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THE EFFECT OF POULTRY LITTER APPLICATION ON AGRICULTURAL PRODUCTION: A META-ANALYSIS OF CROP YIELD, NUTRIENT UPTAKE AND SOIL FERTILITY

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Abstract

Meta-analysis is a statistical technique used to analyze large datasets containing results from numerous individual studies. It appears to be a promising approach in agricultural sciences. This study aimed to conduct a meta-analytic assessment to elucidate the influence of poultry litter (PL) application on crop yield, plant nutrient uptake, and soil fertility as compared to inorganic fertilizer (IF). A meta-analysis based on 116 studies (111 refereed articles and five unpublished data sets) with 2293 observations compared agronomic responses to PL and IF application. The natural log of the response ratio was used as effect size (ES) to express differences in the effects of PL and IF. The variances of estimated effects were estimated using within-study and between-study variation and were used to calculate a weighting factor. A random-effects model was used to test if the ES was significantly different from zero ($\alpha = 0.05$). Crop yield was slightly less when evaluating PL additions during the 1st or 2nd year of application, while significant increases were observed with long-term PL application. Poultry litter influenced plant nutrient uptake with a slightly negative effect being observed for N uptake, but significant positive effects for P and K uptake. Positive effects on soil fertility were also observed with PL significantly increasing CEC, pH and concentration of soil C, P, K, Ca, and Mg compared to IF. Overall, PL can be used as an alternative nutrient source to enhance crop yield, increase plant nutrient uptake, and improve soil fertility.

Keywords: Poultry litter, Meta-analysis, Yield, Nutrient uptake, Soil properties

1. Introduction

Since the last half of the twentieth century, broiler production has experienced rapid expansion worldwide with the United States being by far the largest producer marketing more than 8.5 billion birds annually (USDA-NASS, 2015). Consequently, a significant amount of poultry litter (PL) is being generated, totaling more than 12.8 million metric tons annually (1.5 kg litter per broiler (Mitchell and Tu, 2005; USDA-NASS, 2015). More than two-thirds of all broilers produced in the US are raised in five southeastern states (Georgia, Mississippi, Alabama, Arkansas, and North Carolina); as a result, poultry litter is abundant in this region. The most cost-effective and environmentally safe way of discarding this waste is to land apply it as a nutrient source. Currently, more than 90% of the poultry litter generated is being used as a nutrient source (Moore et al., 1995). In recent years, interest in using PL as a low-cost alternative to inorganic chemical fertilizer sources has increased among row crop producers because of its availability coupled with the potential for improving crop production through soil organic matter additions and soil property improvements (Adeli et al., 2005; Nyakatawa and Reddy, 2000).

Poultry litter contains all the nutrients essential for plant growth and has an approximate 3-3-2 (N-P_2O_5-K_2O) fertilizer grade equivalent (Mitchell and Donald, 1995). Thus, poultry litter may be a valuable nutrient source for row crop production systems. Numerous studies have proven that poultry litter can be used as an effective fertility source (Hirzel et al., 2007; Mitchell and Tu, 2005; Reddy et al., 2004; Tewolde et al., 2009a; Watts and Torbert, 2011; Wiatrak et al., 2004). However, poultry litter may produce yields different to that of commercial fertilizer sources. Mitchell and Tu (2005) reported that no differences in relative yields were observed when broiler litter was applied at the same total N rate as ammonium nitrate. Hirzel et al. (2007) found similar results with corn silage; yield averages obtained from PL additions were comparable to that of urea. Watts and Torbert (2011) also reported that soybean yields were increased 8 out of 9 years when PL was used as a nutrient source. In contrast, a 2.5-year bermudagrass field study showed that forage yield with broiler litter was 64, 48, and 67 % of yield with ammonium nitrate applied at the same N level in these three years, respectively (Woodard and Sollenberger, 2011). Another pasture study indicated that land application of PL provided essential nutrients for hybrid bermudagrass production with no differences in dry matter yield and N uptake compared to that of ammonium nitrate, whereas greater P and K uptake were observed with PL application (Read et al., 2006). Hirzel et al. (2007) also evaluated the influence of PL application on nutrient uptake for corn silage. They reported that no differences in nutrient (N, P, K, Ca, and Mg) uptake were observed between PL or urea application, and thus suggesting PL to be an adequate nutrient source.

The efficacy of poultry litter applications to enhance crop growth (yield and nutrient uptake) depends upon its nutrient availability. Application of PL to cropland can also increase soil organic matter (Watts et al., 2010); thereby improving soil quality and productivity (Kingery et al., 1994). Continuous application of litter or manure can increase the levels of C, N, P, K, Ca and Mg in the soil (Ginting et al., 2003; Mugwira, 1979; Wallingford et al., 1975; Watts et al., 2010; Wood et al., 1996), thus creating a reservoir of soil nutrients for several years after application. Agbede and Ojeniyi (2009) found similar results with sorghum production in southwestern Nigeria; no-till with or without mulch in combination with 7.5 Mg ha^{-1} of PL improved soil organic C, total N, available P, exchangeable K, Ca and Mg concentration and grain yield. Blair et al. (2014) evaluated soil nutrient availability under both greenhouse and field conditions following surface incorporation of composted and formulated pelletized PL for edamame production in Arkansas. They reported that dissolved organic C and inorganic N was increased under field conditions following pelletized PL application, but not following application of composted PL.

There are conflicting results as to the beneficial effects of PL on crop productivity and its influence on increasing the availability of soil nutrients. As a result, there is a need for a comprehensive quantitative review. A few reviews have combined independent studies using quantitative methods to relate the impact of management strategies and environmental effects on crop production. Maillard and Angers (2014) evaluated the impact of animal manure application on soil organic carbon stock changes for both agronomic and environmental purposes. Looking at different soil conditions, Jeffery et al. (2011) compared the relative profitability of biochar with inorganic fertilizer in crop productivity (either yield or aboveground biomass). These studies used meta-analytic methods that have been widely applied in other disciplines, such as the medical, physical, and ecological sciences (Cooper and Hedges, 1994). No one to our knowledge has used this approach in reviewing PL's influence compared to IF on crop production. Therefore, the objective of this review was to use meta-analytic methods to summarize and quantitatively describe the effects of PL on crop productivity, nutrient uptake, and soil fertility.

2. Methods and Materials

Meta-analysis (MA) is a quantitative method for contrasting and combining results from independent studies to estimate treatment effects and their variability or to identify patterns among study results (Hedges and Olkin, 1985). This method is now an important tool for this purpose because it incorporates formal statistical techniques for quantifying the effects observed in multiple independent experiments. The use of meta-analysis allows for increased objectivity of systematic reviews based on studies involving the arrangement of soil properties, as well as environmental and management conditions. However, to undertake MA, the experimental treatments in each study should have a comparable control, which is consistently defined across all studies used. Furthermore, some details of individual studies are necessarily disregarded in exchange for reaching general conclusions (Gurevitch and Hedges, 2001).

2.1 Literature search and study selection

A comprehensive literature review was conducted using the ISI Web of Science search tool with the search terms "poultry litter" for published data up to March 2016, yielding more than 6000 articles. A search of these records using the term "yield or soil" resulted in 1657 articles. The abstracts, materials and methods, and conclusions of these articles were briefly reviewed to identify those with the following criteria:

- Replicated experimental design;
- Clear description of soil and PL used;
- Have at least one PL treatment and comparable against a mineral fertilizer;
- Data containing means and standard deviation (or standard error).

A total of 111 refereed articles were retained. Combined with five unpublished data sets 2293 observations were available for the meta-analysis. This far exceeds the number of observation in any agronomy meta-analysis study that the authors are aware of.

2.2 Statistical analysis

Meta-analysis performed for this study was based on the principals described by Hedges et al. (1999) with all data being analyzed using R ("metafor"; Viechtbauer, 2010). To determine the influence of PL vs. IF on crop yield, nutrient uptake, or soil fertility, the following equation was used to determine effect size:

$$\mathrm{RR} = \frac{Mean_{PL}}{Mean_{IF}} = \frac{\bar{Y}_{PL}}{\bar{Y}_{IF}} \qquad [1]$$

The response ratio (RR) for the i^{th} study was transformed for normality to estimate effect size (ES). Response ratio is the most common metrics of effect size used in plant ecology meta-analysis (Hedges et al., 1999; Koricheva and Gurevitch, 2014) and the log transformation is needed to maintain symmetry in the analysis (Borenstein et al., 2009).

$$\mathrm{ES}_i = ln(\mathrm{RR}) \quad [2]$$

where *ln* is the natural logarithm.

The corresponding variance (v_i) was calculated as

$$v_i = \frac{SD_{PL}^2}{n_{PL} \times \bar{Y}_{PL}^2} + \frac{SD_{IF}^2}{n_{IF} \times \bar{Y}_{IF}^2} \quad [3]$$

where $SD_{PL}^2, n_{PL}, \bar{Y}_{PL}^2$ and $SD_{IF}^2, n_{IF}, \bar{Y}_{IF}^2$ are the squared standard deviation, sample size, and squared mean for PL and IF, respectively.

The weighted total sums of squares for ES_i was calculated as

$$Q_t = \sum_{i=1}^{k} w_i \,(ES_i)^2 - \frac{(\sum_{i=1}^{k} w_i ES_i)^2}{\sum_{i=1}^{k} w_i} \quad [4]$$

which follows a chi-square distribution with k-1 degrees of freedom and where w_i is the inverse of the within-study variance ($w_i = 1/v_i$).

For both the fixed-effect and random-effect analyses, each study was weighted by the inverse of its variance to increase the precision of the mean effect estimate and the power of the analysis (Gurevitch and Hedges, 1999). The difference is the variance of random-effect model (v^*_i), which includes the original (within-studies) variance (v_i) plus the estimate of the between-studies variance (τ^2), which was calculated as

$$\tau^2 = \frac{Q_t - (k-1)}{\sum_{i=1}^{k} w_i - \frac{\sum_{i=1}^{k} {w_i}^2}{\sum_{i=1}^{k} w_i}} \quad [5]$$

where k is the number of studies.

The weighted means were computed as

$$M^* = \frac{\sum_{i=1}^{k} w_i^* ES_i}{\sum_{i=1}^{k} w_i^*} \quad [6]$$

where w^*_i is the weight for each study ($w^*_i = 1/v^*_i$).

Therefore, the variance and the estimated standard error of the summary effect are estimated as

$$v_{M^*} = \frac{1}{\sum_{i=1}^{k} w_i^*} \quad [7]$$

and $SE_{M^*} = \sqrt{v_{M^*}}$ [8]

The 95% lower and upper limits for the summary effect would be computed as

$$CL_{M^*} = M^* \pm 1.96 \times SE_{M^*} \quad [9]$$

To check the heterogeneity in effect sizes, Cochran's Q (Eq.[4]) and Higgins' I^2 were computed as

$$I^2 = \frac{Q - df}{Q} \times 100 \qquad [10]$$

Potential publication bias was assessed statistically through a rank correlation by testing the interdependence of variance and effect size using Kendall's method (Begg and Mazumdar, 1994) and represented graphically with funnel plots of effect sizes versus their standard errors (Borenstein et al., 2009).

3. Results and Discussion

By applying our selection criteria, 111 citations from the literature and five unpublished studies were retained for inclusion in this MA, while some categories within the analysis contained as few as two independent studies (> 10 observations). Analyses were conducted on natural logs and the magnitude of the summary effect was checked to determine whether it statistically differed from zero.

Heterogeneity statistics were calculated for each summary effect. The high heterogeneity for crop yield (I^2 = 96%) was partly due to variations of field conditions/management, PL application strategies, crop types, and study duration, indicating the need for further analysis by introducing moderator variables to reduce heterogeneity. Variances were heterogeneous among a range of study durations and crop types. All response variables evaluated resulted in low or moderate heterogeneity (I^2 ranges from 0 to 62%).

We did not see evidence of publication bias. Visually, the funnel plots for most summary effects looked symmetric which indicated the absence of bias, large and small studies across the range of standard errors had the expected variability around the common effect size. However, the funnel plots for soil residual N, P and plant stem N, P were a little asymmetric which indicated possible publication bias for these summary effects, but within the Begg and Mazumbar rank correlation test, each of these summary effects had small Kendall tau values ($P >$ 0.05), indicating no concern about publication bias.

3.1 Crop yield

Overall, the meta-analysis of 82 independent experiments (905 observations) demonstrated a slightly negative response of crop productivity to poultry litter (-0.0078, CI: -0.0204, 0.0047), when compared to inorganic fertilizer (Fig. 1). This difference can be attributed to nutrient availability between the two fertility sources. For example, N from most chemical fertilizer sources is available at the time of application or a few weeks later. On the other hand when PL is applied, N is released slowly over time and may take multiple years before all of it becomes available. Although few studies collect and integrate data from different experiments of PL application to soil, our results are inconsistent with some meta-analysis studies which focus on the effect of biochar or animal manure on crop production (Jeffery et al., 2011; Liu et al., 2013). In particular, Jeffery et al. (2011) showed that poultry litter had the highest positive effects on crop productivity among a range of biochar feedstock, when compared with the no fertilizer (control) treatment. Therefore, poultry litter can be used as an alternative nutrient source to IF in crop productivity.

Generally, management of crop nutrients and soil fertility mainly depend upon a complex long-term integrated approach rather than a short-term one. Differences in crop yield maybe

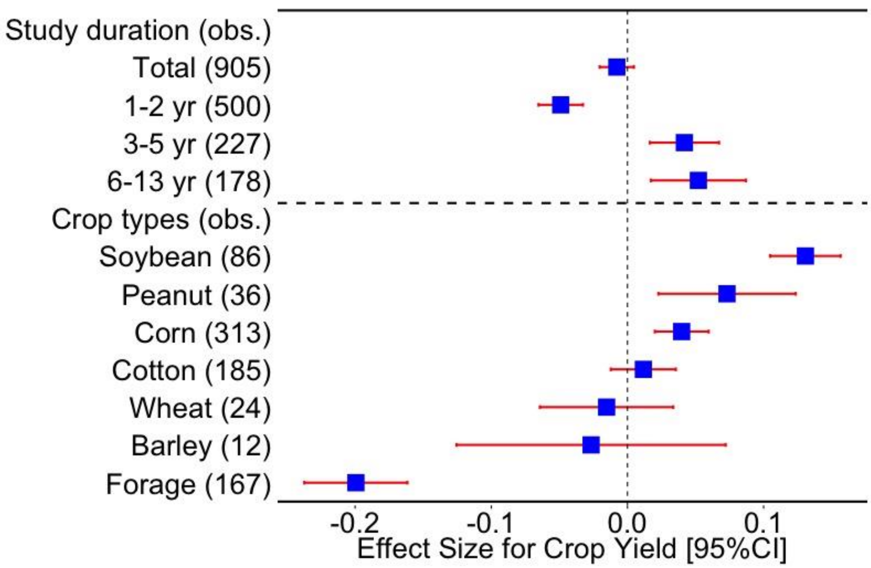

Fig. 1 Mean effect size and 95% confidence interval (horizontal bars) for the effect of PL on crop yield categorized three levels of study durations and seven levels of crop types.

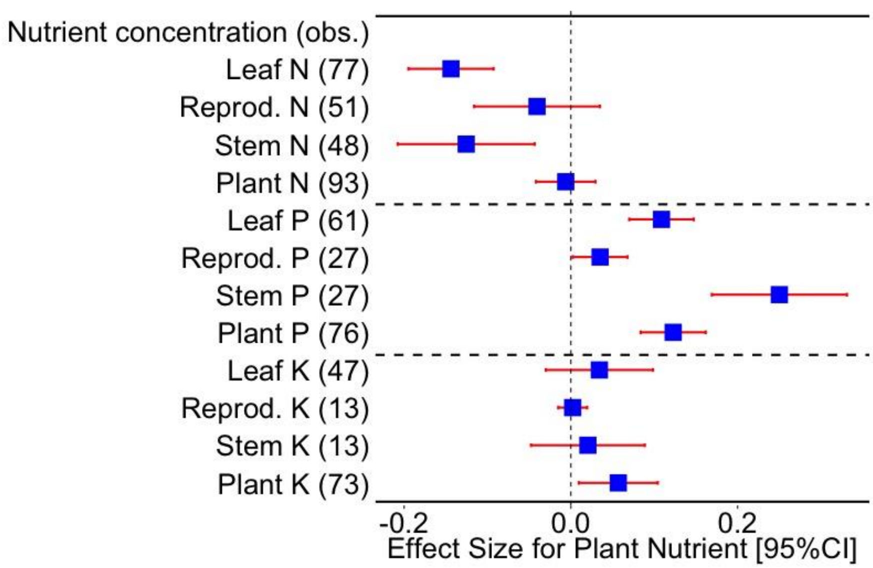

Fig. 2 Mean effect size and 95% confidence interval (horizontal bars) for the effect of PL on plant essential nutrient concentration.

different depending on whether poultry litter is applied only one year or for multiple years. Our analysis showed a positive effect for experimental duration on crop productivity (Fig. 1); crop yield increased (5.05 ± 3.95 %) when PL was applied for multiple years (6 – 13 years). Similarly, Diacono and Montemurro (2010) reviewed long-term studies (3 – 60 years) on the effects of organic amendments and found crop yield increased up to 250% with long-term applications of high rates of municipal solid waste compost. Unlike inorganic N, poultry litter contains high levels of organic N and slow mineralization rates leads to less N available for crops at the time of PL application. On the average, only 55% of the organic N from poultry litter is mineralized and 75 % of total N was available during the first year after application (Moore et al., 1998). Therefore, in a long-term study with multiple years of PL application, plenty of organic N accumulates in the field and mineralizes to inorganic form and becomes available for plant growth.

Statistically significant increases in crop yield were observed for corn ($P < 0.0001$), soybean ($P < 0.0001$) and peanut ($P = 0.0218$) following PL addition to soil, while opposite results were observed for forage crops ($P < 0.0001$). No statistically significant effects were observed for cotton ($P = 0.3404$), wheat ($P = 0.9537$), and barley ($P = 0.5801$) when PL was compared to commercial fertilizer, with barley showing particularly variable effects regarding yield (Fig. 1). Overall, legumes (soybean and peanut) had the highest yield with PL addition compared to IF, whereas *Poaceae* crops (wheat, barley and forage) tended to have lower yields with PL application. This negative response of wheat and barley most likely is attributed to these being grown as winter crops in poultry producing regions and N mineralization is slow when temperatures are low. Forage crops tend to be harvested several times a year; slow-mineralization rates, which affects the nutrient availability from PL, may not satisfy plant requirements.

3.2 Nutrient concentration

The concentration of nutrients in crops is determined by plant uptake and depends on the level of available nutrients in soil (Pederson et al., 2002). Overall, there was a statistically significant effect of PL application to soil on plant nutrient concentrations (Fig. 2). Plant N concentrations with PL application, including leaf N ($P < 0.0001$), reproductive N (reproductive parts include flower and grain, $P = 0.2915$), and stem N ($P = 0.0027$), was less than that with IF application. Generally, researchers focus on grain N concentration rather than on leaf or stems concentration because N concentration in leaves and stems gradually decreases over the course of the growth season (Tewolde et al., 2007). The significantly negative response of leaf and stem N to PL application was likely due to inorganic N being readily available at the time of application while the PL has to be mineralized first. It is also important to highlight that for this MA, approximately 80% of the leaf, stem, and reproductive N observations were collected from cotton, and analysis of the cotton data showed smaller leaf and stem N effect sizes compared to other crops. Therefore, the results of PL effects on cotton leaf and stem N concentration may be largely impacting the meta-analysis results for plant leaf and stem N concentration. Several studies observed that only 42 to 65 % of the PL N is removed from the field in harvested cotton (Halevy, 1976; Mullins and Burmester, 1990; Tewolde et al., 2007), thus, lead to a lower cotton leaf or stem N concentration compared to inorganic N fertilizer with the same N application rate.

When the whole plant was analysed for N concentration, e.g., forage and some vegetable crops, no significant effect was observed when comparing PL addition to IF ($P = 0.7349$). Generally, litter-N exists in both organic and inorganic forms. The inorganic fraction, usually in the ammonium form, may constitute 10 to 60% of the total litter-N (Chadwick et al., 2000; Collins et al., 1999) which is readily available for plant absorption. The organic fraction of litter-N is found in the form of proteins, nucleic acids, and other organic compounds derived from plant or animal tissues, which may constitute 40 to 90% of the total litter-N (Chadwick et al., 2000; Collins et al., 1999); it becomes available only after mineralization via soil microbial activity (Ma et al., 1999). Therefore, it is difficult to predict how much of the N from the organic fraction will be available for plant uptake and utilization during the growing season. In addition, litter-N availability may be influenced by the field conditions (soil properties and weather) and management strategies (PL application time and method, tillage, and study durations), however it the present study it was difficult to conduct N content analysis under such categories due to the limited number of studies.

Poultry litter application significantly increased plant leaf ($P < 0.0001$), stem ($P < 0.0001$), and reproductive ($P = 0.0365$) P content. The effect size was generally small and observed mainly in row crops, including corn, cotton, soybean, barley, peanut; in some instances they were also noted in vegetable and fruit crops. Plant P concentrations measured for the whole plant were significantly larger with PL application ($P < 0.0001$) compared to IF application. Among these 76 plant P observations, 55 were forage (including sorghum sudangrass, turfgrass, bermudagrass, fescue, and forage-mix), which largely influenced the effect size for plant P concentration. Therefore, PL application could improve plant P uptake and increase tissue P concentration in both row crops and forages compared to IF. The results are consistent with the reviews that focus on the effect of manure on forage production (Pant et al., 2004). In this MA, PL application rates was based on crop N requirements, so the input of P from PL was more likely higher than recommended (Bolan et al., 2010) and thus entirely satisfied plant requirements.

Among these K concentration analysis, stem and reproductive K effect size variables only contained 13 observations and most of them were obtained from cotton plants, thus, these two effect size values largely depended on cotton K concentration. There was no difference between IF and PL application on leaf ($P = 0.2964$), stem ($P = 0.5574$), and reproductive ($P = 0.8063$) K content, whereas there was a significant positive response to PL application for plant K content ($P = 0.0185$). Approximately, 85% of plant K concentration data collected from forages (including bermudagrass, fescue, turfgrass, and forage-mix), both composted and fresh PL treatments produced higher forage K than the inorganic NPK treatments (Warman and Cooper, 2000; Warren et al., 2008; Wood et al., 1993) and showed a positively linear response in tissue K concentration with litter application (Warman and Cooper, 2000). Our results were consistent with the previous studies of cotton (Tewolde et al., 2011; Tewolde et al., 2009b), where fertilizing with litter slightly increased bulk leaf K concentration and had approximately the same stem or reproductive K concentration as cotton fertilized with IF. The slightly higher K concentration in plants indicated that K concentration in PL can satisfy plant growth requirements, which mainly due to K in manure being mostly in inorganic forms, therefore virtually all the K is available for plant uptake. Therefore, the use of PL as a nutrient source for

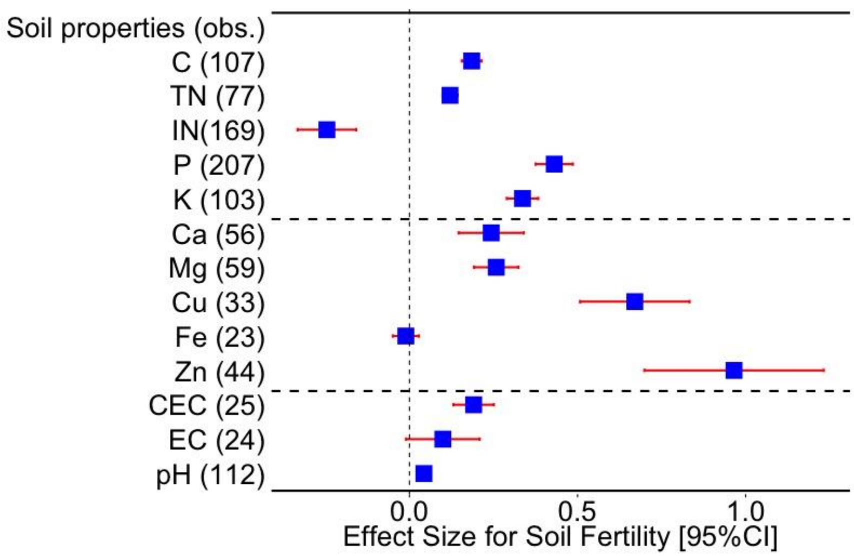

Fig. 3 Mean effect size and 95% confidence interval (horizontal bars) for the effect of PL on soil residual fertility, cation exchange capacity, electrical conductivity and pH.

agricultural crops can provide appreciable quantities of essential major plant nutrients (N, P and K).

3.3 Soil residue fertility

It has been demonstrated that PL contributes to plant growth through its favourable effects on soil physical, chemical, and biological properties (Ghosh et al., 2004). This MA evaluated the residual soil element concentrations, cation exchange capacity (CEC), electrical conductivity (EC), and pH change when PL was added to soil compared to IF application (Fig. 3). There were significant positive responses in soil carbon (C, $P < 0.0001$), total N (including organic and inorganic N, $P < 0.0001$), P ($P < 0.0001$), K ($P < 0.0001$), calcium (Ca, $P < 0.0001$), magnesium (Mg, $P < 0.0001$), copper (Cu, $P < 0.0001$), and zinc (Zn, $P < 0.0001$), whereas significant negative responses in soil inorganic N [including nitrate (NO_3-N) and ammonium (NH_4-N)] when PL added to soil. PL did not change soil Fe concentrations ($P = 0.5871$) when PL and IF application rates were based on the same N rate. Land application of PL can alter the elemental concentration in soils since the litter contains N, P, K, Ca, Mg, sulphur (S), and trace elements (Bolan et al., 2010; Wood et al., 1996). Higher soil C concentrations in PL treatments could be due to direct C input by the litter itself and indirect C input through increased net primary production, for example, roots and plant residues (Aoyama et al., 1999; Bhattacharyya et al., 2010; Maillard and Angers, 2014; Whalen and Chang, 2002). The higher soil total N and lower inorganic N concentration in PL treatments could be due to more than two thirds of the N in PL being present as organic N (including complex organic N and labile organic N) and less than one third as inorganic N (Bolan et al., 2010; Chadwick et al., 2000; Collins et al., 1999) which is available for plant to uptake.

Compared to IF, poultry litter application significantly increased soil CEC ($P < 0.0001$) and pH ($P < 0.0001$). Higher CEC from soil receiving litter could be explained by the organic C contributions which leads to higher cation availability (Lima et al., 2002). Various studies found that greater CEC is associated with greater soil organic matter (SOM) contents, due to a higher degree of oxidation of SOM and a higher surface area for cation adsorption sites (Liang et al., 2006; Sombroek et al., 1993). Electrical conductivity was slightly higher ($P = 0.0752$) in litter-applied soils compared to IF applications, which was consistent with previous long-term studies (He et al., 2008; Kingery et al., 1994). Poultry litter added to the soil mineralizes and release the nutrients and salts to the soil leading to an increase of soil EC and salt content. Poultry litter increased soil pH by 4.39%, which indicates the potential of poultry manure as a liming materials for acidic soils. It has been suggested that soil pH increases following PL application can be attributed to the high Ca content of PL and its effect on soil exchangeable soil Ca (Rasnake et al., 2000) or the chemistry of aluminum (Al) in soil (Azeez and Van Averbeke, 2012). Aluminum is responsible for passive soil acidity, the basic cations in PL could potentially force Al out of the exchange sites and subsequently form complexes with organic molecules decreasing toxicity to plants. Another mechanism for increasing soil pH is due to respiration by microbes from the PL treatments which could increase the carbonate content of soil, hence increasing the soil pH (Azeez and Van Averbeke, 2012).

4. Summary

This MA analysis, shows that depending on management PL application produces comparable yield to that of IF. Crop yield was slightly less when evaluating PL addition during the 1st or 2nd year of application, while significant increases (5.05 ± 3.95 %) were observed with long-term PL application. Crop nutrient and soil fertility management mainly depends upon the complex long-term integrated approach rather than the short-term one, thus, crop productivity had a potential positive trend with study duration. Greater effects on crop productivity were found for soybean, corn, peanut, and cotton rather than wheat, barley, and forage. Plant nutrient uptake was influenced by PL with a slightly negative effect being observed for N uptake, whereas a significant positive effect for P and K uptake. In addition, PL application can influence soil properties and soil fertility. Poultry litter had significantly greater soil CEC and pH, and slightly greater soil EC. Positive effects on soil fertility were observed with PL significantly increasing the concentration of soil C, P, K, Ca, and Mg compared to IF. Overall, PL increases soil organic C and improve soil properties, which contribute to plant growth via increasing the cycling of soil nutrients, thus it can be used as an alternative nutrient source to enhance crop yield, increase plant nutrient uptake, and improve soil fertility.

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