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Soil attributes and crops productivity: changes due to the long time use of animal manure

Atributos do solo e produtividade das culturas: mudanças devido ao longo tempo de uso de dejetos animais

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RESUMEN

Dejetos animais (DA) podem ser utilizados como fonte de nutrientes para culturas e pastagens; promovendo ciclagem de nutrientes e reduzindo custos com aquisição de fertilizantes minerais. Além disso, espera-se que ao longo dos anos modifiquem os atributos químicos, físicos e biológicos do solo. Esta revisão aborda o efeito das aplicações de DA na interface solo-planta, enfatizando os aspectos: (a) características do DA que afetam os atributos edáficos, (b) mudanças nos atributos químicos, físicos e biológicos de solos com histórico de aplicações de DA, (c) efeito da aplicação de DA na produção e rendimento de biomassa das culturas. As mudanças nos atributos edáficos dependem das características do DA e das condições pedoclimáticas. As aplicações de DA no solo associadas a adubação mineral aumentam o carbono orgânico do solo e rendimento das culturas. Agregados, densidade e infiltração de água são favorecidos pela aplicação de DA com alta C:N. A macrofauna, atividade microbiana e biológica aumentam com a aplicação de DA. Finalmente, os aumentos de produtividade nem sempre acompanham a melhoria de todos os atributos edáficos. Os efeitos da aplicação de DA na qualidade do solo são mais pronunciados quando realizados de forma integrada com outras estratégias de manejo e conservação do solo.

Palavras-chave: dejetos suínos e bovinos; carbono orgânico do solo; agregação do solo; atividade biológica; culturas de grãos.

ABSTRACT

Animal manure may be used as a nutrient source for annual and perennial crops and pastures, promoting nutrient cycling and reducing costs with mineral fertilizers acquisition. Additionally, they are expected over the years to modify soil chemical, physical, and biological attributes. This review addresses the effect of animal manure applications on the soil-plant interface, emphasizing the following aspects: (a) animal manure characteristics that affect soil attributes, (b) changes in chemical, physical, and biological attributes of soils with a history of animal manure applications, and (c) effect of animal manure application on crop biomass production and yield. Changes on soil attributes depends on the animal manure and pedoclimatic characteristics. Animal manure applications in soil associated with mineral manure increase soil organic carbon and crop yield. Aggregates, density and water infiltration are favored by applying animal manure with high C:N. Macrofauna, microbial and biological activity increase with animal manure application. Finally, yield increases do not always accompany the improvement of all soil attributes. The effects of animal manure application on soil quality are more pronounced when carried out in an integrated manner with other soil management and conservation strategies.

Keywords: swine and cattle manure; soil organic carbon; soil aggregation; biological activity; grain crops.

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1. Introduction

Southern Brazil concentrates 49.7% of the country's swine production, 46.9% of poultry, 21.2% sheep, 26% of cattle, and 34.2% of milk (IBGE, 2018). That generates and leads to the accumulation of large volumes of animal manure. Application of animal manure to soils as a source of crop nutrients is a feasible procedure to improve crop yield, fruit quality, and soil attributes (Adugna, 2016; Parizotto et al., 2018; Assefa & Tadesse, 2019; Du et al., 2020; Gross & Glaser, 2021; Ferreira et al., 2021a, 2022), besides the disposal of waste from large-scale animal production areas. Animal wastes, such as swine, cattle, poultry, goats, horses, and sheep, are rich in carbon (C), macronutrients such as nitrogen (N), phosphorus (P), and potassium (K), and micronutrients, such as zinc (Zn), manganese (Mn), boron (B), copper (Cu), and iron (Fe). Animal waste has, therefore, have great potential for use in agriculture (CQFS RS/SC, 2016; Gatiboni & Nicoloso, 2019). Research on this topic has sought to elucidate how organic wastes affect soil chemical, physical, and biological properties (Loss et al., 2019a; Rayne & Aula, 2020; Bhunia et al., 2021). In Brazil, in the last decade, numerous studies have evaluated the effects of animal manure application on soil physical (Mellek et al., 2010; Assis Valadão et al., 2011; Homem et al., 2012; Comin et al., 2010; Comin et al., 2013; Barbosa et al., 2015; Andrade et al., 2016; Loss et al., 2017; Melo et al., 2019; Ferreira et al., 2021a; Francisco et al., 2021), chemical (Brunetto et al., 2012; Comin et al., 2013; Lorenzi et al., 2014a,b; Tiecher et al., 2016; De Conti et al., 2016, 2017; Eckhardt et al., 2018; Brunetto et al., 2018; Rigo et al., 2019; Benedet et al., 2020; Lourenzi et al., 2021), and biological (Mariotto et al., 2014; Cherubin et al., 2015; Moura et al., 2016; Morales et al., 2016; Oliveira Filho et al., 2018; Alves et al., 2018; Bertagnoli et al., 2020; Navroski et al., 2021; Ferreira et al., 2022) attributes.

In addition to benefits on soil attributes, the continued addition of animal manure to soils has agronomic importance, increasing land production capacity (Wang et al., 2016; Adugna, 2016; Rayne & Aula, 2020). Such knowledge is essential to assess environmental aspects, such as the magnitude of erosion and pollution processes that occur in areas that receive animal manure as a form of fertilization for crops and pastures, or even to prevent degradation and recover degraded soils (Yague et al., 2016; Hoover et al., 2019; Antoneli et al., 2019).

The changes in soil attributes resulting from animal manure application are due to the interaction between pedoclimatic conditions and characteristics of the organic wastes, in addition to the plant species (Adugna, 2016; Loss et al., 2019a). Besides, there is growing concern about soil health and sustainability, and, therefore, organic fertilizers derived from animals have gained importance as components of integrated plant nutrient management and their effects on soils biology and fertility (Bhunia et al., 2021). Consequently, the focus of that management system is on soil organic matter (SOM) management, involving the coordinated use of mineral fertilizers with organic inputs (Bandyopadhyay et al., 2010; Singh & Ryan, 2015).

Several types of manures are applied to soils as a source of nutrients to increase crop production and improve soil attributes, such as poultry litter and cattle and swine manure, either in liquid or solid form (Glatz et al., 2011; Parizotto et al., 2018; Alves et al., 2018; Eckhardt et al., 2018; Barth et al., 2020; Francisco et al., 2021). Cattle liquid manure applied to complement mineral fertilization increased soybean, wheat, and maize yield in a no-tillage system, and the best dose for all crops was 150 m^3 ha^{-1} year^{-1} (Barth et al., 2020).

In addition to crop yield increase and concerns about environmental quality deterioration, the growing use of organic materials in agricultural areas is also due to increases in fertilizer costs (Comin et al., 2013; Singh & Ryan, 2015). Therefore, instead of using chemically synthesized fertilizers, the application of animal manure, in appropriate doses and accordance with environmental regulation, may result in cost reduction, agro-environmental quality improvement, and better higher productivity, leading to a path towards sustainable agriculture (Bhunia et al., 2021).

This review aims to present the changes resulting from animal manure application, emphasizing the following aspects: (a) Characteristics of animal manure that affect soil attributes; (b) Changes in chemical, physical, and biological attributes of soils with a history of successive applications of animal manure; (c) The effect of animal manure on crop dry mass production and yield.

2. Animal manure characteristics affecting soil attributes

Soil is an open system, subject to the action of biotic and abiotic factors. Those factors contribute to increasing the complexity of interactions that naturally occur after animal manure application.

However, the intensity and rate of changes in soil physicochemical properties depend on animal manure amounts and characteristics, pedoclimatic conditions, and mode and frequency of manure application. State of the art indicates that the effects of animal manure application over successive years of cultivation on soil chemical, physical, and biological attributes still need to be better elucidated in Brazil (Antoneli et al., 2019; Loss et al., 2019; Loss et al., 2019a; Benedet et al., 2020; Francisco et al., 2021; Ferreira et al., 2021a,b, 2022). That is even more important in intensive production systems, carried out in contrasting soil types under tropical and subtropical climate conditions.

Quantity and quality of manure produced by swine, poultry, and cattle throughout the production cycles depend on the quantity and composition of ingested dry matter, feed digestibility and nutrient concentration, animal size, age, and type, climate conditions, and management system, type of deep litter used, and installation cleaning methods (Morse, 1994; Oliveira, 2002; Manitoba, 2015; Orrico Junior et al., 2011). Animal manure dry matter concentrations are 2.5% to 3.5% in liquid manure, up to 89% in poultry litter, and higher dry matter concentration results in higher nutrient content in wastes (Konzen & Alvarenga, 2005; Konzen, 2000; CQFS RS/SC, 2016; Gatiboni & Nicoloso, 2019).

Animal manures consist mainly of feces, urine, food waste, and wastewater from the facilities. As they are rich in carbon, macronutrients (Table 1), and micronutrients, manures have high fertilizing potential and, therefore, direct application to the soil as a source of plant nutrients is widely used in producing regions (Konzen, 2005; Gatiboni & Nicoloso, 2019). Including animal manures into the agricultural production system as a plant source, nutrients make it possible to maximize the system's efficiency, besides alleviation of their environmental impacts. Successive applications of animal manure led to changes in soil chemical (Brunetto et al., 2012; Benedet et al., 2020), physical (Comin et al., 2013; Francisco et al., 2021), and biological attributes (Rayne & Aula, 2020; Ferreira et al., 2022).

Animal manure composition (Table 1) has direct, short-term effects on soil physical-chemical behavior, affecting the electrical potential of colloids, which may affect clay flocculation or dispersion (Homem et al., 2012; Barbosa et al., 2015; Melo et al., 2019). The addition of animal manure can modify SOM dynamics and soil biological activity, carried out by micro, meso, and macrofauna, and root growth (Rayne & Aula, 2020; Bertagnoli et al., 2020). Those soil components affect fluxes of energy, carbon, and plant nutrients in the agricultural system (Braida et al., 2011). There are interactions between carbon total amounts and fractions (Comin et al., 2013; Andrade et al., 2016) and soil physicochemical behavior (Homem et al., 2012; Barbosa et al., 2015). Changes in SOM contents, cation exchange capacity (CEC), soil bulk density, and aggregate size and stability (Lourenzi et al., 2016; Loss et al., 2017; Francisco et al., 2021), as well as in microbial activity and diversity (Rayne & Aula, 2020) should be expected in medium and long terms.

In addition to primary macronutrients (N, P, and K) and OM content in varying concentrations (Table 1) (Konzen, 2000; Miyazawa & Barbosa, 2015; CQFS RS/SC, 2016), animal manures contain other nutrients, such as Fe, Zn, Mn, Cu, B, Ca and Mg.

They also have undigested feed components excreted by animals, which contain 55% to 95% of N and 70% of P ingested (Menzi et al., 2010).

Table 1

Mean concentration of dry matter (DM), organic carbon (OC), and nutrients (N, P, K, Ca e Mg) of some animal wastes

Anima waste	DM	OC	Total-N	P_2O_5	K_2O	Ca	Mg
	---------------- % (m/m)$^{(1)}$ -------------------						
Poultry litter (3 to 4 lots)	75	30	3.2	3.5	2.5	4.0	0.8
Poultry litter (7 to 8 lots)	75	25	3.8	3.0	3.5	4.5	0.9
Cattle solid manure	20	20	1.5	1.4	1.5	0.8	0.5
Swine solid manure	25	30	2.1	2.8	2.9	2.8	0.8
	---------------------- kg m^{-3} ----------------------						%
Cattle liquid manure	4	13	1.4	0.8	1.4	1.2	0.4
Swine liquid manure	3	9	2.8	2.4	1.5	2.0	0.8

(1) Concentration based on material dried in oven at 65 ºC; m/m= mass/mass ratio.

Source: Adapted from the Soil Chemistry and Fertility Commission (CQFS RS/SC, 2016).

This composition contributes to increases in N-NO3- and SOM contents and, consequently, N availability and exchangeable K, Ca, and Mg content, leading to increases in soil pH and base saturation and decreases in aluminum saturation (Lourenzi et al., 2011, 2016; Brunetto et al., 2012; Loss et al., 2019a).

Application of animal manure to soil results in more evident changes in soils that received manure applications with a higher C:N ratio, such as solid manure (Table 1). That directly affects soil attributes and crop growth and yield (Adugna, 2016; Loss et al., 2019a; Francisco et al., 2021). Studies carried out by Assis Valadão et al. (2011), Comin et al. (2013), Ferreira et al. (2021a), and Loss et al. (2021) reported increases in SOM contents and aggregation rates after the application of solid manure, such as swine or poultry litter, as compared with swine or cattle liquid manure. In soils managed in a no-tillage system, widely used in Southern Brazil, the application of animal manure to soils improves crop production and leads to increases in SOM. Consequently, soil microbial and enzyme activities are enhanced, minimizing adverse effects of C and emission N to the atmosphere by volatilization due to retention of C and N by microorganisms, plant biomass, and soil aggregates (Quadro et al., 2011; Loss et al., 2019a,b; Rayne & Aula, 2020; Francisco et al., 2021).

High additions of dry matter and carbon resulting from the application of animal manure, mainly solid manure (Table 1), results in the formation of large and stable aggregates (Loss et al., 2017; Ferreira et al., 2021a). Also, the manure's nutrients help increase plant shoot and root dry matter, improving soil properties due to the root systems, which aggregate soil particles and favor cementation due to exudate release. Organic compounds derived from plant residue decomposition and those derived from organic residues will contribute to increases in biological activity, CEC, and cementation of soil aggregates (Amezketa, 1999; Six et al., 2004; Loss et al., 2019b).

Pedoclimatic conditions directly influence animal manure, especially concerning the time of application, as they are directly related to manure mineralization and, consequently, nutrient availability to plants and potential losses to soil or water. Application of liquid animal manure in annual crops, such as soybeans, maize, and common bean, sown in late spring or early summer, can minimize nutrient run-off losses due to nutrient uptake by the crops, soil microbial activity, leaching, or evapotranspiration, as compared with manure application in autumn or winter (Ahmed et al., 2013).

On the other hand, some studies show adverse effects of animal manure addition on soil physical attributes since it can cause chemical changes to the soil, such as clay dispersion, due to the increase in negative charges (Barbosa et al., 2015; Melo et al., 2019). However, that depends on soil type, rainfall after application, amount of applied manure, and time between applications (Zhou et al., 2013; Barbosa et al., 2015; Loss et al., 2021). In general, manure total dry matter amount, C:N ratio, and concentration of organic carbon and macronutrients positively affect soil chemical, physical and biological attributes. Next, the main effects of the use of animal manure on soil attributes there will highlight.

3. Changes in soils with a history of animal manure application

3.1 Chemical attributes

Soil organic carbon (SOC) and pH-related atrributes

As animal manure have high organic carbon concentrations, they can cause quantitative and qualitative changes in SOC (Figure 1a) and its chemical and physical attributes (Ceretta et al., 2003; Hernández et al., 2006; Lourenzi et al., 2011; Loss et al., 2017; Ventura et al., 2018; 2020; Ferreira et al., 2022).

A study assessing total C contents in soil aggregates, and also C contents in humic (humic acid, fulvic acid, and humin) and granulometric (particulate C and associated with minerals) fractions in a sandy soil (Typic Hapluldut) receiving swine deep litter and swine liquid manure applications for ten years in NTS, found that successive applications of swine deep litter increased SOC and C contents of particulate and mineral-associated organic matter; C from humin, fulvic acid, and humic acid, in comparison with the control (without fertilization) or swine liquid manure (Ventura et al., 2018, 2020). Melo et al. (2019) also found higher contents of SOC and C in humic fractions (humic acid, fulvic acid, and humin) in aggregates of a clayey soil (Rhodic Hapludox) in no-tillage system submitted to 10 years of chicken litter applications or SLM than in the control treatment.

The addition of animal manure to the soil under NTS for a long time (2009-2020) increases the accumulated carbon in the soil (Ferreira et al., 2022).

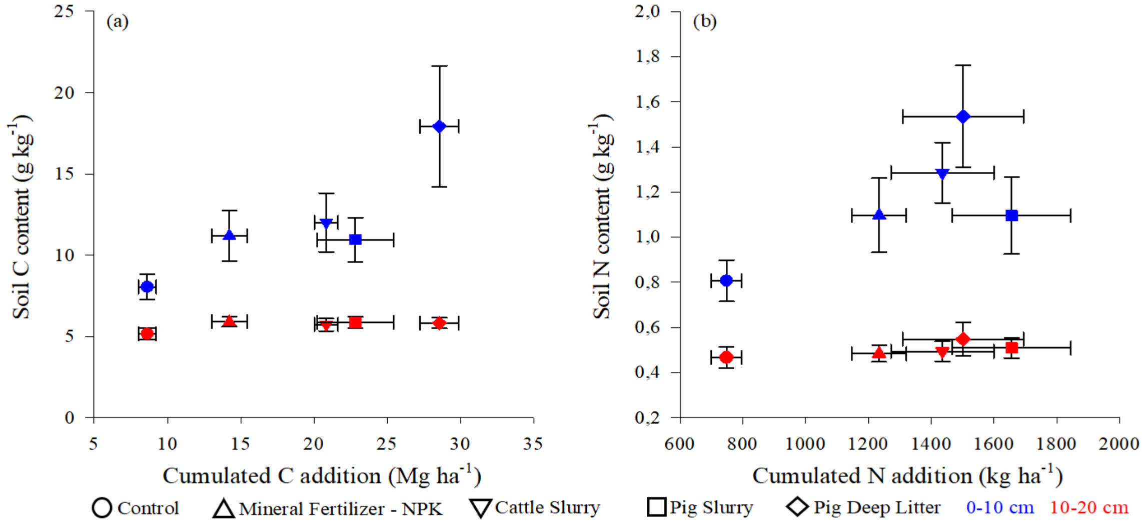

Figure 1. Changes in soil test C (a) and N (b) during the 2009–2020 period in the 0–0.1 and 0.1–0.2 m layers, respectively, as impacted by treatments. Error bars represent standard errors of the means. n=16. Source: Adapted from Ferreira et al. (2022).

According to these authors, the addition of pig slurry, cattle slurry and pig deep-litter increased the accumulation of C in the soil compared to the Control and mineral fertilization (NPK) treatments. This increase ranged from 10 to 15 Mg ha^{-1} of C in the cattle slurry, pig slurry and pig deep-litter treatments, respectively, compared to the control; and ranged from 5 to 15 Mg ha^{-1} of C in the cattle slurry, pig slurry and pig deep-litter treatments, respectively, compared to NPK, at depths of 0-10 and 10-20 cm (Figure 1a).

In conservationist systems such as no-tilage, pastures, and orchards, animal manure is applied onto crops and their residues, and the microbial biomass activity will stimulate C accumulation on the upper soil layers (Adeli et al., 2008; Comin et al., 2013; Lourenzi et al., 2016). The soil C increases are more pronounced in degraded soils and depend on the residue composition and application frequency and quantities over the years (Falleiro et al., 2003; Lourenzi et al., 2011). However, part of the nutrients present in animal manure can be uptaken by plants, increasing root and shoot dry matter production, which can also increase the number of residues and, consequently, C incorporated into the soil (Ciancio et al., 2014; Lourenzi et al., 2014a; Geng et al., 2019). That increase in soil C contents can increase soil CEC values (Brunetto et al., 2012; Lourenzi et al., 2016; Ferreira et al., 2021b, 2022). Animal manure can also modify attributes related to soil acidity (Adeli et al., 2008; Lourenzi et al., 2011; Brunetto et al., 2012), and increase soil pH values, as they have CaCO3 in their composition, which is dissociated, increasing Ca and OH^- in the soil solution (Whalen et al., 2000; Chantigny et al., 2004). In addition, manure has Ca and Mg and can contribute to increasing soil base saturation (Ceretta et al., 2003; Assmann et al., 2007; Lourenzi et al., 2011). Humic and fulvic acids can adsorb H^+ and Al^{+3}, contributing to increasing pH values and reducing Al^{3+} saturation and toxicity (Hue & Licudine, 1999; Lourenzi et al., 2011). Furthermore, organic acids, derived from manure mineralization, SOM or plant residues decomposition, increase Al^{+3} complexation and precipitation, and part of the Al^{+3} in soil solution can be complexed by phosphate ions, present in large amounts in animal manure (De Conti et al., 2017).

Nitrogen, potassium, and phosphorus

N, P, and K are present in animal manure, such as swine and cattle liquid manure, swine deep litter, poultry litter, organic compost, and others (Comin et al., 2013; Lourenzi et al., 2013; Ciancio et al., 2014; Lourenzi et al., 2016; Ventura et al., 2018; Melo et al., 2019; Ferreira et al., 2022). In swine liquid manure, for example, approximately 50% of the N is in mineral form (Basso et al., 2005; Aita et al., 2006), with the remainder in organic form. As these manures have pH values close to neutrality, N losses by ammonia (NH_3) volatilization are increased in storage sites and soils subjected to manure application (Scherer et al., 1995; Basso et al., 2004). The manure mineral N, especially as ammonium (NH_4^+), is transformed to nitrite (NO_2^-) and nitrate (NO_3^-) after application to the soil (Chantigny et al., 2001; Aita et al., 2006). This rapid transformation of NH_4^+ into NO_3^-, added to mineralization of manure organic N, increases

NO_3^- levels - in the soil, especially in the first days after manure application (Chantigny et al., 2004; Assmann et al., 2007; Adeli et al., 2008).

The increase in mineral N availability, especially NO_3^-, in the soil can increase losses of this N form by surface runoff, which generally occurs in areas with a history of manure application on the soil surface (Ceretta et al., 2010a; Lourenzi et al., 2021). Another form of loss is leaching, more relevant in soils with low organic matter and clay contents, which decrease the probability of NO_3^- adsorption (Girotto et al., 2013a). Thus, soils should remain with plants with a high N demand, such as grasses, favoring uptake, plant biomass increase, and N accumulation in plant tissues. On the other hand, well structured and aggregated soils can protect N and C inside aggregates, as observed by Ventura et al. (2018, 2020) and Melo et al. (2019), who found higher total C and N, and C and N from humin, fulvic and humic acids in aggregates of soils receiving swine deep litter, swine liquid manure, and poultry litter for ten years in no-tillage system.

The addition of animal manure to soil under NTS for a long time (2009-2020) increases the nitrogen accumulated in the soil (Ferreira et al. 2022). According to these authors, the addition of pig slurry, cattle slurry and pig deep-litter increased N accumulation in the soil compared to control and NPK treatments. This increase ranged from 600 to 800 kg ha^{-1} of N in the cattle slurry, pig slurry and pig deep-litter treatments, respectively, compared to the control; and ranged from 200 to 250 kg ha^{-1} of N in the treatment's cattle slurry, pig slurry and pig deep-litter, respectively, compared to NPK, at depths of 0-10 and 10-20 cm (Figure 1b).

Animal manure has significant amounts of P (Assmann et al., 2007; Ceretta et al., 2010b; Lourenzi et al., 2014b; Lourenzi et al., 2016), with part of this nutrient is in mineral forms, readily available to plants, and part in organic forms, requiring mineralization. Studies carried out in areas with a long history of cultivation and manure applications, such as areas under no-tillage system in Southern Brazil, showed increases in the soil available P, contributing to plant nutrition (Scherer et al., 2010; Ceretta et al., al., 2010b; Lourenzi et al., 2013; Lourenzi et al., 2016; Rigo et al., 2019; Mergen Junior et al., 2019a; Melo et al., 2019).

Successive applications of animal manure over the years change P distribution in different fractions and, especially, in sandy soils, P increments in labile fractions (Hedley et al., 1982), such as P extracted by anion exchange resin and sodium bicarbonate (Ceretta et al., 2010b; Guardini et al., 2012). Thus, manure application can increase P availability to plants and potential P transfer in the environment, for example, by runoff (Ceretta et al., 2010a, Lourenzi et al., 2014b). Such transfer can involve available or even particulate P, corresponding to P adsorbed with different energy degrees to functional groups of inorganic particles (Lourenzi et al., 2015; 2021). P losses by leaching in soils with a history of manure applications, such as those from subtropical regions, are negligible (Girotto et al., 2013a; Lourenzi et al., 2014b).

P content increase in soils with continuous animal manure application led Gatiboni et al. (2014) to propose P environmental critical limit (ECL-P), initially for soils in Santa Catarina state. ECL-P is a function of soil clay content, representing approximately 80% of soils' ability to retain P (determined by Mehlich 1 extraction method). Thus, Mehlich 1-extracted P concentrations above the ECL-P indicate a high risk of water contamination due to the transfer of P by leaching and, mainly, surface runoff, leading to water eutrophication and reduction in water potability. The ECL-P estimation has been improved, and the trend is to propose more robust estimation models, with more variables, in addition to clay content (Dall'Orsoletta et al., 2021).

Animal manures are also a source of K, which usually is present in the K+ form. Therefore, K present in manure is quickly released, which can increase its contents in the soil solution in available forms (Scherer et al., 2010; Lourenzi et al., 2016). As plants uptake high amounts of K, manure applications cannot always adequately supply the nutritional demand of most crops, which can use the soil reserve, as found by Lourenzi et al. (2013). Those authors evaluated chemical attributes of a Typic Hapluldut after 19 applications of swine liquid manure at doses of 0, 20, 40, and 80 m^3 ha^{-1}, and found that Mehlich 1-extracted K was lower in all doses of swine liquid manure than at the experiment began. Thus, K losses to the environment are usually not significant and, when they do occur, they tend to be by surface runoff of manure residues or inorganic particles (Ceretta et al., 2010a).

Application of animal manure can increase K contents in soil aggregates. An evaluation of K contents in aggregates of sandy soil (Typic Hapludult) and a clayey soil (Rhodic Hapluldox) in the 0-10 cm layer in no-tillage system found higher K contents in soil aggregates subjected to 10 years of swine liquid manure, swine deep litter, and poultry litter applications, as compared with the control (Mergen Junior et al., 2019a; Melo et al., 2019).

Heavy metals and trace elements

Animal manure has metals in its composition, such as Cu, Zn, Mn, and others, mainly derived from animal feed. After application of manure to the soil, Cu and Zn can be adsorbed to colloids by physicochemical bonds, whose lability depends on the content of minerals, Fe, Al, and Mn oxides and hydroxides, carbonates, pH, CEC, and SOM concentration, and quality (Brunetto et al., 2014). Part of Cu and Zn can be adsorbed on sites with high binding affinity, with reactive functional groups present in soil mineral and organic phases, forming inner-sphere complexes. The remainder is distributed in fractions with lower binding energy, such as the soluble and exchangeable fractions (Tessier et al., 1979), which have higher lability and mobility in the soil profile (Brunetto et al., 2016).

Chemical fractionation of soil Cu and Zn allows estimation of soluble, exchangeable forms linked to organic matter or minerals and residual forms (Tessier et al., 1979; Brunetto et al., 2018). The successive manure applications lead to increases in Cu and Zn forms in soils under no-tillage system, along with increases in soluble and exchangeable forms (Girotto et al., 2010; Tiecher et al., 2013; Brunetto et al., 2018). That may increase the potential toxicity of these elements to plants (Girotto et al., 2013b; Tiecher et al., 2016) and enhance the transfer of Cu and Zn by surface runoff, to surface water (Girotto et al., 2013b).

In areas with a history of animal manure applications, the soil solution has high concentrations of organic acids derived from manure or plant residue decomposition, affecting soluble organic carbon. These processes can increase Cu and Zn complexation in the solution, changing the distribution of chemical species, with significant decreases in Cu^{+2} (De Conti et al., 2016). In soils with animal manure applications, much of the Cu in solution is bound to SOC, and that also happens with Zn, which frequently interacts in solution with phosphate ions derived from applied manure (De Conti et al., 2016).

Most of the Cu in soils with a history of applying various animal wastes is complexed in SOM, usually followed by adsorption to the soil mineral fraction. That happens because Cu electronic configuration [Ar]3d104s1 makes this element highly reactive with functional groups of decaying organic materials and SOM that contain S, N, carboxylic and phenolic functional groups (Casali et al., 2008; Couto et al., 2016). That reduces desorption and, consequently, metal mobility in the soil profile. On the other hand, Zn is more adsorbed to the mineral fraction, linked to an increase in the organic fraction (Tiecher et al., 2013).

The furthermore, part of the Zn is in residual forms, similarly to Cu. Mineral and residual forms are more stable and have low availability and mobility, which can minimize the potential for environmental contamination in soils and reduce toxicity to plants (Tiecher et al., 2013; Brunetto et al., 2018).

3.2 Physical attributes

Aggregate stability, soil bulk density, and water infiltration and retention

It is well documented that long-term application of animal manure affects soil physical attributes, such as aggregation (Haynes & Naidu, 1998; Celik et al., 2010; Rauber et al., 2012; Comin et al., 2013; Adugna, 2016; Loss et al., 2017, 2019a, 2021), soil bulk density (Celik et al., 2010; Comin et al., 2013; Adugna, 2016; Loss et al., 2017; Rayne & Aula, 2020), and water infiltration and retention (Haynes & Naidu, 1998; Adugna, 2016; Loss et al., 2019a; Rayne & Aula, 2020). Those effects of continuous manure application on soil physical attributes may be related to increases in SOM or SOC contents (Rauber et al., 2012; Comin et al., 2013; Loss et al., 2021; Francisco et al., 2021), as well as characteristics that each manure has, such as C:N ratio and dry matter content (Table 1).

However, the effects of organic matter additions on soil physical attributes vary with climate, soil type and texture, manure amount, and organic matter quality. Rauber et al. (2018) found that soil management systems and time of application of organic residues affected soil physical attributes, and the physical indicator with the highest sensitivity was soil porosity. Total clay content and flocculation rate formed a second group of physical indicators to separate land-use systems.

Changes in soil physical attributes generally require a higher number of organic residues than those recommended to meet plant nutrient needs, and organic matter quality is more relevant than the amount applied regarding effects on soil aggregate stability (Tisdall & Oades, 1980).

Soil aggregate stability is the ability of aggregates to resist an external pressure, which can be expressed as wet stability and mechanical stability. Changes in macroaggregate class distribution and their stability in water have been observed with successive applications of animal manure (Li et al., 2011; Rauber et al., 2012; Comin et al., 2013; Du et al., 2014; Are et al., 2017; Mergen Junior et al., 2019b; Loss et al., 2017, 2021; Francisco et al., 2021). In a study to evaluate the effects of eight years of swine liquid manure and swine deep litter application on physical attributes and SOC of a Typic Hapludult, Comin et al. (2013) found that swine deep litter application, compared to swine liquid manure, favored the formation of aggregates with a diameter > 4 mm, increasing aggregation rates and aggregate stability. In the evaluation of the effect of injecting swine liquid manure at a 10-cm depth into the soil in comparison with swine liquid manure surface application, NPK, and control treatment, for five years, on soil aggregation, Francisco et al. (2021) found an increase in geometric mean diameter in the 0-5 cm layer with the injection of swine liquid manure in a Typic Hapludult, as compared with the other treatments. In the 5 to 10 cm layer, swine liquid manure injection led to an increase in geometric mean diameter and macroaggregate mass compared to the NPK treatment. In another study evaluating 11 years of applications of swine liquid manure, swine deep litter, and cattle liquid manure, compared to the use of NPK or no fertilization (control), Loss et al. (2021) found increases in weighted mean diameter and geometric mean diameter in the surface layer of a Typic Hapludult with the use of animal manure. However, manure use promoted clay dispersion in the 5-10 and 10-20 cm layers, resulting in lower soil aggregation in depth compared to the control treatment in no-tillage system.

The work by Ferreira et al. (2021a) showed that a 4-year application of swine manure, alone or combined with chemical fertilization, led to an increase in SOC and total N contents in aggregates of a Typic Hapludult, but it did not increase soil aggregation indexes. In the 5-10 cm layer, there was a decrease in weighted mean diameter and geometric mean diameter compared with the control treatment, and microaggregate mass increased in all treatments. The authors attributed these results to negative ΔpH values and increased clay dispersion. However, such an effect of animal manure on aggregate stability was not reflected in crop production. According to Loss et al. (2021), the lowest aggregation indices (weighted mean diameter and geometric mean diameter) found in the 5-20 cm depth layer in the treatments with animal manure did not affect the root development of crops (maize, soybeans, and wheat) in a no-tillage, because highest yields occurred in treatments with manure than in control or NPK treatments. In addition to the higher yields of maize, soybeans, and wheat with manure addition, there were also levels of SOC and total N in deeper soil layers, and that could compensate for lower aggregation found in treatments with animal manure.

Animal manure addition can promote the formation of soil biogenic aggregates, lowering physicogenic aggregates (Melo et al., 2019; Mergen Junior et al., 2019b). In the same works, the addition of swine liquid manure, swine deep litter, and poultry litter increased the formation of biogenic aggregates compared to physiogenic aggregates, in contrast with the control area, which had higher proportions of physiogenic aggregates. The application of swine liquid manure did not change weighted mean diameter and macroaggregates (8.0-2.0 mm) distribution compared to the control, while swine deep litter application increased those parameters compared with swine liquid manure and control treatments.

Animal manure application ability to increase SOM or SOC contents and decrease soil bulk density in upper soil layers is widely known (Celik et al., 2004; Hati et al., 2006, 2008; Mellek et al., 2010; Comin et al., 2013; Andrade et al., 2016; Are et al., 2017, 2018). In a study to assess the potential of poultry manure and biochar to improve physical attributes in degraded soil, Are et al. (2018) found, after two years of applications, that bulk density was 8.8%, 6.9%, 8.1%, and 10.0% lower in the treatments with composted poultry manure + vetiver grass prunes, non-composted poultry slurry, solid non-composted poultry manure, and poultry biochar, respectively than in the control treatment. Compared with the initial bulk density value, which was 1.51 Mg m-3, the treatments reduced bulk density by 3.1%, 1.3%, 2.5%, and 4.4%, respectively, while bulk density in the control treatment increased by 6.0%. The authors also generated a soil physical quality index and found an increase in this index in the poultry manure compost and non-composted and biochar treatments. They attributed the results to the effect of SOM, which improved soil structure and porosity, and water movement (transmission) and storage because there was a close relationship between SOC and many soils physical attributes. This effect was also found by Li et al. (2011) in a study on the effects of poultry litter and cattle manure on physical attributes of Typic Gleyi-Stagnic Anthrosols, and there were significant linear correlations ($p < 0.01$) between SOC and most of the physical properties studied.

Cattle manure application associated with mineral fertilizers (NPK) for three years in a Typic Haplustert reduced bulk density values in the 0-7.5 cm and 7.5-15 cm layers from 1.30 Mg m^{-3} and 1.34 Mg m^{-3} to 1.18 Mg m^{-3} and 1.24 Mg m^{-3}, respectively, concerning the control treatment (Hati et al., 2006). Those authors stated that the bulk density decrease was due to higher SOM content, better aggregation, and increased root growth in the treatment with organic fertilizer associated with chemical fertilization compared to the control. A long-term study using swine liquid manure and swine deep litter, Comin et al. (2013) found an inverse relationship between SOC and bulk density, with bulk density being low in all treatments in the 0-5 cm layer, and swine liquid manure application for eight years in a Typic Hapludult did not change soil physical attributes and SOC, while swine deep litter application increased SOC and decreased bulk density up to the 10-cm layer.

Measures to improve water infiltration and retention processes are fundamental for agricultural productivity. The main processes affecting water infiltration and retention in soils are texture, structure, porosity, organic matter content, clay type, retention capacity and hydraulic conductivity, precipitation, humidity, temperature, compaction, and surface roughness. Therefore, it is necessary to adopt management practices that promote SOM addition associated with management systems and conservation practices (Pan et al., 2018).

SOC is the attribute most frequently reported in long-term studies since it is the most important indicator of soil quality and agronomic sustainability due to its impact on other physical, chemical, and biological soil quality indicators. Long-term studies have consistently shown the benefits of animal manure application, adequate fertilization, and crop rotation to maintain productivity by increasing soil carbon inputs (Reeves, 1997). SOC also has a direct relationship with aggregate formation and stability (Tisdall & Oades, 1982; Oades, 1984), water storage capacity (Haynes & Naidu, 1998, Gülser and Candemir, 2015), and water infiltration in soils (Haynes & Naidu, 1998; Jung et al., 2007; Adeyemo et al., 2019).

Literature reviews have shown that application of animal manure to the soil increases SOC contents, aggregate stability, soil porosity, permeability, hydraulic conductivity, and soil water storage capacity, as well as reduced bulk density and crust formation (Haynes & Naidu, 1998; Assefa & Tadesse, 2019; Ventura et al., 2018; Mergen Junior et al., 2019a, Melo et al., 2019).

Increasing doses of poultry manure to two Alfisols (clay loam and sandy clay loam, respectively) in southwestern Nigeria led to increases in accumulated infiltration rates and SOM content compared to the control treatment (Adeyemo et al., 2019). Application of 10 Mg ha^{-1} of poultry manure provided higher SOM content than the other doses applied to both soils, and with increasing doses, accumulated rate of water infiltration was reduced in the sandy clay loam and increased in clay loam.

Evaluating how increasing manure doses (7.5 t ha^{-1}, 15 t ha^{-1}, and 22.5 t ha^{-1}) combined with fixed levels of chemical fertilizers compared with chemical fertilizers affected maize growth and rainwater use efficiency in semi-arid conditions over three years, Wang et al. (2016) observed that the medium and high manure doses significantly increased soil water storage (0-120 cm) in the maize tasseling phase than the lower dose of manure and chemical fertilizer. The dry matter accumulation and rainwater use efficiency increased with the manure doses.

Evaluating the effects of cattle manure application on a sandy soil (Haplic Lixisol) soil aggregate stability and water holding capacity for three years, Nyamangara et al. (2001) found a 10–38% increase in SOC and the aggregate stability in the 0–10 cm layer compared to the control treatment. There was also an increase in readily available water capacity (moisture difference at 5 and 1500 kPa), but the increase in the actual water capacity (moisture difference at 5 and 200 kPa) was not significant. The increase in soil water retention capacity was more affected by low suction, which is related to the effects of manure on soil macroporosity.

In a test on how much soil water retention depends on SOC content and what is the impact of changing the SOM content on transpiration in soils in the Sierra Nevada basins, which are generally thin, shallow, and have limited storage capacity water, despite a thick top layer rich in organic substances, Kyle et al. (2016) found that soil water retention, particularly saturated moisture content, depends substantially on SOM contents. The measured retention curves indicated that increasing SOM content increases plant-available water. The modeling analysis indicated that the increase in SOM content, besides affecting water available to plants, also influences the time and duration of water stress.

3.3. Biological attributes

Microbial diversity and activity, enzymes, and soil fauna

Soil biological communities are affected by management, plant species, fertilizer amount, and forms (Steinberger & Shore, 2009). The amounts and quality of organic materials, as well as soil physical (texture, aeration, and moisture) and chemical (pH, CEC, nutrients, C:N ratio) attributes, affect microbial abundance and diversity (Pavinato & Rosolem, 2008). Therefore, microbiota assessments can indicate positive or negative impacts of agricultural practices. Stress situations trigger physiological responses in microorganisms that affect soil microbial community performance. Changes in soil microbial communities can be assessed through variables such as microbial biomass, basal respiration, metabolic quotient, and enzyme activity (Steinberger & Shore, 2009; Anderson & Domsch, 2010).

Microbial biomass, the total amount of microorganisms in each volume of soil, is defined as the living component of organic matter and is mainly composed of fungi and bacteria. It carries out soil biological activity soil and is the primary source of enzymes that catalyze transformations occurring in that environment (Vezzani & Mielniczuk, 2009). Changes in microbial biomass occur in days, while SOM content changes can take decades (Silva & Mendonça, 2007). Microbial biomass in soils fertilized with swine manure increases compared to soils without organic fertilizer (Saviozzi et al., 1997; Plaza et al., 2004). Moura et al. (2016) found an increase in microbial biomass and respiration with swine manure application to soils in Southern Brazil. In a long-term experiment in the same region, there were increases in SOC and nitrogen contents and soil microbial biomass and respiration when the soil received swine manure in liquid form and especially as swine deep litter (Morales et al., 2016). The use of swine liquid manure led to higher qCO_2 greater than the addition of swine deep litter, indicating that residues with a high C/N ratio reduce the stress in soil microbiota. Several concomitant factors can explain such changes. The addition of microorganisms as animal manure contributes to increases in microbial biomass carbon, and labile compounds, with low molecular weight and easy transport across cell membranes. Those processes increase the resources available to microorganisms, which can multiply due to favorable conditions temporarily created by animal manure addition. However, this source is depleted over time, and the microbial community changes, favoring species able to decompose more complex or recalcitrant materials (Mcguire & Treseder, 2010).

Microbial basal respiration, measured by CO_2, is an indicator of biological activity, as it reflects organic matter decomposition and soil nutrient cycling (Parkin et al., 1996). There is an increase in CO_2 flux and microbial activity in the first days after swine manure application, with subsequent decreases to values close to those found in soils without fertilization (Plaza et al., 2007; Guerrero et al., 2007). On the other hand, there may be increases in the release of CO_2 with increased swine manure doses (Morales et al., 2016). Generally, high values of basal respiration indicate intense microbial activity since CO_2 flux correlates with catabolic processes' intensity. However, high microbial basal respiration may also indicate SOM losses, especially in situations where C inputs to the soil, by plant residues or other sources of organic matter, are smaller than the outputs. Such situations are undesirable because the decomposition of stable organic matter is detrimental for several soil attributes, such as aggregation, CEC, and water retention. Thus, the information provided by basal respiration must be interpreted together with other parameters that help to understand the processes occurring in soils (Parkin et al., 1996).

The metabolic quotient or specific respiration ratio (qCO_2) is the ratio of respiration to microbial biomass. This indicator, proposed by Anderson & Domch (1990), expresses the efficiency of microorganisms in converting a substrate into cellular tissue. High qCO_2 values indicate low efficiency in C, i.e., higher CO_2 losses and slower microbial growth rates (Anderson & Domch, 1990, 2010; Sparling, 1997). qCO_2 is used to assess environmental effects on soil microbiota since stress conditions decrease efficiency in substrate use by microbial communities (Islam & Weil, 2000). However, qCO_2 can be affected by changes in microbial community structure, substrate availability and immobilization, and varying environmental conditions (Sparling, 1997). The qCO_2 index was used to evaluate the effects of organic fertilization on soil microorganisms (Leita et al., 1999; Plaza et al., 2004, 2007; Assis et al., 2007; GE et al., 2009). Moura et al. (2016) found an increase in qCO_2 with an application of swine manure to soils in Southern Brazil. However, qCO_2 values measured by different researchers in soils receiving manure are contradictory (see, for example, Leita et al., 1999 and Plaza et al., 2004). As there are no clear patterns of behavior, the management system of these soils may have a more significant influence on qCO_2 than the fertilization regime as a sole factor (Islam & Weil, 2000). That leads to the need also to evaluate more specific soil processes related to nutrient and energy fluxes.

Enzymes participate in nutrient cycling in soils and are mainly synthesized by microorganisms; they may be intracellular, which perform catalytic functions inside the cell, and extracellular, excreted to the soil matrix (Laad, 1978). Extracellular enzymes are usually hydrolases that degrade organic compounds into smaller particles, assimilable by cells (Allison et al., 2011). Some extracellular enzymes can persist in the soil environment by adsorption to soil particles, such as clays, or copolymerization with organic compounds. Therefore, in the soil matrix, there may be enzymes that preserve their biological structure and function, remaining outside the cellular control and acting in the initial breakdown of organic macromolecules (Laad, 1978). Enzyme production involves costs and benefits for microorganisms, which depend on environmental conditions, enzyme type, and the substrate they metabolize. The most important benefits for microorganisms are the release of organic monomers or mineral nutrients. Costs include metabolic energy for its production and excretion, a process in which a cell may invest 15% of its C and N (Allison et al., 2011). That high energy cost means that the production of extracellular enzymes has implications at the ecosystem level since it will only occur in situations where the breakdown of complex substances is the sole nutrient source. That pattern suggests that the release of a nutrient from complex organic sources decreases in the presence of less complex forms of that nutrient (Laad, 1978; Arnosti, 2003; Allison et al., 2011). Microbial enzyme activity is sensitive to changes in soil management, including the use of harvest residues, fertilizer application, soil compaction, tillage, and crop rotation. Therefore, enzyme activity has informative potential about the positive and negative effects of agricultural practices have on soils (Dick et al., 1996). As soil enzymes are present in low concentrations, their quantification is performed by their activity, evaluated by the breakdown of a specific substrate (Tabatabai, 1994).

In soil, the most evaluated enzymes are those involved in carbon, nitrogen, phosphorus, and sulfur cycles, as these are the main constituents of organic matter. ß-Glucosidase is involved in the carbon cycle and acts in the hydrolysis of cellobiose and oligosaccharides, releasing glucose as a final product (Das & Varma, 2011). Phosphatases, which act in phosphorus mineralization, are inducible, i.e., synthesized when there is low availability of soil inorganic phosphorus (Allison et al., 2011). Sulfatases act in the sulfur cycle, and the most important is arylsulfatase, which hydrolyzes organic sulfates in soils with low sulfur concentrations (Das & Varma, 2011). Fluorescein diacetate hydrolysis estimates total soil enzymatic activity since this substance is metabolized by soil proteases, lipases, and esterase’s, all of which are involved in organic matter decomposition (Schnurer & Rosswall, 1982). In soils receiving liquid swine manure, Balota (2011) found the higher activity of acid phosphatase and arylsulfatase in no-tillage soil than in soils with conventional tillage. Few studies have evaluated soil enzyme activity in soils with swine manure applications. Therefore, more information is needed to understand enzyme response patterns to the addition of organic materials. Morales et al. (2016) demonstrated that phosphatase and beta-glucosidase activity, although not differently affected by the addition of swine liquid manure or swine deep litter, increased over time and strongly correlated with soil microbial biomass. Souza et al. (2020) observed that fluorescein diacetate is an early indicator of improvement in soil attributes. Soil enzyme activity, specifically b-glucosidase and arylsulfatase, is included in Soil Quality Indicators for tropical soils (Mendes et al., 2021). The adoption of enzyme activity, integrated with other soil attributes to evaluate agricultural management and soil quality is a promising avenue of research.

Soil biota diversity is affected by soil management, including the addition of organic residues. Numerous studies show the effects of animal manure on soil microbiota or mesofauna. Cherubin et al. (2015) showed that swine liquid manure increases microbial biomass and soil mesofauna diversity, but in general, the studies refer to the soil microbiota of soil mesofauna and macrofauna. Many studies use mesofauna as an indicator of soil quality. Alves et al. (2008) observed that the highest diversity of soil macrofauna occurred in the treatment with organomineral fertilization, more than with high doses of swine manure. Soil cover or stubble quantity and quality affect soil macrofauna abundance and diversity. Application of swine liquid manure led to increases (Silva et al., 2016a) or decreases (Silva et al., 2016b) in springtails in soils, and those site-specific effects modified the soil fauna diversity indices.

Segat et al. (2020) used increasing doses of swine manure, which caused springtail mortality, indicating manure toxicity. Liu et al. (2017) found that C-rich organic fertilizers promote a more structured nematode community and preserve ecological resilience, while N-rich animal manure protects crops against plant-attacking nematodes. Oliveira Filho et al. (2018) evaluated soil fauna in areas with 5 to 22 years of animal manure application; mites, springtails, and earthworms were most affected by soil management and manure addition, and mesofauna and macrofauna populations seemed to be predominantly affected by SOM and copper contents. Studies with mesofauna in general work as indicators for longer times, and that is why many works assess the soil microbiota, which responds more promptly to soil management.

Since it is evident that increasing organic residues increase soil microbial biomass (see, for example, Rayne & Aula, 2020), researchers have analyzed the effects of manure application on soil microbial diversity. Application of swine liquid manure to the soil for eight years increased the predominance of certain groups of soil bacteria, evaluated by the DGGE technique, suggesting that raw manure can significantly affect soil microbial diversity (Moura et al., 2016). Bertagnoli et al. (2020) showed that after six years, the addition of poultry litter increased the density of extraradicular hyphae of arbuscular mycorrhizal fungi and the glomalin content of the soil, compared to mineral fertilization and the addition of swine liquid manure. Such effects were related to improvements in soil physical attributes, such as aggregate size.

Ashworth et al. (2017) found that manure addition affected soil bacterial communities more than cover crops, suggesting the potential of animal manure to drive soil microbial diversity. Yang et al. (2019) showed that the addition of poultry litter and cattle manure increase soil microbial diversity, evaluated by high-throughput sequencing, but diversity changes also depended on the grazing systems used in different areas. Navroski et al. (2019) used DGGE to analyze bacterial and fungal diversity in soils receiving swine liquid manure; higher manure doses increase in diversity, bacterial, and archaeal community structures were less affected by the interruption in manure application in fungal communities, which had its diversity reduced due to the increased dominance of some species. In Southern Brazil, swine liquid manure application decreased microbial diversity, evaluated by 16S rRNA sequencing, but those changes were temporary; the metabolically active microbial community was resilient, recovering to the original status seven weeks after manure application (Suleiman et al., 2016). In short, the addition of animal manure affects soil microbial diversity, but such an effect must be evaluated along with other soil traits, such as chemical and physical attributes.

4. Effect of animal manure on crop productivity and dry matter production

4.1. Animal manure and crop productivity

The use of animal manure as a source of nutrients in agricultural crops is an alternative to mineral fertilizers, besides giving appropriate destination to those residues within the production unit itself, promoting nutrient cycling and cost reduction (Dordas et al., 2008; Geng et al., 2019; Locatelli et al., 2019). In this sense, research to assess the potential of animal manure as fertilizers under different soil and climate conditions shows that crops such as maize, beans, wheat, and soybeans have significant yield increases.

In Southern Brazil, studies show positive effects of organic fertilizers on grain and dry matter yields in various crops (Ceretta et al., 2005; Paldolfo & Veiga, 2016; Freitas Alves et al., 2017; Ferreira et al., 2021a). Lourenzi et al. (2014a) evaluated the effect of increasing swine liquid manure doses on grain yield in three maize (Zea mays) and two black beans (Phaseolus vulgaris) crops grown in no-tillage system. The authors found high maize grain yields with the highest manure dose, with average yields of 1.90, 4.50, 5.97, and 9.13 Mg ha^{-1} of grains with swine liquid manure doses of 0, 20, 40, and 80 m^3 ha^{-1}, respectively. Black beans highest yield occurred with doses of 20 and 40 m^3 ha^{-1}, with an average yield of 1.03, 2.15, 2.15, and 2.00 Mg ha^{-1} of grains with doses of 0, 20, 40, and 80 m^3 ha^{-1} of swine liquid manure, respectively. That shows that crop nutrient requirement is one of the main factors to consider when defining the doses of organic fertilizers.

In addition, studies evaluating different organic nutrient sources also demonstrate the efficiency of these sources to increase crop yield. In work using swine liquid manure, swine deep litter, cattle liquid manure, and mineral fertilization, the highest grain yield in maize and black beans crops occurred with swine deep litter application (Ciancio et al., 2014). For maize, the average grain yield in three harvests was 2.80, 6.49, 7.64, 5.90, and 4.91 Mg ha^{-1}, while for black beans, in a single harvest, it was 0.70, 1.89, 2.94, 2.13, and 1.07 Mg ha^{-1} for the control, swine liquid manure, swine deep litter, cattle liquid manure, and mineral fertilization, respectively. These results show that animal manure characteristics are also important for crops response because, in addition to the amounts of applied nutrients, the rate of manure mineralization, slow in solid waste such as swine deep litter, stimulates the release of nutrients throughout the crop cycle (Giacomini et al., 2013). In addition, over time, animal manure application improves the parameters related to acidity (Chantigny et al., 2004; Lourenzi et al., 2011; Brunetto et al., 2012) and increases the availability of nutrients in the soil (Adeli et al., 2008; Scherer et al., 2010; Lourenzi et al., 2013; 2016), favoring crop development.

Animal manure can also be combined with mineral fertilizers, seeking better nutrient uptake efficiency by plants. Ciancio et al. (2014) evaluated the application of swine liquid manure (10, 20, and 30 m^3 ha^{-1}) and turkey manure (1 and 2 Mg ha^{-1}), isolated and combined with urea (mineral fertilizer) in top dressing and found increases in maize and bean grain yield when using organic fertilizer supplemented with urea. Arif et al. (2016), in a study developed in a semi-arid climate, also found increased maize yield in two years, with the combined application of urea (75 and 150 kg ha^{-1}), barn manure (5 and 10 Mg ha^{-1}), and biochar (0, 25 and 50 Mg ha^{-1}). The combination of the highest doses of manure and urea, regardless of the biochar dose, resulted in the highest yields, especially in the first growing season.

In a study evaluating cow dung, poultry manure, and goat manure, applied alone, or combined with mineral fertilizer, Yoganathan et al. (2013) found a higher grain yield of cowpea (*Vigna uniquiculata*) with a combination of poultry manure and mineral fertilization. In addition, these authors point out that for all animal manures, the highest grain yields were observed when the manure was combined with mineral fertilizer than with solely manure. Eliaspour et al. (2020), evaluating the application of animal manure alone and combined with mineral fertilizer, also found greater sunflower grain yield when using animal manure combined with mineral fertilizer than single manure, and 1000-grain weight highest values occurred with the combination of animal manure, mineral fertilizer, and inoculation with *Piriformospora indica*. Use of animal manure is not restricted to grain crops, and Ruangcharus et al. (2021) evaluated the effect of doses of compost (0, 10, and 20 Mg ha^{-1}) obtained from chicken, cow, and swine manure on the yield of sweet potato (Ipomoea potatoes) and nitrous oxide (N_2O) emission. All products increased sweet potato yield, but there were no differences among the nutrient sources; but the authors suggested that compost doses should not be higher than 5.33 Mg ha^{-1} because this dose resulted in yield increase with a reduction in N_2O emission.

Evaluating wheat and corn yields in a long-term experiment (11 years) using animal manure, Ferreira et al. (2021b) found that the addition of pig slurry, cattle slurry and pig deep-litter significantly increased wheat and corn grain production. There are increases from 500 to 1000 kg ha^{-1} of wheat in treatments PS, CS and PL compared to the control (Figure 2a); and increases from 400 to 900 kg/ha of corn in treatments PL, PS and CS compared to the control (Figure 2b).

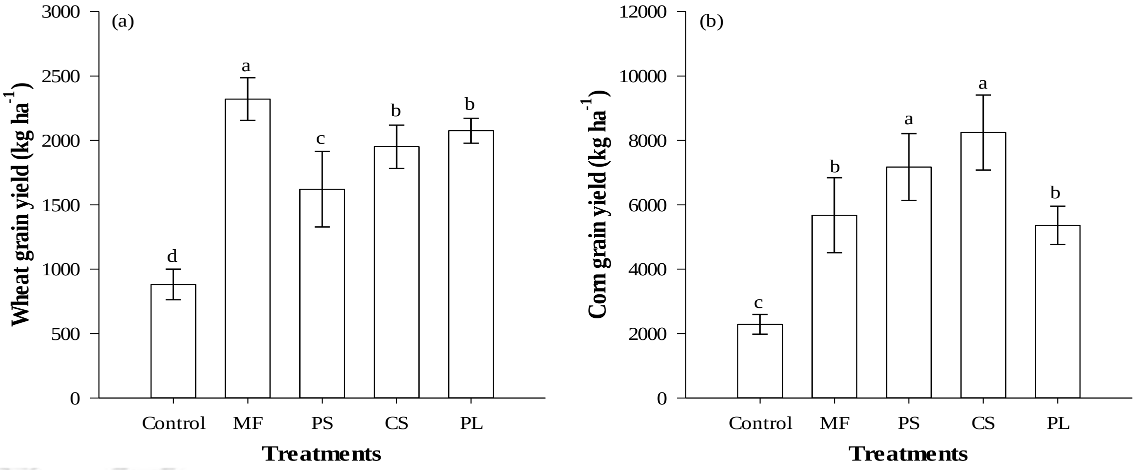

Figure 2. Grain yield wheat (a) and corn (b) crops in no-tillage area after successive applications of different nutrient sources. Vertical bars with the same letter do not differ by the Scott Knott test ($p \leq 0.05$); Control, Mineral fertilizer (MF), Pig Slurry (PS), Cattle Slurry (CS) and Pig deep-litter (PL). Source: Adapted fromFerreira et al. (2021b).

4.2. Dry matter production and nutrient accumulation

The use of animal manure promotes increases in dry matter production and nutrient accumulation in crops. Studies carried out in Southern Brazil show accumulation of nutrients in different species, both grain and cover crops (Ceretta et al., 2005; Aita et al., 2006; Assmann et al., 2007; Ciancio et al., 2014). Lourenzi et al. (2014a) evaluated the application of different doses of swine liquid manure in grain crops and observed dry matter yields of 5.1, 7.9, 9.6, and 12.0 Mg ha^{-1} in three maize cycles, 1.0, 2.2, 2.7, and 3.9 Mg ha^{-1} in two black beans cycles, and 4.5, 10.0, 9.5, and 16.2 Mg ha^{-1} in millet (*Pennisetum americanum* L.) cycle with swine liquid manure doses of 0, 20, 40, and 80 m^3 ha^{-1}, respectively. In cover crops, Lourenzi et al. (2014a) found dry matter yields of 3.3, 5.6, 6.6, and 7.3 Mg ha^{-1} in four cycles of black oats (*Avena strigosa*), 3.6, 5.7, 6.0, and 9.0 Mg ha^{-1} in two black oats + vetch (*Vicia sativa* L.) cycles, and 1.8, 3.0, 2.9, and 2.9 Mg ha^{-1} in a crotalaria (*Crotalaria juncea* L.) cycle, with swine liquid manure doses of 0, 20, 40, and 80 m^3 ha^{-1}, respectively.

In thirteen crop cycles, Lourenzi et al. (2014a) recorded shoot accumulation of 616, 1144, 1455, and 2042 kg ha^{-1} of N, 86, 180, 234, and 321 kg ha^{-1} of P, and 549, 1065, 1216, and 1898 kg ha^{-1} of K at swine liquid manure doses of 0, 20, 40, and 80 m^3 ha^{-1}, respectively. This nutrient accumulation in the aboveground part is equivalent to the apparent recovery of 79, 63, and 55% of the N, 27, 21, and 18% of the P, and 284, 192, and 189% of the K applied in the thirteen crops with swine liquid manure doses of 20, 40 and 80 m^3 ha^{-1}, respectively. The low P recovery rates indicate that the amounts applied with manure are above the crops demand, which can lead to P accumulation in the soil, as observed by Lourenzi et al. (2013) in a work evaluating soil chemical attributes in the same experiment. The apparent recovery for K was over 100%, suggesting that K applied via swine liquid manure was not sufficient to meet the demand by the crops, which caused a reduction in the soil available K during the experiment (Lourenzi et al., 2013).

The combined application of animal manure and mineral fertilizers also increases dry matter yield and nutrient accumulation by crops. Geng et al. (2019) evaluated the replacement of mineral fertilizers by cattle and poultry manure in the proportions of 25, 50, 75, and 100% and found higher maize dry matter yield with replacement of up to 50% of mineral fertilizers by animal manure, especially poultry manure. In addition, they also observed more N accumulation in maize shoots with poultry manure application, and the replacement of 25% of mineral fertilizers by poultry manure corresponds to the highest values. The authors further point out that an appropriate proportion of replacement of mineral fertilizers by organic ones provides sufficient nutrients and improves the soil environment and increases dry matter yield and nutrient accumulation by crops.

In comparing cattle liquid manure applied at different times with inorganic fertilizers for maize N supply, Dordas et al. (2008) found that both nutrient sources promoted increases in maize yield. There were no differences between cattle liquid manure application and the different forms of splitting inorganic nitrogen fertilization, suggesting that manure can be used to replace inorganic fertilizers. Also, in maize, Ch'ng et al. (2015) evaluated compost obtained from apple leaves and poultry manure, and biochar obtained from cattle manure pyrolysis, combined with mineral fertilizers, and found that the combined use of compost, biochar, and mineral fertilizers resulted in the highest crop dry matter, in addition to increased N, P, K, Ca, and Mg accumulation. Those authors point out that compost and biochar can reduce P doses to be applied to crops and reduce P fixation in acidic soils.

5. Final remarks

Animal manure, such as swine, cattle, and poultry manure, with different concentrations of dry matter, carbon, C:N ratio, macro, and micronutrients, depending on their form (liquid or solid), are widely used as a source of crop nutrients. The effect of continued application of those manure on soil attributes depends, in addition to manure characteristics, on pedoclimatic conditions, frequency and amounts applied, and the time of application.

Manure applications, both for short and long periods, increase soil organic carbon, especially when associated with mineral fertilizers, which will enhance this increase due to higher phytomass production by cover plants and crops in the form of the shoot (straw) and root residues. The increase of soil organic carbon may raise soil cation exchange capacity, increasing adsorption of nutrients such as nitrogen, phosphorus, and potassium, and favoring complexation of exchangeable aluminum, which leads to increases in pH and grain yield and dry matter production of crops and cover plants.

Some studies in the literature did not show an increase in soil organic carbon when swine liquid manure was used, and that may be associated with the low organic matter and dry matter concentration in this type of manure. However, other studies with liquid swine manure application for ten years in clayey soils under no-tillage system showed increases in soil organic carbon compared to control with mineral fertilizer. In general, increases in soil organic carbon occur when manure has a high dry matter content and an increased C:N ratio, as observed in poultry litter, swine deep litter, and cattle manure, as well as in compost. Soil aggregate stability also benefits from applying materials with a higher C:N ratio, although strongly determined by soil texture. Soil water infiltration is another attribute that is positively affected, and soil bulk density, which decreases as manure doses are increased.

Regardless of animal manure, studies show an increase in the formation of biogenic soil aggregates in soil with either sandy or clayey textures, which is related to increases in soil fauna, especially earthworms. Macrofauna, microbial populations, and biological activity increase with animal manure application due to the enrichment in soil organic matter and improvement in soil aeration conditions. The joint application of animal manure and mineral fertilizers also promotes improvements in the soil macrofauna, resulting in more soil aggregation and higher aggregate stability.

Another important characteristic of animal manure is the presence of metals such as copper and zinc. In soils with animal waste applications, much of the solution copper is bound to soil organic carbon, which also happens with zinc. Thus, soil organic carbon increase, especially soluble organic carbon, also enhances the complexation of copper and zinc, changing the distribution of these chemical species and decreasing copper and zinc levels in the soil solution.

Finally, increases in yield do not always go together with the improvement of all soil attributes. Conservation practices must support soil management to improve and maintain soil quality. Therefore, the efficiency of animal manure application on soil quality is improved when this practice is carried out in an integrated manner with other soil management and conservation strategies, and manure applications must be performed for an extended period so that soil physical, chemical, and biological attributes are positively affected.

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