizon of "beheaded" soil profile. Alves et al. studied green manures as a component of strategies for recovery degraded areas [69]. Positive effects were noted 365 days after the experiment implementation, such as soil compaction reduction and water infiltration time reduction [69]. Kitamura et al. reported, in another paper concerning the same research, that the treatments also provided results related to the soil macroorganism population [70].

3.3. Advantages and disadvantages of green manures

The main advantages and disadvantages of green manures to tropical weathered soils [58, 62, 63] are listed below.

3.3.1. Advantages

3.3.1.1. Chemical aspects

1. Nitrogen input to the soil because of the green manure association with nitrogen-fixing bacteria;
2. Green manures with deep root systems allow cycling of nutrients that have been leached to deep layers;
3. Increased cation exchange capacity (CEC) due to an increase in soil organic matter content;
4. Green manures make possible to increase or stabilize the content of soil organic matter;
5. The release of organic acids allows the solubilization of more stable forms of phosphorus.

3.3.1.2. Biological aspects

1. They favor the microflora and macroflora and fauna through carbon supply;
2. Some species control nematodes population;
3. They can serve for attracting insect pests and stop disease cycles;
4. They release compounds with allelopathic effect on weeds;
5. They compete for growth resources with weeds.

3.3.1.3. Physical aspects

1. They promote protection against erosion by covering the soil;
2. They enhance stability of aggregates and porosity by adding organic matter and growth and death of roots;
3. They increase water retention by cover the soil and by add organic matter;
4. They allow natural decompression of the soil, when using species with deep root system;
5. They reduce the thermal soil amplitude.

3.3.2. Disadvantages

1. Inadequacy of some green manure species to the production system or the soil and weather conditions;
2. Lack of interest from consultants and farmers in this technology, which adopt immediate postures;
3. Sometimes, green manure involves costs with no direct financial return;
4. Low development of breeding technologies of green manure species;
5. Some green manures can host diseases and pests that attack the commercial crop;
6. Possibility of negative allelopathic effect of green manure residues on the commercial crop;
7. Possibility of competition between green manure plants and the commercial crop by inadequate management of the technology in intercropping systems;
8. Some green manures have incompatible decomposition rates with the nutrient requirements of crops;
9. Uneven seed germination of some species of green manure;
10. Difficulty of obtaining seeds for sowing;
11. Lack of functional decomposition models to predict nutrient release.

4. Crop residues

Crop residues can be defined as any part of the plant without direct economic value produced in the field (derived from the harvest) or after processing on the farm. The crop residues value in agriculture coincided with the success of no-till system, until then, soil revolving or even fire was commonly used to accelerate residue decomposition. More recently, the crop-livestock-forestry integrated system is also an example of crop residues conservation. The no-tillage system implementation is based on three pillars: (*i*) no soil tillage, (*ii*) crop rotation, and (*iii*) permanent soil cover. Although essential, the soil cover maintenance in tropical environment is not a simple task, mainly due to the high rate of straw decomposition from leguminous plants, and is difficult to grow plants in succession (second crop) because adversities such as the rainfall patterns.

The maintenance of residues benefits the agricultural system by conserving the soil free from erosion. The homogeneous distribution of residues in the area with great amount of straw generates a slower runoff and less water and soil loss [71], consequently avoiding topsoil losses, which normally has a great amount of nutrients. Another important feature of crop residues is the maintenance of higher water content in the soil, a problematic factor in the tropical agriculture.

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The crop residue maintenance also contributes to a decrease in the soil surface temperature, ensuring a better condition for the plants and other soil organisms. Another relevant factor is the ratio between the straw production, weed control, and soil compaction reduction capabilities, which is a recurring problem in poorly managed conservation systems.

The longer the time the crop residues are in the soil surface, the greater the positive effects. The residue permanence time in the soil depends on several factors, such as the: (*i*) fragmentation level, (*ii*) amount, (*iii*) chemical composition, (*iv*) contact level with the soil, (*v*) weather conditions, (*vi*) microbial community, and (*vii*) soil type. In addition to the factors discussed in the first part, it is also known that residues with greater contact surface with the soil accelerate the decomposition rate.

Green manures residues can be choosing from plants with high mass production, chemical composition with high C/N ratio and lignin, favoring the permanence of straw, the use of equipment which allows less fragmentation, such as the roll-knife.

Weeds and green manures (or cover plants) can be managed between rows of perennial crops; in this case, we can also use the roll-knife, although normally brush cutters and grinders are used.

Heavy equipment may be required in some situations, such as the scarifier or harrow, for example, in excessive amount of plant residues, rigid materials, or seeder inefficiency.

The residues management options for residues from commercial crops are less flexible, since the fragmentation is performed according to the harvest type, the amount is dependent on the yield and the material chemical composition is usually consequence of the best-adapted material. The legume residues have high decomposition rates, often cooperating little to the soil cover. The cultivation of legumes is usually performed first to leave a N balance for the sequential culture.

In specific cases of succession after grasses cultivation, an increase in N doses or even an anticipate application of nitrogen fertilizer is suggested before sowing, basically due to the N immobilization because the high C/N ratio of grasses.

After reminding here, the crucial importance of crop residues to the soil cover and the main factors affecting its decomposition, we can discuss a second advantage of residues from commercial crops: the potential supply of nutrients. The management of residues from a preceding crop (annual) or residues from the crop itself (perennial) can complement the nutrient supply.

Regarding the green manure, nutrient mineralization from the crop residues depends on the residue quality, soil moisture and temperature, as well as specific soil factors such as texture, mineralogy and acidity, biological activity, and the presence of other nutrients [72]. Most of the nutrients are exported in the harvest, remaining just a portion in the residues. In this part, we are going to see yield increases by the nutrient supply potential of the residues from the main crops in tropical environments.

4.1. Annual crops residues

The nutrient net mineralization from the annual crop residues that precede other crop must be considered in nutritional management. We focus here on annual crops that associate with N_2 fixing bacteria, because they are the major contributor to the nutrient supply (nitrogen) for crops in succession or rotation. Subsequently, we will see the most used crops in tropical environments that leave nutrient to the system.

4.1.1. Soybean

The soybean (*Glycine max*) represents 50% of the global area of leguminous crops and 68% of global production of this family. The annual input of N fixed is 16.4 Tg, which represents 77% of N fixed by legume crops [73]. A crucial fact to these crop success was the priority given to association with *Bradyrhizobium* and BNF in breeding programs [74].

Most of the soybean crop in Brazil is carried out in no-tillage system, and this management provides more root nodulation by the bacteria in the soil, best nodulation (nodulation deep in the soil profile), higher rates of BNF and yields compared to conventional tillage [75, 76]. These factors, combined with the efficient association with *Bradyrhizobium*, allow the non-use of nitrogen fertilizers in this crop.

Approximately 80–83 kg of N is required for each 1000 kg of soybeans produced, from which 51–65 kg are allocated in the seeds and 15–32 kg in the roots, stems, and leaves [74, 77]. The N_2 fixation potential of the soybean can be as high as 360–450 kg/ha [78, 79].

In southern Brazil, Paraguay, Uruguay, and northern Argentina (subtropical) is recurrent to get higher wheat yields (winter planting) when soybean is the preceding crop in the summer compared to the maize, precisely because of the remainder N [80]. The maize, in rotation with soybeans, may have its nitrogen fertilizer rate reduced by 20% in this environment, considering the effect of rotation after a soybean crop with adequate productivity [81]. In a similar environment, some producers in various states of the Midwestern United States reduce 45 kg/ha of the nitrogen fertilizer dose, when maize is planted following soybeans compared to sequential crops of maize [82].

The Cerrado biome (Brazilian savanna) has no winter crops due to insufficient rainfall, and thus the soybean is the main summer crop and, after the harvest, in late summer, usually maize or sorghum is planted ("second crop"). A contribution of 20 kg/ha of N is assumed as a practical parameter in the region for these crops after soybean [83].

The first part of this chapter showed that the C/N ratio and biochemical constitution of the residues are important indicators to predict the nutrient mineralization rate. Regarding the soybean grown in tropical environments, different C/N ratios are observed in the roots (31.6), stems (22.5) and leaves (10.7), as well as larger amounts of lignin–suberin. These data explain the great decomposition rates of shoot residues in the first 20 days after harvest, with N mineralization, especially from leaf residues, under controlled conditions [84].

Unfortunately, there are few long-term field experiments in typically tropical regions, which hinder an accurate estimate of the decomposition rate of soybean residues and mineralization

Figure 2. Residue deposition and homogeneous distribution after the harvest. Photos by Lucas de Ávila-Silva.

of nutrients. A field experiment carried out for 12 years in Brazil (Parana State, Brazil), estimated the residue decomposition percentage according to the time and management, with $y = 93.819^{e-0.0031x}$ ($R^2 = 0.91$) to the no-till and $y = 90.061^{e-0.0054x}$ ($R^2 = 0.92$) to the conventional tillage [85]. The residue decomposition time in that work was autumn–winter, a less rainy period that the summer. Moreover, that is a climate transition region (Cfa subtropical climate in the Köppen classification) with low temperatures and a distinct pluviometric regime compared to Brazilian Midwest (**Figure 2**).

4.1.2. Beans

The genus *Phaseolus* has more than 200 species described [86], but those that have the greatest economic impact are the *Phaseolus vulgaris*, *Phaseolus coccineus*, *Phaseolus lunatus*, *Phaseolus acutifolius*, and *Phaseolus semierectus*, mainly the first. Different from the soybean, common beans have low symbiotic efficiency [87]. The nitrogen fertilizers use is indicated in some situations to achieve good yields, even though they may affect negativity the BNF efficiency. Mean values of 35% and maximum of 70% of N derived from the atmosphere were observed at the plant biomass considering six field experiments in tropical countries and Austria [88]. Some progress is occurring with the best selection of strains, adapted to the conditions of each site [89–92].

Different C/N ratios were observed in stem fractions (79), straw pods (66), and senescent leaves (24) in four varieties of beans [93]. A shorter leaf half-life was observed, although the straw pods also showed low half-life value (both of approximately 70 days). Those authors observed N and P release and half-life following the residue decomposition rate, while the K release was faster (average half-life of 18 days) and showed low difference regarding the material quality. In this case, N and P could be better used by the subsequent crop, while K can be reused by the same crop. The yield of 1350 kg/ha presented a potential for cycling 31.5 kg/ha N and 2.37 kg/ha P from the bean residues [93].

The species *Vigna mungo*, *Vigna radiata*, and *Vigna unguiculata* stand out in the *Vigna* genus, the latter being the most cultivated. These species have short cycle, low water requirement, and good development in low fertility soils; in addition, the BNF is capable of supplying more than 100 kg/ha of N [94, 95]. An increase in millet productivity of 9–24% was observed in an experiment carried out in three different locations in Niger, when cowpea was previous cultivated compared to successive cultivation of millet [96].

A C/N ratio of 15.8 was found in cowpea residues grown in a field experiment evaluating N mineralization depending on the phosphorus content in tissues [97]. In the same experiment, the authors found an increasing in N mineralization (25, 32, and 34%) with increasing P concentration in tissues (1.0, 1.2, and 2 g/kg, respectively) in 8 weeks. This fact demonstrates the close relationship between nutrients interfering in the mineralization process, emphasizing the importance of fertilization management together with residues management. A potential mineralization from 6.8 to 9.2 g of N per kilogram of dry matter of cowpea residues is considered as a practical reference.

4.1.3. Groundnut (peanut)

India is largest producer of peanuts (*Arachis hypogaea*), which usually uses 10–20 kg/ha of N from ammonium sulfate. A large number of farmers in that country use crop rotation with groundnut to take advantage of its ability to improve soil fertility and increase the subsequent crop yield, due to the BNF [98].

The peanut cultivation in Brazil is also carried out with the same goal, but most in rotation with sugarcane. A C/N ratio of 15 and 24, and an addition of 70 and 38% of N from BNF in plant tissues, was, respectively, observed in the IAC-Caiapó and IAC-Tatu varieties, in acid soils [99]. These authors emphasized that the N values from BNF for IAC-Tatu were low because the sampling, which was performed 120 days after sowing, when the plant was in an advanced stage of pods maturation and much of the N had translocated to the grains. About 90% of N was from the shoot in the average for these cultivars. In this same experiment, there was a yield increase of 12.2 (IAC-Caiapó) and 15.5 t/ha (IAC-Tatu) in the sugarcane crop compared with the control. Bagayoko et al. [96] also reported an increase of approximately 39% in average yield of sorghum after groundnut cultivation compared to subsequent sorghum crops; during 3 years of experiment in Kouaré (Burkina Faso), they found N mineral increment available for sorghum.

The groundnut may also be infected by arbuscular mycorrhizal fungi [99], which favors the next culture infection [96] and improves the P cycling.

4.1.4. Chickpea

The chickpea (*Cicer arietinum*) is the second more cultivated legume in the world to obtain grains. Most of the chickpeas production and consumption occur in developing countries (95%). A BNF evaluation by the ^{15}N natural abundance method in different areas of Punjab showed that 58–86% of N (an average of 78%) could be derived from symbiosis, fixing 87–186 kg/ha of N. The average balance of N left by chickpea was 28 kg/ha N in that experiment, the yield ranged from 0.6 to 2.0 t/ha and the N in the soil increased in 38%, on average. The yield increase in the wheat planted in the sequence ranged from 19 to 73%, even with shoot residues removed [100]. Around 90 kg/ha of N fixed was found in a cultivation field in Australia using similar methods [101]. Turpin et al. [102] suggest that chickpeas can fix 146–214 kg/ha of N and contribute with 80–135 kg/ha of N, including the roots.

The ICRISAT work in Kenya reported that chickpea residues contributed from 30 to 35 kg/ha of N to the subsequent wheat crop [103], while the TSBF reported contributions of about 40 kg/ha of N for maize [104].

4.1.5. Difficulties

The absorption and mineralization must be synchronized for an effective N supply by a leguminous species [105]. According Palm, organic residues release about 80% of their nutrients during decomposition, but <20% is absorbed by the crops, often because the lack of synchronization between the release and absorption [106]. There are several studies reporting the decomposition rate and mineralization depending on soil and climatic characteristics, but there is still a lack of field data in some major producing regions and data to create models to predict the nutrients mineralization and availability.

The contribution of N mineralization arising from the root system is noteworthy, for example, Evans et al. [107] and Larson et al. [108] reported negative contribution of N to some tropical legumes when considering only the N from the shoot, with different results found when they accounted the N contained in the nodulated roots. Another factors to consider in the experiments are the biochemical characteristics and C/N ratios of the residues. We must pay attention to the fact that how higher residue decomposition rate, lower will be the vegetation cover time.

4.2. Perennial crop residues

Different from annual crops, nutrients from perennial crop residues are normally used in the same culture, but similarly, they take advantage of nutrients not exported at harvest. A perennial crops peculiarity is the use of residues from processing in the farm. Once seen as an environmental impasse, such residues are currently good sources of nutrients.

4.2.1. Sugarcane

The estimated BNF in sugarcane may reach 0.5 Tg per year [109]. Although the N added by BNF generate savings for the system, the straw C/N ratio is around 97–149 [110, 111] and the stem around 118 [112], promoting an initial immobilization of N. Straw is the main residue left in field, which has high C/N ratio and high lignin content, about 21% [111]. It is estimated that each ton of sugarcane produces 150 kg of sugar, 140 kg of dry bagasse and 140 kg dry matter of straw [113], approximately 17 t/ha of straw [110].

In an experiment with ^{15}N labeled straw, Gava et al. [110] found that the N use efficiency by ratoon cane was 9% (68 kg/ha N) and that the main contribution of N from straw was to maintain or increase the organic N in the soil. Furthermore, this N became available in the second half of the cycle.

Another effective contribution of the sector is the vinasse return to the crops. Each liter of ethanol produced in distillery produces between 12 and 14 L of vinasse, which has 0.5–1.0% of soluble carbon and high levels of K (typically 12 g/L), and contain considerable amounts of other nutrients [114]. Gava et al. [110] used vinasse with the following contents (kg/m^3): 0.41 of N, 0.07 of P_2O_5, 2.72 of K_2O, 0.91 of CaO, 0.38 of MgO, and pH (water) of 4.9. Typically, the dose applied is around 80–100 m^3/ha.

Resende et al. observed a sugarcane yield increase of 12–13% after application of vinasse in a period of 16 years [115]. However, in some situations, vinasse is recurrently applied near of the distillery due to the cost of transportation, occurring concentrated applications with ground water salinization and/or contamination potential.

The filter cake is also a residue from the sugarcane processing used in the field. The sugarcane processing in Thailand produces 3.4% of filter cake and 25–30% of bagasse from the sugarcane fresh material [116]. Each ton of sugarcane crushed generates around 40 kg of filter cake [117], which has variable composition, but with high levels of organic matter (OM), P, N, Ca, substantial amounts of K and Mg [118], as well as Fe, Mn, Zn, and Cu [119].

Two works illustrate the variability of nutrient content in the filter cake. In Brazil, Fravet et al. [120] found pH of 4.5, C/N ratio of 20.9, C/P ratio of 17.65, OM of 20.1%, humidity of 71.4%; Ca of 2.43%, Mg of 0.26%, S of 0.39%, P (H_2O) of 0.33%, P (CNA + H_2O) of 0.40%, P (citric acid) of 0.40%; P_2O_5 (total) of 0.98% and K of 0.25%. In Thailand, Meunchang et al. [116] found pH (water 1:5) of 7.7, C/N ratio of 14, OM of 48%, P (total) of 0.96%, K of 0.39%, Ca of 7.1%, Mg of 0.4%, Cu of 1.9 mg/kg, Zn of 51 mg/kg, Mn of 257 mg/kg, and Fe of 803 mg/kg.

The filter cake can be applied in the entire area at pre-planting in the furrow or planting lines. According to Nunes Júnior [118], 20 t/ha of filter cake on wet base or 5 t/ha on dry base can provide up to 100% of the N required by the plants and 50% of the P, 15% of K, 100% of Ca, and 50% of Mg. In ratoon cane, the application of 70 t/ha of filter cake provided the greatest productivity of sugarcane stalks, regardless of application mode [120].

4.2.2. Coffee

Coffee is the second most traded commodity in the world, behind oil. The coffee husk is a common residue of the processing on farms, accounting for about 50% of the dry fruit harvested [121]. This residue can return to coffee plants for nutrients release, providing around 29 g/kg of N (mostly in the form of nitrate) and 45 g/kg of K [122].Values of 23 g/kg of K-total (7.4 g/kg K-soluble), 14.8 g/kg of N, C/N ratio of 30, and 21 g/kg of lignin have also been found in coffee husks naturally dry. The K release from husks is high (above 90%) and regardless of the coffee bean constitution, decomposition rate, or processing type [123].

Another processing variation is the pulping done by the wet method, which withdraws just the husks, and the pulp and grain are placed to dry along with the parchment. Afterward, the parchment is removed from the coffee bean, which constitutes 12% of the dry fruit harvested. The pulp and parchment have 3.65 and 0.38% of K and 1.85 and 0.59% of N, respectively [124]. The C/N ratio in the pulp is around 24 while in the parchment is 63. In the husk in the same processing, 38.9 g/kg K-total (17.7 g/kg K-soluble), 26.7 g/kg of N, C/N ratio of 16 and 20.9 g/kg of lignin were found [123].

The variation in nutrient content within the same post-harvest processing must be taking into account, but mainly when they are from different processing (**Figure 3**). Composting is also a good option for husk use [125, 126].

Figure 3. Coffee pods stack after processing. This residue returns to farming by providing mainly K and N. Photo by Lucas de Ávila-Silva.

4.2.3. Eucalyptus

Eucalyptus crops with ever shorter cycles (6–7 years) are extremely dependent on the biogeochemical cycling of nutrients from the residues that are added to the soil over the cycle and also at harvest. A eucalypt forest produces an average of 75% of commercial wood, 1.5–3% of leaves, 4–6% of branches, 6–19% of barks, and 10–12% of roots, considering the total biomass, after 7 years [127].

Studies have shown that eucalyptus planted forests can deposit 7–84 tons of dry matter to the soil during 7 years, from old dead branches and dry fruits (25–30%), barks (10–15%) and leaves (55–65%) [128].

The treetops begin to close between the 1st and 2nd year after planting, and the competition causes the disposal of branches and lower leaves that are gradually deposited on the ground. The trees are taller and with small treetops from the 3rd to the 4th year, occurring the deposition of barks. However, the quantities of residue deposited to the ground depend on the eucalyptus species, climate, and evapotranspiration. The components of the eucalyptus forest deposited to the ground are called litterfall, which has great influence on the nutrients availability to the eucalypt [127].

Thus, considering that the estimated content of nutrients accumulated (in relation to the total accumulated in the plant) in the tree tops and eucalyptus bark after 6.5 years has on average 65% of N, 70% of P, 64% of K, 79% of Ca, and 79% of Mg [128], considerable amounts of nutrients are deposited to the ground and are considered in the fertilization management. In addition, the harvest of trees leaves in the area large amounts of residues such as leaves, branches, tree tops, and small trees discarded during harvest. The trees can be pruning and strips in the area or at companies, depending on the harvesting modules used. Some companies separate the so-called woody debris (thick branches, tree tops and small trees) and sell as wood or transformed into wood chips to produce biomass fuel for the company itself, depending on the demand.

However, we must emphasize here the importance of the retention of crop residues in the area because during the harvest the accumulated litterfall on the soil surface has order values of 8–14 t/ha [129, 130]. Studies have been shown that lower amounts of nutrients are required in fertilization when the bark is left in the field at harvest [131–133]. Moreover, the roots also remain in the area, since that the currently practice of stump removal is increasingly scarce due to the large impact on the soil.

The crop residues have nutrient availability potential remaining in the area and can reduce the impact on the soil due to the heavy-machinery used [134, 135]. This is an important fact, since forestry operations can alter the physical and mechanical properties of the soil [136], increasing soil compaction. The productivity of eucalyptus forests may reduce with increasing soil compaction levels [137, 138], due to: (*i*) physical obstruction of developing roots; (*ii*) lower water and nutrients absorption; (*iii*) gas exchange reduction.

Many factors influence the residue decomposition rates in the soil, with later nutrients availability for plants as we mentioned in the item 2. Generally, the leaves have faster biodegradation, since they have C/N ratios of 25–45 and C/P of 250–300, while the branches and trunk have C/N of 350–500 and C/P of 500–700 and the barks have C/N of 150–250 and C/P of 300–450 [127]. However, the nutrients allocated in the residues will not be fully available for eucalyptus plants; thus, many companies conduct tests in their crop areas trying to estimate the decomposition rates of the plant compartments and the recovery rates of applied fertilizers. Many companies use these data to establish the complementary fertilization management, seeking to minimize costs and make a more sustainable system.

Works describing the decomposition rates of different compartments in different environments can be found in the literature [139–143], which can be used for fertilization estimates when perform the tests is not possible. Some modeling programs such as the Nutricalc-UFV, allows us to estimate the different rates that will assist in the fertilization management. The residues have great importance on the nutrient balance of a system, and we cannot ignore the benefits of the construction and permanence of soil organic matter.

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