SOIL HEALTH NEXUS

Synthesis of Short- and Long-term Studies Reporting Soil Quality Metrics under Agricultural and Municipal Biosolid Applications

2016 Manure and Soil Health Working Group Report

Abstract

The principal focus of soil health management is to preserve and improve soil physical, chemical, and biological properties such that conditions for supporting plant growth and ecological function are optimized. Practices such as planting cover crops and minimizing or eliminating tillage, are promoted for improving soil health. However, utilizing livestock manure and municipal biosolids as soil amendments on agricultural cropland has received comparatively less attention as a practice for improving soil qualities. Recycling locally available nutrients, such as livestock manure, prior to importing commercial fertilizer should be promoted as a component of the overall strategy to address nutrient imbalance and net increases of nutrients to regions. Therefore, the review of literature presented here was conducted with two objectives: (1) summarize results of short- and long-term studies reporting chemical, physical, and biological soil properties from application of livestock manure and animal by-products and municipal biosolids to soil, and (2) describe research needs related to manure and soil health based upon identified gaps in knowledge resulting from the literature review.

The effect of manure and municipal biosolids on soil physical and chemical properties has been well documented in previous literature reviews. In general, the effect of manure and municipal biosolids on soil chemical properties is heavily dependent upon the chemical properties of the applied amendment. When applied at appropriate rates, these organic amendments increase soil organic carbon (SOC) and cation exchange capacity (CEC), as well as provide beneficial micronutrients for crops. The application of manure or biosolids decreases bulk density but does not increase water holding capacity of the soil. Studies also indicate that manured soil is more resistant to compaction, especially when wet.

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Unfortunately, the effect of manure and municipal biosolids on soil biological properties has not been as well researched. This is likely due to cost and time constraints related to these measurements. Overall, manure and biosolid application increases abundance of soil fauna, such as bacteria, fungi, and earthworms, but does not seem to increase faunal diversity when compared to inorganic fertilizer. Manure and biosolid application also increases microbial respiration and mineralization, which are indicators of nutrient cycling. However, the application of manure does not affect the abundance of soil microarthropods.

Most of the research published about the impact of manure or biosolids application on soil properties, crop production, and water quality is based on studies where manure is applied annually. When manure and biosolids are applied annually at rates that exceed the nutrient requirements of crops, the risk for leaching, runoff, and accumulation of nutrients is increased. This is especially true in studies that apply manure annually at the crop N rate because P and K are often over applied. Only a few studies have investigated the residual effects of manure or biosolid application. Briefly, future research endeavors should: (1) incorporate quantification of soil biological metrics since soil biology provides ecosystem services, like nutrient cycling, (2) investigate the short- and long-term effects of a single application of manure or biosolids to support an effort to identify the optimal frequency of application for improving soil health, (3) be designed such that nutrient application among treatments is balanced on an annual or multi-year basis, and (4) provide discussion that clearly relates research findings to management decisions relevant to agricultural crop producers.

1. Introduction

The principal focus of soil health management is to preserve and improve soil physical, chemical, and biological properties such that conditions for supporting plant growth and ecological function are optimized. Doran et al. (1996) described soil health as the "continued capacity of the soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, maintain the quality of air and water environments, and promote plant, animal, and human health." Typically, 'healthy' soils are characterized by proficient nutrient cycling, plentiful and diverse organisms, sufficient water infiltration and holding capacity, and productive and healthy crops and vegetation. 'Soil health' differs from 'soil quality' in that biological properties of soils are considered in defining its 'health' (Kibblewhite et al., 2008; de Paul Obade and Lal, 2016).

Soil health considers the interaction of three types of soil properties: physical, chemical, and biological (Doran and Zeiss, 2000; Kibblewhite et al., 2008). Because the properties are interconnected and dynamic, quantifying the heath of a soil and the corresponding impacts of soil management activities can be difficult. Additionally, the properties defining a 'healthy soil' can vary greatly among soil types, climate, vegetation, and many other factors. For instance, a 'healthy' forest soil will have very different properties than a 'healthy' grassland or cropland soil. In general, however, management practices that return and increase soil organic carbon are vital to improving soil health because carbon is the primary energy source in soil systems (Doran et al., 1996; Herrick, 2000; Kibblewhite et al., 2008).

Soil organic matter (SOM) is comprised of organic residues, such as plant materials and animal remains, which are in varying states of decomposition ranging from fresh to completely decomposed, Figure 1. It also includes living and dead microbes and their byproducts; the portion of SOM partitioned to living microbes is known as microbial biomass. Humus, the most stable part of SOM, is decomposed organic material that is resistant to further degradation by soil microbes (Stockmann et al., 2013). Particulate organic matter (POM) is only partially decomposed and is labile in nature. It is this unstable organic matter pool that drives nutrient cycling by living organisms in soil.

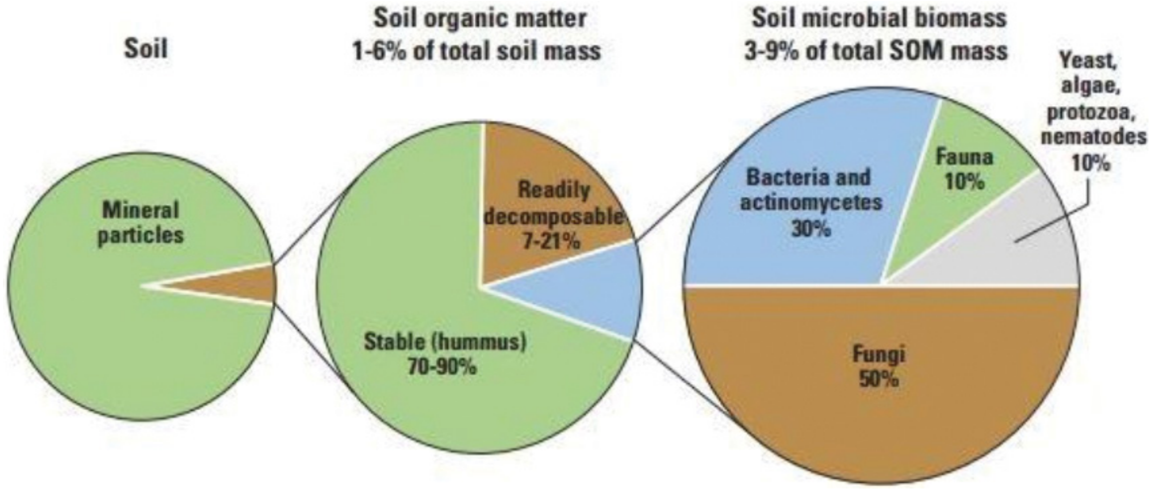

Figure 1. *Composition of soil organic matter (SOM) (Al-Kaisi and Kwaw-Mensah, 2016).*

Soil organic matter is primarily composed of carbon, hydrogen and oxygen, but also includes nutrients such as nitrogen, phosphorous, and potassium, among others. One practice that increases or maintains the soil organic carbon (SOC) content of soil is manure application (Haynes and Naidu, 1998; Edmeades, 2003). Following manure application to soil, approximately 20% of manure organic carbon (C) will persist beyond one year (Bhogal et al., 2009). While much focus is placed on the negative environmental impacts of manure, often a result of improper management, research has demonstrated the role of animal manures in increasing soil aggregate stability and water holding capacity, decreasing bulk density, and reducing runoff and erosion (Haynes and Naidu, 1998; Edmeades, 2003; Wortmann and Shapiro, 2008). Therefore, while some challenges to manure utilization as a soil amendment and crop fertilizer exist, efforts to improve agricultural soil health should embrace the valuable role of manure as a component in comprehensive soil health management.

Practices such as planting cover crops, minimizing or eliminating tillage, and leaving plant residue on cropland are promoted for improving soil health. However, utilizing livestock manure and municipal biosolids as soil amendments on agricultural cropland has received comparatively less attention as a practice for improving soil qualities. An international literature review by Edmeades (2003) investigated the effect of animal manures on soil health properties and crop production metrics compared to mineral fertilizers. The author concluded that, while manure has a beneficial effect on SOC and soil physical properties, the lack of yield improvement and risk of nutrient leaching and runoff from manure do not make it a sustainable option for crop production. However, a similar review conducted by Diacono and Montemurro (2010), which included a focus on the response in soil biological properties following manure application, concluded that composted animal manure and municipal compost increased soil microbial activity and nutrient cycling without increasing environmental risks, such as nutrient leaching and heavy metal accumulation. The environmental risks associated with the improper management of manure and biosolids include heavy metal accumulation, nutrient leaching and runoff, and negative impact on soil biology (Haynes and Naidu, 1998; Edmeades, 2003; Cogger et al., 2006). More recent literature reviews have also refuted the conclusions reported by Edmeades (2003) arguing that when these organic soil amendments are properly managed by applying at an appropriate rate using appropriate methods, potential environmental risks are minimal (Hargreaves et al., 2008; Diacono and Montemurro, 2010).

In certain areas of intensive livestock production, over-application of nutrients can occur when sufficient land is not available to livestock system operators to accommodate manure production. While some livestock production system operators are challenged with managing excess nutrients, application of inorganic fertilizers to nearby cropland represents a net increase of nutrients to the region, contributing to an imbalance and over-application of nutrients as a whole. Recycling locally available nutrients, such as livestock manure, prior to importing commercial fertilizer should be promoted as a component of the overall strategy to meet nutrient reduction goals in sensitive watersheds. As the campaign to improve agricultural soil health has gained momentum among numerous federal, state and regional organizations, including land-grant university extension programs, a comprehensive assemblage of outcomes from manure and soil health-related research studies and identification of knowledge gaps is viewed as an important step towards directing future research and educational programs intended to demonstrate the value of manure to the sustainability of agricultural cropping systems. Therefore, the review of literature presented here was conducted with two objectives: (1) summarize results of short- and long-term studies reporting (a) chemical, physical, and biological soil properties, and (b) indirect indicators of soil health, including climate resilience, from application of livestock manure and animal by-products (i.e. compost) and municipal biosolids to soil, and (2) describe research needs related to manure and soil health based upon identified gaps in knowledge resulting from the literature review. Relevant literature was identified using the Web of Science database in addition to traditional methods of identifying literature through previous literature reviews. Only replicated studies that included manure as the only differing factor were incorporated; thus, many organic agriculture studies were not included since treatments often included differences in cropping rotation and the use of cover crops in addition to manure application.

2. Soil Chemical Properties

The effect of manure and municipal biosolids on soil chemical properties is heavily dependent upon the chemical properties of the applied amendment. Several comprehensive literature reviews have been focused on the effect of manure and municipal biosolids on soil chemical properties like soil carbon and organic matter, nitrogen, phosphorous, potassium, micronutrients, cation exchange capacity, and pH (Choudhary et al., 1996; Haynes and Naidu, 1998; Edmeades, 2003; Cogger et al., 2006; Hargreaves et al., 2008; Diacono and Montemurro, 2010). These same properties are often recommended for assessing soil health (Doran et al., 1996; Karlen et al., 1997; Wienhold et al., 2004; Allen et al., 2011; Obriot et al., 2016). In general, soil chemical properties have been extensively investigated and summarized as evidenced by Table 1 and, thus, will only briefly be discussed in the following section.

PROPERTY	NUMBER OF STUDIES
CHEMICAL	
Nitrogen	82
Potassium	39
CEC	10
Electrical conductivity	25
PHYSICAL	
Aggregation	30
Infiltration	9
Saturated hydraulic conductivity	15
Biological	66
Yield and biomass	63

Table 1. *Number of manure studies investigating soil health properties. Lists of literature found*

2.1. Soil organic matter and carbon

Although most studies have reported an increase in soil carbon (C) due to manure addition, C concentration is difficult to quantify and predict (Khaleel et al., 1981). The rate of soil C increase in soil depends upon many factors that are not related to manure addition, such as temperature, moisture content, cropping system, and soil type. Additional factors include the C:N ratio of the amendment, the application rate, and how the amendment is applied to soil (surface applied, injected, incorporated, etc.). Bhogal et al. (2009) reported that only approximately 20% of manure organic C persist in soil after one year. This is due to the transient nature of labile organic matter and only organic matter that is stabilized persists. The stability of carbon pools are discussed in depth in Diacono and Montemurro (2010) and will not be further detailed here. The addition of 10 Mg ha^{-1} yr^{-1} of farmyard manure over 15 years significantly increased soil organic carbon, labile carbon, and total carbon when compared to inorganic fertilizer and no fertilizer (Choudhary et al., 1996). Total carbon was increased by more than 50% in the top 60 cm of soil. In their review, Edmeades (2003) reported that manure increases SOM by over 300% when compared to inorganic fertilizer. These wide ranges emphasize the high degree of variability in the effect of manure on soil C and SOM.

The majority of research studies focused on the effect of repeated annual additions of manure and municipal biosolids on soil C. Wortmann and Walters (2006) and Reeve et al. (2012) investigated the residual effect of manure application. Soil organic matter content was significantly greater in treatments that had received three years of compost application ending four years previously (Wortmann and Walters, 2006). Reeve et al. (2012) also observed differences in soil organic C between treatments that had previously received a single application of 50 Mg DM ha^{-1} compost and those that had not. When soil was sampled 14 years after the original compost application, there were no significant differences in total organic C. However, when soil was sampled 16 years after the original compost application (two years later), significant differences in total organic C were observed between soils receiving compost application and those not amended with compost.

2.2. Nitrogen, Phosphorous, and Potassium

Most manure studies include measurements of nitrogen (N), phosphorous (P), and potassium (K) in both the soil and amendment since these compounds are mainly used as a source of fertilizer in crop production (see Appendix). When manure is applied on the basis of crop N requirement, P and K are often over applied; application of these nutrients can be more prescriptive when using inorganic fertilizer (Edmeades, 2003). Thus, when manures are applied annually to meet crop N rate requirements or at higher application rates than required by the crops as a means of "disposal" of the manure, P and K will likely accumulate in the soil, increasing the potential for nutrient discharges to surface water during runoff and erosion.

While nearly 100% of P and K applied with manure and biosolids are immediately available to plants, only a fraction of the N is available in the first year. Ammonia nitrogen (or ammonium) is immediately available to crops. However, much of the N applied via organic amendments is organic N, which is unavailable to plants until it has been mineralized in the soil, Figure 2. Approximately 35 to 50% of the organic N in manure and biosolids may become available in the first year following application. In subsequent years, additional N becomes available to crops as soil microbes mineralize organic N, converting it to ammonium. Approximately 15 and 6% of the original organic N becomes available in years two and three, respectively, following manure application.

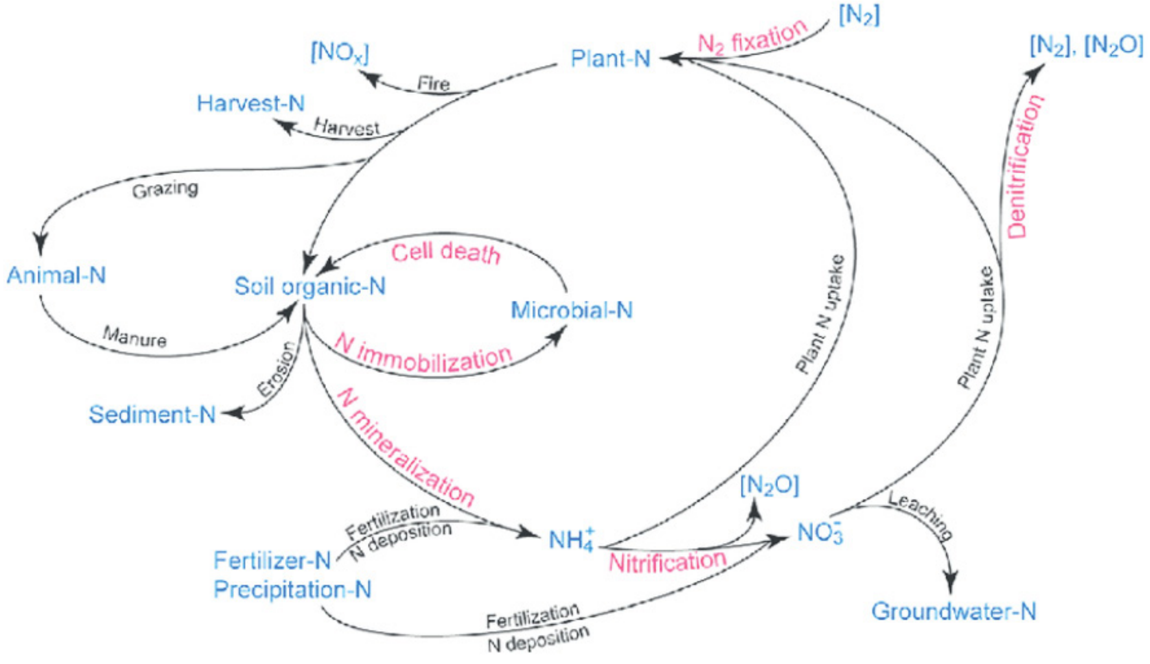

***Figure 2.** Schematic of terrestrial nitrogen cycle where soil microbial processes appear in red and gases appear in brackets (Robertson and Groffman, 2015).*

Many literature reviews have summarized the state of knowledge regarding soil nutrient impacts from manure application, but little has been published regarding the connection between various manure sources and forms of soil phosphorus. Larney and Janzen (1996) reported that extractable P concentration in soil increased significantly more under soil amendment with swine or poultry manure than with beef manure, beef manure compost, or inorganic P fertilizer. While these differences may be due to the total P concentration in the amendments, it is probable that manure increases the availability of soil P by increasing organic P. This increases plant uptake of P because more remains dissolved in water associated with the manure rather than adsorbing to soil particles and becoming immobilized through ligand exchange, a type of soil chemical reaction. This conclusion is supported by results from a study by Ohno et al. (2005) in which the authors concluded that manure (beef or dairy) increased organic P concentration in soil compared to plant residues, but total soil P was unchanged. They also concluded that as dissolved organic carbon (DOC) increased, organic P also increased, indicating that animal manures are good sources of plant available P.

2.3. Other nutrients

Manure also contains other micro- and macronutrients due to dietary needs of livestock that are not typically included in inorganic fertilizer. For example, manure application has increased calcium, magnesium, sodium, and sulfur in soil (Kingery et al., 1994; Edmeades, 2003; Rees et al., 2011; Miller et al., 2013; Miller et al., 2017a). While micronutrients are beneficial to crops, increased soil salinity can be a concern with annual long-term additions of manure due to the addition of potassium and sodium cations, which produce a risk for groundwater contamination since these cations are soluble (Hao and Chang, 2003; Miller et al., 2013; Miller et al., 2017a).

Municipal biosolids also contain additional micro- and macronutrients that inorganic fertilizer does not generally provide. However, with municipal biosolids, the risk for bioaccumulation of trace metals exists. For example, municipal biosolids have been shown to increase soil zinc and copper, which can negatively impact soil biology (Cogger et al., 2006; Hargreaves et al., 2008). Municipal biosolids also contain trace minerals, such as arsenic and lead, which can be harmful to humans and livestock if bio-accumulated in crops.

2.4. pH

The effect of manure and municipal biosolids on pH depends upon the initial pH of the soil, the pH of the amendment, the amount of amendment, and the buffering capacity of the soil. Edmeades (2003) concluded that there is no consistent effect of manure on soil pH, and this was supported by Diacono and Montemurro (2010). However, research has documented that beef manure and beef manure compost provide a short-term liming effect on soils with pH < 6 and help maintain soil pH in soils with pH > 6 (Azeez and Van Averbeke, 2012; Eghball, 2002; Murphy et al., 2005; Whalen et al., 2000). Poultry manure had similar effects when applied at a rate of 4 Mg ha^{-1} yr^{-1} for three years, creating a 0.5 increase in pH compared to the unamended treatment (Khaliq and Kaleem Abbasi, 2015). In their nine-year study, Morales et al. (2016) did not observe significant differences in soil pH among a no amendment treatment and a pig slurry application of 100 kg N ha^{-1} yr^{-1} or the same rate of deep-litter pig manure, which contained wood chips in addition to decomposed pig manure. However, pig slurry decreased soil pH at an application rate of 200 kg N ha^{-1} yr^{-1} as did urea applied at this same rate.

2.5. Cation exchange capacity

In cropping systems, cation exchange capacity (CEC) is important to nutrient retention for plant use. In general, CEC is an inherent soil property that depends upon clay content since clay particles are negatively charged. However, organic matter addition to soil will increase CEC due to its negative charge, thus, the addition of animal manure or municipal biosolids should increase soil CEC. Morlat and Chaussod (2008) were able to positively correlate the total SOC and clay content to CEC. In general, results from field studies indicate that CEC increases with the addition of manure or municipal biosolids (Schjonning et al., 1994; Gao and Chang, 1996; De Lucia et al., 2013; Netthisinghe et al., 2016). Murphy et al. (2005) reported that CEC increased with increasing rates of pig or cattle slurry addition to grassland soil. Since soil C content cannot be straightforwardly increased with organic amendment addition, the timeframe and magnitude of CEC increase is also not straightforward because the two properties are closely related. For example, Cote and Ndayegamiye (1989) found that application of cattle manure increased soil CEC compared to a no amendment control, while the application of pig slurry did not. In another study utilizing pig or cattle slurry, the type of slurry did not matter and both types increased soil CEC compared to treatments of no fertilizer and inorganic fertilizer (Murphy et al., 2005).

The effect of manure and municipal biosolids on soil chemical properties is heavily dependent upon the chemical properties of the applied amendment. When manure and biosolids are applied at rates that exceed the nutrient requirements of crops, the risk for leaching, runoff, and accumulation of nutrients, such as N, P, K, salts and heavy metals, is increased. When manure and biosolids are applied at appropriate rates, however, SOC and CEC are increased. Beneficial micronutrients are also provided for crops.

3. Soil Physical Properties

Physical soil properties, such as bulk density, aggregation, water holding capacity, and infiltration, are often included in soil health assessments (Doran et al., 1996; Karlen et al., 1997; Wienhold et al., 2004; Bronick and Lal, 2005; Allen et al., 2011; Obriot et al., 2016). Similar to chemical properties, the effect of manure and biosolids on physical soil properties has been extensively researched, Table 1. Additionally, several comprehensive literature reviews have summarized these effects (Khaleel et al., 1981; Choudhary et al., 1996; Haynes and Naidu, 1998; Edmeades, 2003; Hargreaves et al., 2008; Diacono and Montemurro, 2010). Thus, these properties will, for the most part, be only briefly discussed in this section.

3.1. Bulk density and porosity

In general, both short- and long-term reductions in bulk density have been demonstrated with manure or municipal biosolid applications across many different soil types (Khaleel et al., 1981; Haynes and Naidu, 1998; Edmeades, 2003; Diacono and Montemurro, 2010; Thangarajan et al., 2013). Incidentally, as bulk density decreases, soil porosity increases. Manure and municipal biosolids typically have lower bulk densities than soil due to a greater proportion of organic carbon, which is less dense than mineral soil particles. Thus, when added to soil, the overall bulk density of the soil is decreased. Khaleel et al., (1981) established a linear relationship between the amount of SOC added by manure and the reduction in soil bulk density. This relationship was later confirmed by Haynes and Naidu (1998). The average reduction in soil bulk density from application of manure or biosolids is approximately 15% (Diacono and Montemurro, 2010).

More recent studies have found similar results. In their 15-year study, Chaudhary et al. (2017) concluded that the addition of farmyard manure (10 Mg ha^{-1}) combined with inorganic fertilizer decreased bulk density by 10% and 5% compared to no amendment or inorganic fertilizer alone, respectively. The bi-annual addition of cattle manure or municipal solid waste (35 or 18 Mg ha^{-1}) resulted in a 7% decrease in bulk density over 15 years in a study conducted by Paetsch et al. (2016). Most of the studies published in the last few years have been focused on long-term manure research sites. However, in a two-year study conducted by Forge et al. (2016) a 5 Mg ha^{-1} addition of poultry layer manure did not affect bulk density. When the application rate was raised to approximately 60 Mg ha^{-1}, though, bulk density decreased by 10% compared to the no amendment control. A decrease in soil bulk density was also observed during a five-year study when cattle compost was surface applied and not incorporated into the soil compared to both inorganic fertilizer and no amendment controls (Guo et al., 2016).

3.2. Compaction

While bulk density is a measure of the state of compaction of soil, the compactibility of a soil is a measure of how susceptible the soil is to compaction. Soil compaction negatively impacts plant growth and biological properties, especially under wet conditions, because soil aeration is decreased (Magdoff, 2001). Compaction of soil within wheel tracks is not often addressed in most manure research studies. Plots in research studies are often too small to utilize full-size tractors and manure spreaders for application, so manure is applied with smaller implements (Khaliq and Kaleem Abbasi, 2015; Bassouny and Chen, 2016) or by hand. However, the movement of heavy agricultural equipment, such as tractors and manure spreaders, across soil increases the risk of compaction. The resiliency of a soil to compaction is an important consideration for agricultural crop producers who apply manure utilizing this heavy equipment.

Soil compactibility is typically measured in-field with a penetrometer or by conducting a Proctor test on soil samples collected from the field (Bradford, 1986; Blanco-Canqui et al., 2015). In most of the reviewed studies that investigated the effect of manure application on compaction, soil bulk density and penetration resistance using a penetrometer were reported (Schjonning et al., 1994; Mosaddeghi et al., 2000; Hati et al., 2006;Bandyopadhyay et al., 2010; Celik et al., 2010; Kumar et al., 2014; Khaliq and Kaleem Abbasi, 2015; Bassouny and Chen, 2016; Sloan et al., 2016). Compared to no amendment, several studies reported decreased penetration resistance with application of manure and municipal biosolids (Hati et al., 2006; Bandyopadhyay et al., 2010; Celik et al., 2010; Khaliq and Kaleem Abbasi, 2015; Bassouny and Chen, 2016; Sloan et al., 2016). When compared to inorganic fertilizer, no differences were observed in penetration resistance in manure amended soil, especially in shallow soil depths (less than 10 cm) (Bandyopadhyay et al., 2010; Celik et al., 2010; Hati et al., 2006; Khaliq and Kaleem Abbasi, 2015; Kumar et al., 2014). Sloan et al. (2016) found that after three years of municipal biosolids application, penetration resistance decreased in the top 20 cm compared to no amendment. However, after six years of application, penetration resistance was no longer significantly different in the top 10 cm of soil but was significantly reduced in depths from 10-20 cm.

Two studies investigated the effect of manure application on compaction measured by the Proctor test (Ekwue and Stone, 1995; Blanco-Canqui et al., 2015). The Proctor test incorporates soil moisture measurements in order to determine the critical water content at which soil can be most compacted. From their 71-year study, Blanco-Canqui et al. (2015) concluded that the addition of cattle manure decreased compaction under wet conditions more so than inorganic fertilizer or no amendment. The maximum Proctor bulk density was decreased by 5%. The critical water content was also 14% greater under the manure treatment. Ekwue and Stone (1995) also concluded that the addition of manure decreased maximum bulk densities while increasing critical water contents. The results from these two studies indicate that manured soil is more resistant to compaction, especially under wet soil conditions, than non-manured soils.

3.3. Aggregation and aggregate stability

Soil aggregates are composed of soil particles that stick together and form clods ranging in magnitude from micrometers to centimeters. Aggregate stability is a measure of how resistant soil aggregates are to breakdown, primarily through water forces. Aggregation and aggregate stability affect plant root growth and water movement in soil by either inhibiting or permitting these actions. Manure and municipal biosolid applications increase soil aggregation (Diacono and Montemurro, 2010). Haynes and Naidu (1998) surmised that when fresh manure is added to soil, the effect on aggregation is quick but not long lasting; however, when composted manure is added, soil aggregation increases slowly and persists longer. In a five-year study, Celik et al. (2004) compared the effect of cattle manure or compost (25 Mg ha^{-1} yr^{-1}) on aggregate mean weight diameter to no fertilizer or inorganic fertilizer treatments. The authors found that the mean weight diameter of the soil aggregates was significantly greater in the manure treatment compared to the two controls while the compost treatment was only significantly greater than the inorganic fertilizer treatment. Bashir et al. (2016) concluded that composted amendments yielded longer-term improvement in soil aggregation due to more stable C within aggregates. Improvement in soil aggregation is often attributed to an increase in SOC (Haynes and Naidu, 1998; Bhattacharyya et al., 2007). However, there are other factors that likely increase aggregation. For example, Bashir et al. (2016) applied equal amounts of organic C to soil via poultry litter, farmyard manure, and municipal biosolids and cited differences in aggregation. They found positive correlations between microbial binding agents, which are by-products of microbial activity, and aggregation in poultry litter.

3.4. Infiltration and saturated hydraulic conductivity

Manure application has been shown to increase infiltration rate. Both Wortmann and Walters (2006) and Gilley and Risse (2000) presumed that reduced runoff due to manure application was due to increased infiltration rate. Infiltration rate was increased by 80% due to eight years of farmyard manure application (10 Mg ha^{-1} yr^{-1}) (Bhattacharyya et al., 2007; De Lucia et al., 2013). Sloan et al. (2016) also noted an increase in infiltration rate due to biosolid addition but did not report the data. However, Sathish et al. (2016) reported no significant differences in infiltration rate with two years of farmyard manure application (10 Mg ha^{-1} yr^{-1}). The lack of differences could be due to the cropping system or the shorter length of time compared to Bhattacharyya et al. (2007).

Saturated hydraulic conductivity is another measurement used to characterize infiltration rate of soil because as soil becomes saturated, the rate of infiltration approaches the saturated hydraulic conductivity of the soil. Thus, just as infiltration rate increases with manure amendment, saturated hydraulic conductivity also increases. However, these increases are highly variable; Khaleel et al. (1981) reported increases ranging from 18% to 500%, depending upon the soil texture. More recently, Khaliq and Kaleem Abbasi (2015) and Chakraborty et al. (2010) also concluded that manure addition increases saturated hydraulic conductivity. However, Bassouny and Chen (2016) found that in a silty clay soil, saturated hydraulic conductivity was reduced by over 60% when compared to no amendment even though bulk density was decreased. In this situation, organic matter probably blocked soil pores, so the decrease in saturated hydraulic conductivity was the result of reduced pore connectivity not a reduced number of pores.

3.5. Water holding capacity

Manure application does not alter water holding capacity of soil (Khaleel et al., 1981). Since the addition of manure increases both the permanent wilting point and the field capacity of soil, the overall available water holding capacity, which is the difference of the two measurements, is not significantly changed. More recent studies have supported this conclusion. Blanco-Canqui et al. (2015) found that annual application of beef manure (27 Mg ha^{-1}) for 71 years significantly increased the permanent wilting point and field capacity of soil but did not affect soil water holding capacity when compared to no fertilizer addition. Similarly, Sathish et al. (2016) found that the annual application of farmyard manure (10 Mg ha^{-1}) for 20 years did not affect soil water holding capacity when compared to both inorganic fertilizer and no fertilizer addition. However, water holding capacity was significantly increased with the application of a mixture of pig and poultry manure (10 Mg ha^{-1} yr^{-1}) for 15 years (Bassouny and Chen, 2016). Water holding capacity was increased by 7% and 13% compared to inorganic fertilizer and no fertilizer, respectively; the field capacity and permanent wilting point were significantly increased in the manure treatment as well. The conflicting results are likely due to soil type. In the study by Bassouny and Chen (2016), the soil type was a silty clay while the other two were sandy loams.

Physical soil properties are altered with the application of manure or biosolids. Bulk density decreases which, subsequently, increases soil porosity. In general, however, manure and biosolid application does not increase water holding capacity of the soil. Studies also indicate that manured soil is more resistant to compaction, especially when wet. Aggregate stability is increased due to an increase in SOC and microbial activity, and infiltration rate is also increased. Both of these effects lead to less runoff and erosion.

4. Soil Biological Properties

Soil biological indicators, such as abundance, activity, and diversity of soil fauna, are important considerations when evaluating soil health. The soil food web provides many ecosystem goods and services that generate interconnection between soil biology and soil physical and chemical properties, such as nutrient cycling and transformation, soil stability, and biological control of pests (Kibblewhite et al., 2008). The soil food web is made up of many trophic levels where organisms at each level consume those at lower levels, Figure 3. Soil biological characteristics are useful soil health indicators because they are sensitive to management and well-correlated with beneficial soil functions (Doran and Zeiss, 2000). For example, soil fungi improve soil structure by forming hyphae that bind soil particles, increasing aggregate stability, and are negatively affected by tillage (Bronick and Lal, 2005). However, it is important to consider multiple aspects of the food web because the presence of upper trophic levels indicates a large enough population of lower levels to sustain them. Soil is 'healthier' with greater soil biodiversity, higher microbial activity, and greater faunal abundance (Obriot et al., 2016). Despite its importance, few studies have investigated the impact of manure on soil biology, Table 1.

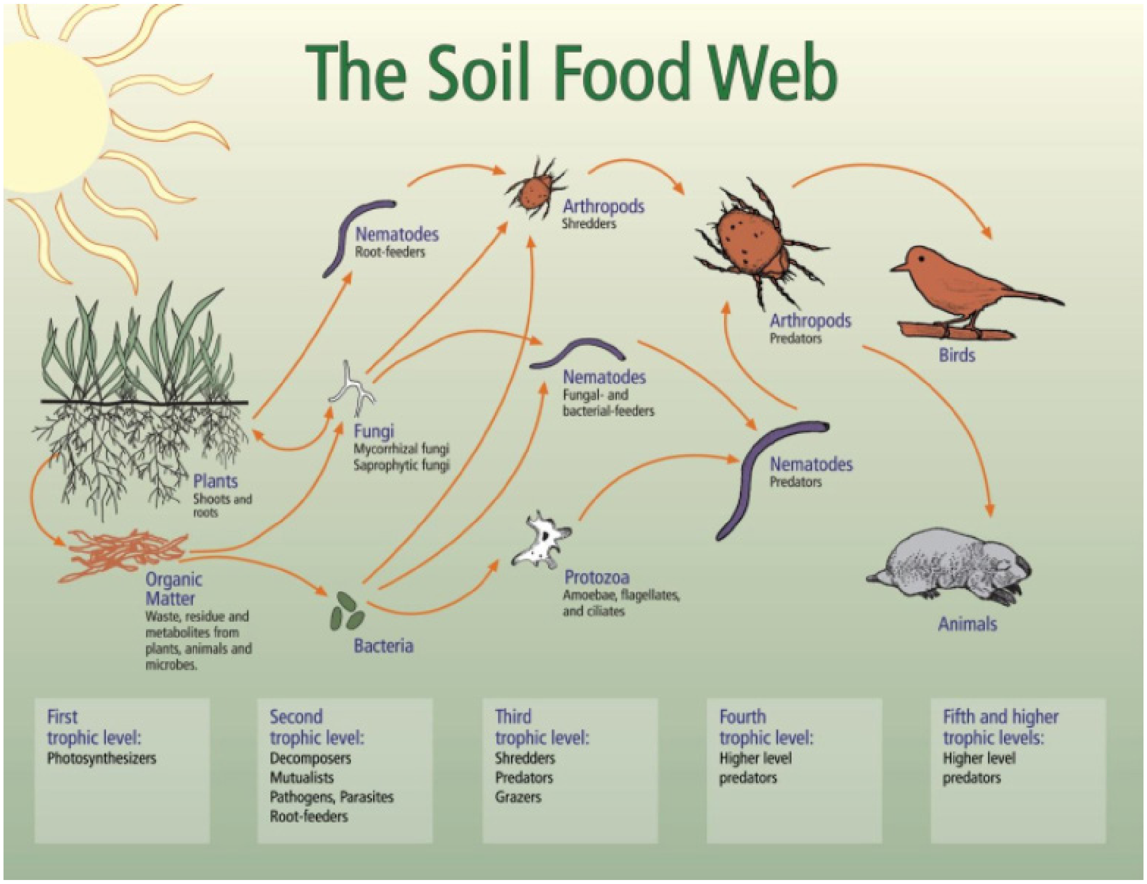

Figure 3. *Components of trophic levels in the soil food web (Ingham et al., 2000).*

4.1. Microbial abundance, diversity and activity

Microbial biomass carbon (MBC), or called simply 'microbial biomass', is a component of SOM that is used as a measure of microbial abundance in the soil (Vance et al., 1987). MBC responds to soil management practices more readily than SOC as MBC is affected by factors such as soil moisture, temperature, pH, and soil structure. For example, tillage practices that destroy natural soil structure and introduce oxygen to the soil have lower MBC than no-tillage (Wortmann et al., 2008). Another important factor is the quality and quantity of soil C since it is the energy source for microbes. Unstable C found in crop residues, manure, and other animal byproducts is decomposed by microbes and assimilated. Only the C that is assimilated in the living microbial biomass is released via carbon dioxide when soil microbes are lysed. Therefore, MBC is measured by either fumigation-extraction or fumigation-incubation (Brookes et al., 1985; Vance et al., 1987).

In general, manure or biosolid application increases MBC in soils, Table 2 (Fraser et al., 1988; Leita et al., 1999; Lalande et al., 2000; Min et al., 2003; Manna et al., 2005; Adeli et al., 2008; F. Bastida et al., 2008; Zhao et al., 2009; Chakraborty et al., 2011; Giacometti et al., 2013; Li et al., 2015; Foster et al., 2016; Sathish et al., 2016). MBC increases ranged between 10% (Manna et al., 2005) and nearly 200% (Sathish et al., 2016). Both of these long-term studies used the same treatments on the same soil type in India. However, the climate and cropping system were different. These results are similar to the effect of organic amendments on SOC; both properties increase with the addition of manure or biosolids, but the effect on soil is difficult to predict. Additionally, MBC concentrations were highly variable, ranging from approximately 40 mg C kg^{-1} soil to 1400 mg C kg^{-1} soil. Variation could be due to differences that were not consistent across studies, such as cropping system, climate, seasonality, soil type, and measurement method.

For studies investigating the effect of manure on MBC, most did not balance nutrient application rates between treatments. The majority of studies compared manure or biosolid application with either a no amendment control or an inorganic fertilizer amendment, Table 2. Additionally, many of the studies applied inorganic fertilizer with the organic amendments. Only two studies applied manure and biosolids so that the N application was equal between treatments (Ros et al., 2006a; Li et al., 2015). In their 12 year study, Ros et al. (2006a) found that cattle manure compost and sewage sludge compost did not increase MBC compared to inorganic nitrogen fertilizer. However, Li et al. (2015) concluded that dairy compost did increase MBC compared to inorganic fertilizer when applied at equal rates. Similarly, when manure is applied at equal organic C rates, Bhogal et al. (2009) estimated a linear relationship where an addition of 10 Mg ha^{-1} of organic C would increase MBC by 11%.

Only two studies have investigated the residual effect of manure or biosolid application on MBC. In both instances, beef manure compost was studied. Braman et al. (2016) concluded that there were no differences in MBC concentrations four years after an application of beef compost (20 Mg ha^{-1}). However, Reeve et al. (2012) determined that MBC was increased 19% from a 50 Mg DM ha^{-1} application of dairy manure 16 years previously. It would be difficult to infer the overall effect of a single application of beef manure compost on MBC over time based on these two studies alone. The application rates were vastly different as well as climatic and management factors. However, since manure compost is typically has a high C:N ratio, the microbial population tends to be smaller and slower growing (Ros et al., 2006a).

Reference	Waste Type	Application Method	Control	Location	Duration, yrs	Nutrient Application	Soil Type	ΔMBC	Δ CO_2	Δ qCO
Adeli et al. (2008)	Swine effluent, 10-15 cm ha^{-1}	Irrigated	Non irrigated site w/ same soils	Mississippi	15	Not balanced	alkaline silty clay	12%		
							acidic silty clay	23%		
							silty clay loam	55%		
Bastida et al. (2008b)	Sewage sludge, 120 Mg ha^{-1}	Incorporated	No amendment	Spain	2	Not balanced	sandy clay loam	87%	ns	
	Composted sewage sluge, 120 Mg ha^{-1}	Incorporated	No amendment					98%	135%	
Chakraborty et al. (2011)	Farmyard manure, 10 Mg ha^{-1} + 100% NPK	Not stated	100% NPK	India	37	Not balanced	sandy loam	19%	81%	
Foster et al. (2016)	Beef Manure, 30 Mg ha^{-1} + 100% NPK	Broadcast and incorporated	100% NPK	Colorado	1	Not balanced	sandy clay loam	15%		
Franco-Otero et al. (2012)	Municipal solid waste, 30 Mg ha^{-1}	Broadcast and incorporated	100% NPK	Spain	0.5	Not balanced	clay loam	ns		
	Sewage sludge, 30 Mg ha^{-1}	Broadcast and incorporated	100% NPK					ns		
Fraser et al. (1988)	Beef manure, 2.6-13.9 Mg ha^{-1}	Incorporated	NPK fertilizer	Nebraska	8	Not balanced	silty clay loam	10-26%		
Giacometti et al. (2013)	Beef manure, 6-7.5 Mg DM ha^{-1}	Incorporated	No amendment	Italy	44	Not balanced	sandy clay loam	0-46%		-45%-0
Lalande et al. (2000)	Swine Manure, 30 m^3 ha^{-1}	Injected	100% NPK	Quebec	17	Not balanced	silt loam	ns		
	Swine Manure, 60 m^3 ha^{-1}	Injected	100% NPK					ns		
	Swine Manure, 90 m^3 ha^{-1}	Injected	100% NPK					119%		
	Swine Manure, 120 m^3 ha^{-1}	Injected	100% NPK					ns		
Leita et al. (1999)	Farmyard manure, 500 kg N ha^{-1}	Incorporated	200 kg N/ha via NPK	Italy	12	Not balanced	sandy loam	77%		110%
	Composted municipal refuse, 500 kg N ha^{-1}	Incorporated	200 kg N/ha via NPK					44%		170%
	Composted municipal refuse, 500 kg N ha^{-1} + 200 kg N via NPK	Incorporated	200 kg N/ha via NPK					31%		205%
	Composted municipal refuse, 1000 kg N ha^{-1}	Incorporated	200 kg N/ha via NPK					102%		320%
	Composted municipal refuse, 1000 kg N ha^{-1}	Incorporated	200 kg N/ha via NPK					156%		410%

Table 2. *Manure studies investigating microbial biomass carbon (MBC), respiration (CO2), and metabolic respiration quotient (qCO2) where “ns” indicates not significantly different with respect to the control.*

Reference	Waste Type	Application Method	Control	Location	Duration, yrs	Nutrient Application	Soil Type	ΔMBC	Δ CO_2	Δ qCO
Li et al. (2015)	Dairy Compost, 100% N	Broadcast and incorporated	100% N Via NPK	China	25	N rate	silt loam	178%		
	Dairy Compost, 50% N + 50% N via NPK	Broadcast and incorporated	100% N Via NPK					107%		
	Dairy Compost, 200% N	Broadcast and incorporated	200% N Via NPK					119%		
Manna et al. (2005)	Farmyard Manure, 10 Mg ha^{-1} + 100% NPK	Not stated	100% NPK	India	30	Not balanced	sandy loam	45%	34%	
							sandy clay loam	10%	ns	
							clay	22%	29%	
Min et al. (2003)	Deep pack dairy manure, 780 kg N ha^{-1}	Broadcast and incorporated	310 kg N/ha via NPK	Maryland	4	Not balanced	silt loam	60%		-30%
	Deep pack dairy manure, 360 kg N ha^{-1}	Broadcast and incorporated						44%		
Ros et al. (2006a)	Cattle manure compost, 175 kg N ha^{-1}		175 kg N	Austria	12	N rate	silt loam	ns	10%	ns
	Sewage sludge compost, 175 kg N ha^{-1}		175 kg N			N rate		ns	58%	59%
	Cattle manure compost, 175 kg N ha^{-1}+ 80 kg N ha^{-1} via NPK		175 kg N			Not balanced		ns	ns	ns
	Sewage sludge compost, 175 kg N ha^{-1}+ 80 kg N ha^{-1} via NPK					Not balanced		ns	40%	32%
Sathish et al. (2016)	Farmyard Manure, 10 Mg ha^{-1}	Broadcast and incorporated	100% NPK	India	20	Not balanced	sandy loam to sandy clay loam	119%		
	Farmyard Manure, 10 Mg ha^{-1} + 50% NPK	Broadcast and incorporated	100% NPK					94%		
	Farmyard Manure, 10 Mg ha^{-1} + 100% NPK	Broadcast and incorporated	100% NPK					194%		
Zhao et al. (2009)	Swine manure, 75 Mg ha^{-1} + NP fertilizer	Not stated	NP fertilizer; no amendment	China	25	Not balanced	silty clay	93%	123%	

Table 2. *continued*

Microbial biomass nitrogen (MBN) is the measure of N assimilated into soil bacteria and fungi. Similar to MBC, it is measured by either fumigation-extraction or fumigation-incubation (Brookes et al., 1985; Vance et al., 1987). Essentially, total soil N is measured prior to and after soil biology is lysed, and the difference is attributed to N immobilized in soil microbes, Figure 2. Since amendments like manure and biosolids have a low C:N ratio, mineralization of N tends to dominate over immobilization, which makes N available for crop utilization. When microbes utilize food stocks with high C:N ratios, such as corn residue, more N is immobilized and less is available for crop utilization. With an abundance of both C and N present, soil microbial populations increase because their needs are easily met, and they can reproduce as long as other soil conditions, such as temperature and moisture, are adequate (Robertson and Groffman, 2015).

The effect of manure and biosolid application has not been as widely researched as the effect on MBC, Table 3. In fact, the effect of biosolid application on MBN has not been investigated. In most studies, manure application increased MBN (Lalande et al., 2000; Manna et al., 2005; Adeli et al., 2008; Li et al., 2015; Sathish et al., 2016). These increases ranged from 18% (Adeli et al., 2008) to 178% (Li et al., 2015). MBN concentration in soil was variable, ranging from 12.3 mg N kg^{-1} soil to 119 mg N kg^{-1} soil. Only one study was designed to have N applied at equal rates to all (Li et al., 2015). The authors concluded that dairy compost increased MBN by 178% compared to inorganic fertilizer. Additionally, when half the N was applied via manure and half via inorganic fertilizer, MBN was still increased by over 100%. Bhogal et al. (2009) also applied equal rates of N in their study. They were able to obtain a linear relationship between MBN and N application rate; for every 1 t manure N ha^{-1} applied, MBN increases by 88% compared to the same amount of N applied via inorganic fertilizer.

There are several indicators for assessing microbial diversity in soil. However, due to cost and time constraints, this metric is only occasionally included (Doran and Zeiss, 2000; Kibblewhite et al., 2008; Allen et al., 2011). One common measurement of microbial diversity is an assessment of phospholipid fatty acids (PLFA). This measurement estimates the abundance of specific cellular components for bacteria, fungi, and protozoa. The relative abundance of each type of organism gives insight into the diversity. DNA analysis has also been utilized to characterize the diversity of soil microbial communities (Li et al., 2015). For the studies that reported community composition data, the majority concluded that while bacterial and fungal populations increased with manure and biosolid application, the ratio of bacterial and fungal populations did not change (Elfstrand et al., 2007; Bastida et al., 2008a; Bastida et al., 2008b; Giacometti et al., 2013). Marschner et al. (2003) did report an increase in the ratio of bacterial to fungal populations. Overall, however, results indicate that while microbial abundance increases, microbial diversity does not change.

Unfortunately, grouping soil microbes into three broad phylogenies (bacteria, protozoa, and fungi) is not a very specific indicator of diversity. Some authors also reported more specific indicators of diversity by further grouping bacteria into either gram-positive or gram-negative categories. Gram-positive bacteria are larger in size and able to resist water stress better than gram-negative bacteria due to thicker cell walls. Three studies did not find differences in the ratio of gram-positive and gram-negative bacteria (Elfstrand et al., 2007; Bastida et al., 2008a; Bastida et al., 2008b). Four other studies, however, reported an increase in the ratio of gram-positive to gram-negative bacteria due to organic amendment application (Giacometti et al., 2013; Marschner et al., 2003; Peacock et al., 2001; Zhong et al., 2010). The shift to a gram-positive dominated bacterial population compared to inorganic fertilizer has been linked to the quality of organic matter available for microbial utilization (Giacometti et al.,

Reference	Waste Type	Application Method	Control	Replication Comments	Location	Length of Study, yrs	Nutrient Application	Soil Type	MBN, mg/kg	ΔMB
Adeli et al. (2008)	Swine effluent, 10-15 cm ha^{-1}	Irrigated	Non irrigated site with same soil types	One field	Mississippi	15	Not balanced	alkaline silty clay	95.6	45%
								acidic silty clay	88.4	33%
								silty clay loam	62.1	18%
Foster et al. (2016)	Beef Manure, 30 Mg ha^{-1} + 100% NPK	Broadcast and incorporated	100% NPK	4	Colorado	1	Not balanced	sandy clay loam	12.3	ns
Lalande et al. (2000)	Swine Manure, 30 m^3 ha^{-1}	Injected	100% NPK	4	Quebec	17	Not balanced	silt loam	83	ns
	Swine Manure, 60 m^3 ha^{-1}	Injected	100% NPK						89	ns
	Swine Manure, 90 m^3 ha^{-1}	Injected	100% NPK						119	55%
	Swine Manure, 120 m^3 ha^{-1}	Injected	100% NPK						100	ns
Li et al. (2015)	Dairy Compost, 100% N	Broadcast and incorporated	100% N Via NPK	4	China	25	N rate	silt loam	83.4	178%
	Dairy Compost, 50% N + 50% N via NPK	Broadcast and incorporated	100% N Via NPK						62.1	107%
	Dairy Compost, 200% N	Broadcast and incorporated	200% N Via NPK						109.9	119%
Manna et al. (2005)	Farmyard Manure, 10 Mg ha^{-1} + 100% NPK	Not stated	100% NPK	4	India	30	Not balanced	sandy loam	18.7	34%
								sandy clay loam	14.5	ns
								clay	16.4	23%
Sathish et al. (2016)	Farmyard Manure, 10 Mg ha^{-1}	Broadcast and incorporated	100% NPK	2	India	20	Not balanced	sandy loam to sandy clay loam	32.5	38%
	Farmyard Manure, 10 Mg ha^{-1} + 50% NPK	Broadcast and incorporated	100% NPK						31.7	35%
	Farmyard Manure, 10 Mg ha^{-1} + 100% NPK	Broadcast and incorporated	100% NPK						36.4	55%

Table 3. *Manure studies investigating microbial biomass nitrogen (MBN) where "ns" indicates not significantly different with respect to the control.*

2013; Marschner et al., 2003; Zhong et al., 2010). From these studies, it is difficult to determine the effect of manure application on soil microbial diversity. However, several studies have cited pH to be the main driver affecting microbial diversity and not management practices, like organic amendment application (Giacometti et al., 2013; Wakelin et al., 2008; Zhong et al., 2010).

There are many ways to quantify microbial activity, including microbial respiration, mineralization, substrate use efficiency, and enzyme activity. Microbial activity, like diversity, is only occasionally included as an indicator for soil health (Allen et al., 2011). However, several studies have included activity metrics in their assessment of the impact of manure on soil health. Respiration and substrate use efficiency are often measured as indicators for microbial activity when MBC is also measured. In the majority of studies that measured microbial respiration, carbon dioxide respiration rate was increased between 10% and 135%, Table 2 (Manna et al., 2005; Ros et al., 2006a; Bastida et al., 2008b; Zhao et al., 2009; Chakraborty et al., 2011). In one study, the microbial respiration rate increased without a corresponding increase in MBC, indicating a higher efficiency of substrate use (Ros et al., 2006a). However, Giacometti et al. (2013) and Min et al. (2003) both reported reduced substrate use efficiency, which is likely linked to higher availability of C. Additionally, a few studies also investigated the N mineralization potential. In general, the addition of manure increased N mineralization compared to inorganic fertilizer and no fertilizer (Cote and Ndayegamiye, 1989; Monaco et al., 2008).

4.2. Other components of soil food web

Mesofauna, such as microarthropods and nematodes, are components of higher soil trophic levels, Figure 3. Their overall populations and diversity are often indicative of soil health due to sufficient populations and diversity of lower trophic food sources (Kibblewhite et al., 2008). Microarthropod population and diversity play an important role in the soil ecosystem by serving as both predators and prey, which both assist in nutrient cycling. Since mites (Acari) and springtails (Collembola) are the most abundant soil microarthropods, they are typically sampled (Kautz et al., 2006; Booher et al., 2012; Coleman and Wall, 2015). Two studies have investigated the effect of long-term manure application on microarthropod abundance and diversity. In their 17 year study, Miller et al. (2017b) found that neither Collembola nor Acari populations were significantly affected by beef nor swine manure application. Similarly, Booher et al. (2012) found that in 15 years of swine manure application, overall mite abundance was not affected. However, the authors did find that beef manure increased mite populations. In that study, the N application rate was not found to be important, so even low manure application rates increased mite populations. However, other studies have concluded that organic amendment application does not affect microarthropod abundance or diversity (Da Silva et al., 2016; Kautz et al., 2006; Miller et al., 2017b; Tessaro et al., 2011).

Nematodes are considered to be both beneficial and harmful in soil as they serve many functions in the soil food web. Due to their varied functions and higher trophic level, nematodes have been proposed to be used as bioindicators for overall soil quality (Yeates and Bongers, 1999). Nematodes, which are categorized by what they primarily feed on, can consume a wide range of organisms and substrates, such as plants, fungi, bacteria, and protozoa. Additionally, by feeding on lower trophic groups, nematodes assist in mineralizing soil nutrients. Cogger et al. (2006) concluded that biosolid application increased total nematode population, while decreasing overall nematode biodiversity. More recently, Forge et al. (2013) established that composted dairy manure (45 Mg ha^{-1}) increased populations of bacterial and fungal feeding nematodes but did not affect nematode biodiversity. Since manure application increases microbial abundance, these results are not surprising as it indicates that populations are sufficient to sustain higher trophic levels (Fraser et al., 1988; Leita et al., 1999; Lalande et al., 2000; Min et al., 2003; Manna et al., 2005; Adeli et al., 2008; F. Bastida et al., 2008b; Zhao et al., 2009; Chakraborty et al., 2011; Giacometti et al., 2013; Li et al., 2015; Foster et al., 2016; Sathish et al., 2016). However, lower rates of manure application (1 – 5 Mg ha^{-1}) have not been shown to change nematode populations or diversity (Ito et al., 2015; Forge et al., 2016). Unfortunately, these studies did not include microbial biomass measurements in order to assess the abundance of fauna at lower trophic levels that nematodes consume. The effects of manure application on root lesion nematodes, which are harmful to crops, have been mixed. Cogger et al. (2006) concluded that biosolid application increased the populations of root lesion nematodes. More recently, Forge et al. (2013) found that a dairy compost application rate of 45 Mg ha^{-1} had no effect on root lesion nematode populations while a later study by Forge et al. (2016) concluded that 55 Mg ha^{-1} of broiler manure reduced their population.

Earthworms, which are soil macrofauna, consume plant litter and SOM (Coleman and Wall, 2015). They assist in litter and organic matter decomposition. Additionally, earthworms influence soil structure by creating macropores due to burrowing activities and creating soil aggregates (i.e. casts). Earthworm abundance has been shown to significantly increase with both high and low organic amendment application rates. Rees et al. (2011) found that a low rate of broiler manure (4 Mg ha^{-1} yr^{-1}) more than doubled earthworm abundance while Yagüe et al. (2016) demonstrated that abundance increased with a dairy manure application rate of 60 Mg ha^{-1} yr^{-1}. Additionally, there is evidence that the increase in earthworm abundance has a residual affect after amendment application. Baker et al. (2002) applied a single application of three biosolid rates (30, 60, and 120 Mg ha^{-1}) and found that all three rates had increases of earthworm abundance six years after application compared to inorganic fertilizer. In another study, inorganic fertilizer decreased earthworm abundance and density compared to treatments of either no amendment or beef manure compost (Guo et al., 2016). The same relationship was not found by Yagüe et al. (2016), however.

Overall, manure and biosolid application increases abundance of soil fauna, such as bacteria, fungi, and earthworms, but does not seem to increase faunal diversity when compared to inorganic fertilizer. Manure and biosolid application also increases microbial respiration and mineralization, which are indicators of nutrient cycling. However, the application of manure does not affect the abundance of soil microarthropods, like Collembolla or Acari. However, compared to soil physical and chemical properties, not much research investigated the effect of manure and biosolids on biological soil properties. MBC is the most commonly utilized metric for assessing soil biological properties. However, this measurement only indicates the abundance of soil microbes and not the activity or diversity, which gives insight into the soil food web.

5. Manure and soil health

Few studies that have investigated the impact of manure on soil have incorporated metrics from all three properties contributing to soil health – physical, chemical, and biological – and even fewer have also included investigation of crop production metrics, which are important for agricultural producers, Table 4. Most of these comprehensive studies were published after 2009 and included greater than five years of data from field experiments. In these studies, the most common chemical, physical, and biological properties investigated were SOC, bulk density, and MBC, respectively. The results from these studies have been reported in previous sections of this paper. Briefly, regardless of manure type, study location, and length of study, SOC and MBC increased under animal manure treatments compared treatments of

Reference	Waste Type	Application Method	Control	Location	Duration, yrs	Nutrient App.	Crop	Chemical^a	Physical^b	Biological^c	Crop Metrics
Bhogal et al. (2009)	Beef Manure, 250 kg N ha^{-1}	Incorporated	No amendment	United Kingdom	8	N rate	Combinable crops (cereals, rape, etc.)	C; N; P; K; Micronutrients ; pH	AWC; BD; AS; porosity	MBC; MBN; Respir.; PMN	Biomass; yield
	Beef Slurry, 250 kg N ha^{-1}	Incorporated									
	Swine Manure, 175 kg N ha^{-1}	Incorporated									
	Swine Slurry, 175 kg N ha^{-1}	Incorporated									
	Broiler Litter, 0-25 N ha^{-1} (6 rates)	Incorporated									
Forge et al. (2016)	Boiler Litter, 16 or 23 m^3 ha^{-1}	Incorporated	No amendment	British Columbia	2	Not balanced	Raspberry	N; C; Micronutrients ; CEC; pH	BD; AWC; AS	Nematode abundance	Primocane Vigor
	Boiler Litter, 250 m^3 ha^{-1}	Incorporated									
	Poultry Compost, 250 m^3 ha^{-1}	Incorporated									
Fraser et al. (1988)	Beef manure, 2.6-13.9 Mg ha^{-1}	Incorporated	NPK fertilizer	Nebraska	8	Not balanced	Oat/clover-corn-soybean-corn	N; C; pH; P	BD	MBC; PMN; Respir;	
Guo et al. (2016)	Beef manure compost, 4.4 Mg ha^{-1}	Surface applied	NPK fertilizer; no amendment	China	5	NPK balanced except no amendment	Wheat-maize	C; N	BD	Earthworm	Yield
	Beef manure compost, 8.9 Mg ha^{-1}	Surface applied									
	Beef manure compost, 13.3 Mg ha^{-1}	Surface applied									
	Beef manure compost, 17.8 Mg ha^{-1}	Surface applied									
Manna et al. (2005)	Farmyard Manure, 10 Mg ha^{-1}+ NPK	Not stated	NPK fertilizer; no amendment	India	30	Not balanced	Wheat, Jute, Rice, Soybean, Sorghum	C; N; pH; CEC; P; K	AS; BD	MBC; MBN; Respir	Yield; crop composition

Table 4. *Comprehensive manure and soil health studies*

Reference	Waste Type	Application Method	Control	Location	Duration, yrs	Nutrient App.	Crop	Chemical	Physical	Biological	Crop Metrics
Martens and Frankenberger (1992)	Poultry manure, 25 Mg ha^{-1}	Incorporated	No amendment	California	2	Not balanced	Fallow	C	AS; BD; Infiltration	Respir;	
	Sewage sludge, 25 Mg ha^{-1}	Incorporated									
Miller et al. (2017b)	Stockpiled beef manure, 13 Mg ha^{-1}	Incorporated	No amendment	Alberta	17	Not balanced	Barley	N; C	BD	Micro-arthropods	
	Composted beef manure, 13 Mg ha^{-1}	Incorporated									
Morlat and Chaussod (2008)	Beef manure compost, 10 Mg ha^{-1}	Incorporated	No amendment	France	28	Not balanced	Grapevine	C; N; P; K; Micronutrients; pH; CEC	BD	MBC	
	Beef manure compost, 20 Mg ha^{-1}	Incorporated									
Rees et al. (2011)	Poultry manure, 4 Mg ha^{-1}	Incorporated	No amendment	New Brunswick	3	Not balanced	Potatoes	C; P; K; Micronutrients; pH	BD; AWC; AS; Infiltration	Earthworm	Yield
Sathish et al. (2016)	Farmyard Manure, 10 Mg ha^{-1}	Incorporated	NPK fertilizer; no amendment	India	20	Not balanced	Finger millet; Finger millet-groundnut	C; N; P; K; Micronutrients; pH	BD; AWC; Infiltration	MBC; MBN	Yield
	Farmyard Manure, 10 Mg ha^{-1}+ 50% NPK	Incorporated									
	Farmyard Manure, 10 Mg ha^{-1}+ 100% NPK	Incorporated									
Yagüe et al. (2016)	Dairy Manure, 30 Mg ha^{-1}	Incorporated	NPK fertilizer; no amendment	Spain	11	Not balanced	Irrigated Maize	C	AS; porosity	Earthworm	Yield
	Dairy Manure, 60 Mg ha^{-1}	Incorporated									
Zhao et al. (2009)	Swine manure, 75 Mg ha^{-1}+ NP	Not stated	NP fertilizer; no amendment	China	25	Not balanced	Wheat-maize	C; N; P; pH	BD; AS	MBC; Respir	Yield

Table 4. *continued*

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[a] C- carbon; N- nitrogen; P- phosphorous; K- potassium; CEC- cation exchange capacity

[b] AWC- available water holding capacity; BD- bulk density; AS- aggregate stability

[c] MBC- microbial biomass carbon; MBN- microbial biomass nitrogen; Respir- respiration rate; PMN- potentially mineralizable nitrogen

no fertilizer amendment and/or inorganic fertilizer. Additionally, soil bulk density decreased under manure treatments. For the studies that also included crop metrics, yield was the primary element investigated. Some studies reported yield improvements under manure treatments (Manna et al., 2005; Bhogal et al., 2009; Zhao et al., 2009; Rees et al., 2011; Forge et al., 2016) while others reported no differences (Manna et al., 2005; Guo et al., 2016; Sathish et al., 2016; Yagüe et al., 2016).

In the majority of these studies, nutrient application rates were not balanced among treatments, with only two designed with balanced nutrient applications among treatments. Bhogal et al. (2009) applied all manure treatments at the required N rate of the crop, and Guo et al. (2016) balanced the control and manure applications so that all treatments received equal amounts of N, P and K. Their experimental design allowed Bhogal et al. (2009) to obtain linear equations with statistical significance in order to relate N and organic C applied by manure to soil properties. For instance, they concluded that for every 10 tons of manure applied, SOC and MBC increased 3% and 11%, respectively, while bulk density decreased 0.5%. Guo et al. (2016) established that SOC and total N concentrations increased under composted cattle manure applications compared to inorganic fertilizer despite all treatments receiving equal quantities of all applied nutrients.

By measuring multiple soil properties, several authors were able to better understand how soil health properties are interconnected. For example, Zhao et al. (2009) found positive correlations between SOC and pH as well as between MBC and SOC. However, there were no correlations between crop yield and any of the measured soil properties. In addition to determining relationships between soil health metrics, Sathish et al. (2016) was also able to determine which metrics were most important under either a rotational cropping system or a monoculture in India. In the finger millet-groundnut system, several soil chemical properties and biological properties were the most important for determining soil quality, but properties like bulk density and water holding capacity were not found to be important. These results are specific to this cropping system, location, and management practices. However, if more research is conducted about the interconnectedness of soil health properties under manure or biosolid applications, this information can be utilized to potentially reduce sampling needs for soil health assessment.

6. Conclusions

The effect of manure and municipal biosolids on soil physical and chemical properties has been well documented in previous literature reviews. In general, the effect of manure and municipal biosolids on soil chemical properties is heavily dependent upon the chemical properties of the applied amendment. When applied at appropriate rates, these organic amendments increase SOC and CEC, as well as provide beneficial micronutrients for crops. The application of manure or biosolids decreases bulk density which, subsequently, increases soil porosity. However, manure and biosolid application does not increase water holding capacity of the soil. Studies also indicate that manured soil is more resistant to compaction, especially when wet; aggregate stability is increased due to an increase in SOC and microbial activity, and infiltration rate is also increased. Both of these effects lead to less runoff and erosion.

However, the effect of manure and municipal biosolids on soil biological properties has not been well researched. This is likely due to cost and time constraints related to these measurements. Overall, manure and biosolid application increases abundance of soil fauna, such as bacteria, fungi, and earthworms, but does not seem to increase faunal diversity when compared to inorganic fertilizer. Manure and biosolid application also increases microbial respiration and mineralization, which are indicators of nutrient cycling. However, the application of manure does not affect the abundance of soil microarthropods, like Collembolla or Acari. When compared to soil physical and chemical properties, not much research has investigated the effect of manure and biosolids on biological soil properties. MBC is the most commonly utilized metric for assessing soil biological properties. This measurement only indicates the abundance of soil microbes and not the activity or diversity, which gives insight into the soil food web.

Most of the research published about the impact of manure or biosolids application on soil properties, crop production, and water quality is based on studies where manure is applied annually. When manure and biosolids are applied annually at rates that exceed the nutrient requirements of crops, the risk for leaching, runoff, and accumulation of nutrients, such as N, P, K, salts and heavy metals, is increased. This is especially true in studies that apply manure annually at the crop N rate because P and K are often over applied. Only a few studies have investigated the residual effects of manure or biosolid application. Additionally, few of these studies had balanced nutrient applications among treatments.

It was a challenge to draw generalized conclusions for this report because there are numerous variables that need to be taken into account when summarizing and synthesizing the effect livestock manure, animal by-products, and municipal biosolids have on soil health. For instance, there are a large number of amendments (liquid swine manure, solid beef manure, beef effluent, dairy manure, municipal biosolids, poultry litter, etc.) as well as numerous methods for application (injection, broadcast, and irrigation). The timing (fall, spring, in-season), rate, and frequency (annual, single application, multi-year) also affect soil properties. Additional confounding factors include tillage and cover crop use because both of these have been shown to significantly affect soil C (Blanco-Canqui et al., 2015).

Practices such as planting cover crops and minimizing or eliminating tillage, are promoted for improving soil health. However, utilizing livestock manure and municipal biosolids as soil amendments on agricultural cropland has received comparatively less attention as a practice for improving soil qualities. Recycling locally available nutrients, such as livestock manure, prior to importing commercial fertilizer should be promoted as a component of the overall strategy to address nutrient imbalance and net increases of nutrients to regions. When applied at appropriate rates, manure and biosolids have the potential to positively impact soil health by improving the physical stability of soil and increasing soil nutrient cycling to provide nutrients for crops.

7. Recommendations

This report compiled a comprehensive assemblage of outcomes from manure and soil health-related research studies and identified knowledge gaps in the current state of science and understanding. The following are recommendations for directing future research and educational programs intended to demonstrate the value of manure to the sustainability of agricultural cropping systems.

1. Soil health properties are inter-related, yet few studies have focused on the impact of manure on multiple soil health properties. While many chemical and physical properties have been linked together, such as pH with CEC and soil organic C with bulk density, relationships have not been well established between biological properties and soil chemical and physical properties, especially within the context of manure or biosolid application. Thus, soil biological metric quantification should be incorporated into future research.

2. Many of the studies discussed in this literature review focused on the effects of repeated manure or municipal biosolids applications on individual soil health properties. It has been well-established that repeated applications of manure increase the risk of nutrient leaching and runoff, especially when manure is applied annually at the rate for crop N requirement. Therefore, future research should focus on the short- and long-term impacts of a single application of manure or biosolids to support an effort to identify optimal frequency of application for improving soil health.

3. Future field research should also balance nutrient applications of N, P, and K in order to compare the effect of manure to inorganic fertilizers on crop yield and soil quality on an annual or multi-year basis. Research that focuses on the impact of manure application should also include inorganic fertilizers if manure is not applied every year since agricultural producers would likely apply inorganic fertilizer in years when manure is not applied. In this way, researchers will be able to assess the effects of traditional utilization of manure. Additionally, if manure or biosolids are applied at nutrient rates below crop requirements, researchers should also have treatments that have additional inorganic fertilizer added.

4. Manure research should also provide discussion that clearly relates research findings to management decisions relevant to agricultural crop producers. For example, if an area is prone to heavy rainfall during times when manure is traditionally applied, research should focus on identifying appropriate rates of manure or biosolid application that would increase resilience (i.e. increased infiltration and increased resistance to soil compaction) without increasing environmental risk of nutrient leaching, runoff, or accumulation.

5. Challenges also exist when interpreting soil tests for biology due to differences in methods and interpreting results. There are also many metrics to assess soil biological properties (e.g. abundancy and diversity of soil fauna, respiration, mineralization, substrate use efficiency, and enzyme activity). Utilizing all of these metrics when assessing soil health is not feasible due to cost and time constraints. Thus, researchers should look to provide consensus about which tests provide the most value.

6. Researchers should be more transparent with their research data, especially once it has been published. Due to publication page limitations and formatting issues, it is not common for all data to be presented within publications. This is especially true if the particular metric was not found to have a significant change due to the treatment. However, as the state-of-the-science in manure management progresses, this data is important and can help guide future research. Additionally, it is important to specify the source of manure, biosolid, or animal by-product utilized. As waste management systems and animal production systems continue to evolve, this is important information for other researchers.

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Appendix

Carbon

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- Elzobair et al. (2016)
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- Kukal et al. (2009)
- Kumar et al. (2014)
- Laird et al. (2017)
- Lazcano et al. (2016)
- Leita et al. (1999)
- Li et al. (2015)
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- Ma et al. (2016)
- Manna et al. (2005)
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- Martens and Frankenberger (1992)
- Matsi et al. (2015)
- Meersmans et al. (2012)
- Miller et al. (2017b)
- Miller et al. (1985)
- Min et al. (2003)
- Monaco et al. (2008)
- Morales et al. (2016)
- Morlat and Chaussod (2008)
- Nardi et al. (2004)
- Netthisinghe et al. (2016)
- Ohno et al. (2005)
- Paetsch et al. (2016)
- Parham et al. (2002)
- Peacock et al. (2001)
- Peltre et al. (2017)
- Plaza et al. (2002)
- Qi et al. (2016)
- Rees et al. (2011)
- Reeve et al. (2012)
- Ros et al. (2006a)
- Ros et al. (2006b)
- Sathish et al. (2016)
- Schjonning et al. (1994)
- Shukla et al. (2006)
- Sleutel et al. (2006)
- Sloan et al. (2016)
- Sørensen (2001)
- Steiner et al. (2007)
- Stenger et al. (2001)
- Tian et al. (2015)
- Triberti et al. (2008)
- Wortmann and Walters (2006)
- Wu et al. (2004)
- Yagüe et al. (2016)
- Yan et al. (2016)
- Yang et al. (2011)
- Zhao et al. (2009)
- Zhong et al. (2010)

Nitrogen

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Adeli et al. (2008)
Ahmed et al. (2013)
Banashree et al. (2017)
Bastida et al. (2008a)
Bélanger et al. (2017)
Bhogal et al. (2009)
Chakraborty et al. (2011)
Choudhary et al. (1996)
Cogger et al. (2006)
Cote and Ndayegamiye (1989)
De Lucia et al. (2013)
Domingo-Olivé et al. (2016)
Dorado et al. (2003)
Eghball (2002)
Elfstrand et al. (2007)
Elzobair et al. (2016)
Erhart et al. (2005)
Evans et al. (1977)
Ferguson et al. (2005)
Fernandez et al. (2016)
Forge et al. (2016)
Forge et al. (2013)
Foster et al. (2016)
Franco-Otero et al. (2012)
Fraser et al. (1988)
Gao and Chang (1996)
Garland et al. (2010)
Ghosh et al. (2011)
Giacometti et al. (2013)
Gonzatto et al. (2016)
Guo et al. (2016)
Hartl and Erhart (2005)
Houot and Chaussod (1995)
Hueso et al. (2012)
Ito et al. (2015)
Kautz et al. (2006)
Khaliq and Kaleem Abbasi (2015)
Kingery et al. (1994)
Kulesza et al. (2016)
Laird et al. (2017)
Larney and Janzen (1996)
Lazcano et al. (2016)
Li et al. (2015)
Lithourgidis et al. (2007)
Ma et al. (2016)
Manna et al. (2005)
Marschner et al. (2003)
Matsi et al. (2015)
Miller et al. (2017b)
Monaco et al. (2008)
Morales et al. (2016)
Morlat and Chaussod (2008)
Netthisinghe et al. (2016)
Ovejero et al. (2016)
Whalen and Chang (2002)
Parham et al. (2002)
Paul et al. (2016)
Peacock et al. (2001)
Peltre et al. (2017)
Plaza et al. (2002)
Qi et al. (2016)
Reeve et al. (2012)
Ros et al. (2006a)
Ros et al. (2006b)
Sathish et al. (2016)
Saviozzi et al. (1999)
Shukla et al. (2006)
Sloan et al. (2016)
Sørensen (2001)
Stange and Neue (2009)
Steiner et al. (2007)
Stenger et al. (2001)
Sutton et al. (1982)
Tian et al. (2015)
Triberti et al. (2008)
Whalen and Chang (2002)
Whalen et al. (2000)
Yan et al. (2016)
Zhang et al. (2006)
Zhao et al. (2009)
Zhong et al. (2010)

Phosphorous

Adeli et al. (2008)
Ahmed et al. (2013)
Banashree et al. (2017)
Bastida et al. (2008a)
Bhogal et al. (2009)
Biederman et al. (2017)
Choudhary et al. (1996)
Cogger et al. (2006)
Colvan et al. (2001)
Curless et al. (2012)
De Lucia et al. (2013)
Domingo-Olivé et al. (2016)
Dorado et al. (2003)
Evans et al. (1977)
Ferguson et al. (2005)
Fernandez et al. (2016)
Forge et al. (2013)
Foster et al. (2016)
Franco-Otero et al. (2012)
Fraser et al. (1988)
Garcia et al. (2007)
Ghosh et al. (2011)
Glaesner et al. (2011)
Khaliq and Kaleem Abbasi (2015)
Kingery et al. (1994)
Laird et al. (2017)
Larney and Janzen (1996)
Li et al. (2015)
Lithourgidis et al. (2007)
Ma et al. (2016)
Manna et al. (2005)
Matsi et al. (2015)
Morlat and Chaussod (2008)
Murphy et al. (2005)
Netthisinghe et al. (2016)
Ohno et al. (2005)
Parham et al. (2002)
Qi et al. (2016)
Rees et al. (2011)
Reeve et al. (2012)
Ros et al. (2006a)
Sathish et al. (2016)
Siddique and Robinson (2004)
Sloan et al. (2016)
Steiner et al., (2007)
Sutton et al. (1982)
Tian et al., (2015)
Whalen and Chang (2002)
Whalen et al. (2000)
Wortmann and Shapiro (2008)
Wortmann and Walters (2006)
Zhang et al. (2006)
Zhao et al. (2009)
Zhong et al. (2010)

Potassium

Adeli et al. (2008)
Ahmed et al. (2013)
Banashree et al. (2017)
Bastida et al. (2008a)
Bhogal et al. (2009)
Biederman et al. (2017)
Choudhary et al. (1996)
Curless et al. (2012)
De Lucia et al. (2013)
Domingo-Olivé et al. (2016)
Dorado et al. (2003)
Evans et al. (1977)
Fernandez et al. (2016)
Forge et al. (2013)
Franco-Otero et al. (2012)
Garcia et al. (2007)
Ghosh et al. (2011)
Hao and Chang (2003)
Khaliq and Kaleem Abbasi (2015)
Laird et al. (2017)
Lithourgidis et al. (2007)
Ma et al. (2016)
Manna et al. (2005)
Matsi et al. (2015)
Miller et al. (2013)
Miller et al. (2017a)
Morlat and Chaussod (2008)
Murphy et al. (2005)
Qi et al. (2016)
Rees et al. (2011)
Reeve et al. (2012)
Ros et al. (2006a)
Sathish et al. (2016)
Steiner et al. (2007)
Sutton et al. (1982)
Turner et al. (2010)
Whalen et al. (2000)
Zhang et al. (2006)
Zhong et al. (2010)

Micronutrients

- Abaye et al. (2005)
- Adeli et al. (2008)
- Banashree et al. (2017)
- Bastida et al. (2008a)
- Bhogal et al. (2009)
- Choudhary et al. (1996)
- Clemente et al. (2006)
- Cogger et al. (2006)
- Curless et al. (2012)
- De Lucia et al. (2013)
- Dorado et al. (2003)
- Elfstrand et al. (2007)
- Erhart et al. (2008)
- Evans et al. (1977)
- Fernandez et al. (2016)
- Forge et al. (2013)
- Franco-Otero et al. (2012)
- Ghosh et al. (2011)
- Hao and Chang (2003)
- Khaliq and Kaleem Abbasi (2015)
- Kingery et al. (1994)
- Laird et al. (2017)
- Leita et al. (1999)
- Mahmoodabadi et al. (2012)
- Matsi et al. (2015)
- Miller et al. (2013)
- Miller et al. (2017a)
- Miller et al. (1985)
- Morlat and Chaussod (2008)
- Murphy et al. (2005)
- Netthisinghe et al. (2016)
- Rees et al. (2011)
- Reeve et al. (2012)
- Sathish et al. (2016)
- Sloan et al. (2016)
- Steiner et al. (2007)
- Turner et al. (2010)
- Whalen et al. (2000)
- Zhang et al. (2006)

Cation Exchange Capacity

- Cogger et al. (2006)
- Cote and Ndayegamiye (1989)
- De Lucia et al. (2013)
- Gao and Chang (1996)
- Morlat and Chaussod (2008)
- Murphy et al. (2005)
- Netthisinghe et al. (2016)
- Schjonning et al. (1994)
- Steiner et al. (2007)
- Whalen et al. (2000)

pH		
Abaye et al. (2005)	Foster et al. (2016)	Paetsch et al. (2016)
Adeli et al. (2008)	Franco-Otero et al. (2012)	Parham et al. (2002)
Ahmed et al. (2013)	Fraser et al. (1988)	Peacock et al. (2001)
Azeez and Van Averbeke (2012)	Garcia et al. (2007)	Peltre et al. (2017)
Banashree et al. (2017)	Giacometti et al. (2013)	Plaza et al. (2002)
Bastida et al. (2008a)	Kautz et al. (2006)	Ros et al. (2006a)
Bhogal et al. (2009)	Khaliq and Kaleem Abbasi (2015)	Sathish et al. (2016)
Biederman et al. (2017)	Kingery et al. (1994)	Schjonning et al. (1994)
Chakraborty et al. (2011)	Kumar et al. (2014)	Shukla et al. (2006)
Clemente et al. (2006)	Laird et al. (2017)	Sloan et al. (2016)
Cote and Ndayegamiye (1989)	Li et al. (2015)	Steiner et al. (2007)
Curless et al. (2012)	Miller et al. (2013)	Tian et al. (2015)
De Lucia et al. (2013)	Miller et al. (2017a)	Turner et al. (2010)
Dorado et al. (2003)	Miller et al. (1985)	Whalen et al. (2000)
Eghball (2002)	Min et al. (2003)	Wortmann and Walters (2006)
Elfstrand et al. (2007)	Morales et al. (2016)	Wuddivira et al. (2009)
Elzobair et al. (2016)	Morlat and Chaussod (2008)	Zhang et al. (2006)
Fernandez et al. (2016)	Murphy et al. (2005)	Zhao et al. (2009)
Forge et al. (2013)	Netthisinghe et al. (2016)	Zhong et al. (2010)

EC		
Adeli et al. (2008)	Hao and Chang (2003)	Plaza et al. (2002)
Azeez and Van Averbeke (2012)	Kingery et al. (1994)	Sathish et al. (2016)
Bastida et al. (2008a)	Kumar et al. (2014)	Shukla et al. (2006)
De Lucia et al. (2013)	Lithourgidis et al. (2007)	Sloan et al. (2016)
Domingo-Olivé et al. (2016)	Mahmoodabadi et al. (2012)	Turner et al. (2010)
Eghball (2002)	Miller et al. (2013)	Wuddivira et al. (2009)
Evans et al. (1977)	Miller et al. (2017a)	Zhang et al. (2006)
Forge et al. (2013)	Min et al. (2003)	Zhao et al. (2009)
Franco-Otero et al. (2012)		

Bulk Density

- Banashree et al. (2017)
- Bandyopadhyay et al. (2010)
- Barzegar et al. (2002)
- Bashir et al. (2016)
- Bassouny and Chen (2016)
- Benbi et al. (2016)
- Bhogal et al. (2009)
- Blanco-Canqui et al. (2015)
- Celik et al. (2004)
- Celik et al. (2010)
- Chakraborty et al. (2010)
- Chaudhary et al. (2017)
- Das et al. (2016)
- Domingo-Olivé et al. (2016)
- Eghball (2002)
- Ekwue and Stone (1995)
- Forge et al. (2016)
- Fraser et al. (1988)
- Guo et al. (2016)
- Hati et al. (2006)
- Khaliq and Kaleem Abbasi (2015)
- Kukal et al. (2009)
- Manna et al. (2005)
- Martens and Frankenberger (1992)
- Miller et al. (2017b)
- Morlat and Chaussod (2008)
- Mosaddeghi et al. (2000)
- Paetsch et al. (2016)
- Pagliai et al. (2004)
- Rees et al. (2011)
- Sathish et al. (2016)
- Schjonning et al. (1994)
- Shukla et al. (2006)
- Sloan et al. (2016)
- Wortmann and Walters (2006)
- Yagüe et al. (2016)
- Yang et al. (2011)
- Zhao et al. (2009)

Compaction

- Bandyopadhyay et al. (2010)
- Bassouny and Chen (2016)
- Blanco-Canqui et al. (2015)
- Celik et al. (2010)
- Ekwue and Stone (1995)
- Hati et al. (2006)
- Khaliq and Kaleem Abbasi (2015)
- Kumar et al. (2014)
- Mosaddeghi et al. (2000)
- Schjonning et al. (1994)
- Sloan et al. (2016)

Aggregation

- Bandyopadhyay et al. (2010)
- Barzegar et al. (2002)
- Bashir et al. (2016)
- Benbi et al. (2016)
- Bhattacharyya et al. (2007)
- Bhogal et al. (2009)
- Celik et al. (2004)
- Celik et al. (2010)
- Chakraborty et al. (2010)
- Das et al. (2016)
- Domingo-Olivé et al. (2016)
- Forge et al. (2016)
- Ghosh et al. (2011)
- Hati et al. (2006)
- Khaliq and Kaleem Abbasi (2015)
- Kukal et al. (2009)
- Manna et al. (2005)
- Martens and Frankenberger (1992)
- Min et al. (2003)
- Mosaddeghi et al. (2000)
- Netthisinghe et al. (2016)
- Rees et al. (2011)
- Shukla et al. (2006)
- Whalen and Chang (2002)
- Wortmann and Shapiro (2008)
- Wuddivira et al. (2009)
- Yagüe et al. (2016)
- Zhao et al. (2009)

Infiltration and Saturated Hydraulic Conductivity		
Alliaume et al. (2014)	De Lucia et al. (2013)	Rees et al. (2011)
Bandyopadhyay et al. (2010)	Gilley and Risse (2000)	Sathish et al. (2016)
Barzegar et al. (2002)	Hati et al. (2006)	Shukla et al. (2006)
Bassouny and Chen (2016)	Khaliq and Kaleem Abbasi (2015)	Sloan et al. (2016)
Bhattacharyya et al. (2007)	Martens and Frankenberger (1992)	Wortmann and Walters (2006)
Celik et al. (2004)	Mosaddeghi et al. (2000)	Wuddivira et al. (2009)
Chakraborty et al. (2010)	Pagliai et al. (2004)	Yang et al. (2011)

Water Holding Capacity and Volumetric Water Content		
Abaye et al. (2005)	Dorado et al. (2003)	Rees et al. (2011)
Barzegar et al. (2002)	Forge et al. (2016)	Sathish et al. (2016)
Bassouny and Chen (2016)	Guo et al. (2016)	Schjonning et al. (1994)
Bhogal et al. (2009)	Lazcano et al. (2016)	Shukla et al. (2006)
Blanco-Canqui et al. (2015)	Martens and Frankenberger (1992)	Wang et al. (2013)
Celik et al. (2004)	Miller et al. (2017b)	Yang et al. (2011)
Das et al. (2016)	Mosaddeghi et al. (2000)	

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- Adeli et al. (2008)
- Baker et al. (2002)
- Banashree et al. (2017)
- Barbarick et al. (2004)
- Bastida et al. (2008a)
- Bastida et al. (2008b)
- Bhogal et al. (2009)
- Biederman et al. (2017)
- Booher et al. (2012)
- Braman et al. (2016)
- Cavalli and Bechini (2014)
- Chakraborty et al. (2011)
- Clemente et al. (2006)
- Colvan et al. (2001)
- Cote and Ndayegamiye (1989)
- Da Silva et al. (2016)
- Dorado et al. (2003)
- Elfstrand et al. (2007)
- Elzobair et al. (2016)
- Fernandez et al. (2016)
- Forge et al. (2016)
- Forge et al. (2013)
- Foster et al. (2016)
- Franco-Otero et al. (2012)
- Fraser et al. (1988)
- Garcia et al. (2007)
- Garland et al. (2010)
- Ghosh et al. (2011)
- Giacometti et al. (2013)
- Guo et al. (2016)
- Heidari et al. (2016)
- Houot and Chaussod (1995)
- Hueso et al. (2012)
- Ito et al. (2015)
- Kautz et al. (2006)
- Lalande et al. (2000)
- Lazcano et al. (2016)
- Leita et al. (1999)
- Li et al. (2015)
- Ma et al. (2016)
- Manna et al. (2005)
- Marschner et al. (2003)
- Martens and Frankenberger (1992)
- Miller et al. (2017b)
- Min et al. (2003)
- Monaco et al. (2008)
- Morales et al. (2016)
- Morlat and Chaussod (2008)
- Parham et al. (2002)
- Peacock et al. (2001)
- Peltre et al. (2017)
- Qi et al. (2016)
- Rees et al. (2011)
- Reeve et al. (2012)
- Ros et al. (2006a)
- Ros et al. (2006b)
- Sathish et al. (2016)
- Sørensen (2001)
- Stenger et al. (2001)
- Tessaro et al. (2011)
- Tian et al. (2015)
- Wu et al. (2004)
- Yagüe et al. (2016)
- Zhao et al. (2009)
- Zhong et al. (2010)

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Alliaume et al. (2014)
Balemi (2012)
Banashree et al. (2017)
Bandyopadhyay et al. (2010)
Barzegar et al. (2002)
Bastida et al. (2008a)
Bastida et al. (2008b)
Bélanger et al. (2017)
Benbi et al., (2016)
Bhogal et al. (2009)
Blanco-Canqui et al. (2015)
Celik et al. (2010)
Curless et al. (2012)
Das et al. (2016)
De Lucia et al. (2013)
Domingo-Olivé et al. (2016)
Elfstrand et al. (2007)
Erhart et al. (2005)
Evans et al. (1977)
Ferguson et al. (2005)
Fernandez et al. (2016)
Forge et al. (2016)
Forge et al. (2013)
Foster et al. (2016)
Franco-Otero et al. (2012)
Garland et al. (2010)
Gonzatto et al. (2016)
Guo et al. (2016)
Hati et al. (2006)
Houot and Chaussod (1995)
Ito et al. (2015)
Klepper et al. (2010)
Kukal et al. (2009)
Kulesza et al. (2016)
Kumar et al. (2014)
Laird et al. (2017)
Larney and Janzen (1996)
Lazcano et al. (2016)
Lithourgidis et al. (2007)
Manna et al. (2005)
Matsi et al. (2015)
McFarland et al. (2010)
Netthisinghe et al. (2016)
Ovejero et al. (2016)
Rees et al. (2011)
Reeve et al. (2012)
Sathish et al. (2016)
Savala et al. (2016)
Shukla et al. (2006)
Sleutel et al. (2006)
Sloan et al. (2016)
Steiner et al. (2007)
Suge et al. (2011)
Sutton et al. (1982)
Triberti et al. (2008)
Uka et al. (2013)
Wortmann and Walters (2006)
Yagüe et al. (2016)
Yang et al. (2011)
Zhang et al. (2006)
Zhao et al. (2009)
Zhong et al. (2010)