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Multi-Analytical Interactions in Support of Sugarcane Agroecosystems Sustainability in Tropical Soils

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Abstract

The risks of sugarcane management on soil microbes and their relationships with soil physicochemical factors and biogeochemical processes have not been described from an integrated perspective for different agronomic practices. Here, we provide a platform for multi-analytical interactions between ecologists analyzing the soil microbes at multiple ecological levels and geoscientists measuring the release of greenhouse gases and the physicochemical soil factors including labile fractions from soil organic matter in tropical sugarcane management systems. We compile the benefits and risks of nutrient management and soil amendments as well as of crop residue and harvest management in sugarcane soils on belowground microbial life and biogeochemical processes mediated by soil microbial communities, and we demonstrate that the massive planting of the crop brings environmental risks that include a potential impact on tropical soil ecosystem sustainability. We emphasize that soil management and harvest management are critical for supporting the sustainable development of biofuel production in tropical areas.

Keywords: soil microbes, biogeochemical processes, greenhouse gases, soil management, harvest management, ecosystem sustainability

1. Introduction

Although sugarcane (*Saccharum* spp.) has been traditionally cultivated for sugar production, it has emerged in the past few decades as one of the best crops for biofuel production [1]. Currently, world sugarcane production is close to 1.6 billion tons annually and is concentrated in the tropical regions, particularly in the developing nations in Latin America, Africa, and Asia [2] (**Figure 1**). Brazil is the world's largest sugarcane producer, followed by India, China, Pakistan, Thailand, and Mexico. As a result of the increased economic importance of sugarcane, the requirements for large-scale production in an environmentally sustainable manner have also increased. However, massive planting of the crop brings environmental risks that include a potential impact on tropical soil ecosystem sustainability (**Figure 1**), which is still an open question for soil microbes and microbial-mediated processes that lead to greenhouse gas (GHG) emissions.

Soil functions are effective only as long as the capacity for the interactions between the physical, chemical, and biological processes is preserved. The increased need for fertilizers due to the expansion of sugarcane production is a threat to the ability of the soil to maintain its potential for self-regulation in the long term, i.e., its sustainability [3]. Soil management practices used in sugarcane agriculture require synthetic mineral fertilizers (nitrogen/phosphorus/potassium—NPK) [4] and full recycling of waste products from the ethanol production to sugarcane fields in the form of organic fertilizer [5]. Sugarcane vinasse is a by-product of the
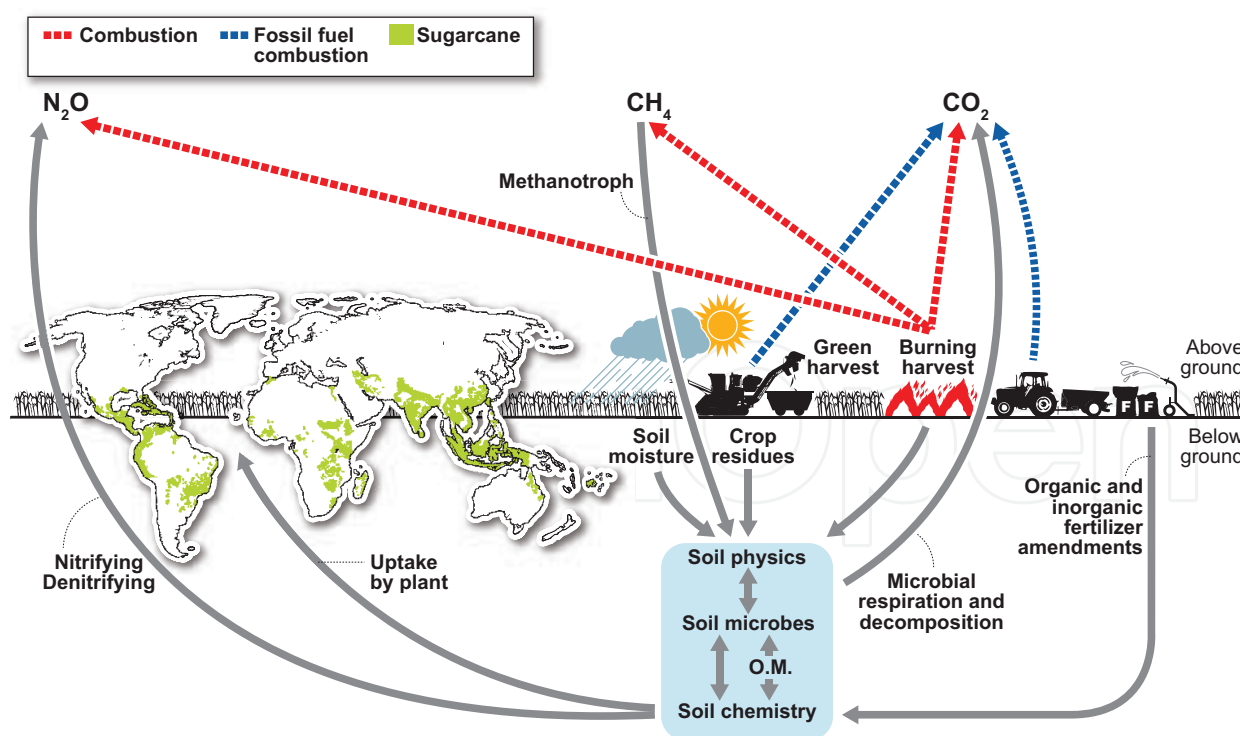

Figure 1. Infographic of the belowground-atmospheric potential impacts of large-scale sugarcane production from a soil ecological and integrated perspective. The map shows sugarcane production in the world. Gas emissions from combustion are shown from burning harvest. Carbon dioxide (CO_2) emissions are shown from fossil fuel combustion aboveground.

sugar-ethanol industry, also known as stillage [6]. Its chemical composition varies depending on the mill plant used for the production of ethanol and the distillation process [7]. In general, sugarcane vinasse is composed of water (93%) and organic solids and minerals (7%) [7]. It has high levels of organic matter but is low in N and P. The main non-water component of sugarcane vinasse is organic matter that exists in the form of organic acids and cations such as K, calcium (Ca), and magnesium (Mg) [7]. Since the 1960s, vinasse has been used as a liquid fertilizer in the sugarcane fields of Brazil to solve the ecological problem of its disposal within the environment. Studies from the late 1980s have recommended the use of N fertilizer in combination with vinasse in sugarcane fields [8], and a more recent study has recommended the use of N fertilizer with straw retention [9].

The inorganic and organic fertilizer amendments, primarily used to increase nutrient availability to plants, and the management of sugarcane harvest residue are likely to affect the physical [10, 11], chemical [10, 12–14], and microbiological [13–21] attributes of sugarcane soils as well as the GHG emissions from sugarcane areas [19, 22–26]. Soil microbes comprise a major fraction of the total living soil biomass [27]. Many of the abovementioned studies have highlighted that numerous microbial groups are highly correlated with specific soil factors. The studies reported differences in the soil microbial community related to management practices for sugarcane due to the effects of soil factors. Despite increased attention to the soil microbial community and its relationship with soil characteristics in sugarcane-cultivated areas, little progress has been made in elucidating the implications of the agricultural practices on the functional roles of this community in tropical sugarcane agriculture [16].

With this in mind, this chapter was aimed at examining the available data on the subject as a contribution to update the knowledge on the benefits and risks of nutrient management and soil amendments as well as of crop residue and harvest management in sugarcane soils on belowground microbial life, soil physical and chemical factors, and biogeochemical processes mediated by soil microbial communities. We summarize, in this chapter, the impacts of these management practices on soil microbes at multiple ecological levels, on soil physicochemical attributes including labile fractions from soil organic matter and on GHG emissions (mainly nitrous oxide due to nitrogen losses in sugarcane production systems). Based on multi-analytical interactions, we emphasize that soil management and harvest management are critical for supporting the sustainable development of biofuel production.

2. Nutrient management and soil amendments

Sugarcane is a semi-perennial crop replanted after 3–7 ratoon cycles, depending at least in part on the soil fertility and crop variety [5]. After a relatively long time receiving fertilizers and recycling crop residue on an annual basis, the soil ecosystem sustainability and multi-functionality can become compromised in most production areas [28]. The impacts of these management practices, and inorganic and organic fertilizer amendments on soil microbes and GHG emissions, as well as on soil physicochemical factors including labile fractions from soil organic matter in sugarcane fields worldwide are addressed below based on a soil multi-analytic perspective.

2.1. Application of mineral fertilizers

Annually, sugarcane production fields are amended with inorganic sources of N, P, and K as well as other, more sporadic, amendments, such as Ca, Mg, sulfur (S), and micronutrients. However, the macronutrients, such as P, K, Ca, Mg, and S, are also fundamental for the development of sugarcane and when used in association, they could reflect increases of productivities.

Urea is considered the most widely used N fertilizer in sugarcane fields, followed by ammonium sulfate and ammonium nitrate [29]. However, more than 25% of the N applied in the form of urea to surface soil during the sugarcane ratoon cycles can be volatilized to ammonia [29]. Consequently, urea is applied only during the sugarcane vegetative stage in Brazil. The use of liquid urea with crop residue blankets has been reported to avert N volatilization in Australia [30]. Both urease and nitrifier inhibitors can alternatively be used to reduce N losses as ammonia [31].

Nitrification, i.e., the biological oxidation of ammonia into nitrite, followed by the oxidation of nitrite into nitrate can produce nitrous oxide (N_2O) as a by-product. Soares et al. [19] reported reduced N_2O emissions from a sugarcane field in Brazil after DMPP (3,4-dimethylpyrazole phosphate)-coated urea applications (**Table 1**), with fewer effects on the microbial community diversity and composition in comparison with treatments using urea or calcium nitrate. However, Wang et al. [32] did not find similar results for well-drained soil in Australia (**Table 1**), even after applying three times more DMPP-coated urea than that used on the Brazilian soil. These results may be at least in part due to the expected differences in soil microbial communities between the soil types and geographical regions.

Archaea and bacteria are key drivers of N in the redox process of denitrification of nitrate to form N_2O in the soil [20]. Soares et al. [19] showed that N_2O emissions in sugarcane soils were significantly correlated with bacterial *amo*A genes but not with denitrification-related genes (*nir*K, *nir*S, and *nos*Z), suggesting that ammonia-oxidizing bacteria via nitrification are the main contributors to emissions of N_2O when urea is used as a fertilizer. In turn, Fracetto et al. [33] showed an increase in denitrifying gene abundance (*nir*S, *nir*K, *nor*B, and *nos*Z) after ammonium nitrate application to the soil, with N_2O emissions associated with *nor*B gene abundance. However, denitrification may contribute to much of the N_2O emissions from sugarcane cultivation systems [19, 34], and denitrification is at least in part associated with soil moisture content [35]. In soils with 75% water-filled pore space (WFPS), denitrification has been shown to be the most important process in N_2O emissions, while nitrification has been shown to be the most important process in soils with 60% WFPS [35]. Denitrification is a respiratory process that regularly occurs in the absence of O_2, in which NO_3^- is used as an electron acceptor. However, although large denitrification rates are associated with low concentrations of O_2, aerobic denitrification has also been demonstrated for some bacteria [34].

The N fertilizer dose has been associated with changes in microbial communities [13, 17] and in abundance of functional genes associated with nitrification and denitrification in the sugarcane soil and rhizosphere [36]. Although fungal species richness in the sugarcane soil and rhizosphere has not shown variation to N fertilizer applied to the soil at different

rates, changes in *Ascomycota* and *Basidiomycota* abundance were detected in these soils, with *Basidiomycota* abundance negatively affected by increasing N dose [17]. Gumiere et al. [18] evaluated the diversity and abundance of fungal communities in soils used for the cultivation of sugarcane and demonstrated that the distribution of fungal species abundance fits better a neutral model that assumes biogeographical patterns than models that assume environmental filtering. Recently, fungi have being presented as contributors to the N_2O released from soils, and pH was the parameter that explained the majority of this share [37]. Nitrous oxide production was confirmed *in vitro* as a common trait of fungi [38]. Considering the relevance of pH to the N_2O emissions attributed to fungi, this subject needs to be covered to understand the processes that result in the release of gas in sugarcane soils, since the crop grows predominantly in acidic soils (**Table 1**). In addition, since N application changes the fungal community, it may also change the balance of N_2O produced by this group of soil microorganisms.

Reference	N dose (kg ha^{-1})	Crop stage	Straw blanket	Soil type	Redox status	N source	Annual N-N$_2$O emission (g ha^{-1})	Soil pH	Soil OM (%)	Sampling events	Time covered (days)
Soares et al. [19]	0	3rd ratoon	Removed	Oxisol	Well-drained	–	286	5.1	2.3	41	278
	120					Urea	2301				
	120					Urea + DCD	531				
	120					Urea + DCD-R	350				
	120					Urea + DMPP	2165				
	120					Urea + DMPP-R	410				
	120					PSCU	353				
	120					Ca(NO$_3$)$_2$	329				
Wang et al. [32]	0	5th ratoon	9.4 t ha^{-1}	Lixisol	Well-drained	–	1700	4.8	2.8^d	38	328
	80					Urea	2600				
	150					Urea	3600				
	80					PCU	3952^a				
	80					DMPP	2300^b				
	80		Removed			Urea	1976^c				
	0	1st ratoon	Burnt (2.9 t ha^{-1} remained)	Gleysol	Flood-plain	–	12,200	4.9	16.9^d	38	343
	80					Urea	23,200				
	160					Urea	28,200				
	80					PCU	16,100				
	80					DMPP	20,700				
	80		removed			Urea	16,000				

Reference	N dose (kg ha⁻¹)	Crop stage	Straw blanket	Soil type	Redox status	N source	Annual N-N₂O emission (g ha⁻¹)	Soil pH	Soil OM (%)	Sampling events	Time covered (days)
Carmo et al. [23]	0	1st ratoon	Removed	Oxisol	Well-drained	–	107	4.5	2.2	21	335
	120		Removed			NH_4NO_3	2091				
	120		7 t ha⁻¹			NH_4NO_3	3286				
	120		14 t ha⁻¹			NH_4NO_3	3019				
	120		21 t ha⁻¹			NH_4NO_3	4170				
	142		Removed			NH_4NO_3 + Vin.	3024				
	142		7 t ha⁻¹			NH_4NO_3 + Vin.	5869				
	142		14 t ha⁻¹			NH_4NO_3 + Vin.	7034				
	142		21 t ha⁻¹			NH_4NO_3 + Vin.	7464				
	0	Plant cane	–	Lixisol	Well-drained	–	577	4.5	2.2	20	314
	60		–			Urea	1377				
	60		–			Urea + Vin.	2212				
	85		–			Urea + Vin.	3261				
	85		–			Urea + Vin. + FC	3566				
Pitombo et al. [26]	0	1st ratoon	Removed	Oxisol	Well-drained	–	1605	5.1	2.3	48	274
	100					NH_4NO_3	1811				
	161					NH_4NO_3 + Vin.	3763				
	61					Vin.	2583				
	37					Concentrated Vin.	2106				
	0		10 t ha⁻¹			___	1810				
	100					NH_4NO_3	2870				
	161					NH_4NO_3 + Vin.	5699				
	61					Vin.	3490				
	37					Concentrated Vin.	2500				
Pitombo et al. [20]	100	2nd ratoon	0 t ha⁻¹	Oxisol	Well-drained		NH_4NO_3	5237	5.2	2.8	37	246
	100		5.6 t ha⁻¹			NH_4NO_3	4548				
	100		8.5 t ha⁻¹			NH_4NO_3	3204				
	100		11.3 t ha⁻¹			NH_4NO_3	3347				

Reference	N dose (kg ha⁻¹)	Crop stage	Straw blanket	Soil type	Redox status	N source	Annual N-N$_2$O emission (g ha⁻¹)	Soil pH	Soil OM (%)	Sampling events	Time covered (days)
Allen et al. [30]	0	3rd and 4th ratoon	Kept	Hydro-sol	Flood-plain	–	2860	~5	5.2^d	30	~365
	2 × 50					Liquid urea	3860				
	100					Liquid urea	3930				
	2 × 100					Liquid urea	5810				
	200					Liquid urea	9560				
Paredes et al. [39]	0	2nd ratoon	Kept	Oxisol	Well-drained	–	3920	5.4	2.6^d	69	211
	100					(NH$_4$)$_2$SO$_4$	Not presented				
	118					(NH$_4$)$_2$SO$_4$ + Vin.					
	118					(NH$_4$)$_2$SO$_4$ + Vin.					
	18					Vin.					
	18					Vin.					

DCD, dicyandiamide; DMPP, dimethylpyrazole phosphate; PSCU, polymer sulfur coated urea; PCU, polymer coated urea; Vin., vinasse; FC, filter cake.

[a]Calculated based on data available at Results section (52% higher than treatment with 80 kg urea).

[b]Estimated from the plot.

[c]Calculated based on data available at Results section (24% lower than treatment with 80 kg urea).

[d]Obtained based on TOC*1.724.

Table 1. Annual nitrous oxide (N$_2$O) emissions from sugarcane production fields after nitrogen fertilizers applications to tropical soils with contrasting characteristics.

Sugarcane fields are widely distributed around the globe in tropical regions, and the crop grows both in deep well-drained soils and in floodplains (**Figure 1** and **Table 1**). This contrast limits the conclusion about which processes predominate in sugarcane fields. While the emissions can reach more than 20 kg ha⁻¹ N-N$_2$O y⁻¹ in the floodplains, the amount drops to approximately 2.4 kg ha⁻¹ N-N$_2$O y⁻¹, on average, in well-drained soils. When analyzing the effect of water saturation on N$_2$O fluxes, Denmead et al. [40] verified that at 70% of WFPS, the N$_2$O fluxes reach their highest values in the field and that this result would be due to the sum of N$_2$O produced by both nitrification and denitrification processes. However, this hypothesis still needs to be addressed in a variety of soils to improve the understanding of the processes that result in N$_2$O release in sugarcane soils.

Concerning the GHG emissions in sugarcane soils amended with mineral fertilizers, the emissions based on ammonium nitrate sources can vary from 1811 g ha⁻¹ to 5237 g ha⁻¹ [20, 26], and from 0.85 to 1.68% when urea is applied to the Brazilian tropical soils [19, 23, 32]. In Australia, the amount of N$_2$O released and, consequently, the fertilizer emission factor vary broadly depending on the soil redox status and N dose applied (**Table 1**). The emission factor

for flooded areas has reached values higher than 20% [32, 40]; for well-drained areas, it has reached up to 1% for the standard fertilizer doses, but it increases for higher N doses [30].

The carbon dioxide (CO_2) and methane (CH_4) emissions in sugarcane soils are also directly related to the N fertilizer dose [23] and its effects on the metabolizable nutrient availability [22] and the soil microbial community [13]. Urea may be metabolized by *Nitrospira*, resulting in ammonia and CO_2 [41]. For instance, urea applied in pure form or as part of other organic amendments is hydrolyzed and results in CO_2. Urease is produced by a broad range of soil organisms—from bacteria to plants [42]. There are also possible indirect effects. The N fertilizers in agriculture also affect the soil capacity to consume CH_4 [43]. The oxidation of NH_4^+ and CH_4 are homologous functions, and they can be mediated by the same enzyme in methane-oxidizing bacteria and ammonia-oxidizing bacteria [44, 45]. This implies that NH_4^+ can inhibit the oxidation of CH_4 by competing for active sites [43, 45]. The specificity of a bacterial group in relation to another can cause the collapse of competition between groups either because of lack of energy or source of C, since the accumulation of toxic species of N follows the evolution of the oxidation of NH_4^+, which results in low consumption of CH_4 and greater availability of N for nitrification, denitrification, and formation of N_2O.

2.2. Use of organic fertilizers

As an alternative to mineral fertilization in sugarcane production fields, waste products from ethanol production (vinasse and filter cake), sewage sludge, green manures, inoculants of atmospheric N-fixing bacteria and phytohormones are commonly applied to the soil in the form of organic fertilizer to promote plant growth [46]. These organic fertilizers represent an important contribution of the N, P, K, and organic matter, mainly soil labile organic fractions, such as dissolved organic C and N, and others C-light organic fractions [47–49], in the sugarcane agroindustry [25]. Soil labile organic C can be defined as the soil organic matter fraction that sustains the soil food web and therefore directly influences nutrient cycles and many biologically related soil properties [50].

The filter cake, a solid organic residue of the sugarcane processing in the mill that is rich in P, is used mainly in cane-plants, at 10–30 t ha^{-1} when applied in the furrow and, 80–100 t ha^{-1} when applied in the total area, in pre-planting, replacing the phosphate fertilization partially or totally, depending on the dose of P_2O_5 recommended. The vinasse is mainly used in sugarcane, supplying all the K_2O and part of the N, being very poor in P. Vinasse, depending on its chemical composition and soil fertility, is applied in the range of 60–120 m^3 ha^{-1} by tank vehicles or 150–250 m^3 ha^{-1} by irrigation-sprinkler [51].

Although organic fertilizers are used to increase sugarcane productivity through nutrient availability to plants, they can also affect soil microbial community and physicochemical soil factors [7, 14, 20, 52], and key biogeochemical processes associated with GHG emissions, such as decomposition, respiration, nitrification and denitrification [23, 25, 53]. Moreover, the use of organic residues has resulted in the increase of C and N labile organic forms [47–49], which has been used as soil quality indicator due to rapid alteration according to soil practice management [54]. It is generally assumed that plant litter and humus are the two most important

sources of dissolved organic matter in soils, and its release into solution occurs through physicochemical decomposition and leaching from litter and formation of humic substances [55].

Omori et al. [52] reported increases in bacterial diversity after vinasse application to the soil and revealed that this by-product of the sugar-ethanol industry promotes the participation of soil microbial community members in N and Fe cycling. The authors showed that *Acidobacteria* Gp3 and Gp4 were most abundant in the vinasse-amended soil. In addition, bacterial community members belonging to *Actinomycetales* were more diverse in vinasse-amended soil than in soils without vinasse. Navarrete et al. [14] reported effects of combined applications of vinasse and N fertilizer to the soil on bacterial communities in sugarcane soils. *Acidobacteria*, *Actinobacteria*, and *Verrucomicrobia* were the bacterial phyla most affected in these soils. The authors identified increases in CO_2 and N_2O emissions shortly after the addition of both vinasse and N fertilizer to the soils, thus increasing the microbial-N biomass, decreasing the microbial-C biomass and altering the soil chemical factors that were correlated with the microbial biomass. Regarding the soil chemical factors, the K and S were negatively correlated with microbial biomass and the soil pH was positively correlated with microbial-C biomass. The long-term organic inputs has evidenced clear trend of increasing microbial-C biomass when compared with conventional practice management [47, 56]. In turn, Dias [53] reported that vinasse can increase the abundance of nitrous oxide reductase (*nos*Z) gene but not the copy number of both nitrite reductase (*nir*K) and methyl coenzyme-M reductase (*mcr*A) genes in sugarcane soils.

While vinasse is broadcast on the soil during the vegetative stage and on the ratoons, filter cake is typically used only during the vegetative sugarcane stage with mineral fertilizer added in the furrows (**Table 1**). Using a molecular approach based on 16S rRNA gene sequencing, Omori [57] revealed *Actinobacteria* as the predominant phylum in the bacterial community related to the degradation of plant biomass and the production of antimicrobials in sugarcane soil containing filter cake semi-composting, which is possibly related to the high amount of lignocellulosic material available in the filter cake. The authors also reported *Firmicutes* and *Proteobacteria* in the soil at different stages of the composting process. In turn, Hernández et al. [58] used a culture-dependent approach and showed that filter cake application to the sugarcane soil increases colonies of phosphate-solubilizing microorganisms, total bacteria, and fungi. In addition, Tellechea et al. [59] showed higher microbial activity in sugarcane soil with filter cake application based on traditional methods of CO_2 determination. These results are an important indicative that the microorganisms present in the filter cake are able to increase available P in the soil solution and then to improve its absorption by plants, which can be highlighted in the tropical soil condition, such as Oxisol, that has high P content adsorbed in the soil by the internal sphere complex (unavailable for plants).

Carmo et al. [23] and Siqueira Neto et al. [25] provided a comprehensive characterization of GHG emissions associated with the use of vinasse and filter cake as organic fertilizer application practices for planting and regrowth of sugarcane were commonly used in Brazil. Carmo et al. [23] reported significant differences in daily fluxes from soils with organic fertilizers and those with no fertilizer (organic or mineral) (**Table 1**). Daily fluxes from soils that included the application of filter cake and vinasse in combination with mineral fertilizer were significantly

increased in comparison with those observed in the treatment that included only mineral fertilizer. Cumulatively, the highest emissions were observed for ratoon sugarcane treated with vinasse, especially as the amount of crop residue on the soil surface increased. Normally, the flow of CH_4 is variable, indicating the ability of the soil to serve either as source or as sink of this GHG [53]. In general, filter cakes can be associated with a lower emission factor compared with other organic or synthetic fertilizers [25]. In turn, the vinasse application can increase N_2O emissions from sugarcane soils, especially during the first couple of days after application [26, 53]. The applied vinasse generates a high emission factor analogous to the emission factor observed for urea application.

Another organic fertilizer is sewage sludge. Although sewage sludge is also very lacking in K, it has high levels of P [60]. This organic fertilizer can improve soil's physical and chemical characteristics and can increase sugarcane productivity, acid phosphatase activity, and biomass [61]. These authors also highlighted the beneficial effect of B, Zn, and Cu from sewage sludge in association with available P that provided increase in the stalks production. However, its use requires some care, as there is the possibility of pathogen and heavy metal contamination. The application of sewage sludge may increase the concentrations of As, Cd, Cu, Ni, Pb, and Zn in the soil, and the quality standard established by the legislation for agricultural soils must be respected [62]. However, the incorporation into soils of sewage sludge rich in C has been shown to increase the amount of dissolved organic matter in soils. Dissolved organic matter can facilitate metal transport in soil through formation of soluble metal-organic complexes [63, 64]; in contrast, they are also able to mobilize some heavy metals sorbed from soil or sewage sludge, being the soil organic matter one of the most important solid phases that adsorb heavy metals, such as Cu and Cd in acid sandy soils. Thus, soils amended with sewage sludge display different physicochemical properties, especially in terms of dissolved organic matter in soil, which will affect behavior of metals in soils. The application of sewage sludge can also provide an increase in CO_2 emissions in soils [65]. However, the impact of sewage sludge in the environment on the soil microbial community has not yet been reported for sugarcane agriculture.

The incorporation of ecological practices into sugarcane production and management has the potential to arrest and ameliorate the negative effects of monocropping on soil degradation and yield decline. Historically, the production of green manure as a cover or break crop has been shown to improve the physical, chemical, and biological characteristics of the soil for many crops in production agriculture. Schumann et al. [66] published an interesting review of green manuring practices in sugarcane production. However, only recently, the effects of green manure on soil microbial populations, diversity, and activity in sugarcane soils have been reported [67], in which decrease in the total bacterial population in the soil was revealed, while that of fungi and actinomycetes increased. In addition, Ambrosano et al. [68] verified that green manure is an alternative source of N for sugarcane crops and can supplement or even replace mineral N fertilization. Moreover, green manure associated with mineral N fertilizer altered the soil chemical factors, increasing Ca and Mg contents, sum of bases, soil pH and base saturation, and as a consequence decreased the potential acidity.

N-fixing biofertilizers are useful to economize the nitrogenous fertilizers and to increase the cane yield. N inputs to the soil can naturally occur as a consequence of the metabolism of N_2-fixing microbes. Even though N_2 reduction by nitrogenases is an exergonic process, the flow of energy generated is very expensive, requiring much ATP; for this region, nitrogenases are inhibited by NH_3 [69]. However, in sugarcane, endophytic symbiosis with N_2-fixing microbes is known to occur, and they have been reported for more than 25 years [70]. Although biological N fixation is a natural process in sugarcane, it can be optimized by using more specific and efficient bacteria. The multiplicity of beneficial effects of microbial inoculants, particularly plant growth promoters, emphasizes the need for further strengthening their research and use in sugarcane agriculture.

3. Crop residue and harvest management

Soil residue management focusing in soil quality (conservation) and its energetic use are emerging study subjects regarding the sugarcane crop worldwide. In areas under sugarcane cultivation, different sugarcane harvest systems are commonly applied, such as manual handling with burnt sugarcane (burnt harvest) and mechanical harvesting (green harvest). In Brazil, the world's largest producer of sugarcane, harvest practices for sugarcane are undergoing a change, with the increased introduction of mechanical harvesting. This change is regulated by state legislation. For instance, the states of São Paulo and Goiás, which produce more than half of the sugarcane in Brazil, have similar deadlines to completely change their harvest systems. In these states, sugarcane burning is scheduled to be completely phased out progressively during the next 15 years, depending mainly on land declivity due to mechanization limitations.

Without burning, in average, 8–30 Mg ha^{-1} dry mass of straw is generated [9, 71, 72], which has 54% dry leaves and 46% tops [73]. The average crop residue produced every year is approximately 10 Mg ha^{-1} of material with a C:N ratio of approximately 100 [74], that reflects the presence of lignocellulosic composition in the straw, which accounts for 19–34% lignin, 29–44% cellulose, and 27–31% hemicelluloses [75–79]. This characteristic implies in high recalcitrance of residues, that has slow decomposition rate on soil. Around 30–60% of soil moisture content is kept after harvest [80, 81]. There is discussion regarding the feasibility of sugarcane biomass utilization in the industry versus keeping it in the field to improve soil quality and guarantee the long-term sustainability.

Both practices in sugarcane harvest, i.e., burnt and green harvests, have the potential to influence soil physicochemical, microbiological factors, as well as, soil organic fractions. Sugarcane burning as a preharvesting method is a millenary technique to eliminate all leaves and tops around the sugarcane plant, which helps with manual harvest [82] and transport [83]. However, it is known that burnt harvest has the potential to negatively alter the physical, chemical, and biological soil characteristics [21, 84], to increase GHG emissions [85–87], and to decrease soil organic matter [88]. Moreover, particulate matter and smoke from leaf burning released into the atmosphere represent health hazards [89].

In contrast, the maintenance of sugarcane plant residue as a surface blanket positively affects the physical, chemical, and biological soil characteristics. However, these positive effects cannot be observed if soil tillage operations are considered [28]. Conservation agricultural systems, such as minimal soil disturbance (reduced tillage or no tillage), have been sought as an option to conventional tillage practices in order to reduce production costs and improve the soil fertility status [90]. According to Rachid et al. [91], there are no effects from different levels of sugarcane plant residue on the soil bacterial community. However, the authors reported that the soil fungal community can be impacted, and after 12 months, the community can present different structures among the different levels of sugarcane plant residue blankets. Although the physical and chemical characteristics are important for soil quality and sustainability, microorganisms are the main drivers of the nutrient turnover processes in the soil [16] and of the regulation of many atmospheric constituents, such as GHG. In addition, soil microbes have shown many responses to abiotic soil factors, which are clearly affected by microenvironmental changes [14, 92–94].

The current main information related to the impact of sugarcane harvest management on the soil microbial community, soil physicochemical factors, including labile organic C fractions, and GHG emissions at multiple scales are reported below, taking into account the development of more sustainable sugarcane productions systems.

3.1. Burnt harvest management

Sugarcane burning has been used for many years on sugarcane crops, and it is still being used currently. Given that soil microbes represent the majority of biodiversity in terrestrial ecosystems and are intimately involved in key ecosystem functions, such as soil fertility, increased attention has recently been paid to microbial communities present in soils under burnt and unburnt sugarcane. According to Souza et al. [13], the level of microbial-C biomass in the soil is lower in burnt sugarcane systems than in sugarcane harvesting without burning. The authors suggested that microbial-C biomass is a reliable indicator of soil quality for monitoring soils under different sugarcane harvesting systems. In turn, Rachid et al. [15] used a molecular approach to evaluate the effect of sugarcane burning and green harvest methods on the soil microbes in the Brazilian Cerrado, and they showed significant differences on the soil bacterial community and its structure between burnt and green harvest systems, with the *Firmicutes* phylum and *Acidobacteria* classes being the groups most affected by sugarcane burning. In general, significant structural changes of the community were observed, with the burnt harvest management having a greater impact than green harvest management on the native Cerrado soil communities. The authors concluded that due to the great variability of the Cerrado ecosystem, further research is required to confirm these findings with soil samples from different sites and seasons in order to address the impact due to changes in management over the years. Val-Moraes et al. [21] also used a molecular approach to evaluate the effect of sugarcane burning and green harvest methods on the soil microbes, and they showed that liming in the sugarcane burnt system and that green harvest practices affect the soil bacterial community. The authors revealed higher bacterial diversity in sugarcane soils than in native forest soil, with burnt sugarcane soil accounting for a higher richness of unique operational taxonomic units (OTUs) than native forest soil. The authors also observed

similar bacterial communities in green sugarcane and native forest soils, while the bacterial community from burnt sugarcane soil was most distinct from the others. *Acidobacteria* and *Alphaproteobacteria* were the most abundant bacterial phylum and class, respectively, across the different soils, with *Acidobacteria* Gp1 accounting for a higher abundance in green sugarcane and native forest soils than in burnt sugarcane soils. In turn, *Acidobacteria* Gp4 abundance was higher in burnt sugarcane soils than in other soils.

In burnt harvest systems, C, N, and S from sugarcane plants volatilize, although they could return to the soil [12]. However, there is an overall tendency of the burnt straw to decrease soil fertility in the long term. The fertilization associated with burnt straw induced by 59 years in Africa [12] and by 35 years in Brazil [95] resulted in decrease of P, K, cation exchangeable capacity, and decrease in Ca and Mg content. In addition, the soil becomes physically exposed due to decreasing of soil organic matter [96] that has great function to binding polysaccharides, fungal hyphae, and humic substances with soil mineral particles forming the soil aggregates [97] and increasing the availability of nutrients [96], which accelerates the loss of chemical fertility [98]. In addition, the harvest burnt also decreases the stability of aggregate on soil surface [10, 12].

Concerning GHG emissions, Figueiredo and La Scala Jr. [86] reported that burnt harvesting increased GHG emissions by 1484.0 kg CO_2 eq. ha^{-1} y^{-1} compared with the green harvest system. However, the authors emphasized that fertilizer application to the soil can also influence GHG emissions. Azevedo et al. [99] reported that burnt sugarcane harvesting intensifies CO_2 and carbon monoxide (CO) emissions. Macedo et al. [100] reported emissions of 6.5 kg CH_4 ha^{-1} in sugarcane burning. With increasing introduction of mechanical harvesting, a reduction of 39.3% (from 1.053 to 0.639 t CO_2 eq. ha^{-1}) of GHG emissions was estimated in the state of São Paulo between 1990 and 2009 [101]. According to Capaz et al. [101], there is an increase on ozone and CO content during the sugarcane harvest season due to the burning technique. In synthesis, comparing both harvest management systems, the burnt harvest system presents higher GHG emissions, which range from 558.5 kg C_{eq} ha^{-1} y^{-1} to 2209.2 kg C_{eq} ha^{-1} y^{-1} more than that produced by the green harvest system [102].

3.2. Green harvest management

Green harvest has become a recommended approach for sugarcane harvesting. Studies have shown that the soil microbial community is more abundant, active, and diverse in green sugarcane soil than in burnt sugarcane soil [103–105], which influences positively on the soil physicochemical factors. According to Graham et al. [103], the microbial metabolic quotient decreases with increasing soil depth, with significant increases in microbial-C biomass up to 30 cm of soil depth. In addition, microbial-C biomass was significantly higher in rows than in between rows as well as the bulk density was decreased since the green harvest to foster the increase of soil C status [104].

The light fraction from organic matter is another soil quality management parameter that has a chemical composition comparable to that of plant materials [106] and thus, it may be affected by fluctuations in different management practices. Although it represents a small proportion of total soil mass, it contains a significant part of the total soil C and N, so that

its evaluation can provide an early indication of changes in land use and soil management [107]. Brandani et al. [108] verified that burnt harvest combined with organic management was a strategy for long-term storage of total C and N in the light organic fraction, which were related to the quality (diversity) and quantity (frequency) of organic residue addition [107].

Based on a molecular fingerprinting approach, Wallis et al. [109] showed distinct bacterial communities in sugarcane soil under a crop residue blanket in a burnt harvest system. In turn, Rachid et al. [84] reported effects of sugarcane green and burnt harvest management on soil bacterial communities and microbial functional genes. The authors revealed that changes in the soil bacterial community were related to harvest management systems, while soil fungal communities were more sensitive to changes in the crop residue retention levels, probably due to the use of the crop residue as a substrate [91]. Regarding the microbial functional genes, changes in the community structure of ammonia-oxidizing bacteria (*amo*A gene) were correlated with the C:N ratio in the soil, while no significant correlations were revealed between the denitrifying bacteria community structure (*nir*K gene) and the analyzed soil chemical factors.

As mentioned above, the main characteristic of the transition from burning sugarcane to green harvest is the retention of sugarcane plant residue on the soil surface [11, 12]. The sugarcane plant residue retention is an effective practice to: (i) reduce infiltration and soil loss rates [110]; (ii) protect the soil surface from high temperature ranges [110–112]; (iii) maintain the soil moisture levels [110, 113]; (iv) increase earthworm populations and soil microbial biomass [110], which are responsible for organic matter decomposition [95, 113], increasing carbon stocks in the 0–10-cm topsoil layer [83]; (v) increase soil stability and help spread micro and macroaggregates in the soil, which are important for maintaining the soil microbial diversity through the conservation of their microhabitats [12, 98]; and (vi) reduce the necessity of weed control [110]. Hence, green harvest can improve the soil structure and increase sugarcane yield [104, 110] and decrease soil erosion losses [10].

Studies have shown that green harvest may be related to decreases in soil porosity and increases in soil compaction as a consequence of the traffic from harvesters [114], being therefore limited with regard improvement of soil physical factors such as soil bulk density and penetration resistance [98], which could influence negatively on the initial development of root systems, as well as the nutrient availability for plants. However, increases in soil organic matter content and improvements in soil aggregation can gradually reduce the soil compaction [110]. Due to the trend for equilibrium in soil organic matter accumulation, deep drainage and increased soil moisture can promote N losses and denitrification even at low rates [113]. However, the increase in soil carbon by crop residue retention during the ratoon cycles can be lost during tillage operations during the sugarcane replanting period [87], inducing similar soil carbon concentrations for burnt and green sugarcane systems [113].

Nutrient recycling is one of the main reasons for maintaining straw in the field [105]. However, in the first year of sugarcane production, only approximately 20% of the crop residue is available for mineralization and then for denitrification and nitrification, resulting in N_2O emissions from sugarcane plant residues of 71.61 kg CO_2 eq. ha^{-1} y^{-1} [115]. Nitrous

oxide emissions of 420 kg CO_2 eq. ha^{-1} were estimated when the total N in crop residue and default values were considered [100]. Because of the high C:N ratio of sugarcane residue, which can range from 70:1 to 120:1 [22], the soil N immobilization should occur in the first phase of straw decomposition. Nevertheless, because gradual availability of others macro and micronutrients from straw decomposition a decrease in N_2O emissions is expected [116]. Fortes et al. [90] observed in a long-term study developed on an Oxisol, that the amounts of straw nutrients released to the soil-plant system (in kg ha^{-1} and in percentage of initial content) were of 12.7 (31%) of N, 0.7 (23%) of P, 43.1 (92%) of K, 18.2 (54%) of Ca, 8 (70%) of Mg, and 4.6 (65%) of S, after the three crop cycles.

Concerning N_2O emission, Pitombo [26] showed that amounts of crop residue from 0 to 11.3 Mg ha^{-1} progressively reduced annual N_2O emissions from sugarcane soils, despite that the highest gas fluxes were verified in the treatments with more residue accumulation (**Table 1**). Nevertheless, the effects of crop residue on N_2O emissions are still unclear in sugarcane soils. Siqueira Neto et al. [25] did not find differences in N_2O emissions from treatments without or with 15 Mg ha^{-1} of sugarcane residue on the soil surface. Nitrous oxide fluxes seem to be higher when crop residue is combined with inorganic N [20, 26, 33]. However, only small areas in sugarcane fields receive inorganic fertilizer, while the majority of the field is important to the N_2O balance [26].

In the first years after conversion from burnt to green harvest, the N fertilizer dose applied to green sugarcane is approximately 30% higher than in burnt sugarcane, increasing GHG emissions by 27% in comparison with burnt sugarcane [99, 100]. Over the years, more crop residue is added to the system, increasing the quantity of readily decomposable organic matter and decreasing N fertilizer inputs [12].

GHG emissions due to fossil fuel consumption of green harvest are related to the diesel use in sugarcane agricultural devices and trucks during the mechanical harvest and stalk transportation [117] (**Figure 1**). They account for nearly 300 kg CO_2 eq. ha^{-1} y^{-1} during harvest operation, with a mean diesel consumption of 74 L ha^{-1} y^{-1} for a 5-year crop cycle [85, 86]. Considering diesel consumption during extraction, processing, and distribution, the GHG emissions increase from 466 kg CO_2 eq. ha^{-1} y^{-1} (in burnt sugarcane) to approximately 750 kg CO_2 eq. ha^{-1} y^{-1} in a 6-year crop cycle [116].

Green harvest results in a total CO_2 sequestration of 1173.3 kg CO_2 eq. ha^{-1} y^{-1} [99, 100]. However, Acreche et al. [118] reported 43% more CO_2 emissions from tillering in the green harvest system and 247% more N_2O emissions from post-fertilization than in burnt sugarcane, and the authors reported meaningful CH_4 emissions rates compared with those of CO_2 and N_2O.

Although green harvest showed high GHG emissions due N fertilizer application and fossil fuel consumption, in the first years of the conversion, reduction in the emissions is expected. According to Panosso et al. [112], CO_2 emissions were 32% greater in burnt sugarcane, even 7 years after converting to a green harvest system. In the first years after conversion from burnt to green harvest, Figueiredo and La Scala Jr. [85, 86] reported emission reductions of 310.7 kg CO_2 eq. ha^{-1} y^{-1}, excluding soil carbon sequestration resulting from the crop residue retention.

4. Considerations

The large-scale planting of sugarcane crops in tropical regions brings risks that include a potential impact on the soil ecosystem sustainability. To be precise, these environmental risks begin from changes in the soil microbial community, soil physicochemical factors, and GHG emissions from the land use conversion to sugarcane fields. After a relatively long time of fertilizer applications and recycling crop residue on an annual and cyclical (plant stage and ratoons) basis, the ability of the sugarcane soil to maintain its potential for self-regulation in the long term, i.e., its sustainability is threatened. Nutrient management, soil amendments, crop residue, and harvest management in sugarcane soils affect soil microbes at multiple ecological levels, i.e., biomass, community structure, abundance and composition, and taxonomic and functional groups. Consequently, biogeochemical processes mediated by soil microbes are also affected, disturbing the GHG emissions from the soil to the atmosphere in these sugarcane agricultural areas (**Figure 1**).

It is understood that sugarcane renewal is a critical stage for disturbance of the soil ecosystem, in which soil microbes and GHG emissions are affected by soil tillage. Hence, new sugarcane varieties able to delay the need for renewing their planting can cooperate to mitigate below-ground atmospheric risks of sugarcane agroecosystems for tropical soil sustainability. In addition, it is recommended to develop technologies for renewing sugarcane cultivation which are able to avoid severe impacts to the soil environment. It is also necessary to enhance farmer access to nitrification inhibitors and controlled-release fertilizers, which have a small market share because of high prices. Although more attention must be devoted to understanding the combined effects of nitrification inhibitors and organic fertilizers on soil microbes and GHG emissions, especially in warm tropical soils, the importance of these products has increased due to the agronomic and environmental benefits already revealed.

In addition, new efforts are needed to quantify the effects of land use changes in sugarcane agricultural fields in tropical regions as well as the effects of nutrient management, soil amendments, crop residue, and harvest management in these agricultural areas on soil microbes and GHG emissions, also taking into account the microbial interactions with physical and chemical factors. Nevertheless, our chapter provides clear signals of the predictable nature of the soil microbe, soil physicochemical factors including labile fractions from soil organic matter, and GHG emission responses to agronomic practices in sugarcane agriculture, which can be used to conceptualize future studies on the understanding of human decision-making for tropical soil sustainability.

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