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Apparent Soil Electrical Conductivity Used to Determine Soil Phosphorus Variability in Poultry Litter-Amended Pastures

P. P. Motavalli[1*], R. P. Udawatta[1] and S. Bardhan[2]

[1]Department of Soil, Environmental and Atmospheric Sciences, University of Missouri, Columbia, Missouri 65211 USA.
[2]Center for Agroforestry, University of Missouri, Columbia, Missouri 65211 USA.

Authors' contributions

This work was carried out in collaboration between all authors. Authors PPM and RPU designed the study and author PPM wrote the first draft of the manuscript. Author PPM coordinated the field trials and performed the statistical analysis with advisement from author RPU. Authors SB and RPU assisted with writing the manuscript. All authors read and approved the final manuscript.

Research Article

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ABSTRACT

The objectives of this research were to determine the relationship between soil apparent electrical conductivity (EC_a) and soil P distribution, and to compare the effectiveness of noncontact mobile electromagnetic induction (EM) and direct contact methods for relating EC_a to soil P. Studies were conducted at two locations in Southwest Missouri on a long-term forage fertility plot site and three 1 to 1.5 ha sites within beef cattle pasture fields, all having received long-term poultry litter applications. For the long-term plot site, both the direct contact EC_a sensor deep reading and the EM-38 (Geonics) sensor in the shallow mode had significant positive correlations with soil test Bray-1 P at both the 0 to 5 and 5 to 15 cm sampling depths. Significant spatial variation in soluble, soil test Bray-1 and total P were observed by landscape position within pasture fields. In general, soil EC_a was not significantly correlated with soluble, soil test Bray-1 and total P at each individual pasture site, but when data was combined over all three sites, significant relationships were observed between EC_a measured by the EM-38 sensor and soil soluble P, soil test Bray-1 P and total P, especially when the vertical (deep) mode was used. The difference in performance of the two sensors between the two studies was attributed to the proportion of

**Corresponding author: Email: motavallip@missouri.edu;*

coarse fragments contained in the soils and soil water content. These results suggest that soil EC_a measurements may provide some useful information for evaluating spatial variation in soil P due to manure applications. However, further research is needed to assess the processes and factors affecting this relationship before it can be recommended for use for improved soil P management in individual farm fields with varying environmental conditions and management practices.

Keywords: Soil apparent electrical conductivity; poultry litter; phosphorus; pasture.

1. INTRODUCTION

Rapid expansion and intensification of poultry production in southwestern Missouri and other states in the Ozark Highlands has increased the risk of surface and groundwater phosphorus (P) contamination from poultry litter applications to pastures [1, 2, 3]. The implementation of effective nutrient management practices to reduce the risk of P water pollution in this region and regions similar to it around the world have been complicated by several factors, including spatial variability in soil P distribution due to differences in land use practices (e.g., non-uniform manure applications and redistribution of nutrients with grazing), soil resources, and hydrogeologic features [4, 5, 6]. Assessing spatial variability of soil P within individual pastures amended with animal waste may require an increasing number of subsamples as soil P variance are higher [7] and possibly the use of grid soil sampling techniques for environmental P management [6]. However, the higher costs for additional soil P testing may limit the capability of many producers to conduct such testing, especially if higher-costing, specialized analytical testing procedures are required for environmental P management.

Assessment of spatial variation in soil P and other soil properties may also be needed to accurately estimate and predict P transport from runoff and erosion that reaches water resources. Approximately 90% of the annual P lost from watersheds generally occurs from less than 10% of the watersheds during one or two storms [8]. Since loss of P from terrestrial sources to water bodies is controlled by the interaction of P source factors (i.e. soil, crop, land management) with transport processes (i.e. runoff, erosion, channel processes) [9,10], several approaches are being developed to assess the potential risk for P contamination of water resources, including use of a weighted P index that accounts for source, transport and management factors [11,12]. Another proposed approach has been the establishment of soil P thresholds which set maximum limits for soil P above which there is a greater risk of P water pollution [13]. A common element to all these approaches is the need for a rapid, accurate method to estimate environmentally-significant P forms and concentrations in affected soil resources.

Measurement of spatial variation in apparent soil electrical conductivity (EC_a) is being used for several applications in precision agriculture [14]. Variation in soil EC_a has been related to a number of soil properties, including salinity, bulk density, pH, soil water content, clay content, clay mineralogy, varying depths of conductive soil layers, CEC, exchangeable Ca^{+2} and Mg^{+2}, and soil NO_3^- and Cl^- [15,16,17,18,19]. Within-field spatial variation in EC_a has been related to top soil thickness in claypan soils using mobile electromagnetic induction (EM) and direct soil contact systems [15,19]. Apparent soil electrical conductivity measurements differ from electrical conductivity (EC_e) of a saturated soil paste or aqueous soil extracts [20] in that EC_a measurements are taken in situ under field conditions and measure the bulk soil electrical conductivity. Due to the multiple factors that contribute to observed soil EC_a, soil properties, such as CEC, texture, pH and water-holding capacity, may also need to be measured to estimate soil nutrient levels [21].

Apparent electrical conductivity has been used to measure the variability between dry and wet conditions in paddy fields in Bangladesh [22]. Based on their findings, the authors concluded that using EC_a would make it possible to achieve precision soil fertility management. Similar findings have also been reported from paddy fields in Malaysia [23]. Apparent soil electrical conductivity has been used to predict soil texture [24], soil compaction [25] and various soil properties and yield characteristics [26]. Another potential application of EC_a is environmental monitoring of nutrients applied from animal manures [27,18,21]. For example, Eigenberg and Nienaber [18] were able to use EC_a to identify areas of variable soil nutrient accumulation from beef manure in an abandoned feedlot. They attributed a build-up of soil NO_3^- and Cl^- as the predominant ions affecting EC_a. Similarly, applications of animal manure, such as poultry litter, have resulted in higher soil EC_e [28]. Soil EC_e can be affected by several factors including the manure source, application rate, tillage practices and climate [29].

With the increase in poultry production in the Ozark Highlands during the last decade, new tools and procedures are needed to quantify soil P accumulation due to poultry litter applications in this region. This information may assist in selection of appropriate management practices to reduce environmental P loss. However, the potential relationship between EC_a and soil P across poultry-litter amended landscapes has not been well-studied. Moreover, a comparison of EC_a measuring methods under the soil and landscape characteristics of this region has not been conducted.

The objectives of this study were: i) to determine if variation in soil EC_a would relate to soil P distribution across pastured landscapes that have received long-term poultry litter amendments in the Ozark Highlands, and ii) to compare the effectiveness of EM and direct contact methods for assessing variation in EC_a and soil P.

2. MATERIALS AND METHODS

2.1 Long-Term Plot Study

The study was conducted on an existing long-term forage fertility experiment planted to Bermuda grass (*Cynodon dactylon* (L.) Pers.) located at the University of Missouri Southwest Center (37º04.523' N, 93º 52.924' W) in Mt. Vernon, Missouri. Average annual rainfall and minimum and maximum temperatures at the Southwest Center are 1098 mm, 6.8ºC and 19.4ºC, respectively. The experimental design was a randomized complete block with three replications. Nitrogen treatments included broadcast-applied N fertilizer (as ammonium nitrate) and fresh or composted broiler litter at equivalent rates of a total of 0, 56, 112 and 168 kg N ha^{-1} divided into four equal applications each year starting in May and ending in August [30]. Litter and fertilizer treatments were applied from 1992 to 1995 and fertilizer only was applied from 1996 to 1998 resulting in a wide range in soil test Bray-1 P (10 to 574 mg P kg^{-1}) measured in the litter-amended plots when selected plots were used for a soil P runoff study in 1999 (John Lory, pers. comm., 2003). Plots were 3 m wide and 6 m long and the soil in the experimental area was classified as a Creldon silt loam (fine, mixed, active, mesic Oxyaquic Fragiudalf).

Soil samples were collected in May, 2003 from 11 of the fresh litter-amended plots at depths of 0 to 5 and 5 to 15 cm using a stainless steel push probe and compositing 15 subsamples per plot. Sampling depth corresponded to commonly recommended depths for environmental (0 to 5 cm depth) and agronomic (0 to 15 cm) soil testing. Deeper sampling was prevented by the presence of large coarse fragments in the subsoil which is a common characteristic of soils in this region. Gravimetric soil water content was determined on all samples by oven drying a subsample at 105ºC. All remaining soil was subsequently air-dried, ground, and passed through a 2-mm sieve. Soil bulk density was also determined at the site to a depth of 15 cm using an excavation method [31] and coarse fragments >2 mm diameter determined by sieving.

Soil EC_a was determined using both a noncontact electromagnetic induction sensor (EM-38, Geonics, Ltd.) and a six-tine direct contact electrical conductivity meter constructed for research studies (fabricated by Veris Technologies, Inc., Salina, KS; Fig. 1). The EM-38 was placed in both horizontal and vertical dipole modes, and then in the horizontal mode on a PVC stand 75 cm above the soil surface. The effective depth of measurement for the EM-38 in the horizontal dipole mode is approximately 75 cm and in the vertical dipole mode approximately 150 cm [32,33] Placement of the EM-38 in the horizontal dipole mode on a non-conducting stand was designed to reduce the effective depth of measurement. Apparent electrical conductivity readings on the instrument are in mS m^{-1}.

The six-tine direct contact electrical conductivity meter was constructed using a wooden beam (10 x 10 x 92 cm) with steel tines (0.62 cm diameter; 8.1 cm length) inserted through the beam at designated spacings (Fig. 1). The two inner tines were spaced 10 cm apart and were used for transmitting an electrical charge. The next two tines, spaced 10 cm from the inner tines, were receivers for measuring EC_a in shallow depths; and the outer tines spaced 29 cm apart were receivers for measuring EC_a deeper in the soil profile. This positioning and spacing of the transmitter and receiver tines allowed for measurement of EC_a at relatively shallow depth (approximately 25 cm) and a deeper depth (approximately 60 cm) when the tines were pushed into the soil at each sample location. The instrument was fitted with an electronic logger which gave EC_a readings in mS m^{-1}. For both the EM-38 and direct contact EC_a sensors, three readings were taken from each plot for all three replications of the experiment.

2.2 Three Pasture Fields Study

Areas within three pasture field sites measuring approximately 1 to 1.5 ha were selected to represent a major soil association and land management common to landscapes receiving broiler litter in Southwestern Missouri. Soil at the Newton County site (Farm 1) in Southwestern Missouri was a Tonti-Scholten complex (Tonti silt loam: fine-loamy, mixed, mesic Typic Fragiudults; Scholten gravelly silt loam: loamy-skeletal, siliceous, active, mesic Typic Fragiudults). Soil texture ranged from a silt loam to gravelly silt loam and slopes ranged from 2 to 8%. The soil at the McDonald County site (Farm 2) was also a Tonti-Scholten complex with slopes ranging from 1 to 9%. The Barry County site (Farm 3) contained Tonti silt loam and Nixa very cherty silt loam (loamy-skeletal, siliceous, active, mesic Glossic Fragiudults) with slopes between 0 to 11%. The vegetation on all three sites was a mixture of orchard grass (*Dactylis glomerata* L.) and fescue (*Festuca arundinacea* Schreb.) which were periodically grazed with beef cattle. All sites received long-term (>10 yr) annual broiler litter applications at rates of 4.5 to 7 Mg litter ha^{-1}. Litter application was suspended at least two years prior to sampling on all three sites.

Soils were sampled in June 2001 to a depth of 0 to 5 and 5 to 15 cm in a 12 by 12-m grid at geographically-referenced locations determined using a differential geographic positioning system (DGPS) beacon receiver (Starlink Invicta 210; Northern Navigation, Mitchell, SD) in June, 2001. Deeper sampling was prevented by the presence of large coarse fragments in the subsoil horizons. Approximately 5 to 10 random sampling points within the grid were also included at each site. Sample grid and random locations encompassed the entire range of hillslope positions, from the summit to the toeslope. The respective sample areas were unequal among positions. Terrain attributes (slope and landscape position) were determined at each sample point by measuring slope with a clinometer and landscape position was determined visually and classified into one of five categories (summit, shoulder, backslope, footslope, and toeslope drainage area). Soil bulk density was determined at each landscape position to a depth of 15 cm using the core method [31] and coarse fragments >2-mm diameter were determined by sieving.

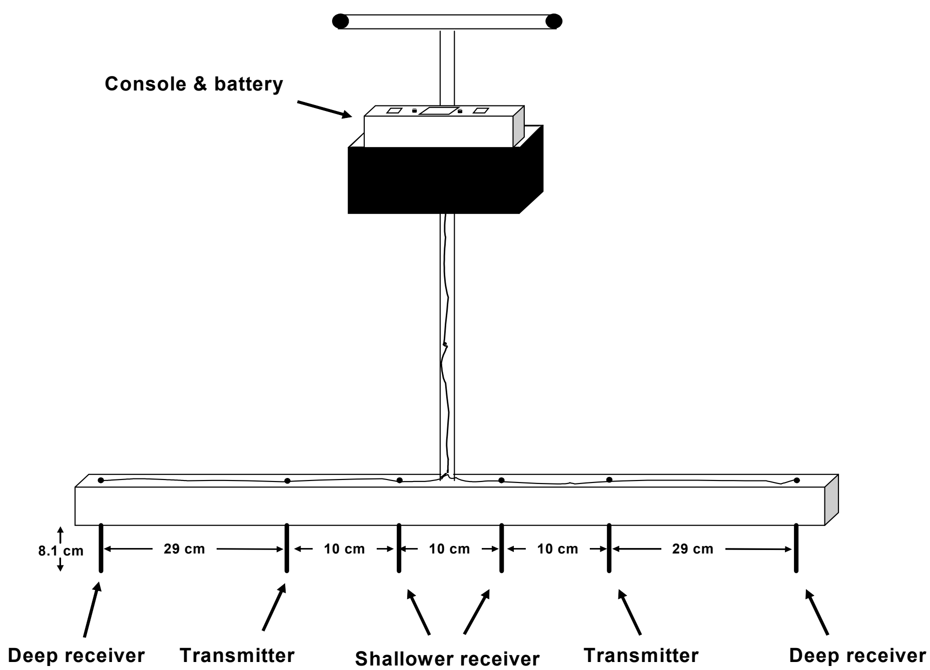

Fig. 1. Design of the direct contact soil EC_a sensor with capacity for shallow and deep readings

Apparent electrical conductivity measurements were obtained in June, 2002 at the same geographically-referenced grid and random points in which soils were sampled. EC_a measurements were taken for both the horizontal and vertical dipole modes of the EM-38 (Geonics, Ltd.) and in the shallow and deep modes of the six-tine direct contact electrical conductivity sensor.

A subset of grid sampling locations from 2001 were soil sampled in 2002 to determine gravimetric soil water content at the time of EC_a measurements and assess if soil properties considered in this study had changed from the previous year. Very highly significant correlations for Bray-1 P ($r = 0.79$, $P < 0.0001$) were observed among the grid and random samples between years (data not shown). Soil samples collected in both 2001 and 2002 were air-dried, ground and sieved through a 2-mm sieve. Gravimetric soil water content was determined for the 2002 soil samples by oven drying three subsamples of each sample at 105ºC.

2.3 Soil Analysis

Soil samples collected from both studies were extracted for soluble P with 0.01 M $CaCl_2$ and for soil test P with the Bray-1 [34] extractant and analyzed colorimetrically using the ascorbic acid molybdenum-blue method [35,36]. Total soil P in the soils collected from the three pasture field sites was determined using a perchloric acid digestion procedure and colorimetric analysis of the digests [37]. Soil total organic C was determined using the heated dichromate oxidation method [38]. Particle size was analyzed using the pipette method [39] and soil pH was determined in a 1:1 (w/v) ratio of soil to extracting solution in either distilled water or 0.01 M $CaCl_2$. Effective soil CEC (ECEC) was calculated by summing exchangeable Ca^{+2}, Mg^{+2} and K^+ (extracted with 1 M NH_4OAc) with neutralizable acidity. Soil electrical conductivity (EC_e) in a 1:1 (w/v) extract with water was determined using the procedure recommended by Whitney [40].

2.4 Statistical Analysis

Analysis of variance (ANOVA) for evaluating differences in soil properties among farm sites and landscape position were determined by PROC GLM [41]. Duncan's multiple range test (DMRT) at the 0.05 significance level was used to separate the means. Pearson linear correlation analysis for soil EC_a and soil properties were performed using PROC CORR and linear regression by PROC GLM [41].

3. RESULTS AND DISCUSSION

3.1 Long-Term Plot Study

Repeated surface applications of broiler litter treatments resulted in soil test Bray-1 P levels ranging from 16.5 to 754.5 mg P kg^{-1} in the 0 to 5 cm depth and from 5.5 to 219.0 mg P ha^{-1} in the 5 to 15 cm depth when measured in 2003 (Table 1). Soil EC_e, total organic C, exchangeable K, ECEC and pH were also significantly increased with the litter applications at the 0 - 5 cm depth. Only soil pH, exchangeable K, and ECEC were significantly increased with litter applications in the 5 - 15 cm depth. Increases in these soil properties mostly at the surface 0 to 5 cm depth was probably because litter was surface- applied and not incorporated. Other studies have observed similar short- and long-term changes in soil properties with repeated animal manure applications [42,43,28]. Many pasture fields in southwest Missouri receiving poultry litter are grazed with beef cattle, and, therefore, soil P removal may often be lower than the long-term forage plot study which had 3 to 4 cuttings of forage harvested and removed from the field each year.

Both the EM-38 and direct contact sensor devices gave EC_a measurements that were significantly related to soil test P at both sampling depths (Fig. 2A-D). For the direct contact sensor, the deep reading was significantly related to EC_a (Fig. 2B and D) and the EM-38 sensor had significant relationships with EC_a only in the horizontal (shallow) mode (Fig. 2A and C). In general, EC_a measurements were lower using the direct contact sensor compared to the EM-38 sensor (Fig. 2A-D). Lower overall EC_a readings for the Creldon soil in southwest Missouri compared to those observed for claypan soils in north central Missouri

[15] may be possibly attributable to several factors, including a lower ECEC and a higher proportion of coarse fragments in the Creldon soil, and a relatively shallow Bt horizon in the claypan soil.

Table 1. Selected soil properties by depth from the long-term plot study

Soil Property	Depth	Average	Std†	Range Minimum	Range Maximum
	-- cm --				
Bray 1 P (mg kg^{-1})	0 – 5	260.8	256.5	16.5	754.5
	5 – 15	80.0	75.8	5.5	219.0
EC_e (dS m^{-1})	0 – 5	537	155	319	703
	5 – 15	243	76	114	329
Organic C (%)	0 – 5	2.2	0.3	1.8	2.6
	5 – 15	1.0	0.1	0.8	1.2
Exch. K (mg kg^{-1})	0 – 5	300	49	226	376
	5 – 15	169	61	82	252
ECEC ($cmol_c$ kg^{-1})	0 – 5	16.5	2.4	13.2	20.2
	5 – 15	13.0	1.3	11.2	15.5
pH	0 – 5	6.2	0.4	5.4	6.8
(0.01 M $CaCl_2$)	5 – 15	6.2	0.4	5.4	6.7

†*Standard deviation (n = 11)*

The significant relationships observed between soil Bray-1 P and the two EC_a sensors are not easily explained. Both instruments are integrating differences in soil properties at a greater depth than may be expected with surface-applied poultry litter applications. However, elevating the EM-38 sensor on a stand 75 cm above the soil surface so that the EC_a measurement would be more weighted to the surface soil did not improve the relationship (Table 2 and Fig. 2A and C). Similarly, the shallow reading of the direct contact sensor did not show a better relationship with soil Bray-1 P compared to the deep reading (Table 2 and Fig. 2B and D).

The equivalent conductances of inorganic P ions common in soils (e.g. $H_2PO_4^-$ and HPO_4^{-2}) are generally lower than those for N (e.g. NH_4^+ and NO_3^-) and K (e.g. K^+) ionic species [44]. Therefore, previous studies which have examined the use of EC_a measurements to evaluate animal manure applications on soil nutrients have focused on changes in soil N [27]. However, the relationship of EC_a with soil Bray-1 P could also be caused by concomitant changes in other soil properties (e.g. EC_e) that occur when poultry litter is applied [21]. For example, EC_a was significantly correlated with soil exchangeable K (r = 0.66, P ≤ 0.05, 0 - 5 cm depth) and pH (r = 0.64, P ≤ 0.05, 5 - 15 cm depth) using the EM-38 sensor in the horizontal (shallow) mode (Table 2). Soil EC_a measured by the direct contact sensor for the shallow reading was significantly correlated with soil total organic C (r = 0.63, P ≤ 0.05, 0 - 5 cm depth), ECEC (r = 0.87, P ≤ 0.001, 0 - 5 cm ; r = 0.89, P ≤ 0.001, 5 - 15 cm depth) and pH (r = 0.63, P ≤ 0.05*, 0 - 5 cm; r = 0.66, P ≤ 0.05, 5 - 15 cm depth) (Table 2). In addition to these same soil properties, the direct contact sensor deep readings of soil EC_a significantly correlated with soil exchangeable K (r = 0.62, P ≤ 0.05, 0 - 5 cm depth (Table 2). The lack of an anticipated relationship between EC_a measured by either sensor and EC_e in the top 15 cm of soil may possibly be because soluble salts had effectively leached out of that soil depth since the last litter application was 8 years prior to the soil sampling of this study.

3.2 Three Pasture Fields Study

All three pasture sites (designated as Farms 1 - 3) showed significant differences in several soil properties at both sampling depths among landscape positions (Tables 3 and 4). Farm 2 had significantly higher soluble, soil test Bray-1, and total P in the lower landscape positions of the field compared to the upper landscape positions (Tables 3 and 4). In contrast, Farms 1 and 3 generally had significantly higher soluble, soil test Bray-1, and total P in the upper landscape positions of the field compared to the lower landscape positions (Tables 3 and 4). Several other soil properties including soil sand, silt and clay contents, pH (water), total organic C and EC_e also had significant differences among sites and landscape position (Tables 3 and 4). Spatial differences in soil P distribution and other soil properties may result from both management practices and natural variation in soil and hydrogeologic features across these grazed and litter-amended landscapes [4,5,6].

Correlation of EC_a with soil P and other soil properties at each of the three pasture sites generally did not show a significant relationship between EC_a and soil P except for the shallow and deep direct contact soil EC_a readings and Bray-1 P in Farm 1 and the EM-38 and direct contact EC_a readings and total P in Farm 3 (Table 5). However, when data from all three pasture sites were combined, very highly significant relationships ($P<0.001$) between EC_a measured by the EM-38 sensor and soil soluble P, soil test Bray-1 P and total P were observed, especially when the vertical (deep) mode was used (Table 5). The higher correlation of EC_a and soil P when data from the individual farms were combined may partly be explained by the general grouping of the EC_a data from each farm (e.g. Fig. 3D). The lack of a consistent relationship between EC_a and soil P at the individual farm field level may also hamper the practical utility of using this measurement for soil P management.

Soil EC_a using the EM-38 sensor in the horizontal (shallow) mode had a relatively lower response to changes in soil test Bray-1 P (Fig. 3A and B) but an overall higher magnitude of reading compared to when the instrument was used in the vertical (deep) mode (Fig. 3C and D). A similar trend of lower magnitude of EC_a in the vertical mode compared to the horizontal mode was also observed in the long-term plot study (Fig. 2A and C). The direct contact EC_a sensor showed little relationship with soil P, although the direct contact sensor shallow EC_a reading at the 0 to 5 cm depth had weak but significant ($P \le 0.05$) correlations with soluble P and Bray 1 P (Table 5).

These results contrast with those found by Eigenberg and Nienaber [18] who measured EC_a beneath former beef cattle feedlot manure compost rows in Nebraska and observed a highly significant negative correlation between soil P levels and EC_a. They attributed the lower concentration of soil P under the manure compost rows to the effects of organic acids leaching from the manure and solubilizing the P, promoting plant P uptake or enhancing P leaching.

A possible explanation for observed differences among the sensor types and reading depths in relating EC_a to soil P between the long-term plot study and the three pasture fields study could be the relatively higher proportion of coarse fragments (>2 mm diameter) among the three pasture fields in the 0 to 15 cm depth (25.1 ± 14.6 % on a volume basis compared to that of the long-term plot study (0.9 ± 0.4 % on a volume basis). Coarse fragments at the pasture sites, especially on more highly-eroded backslope positions, impeded complete insertion of the prongs of the direct contact sensor. This variable contact of the direct contact sensor tines with the soil may have contributed to measurement error compared to the EM-38 sensor.

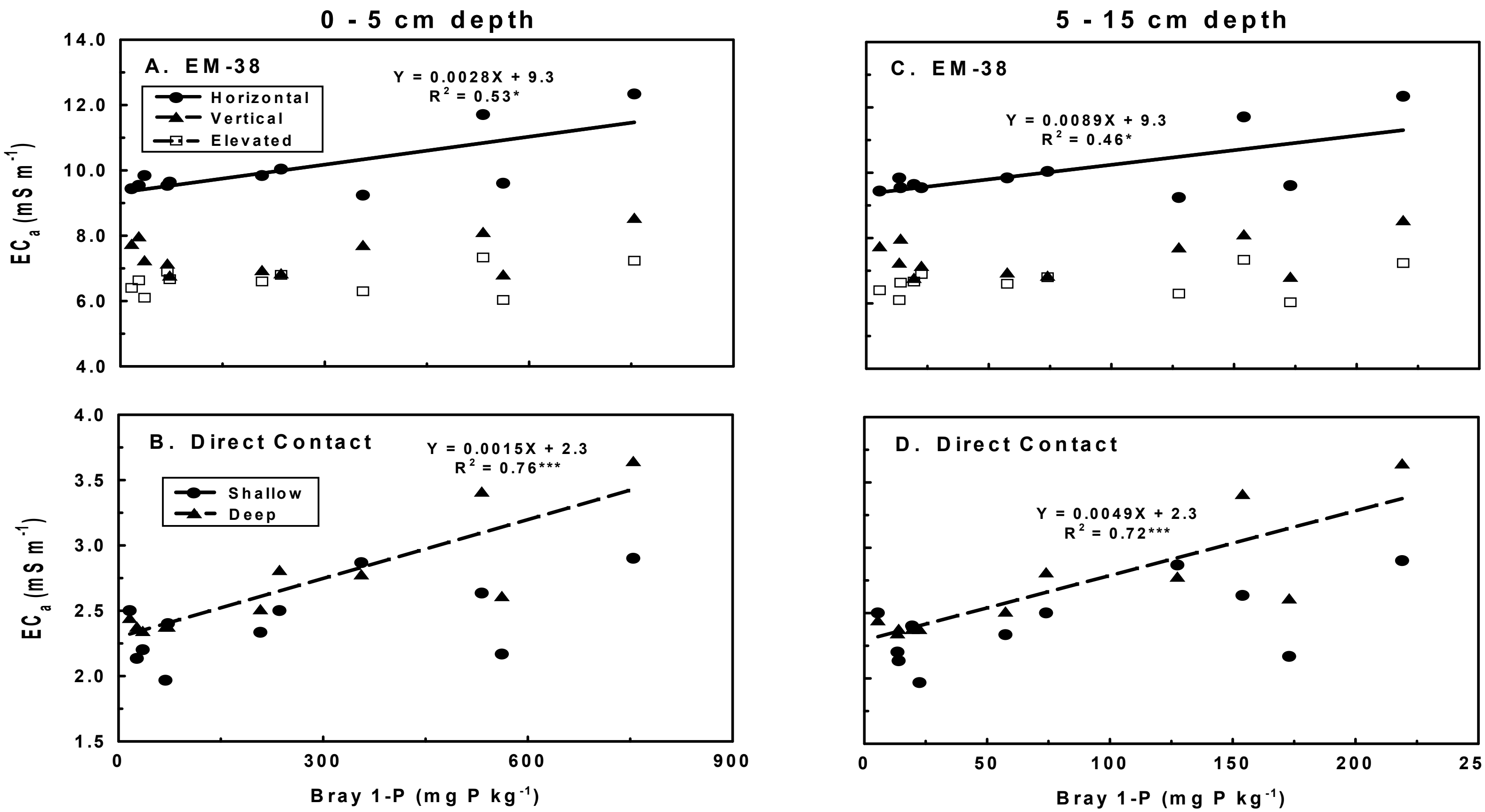

Fig. 2. Changes in soil apparent electrical conductivity (EC_a) in response to a range of soil Bray-1 P in the long-term plot study in southwest Missouri using A) the EM-38 sensor at the 0 - 5 cm depth, B) the direct contact sensor at the 0 - 5 cm depth, C) the EM-38 sensor at the 5 - 15 cm, and D) the direct contact sensor at the 5 - 15 cm depth. n = 11.

Table 2. Correlation coefficients (r) between EC_a measured by different sensors and soil properties at different depths (cm) of the poultry-manure amended soils in the long-term plot study in southwest Missouri (n = 11).

EC_a by Method of Measurement	Soil Properties Bray-1 P		EC_e (1:1)		Total org. C		Exch. K		ECEC		pH ($CaCl_2$)		Soil water content	
	0 - 5	5 - 15	0 - 5	5 - 15	0 - 5	5 - 15	0 - 5	5 - 15	0 - 5	5 - 15	0 - 5	5 - 15	0 - 5	5 - 15
	r													
EM-38														
Horizontal	0.73*	0.68*	0.50	0.21	0.33	-0.14	0.66*	0.54	0.59	0.40	0.55	0.64*	-0.48	-0.32
Vertical	0.40	0.40	0.16	-0.36	0.04	-0.34	0.24	0.10	0.38	0.42	0.12	0.20	-0.52	-0.28
Elevated	0.36	0.31	0.01	-0.20	0.07	-0.02	0.36	0.17	0.42	0.25	0.31	0.39	-0.50	-0.38
Direct Contact														
Shallow	0.59	0.60	0.37	0.17	0.63*	0.28	0.46	0.22	0.87***	0.89***	0.63*	0.66*	-0.06	-0.37
Deep	0.87***	0.85***	0.50	0.24	0.62*	0.12	0.76**	0.57	0.83**	0.72*	0.75**	0.81**	-0.36	-0.49

, **, * Significant at $P \leq 0.05$, 0.01 and 0.001, respectively.*
[†] Gravimetric soil water content

Table 3. Selected soil characteristics (0 – 5 cm depth) of three Southwest Missouri pasture sites by landscape position.

Site	Landscape position	Soil texture Sand	Silt	Clay	pH (water)	Total org. C	EC_e	Soil P Soluble	Bray-1	Total
		%				- % -	- dS m^{-1} -	mg kg^{-1}		
Farm 1	Summit	8.5	76.5	15.0	5.8	3.1	419	8.4	119.1	999
	Shoulder	10.0	74.6	15.4	5.8	3.4	450	12.5	137.9	979
	Backslope	11.5	70.6	17.9	6.3	3.9	463	8.6	116.7	979
	Footslope	12.6	72.4	15.0	6.7	2.2	394	0.1	22.5	454
	$DMRT_{(0.05)}$†	2.1	2.6	2.3	0.3	0.6	NS	3.5	27.5	NS
Farm 2	Summit	9.3	76.4	14.3	6.0	3.4	694	13.7	175.4	1302
	Shoulder	10.6	75.2	14.2	6.1	3.9	781	15.2	197.9	1771
	Backslope	10.2	74.2	15.6	6.1	3.9	827	16.6	236.7	2015
	Footslope	9.3	74.3	16.4	6.2	4.1	789	12.6	233.4	2231
	$DMRT_{(0.05)}$	NS	1.8	1.3	NS	0.4	116	NS	36.0	622
Farm 3	Summit	7.6	82.0	10.4	5.7	3.2	551	4.4	94.8	650
	Shoulder	9.6	79.9	10.5	5.5	3.6	541	4.4	88.2	735
	Backslope	12.0	74.6	13.4	5.9	3.4	477	4.0	82.1	784
	Footslope	10.4	72.6	17.0	6.2	3.0	357	1.4	54.1	681
	$DMRT_{(0.05)}$	1.8	2.8	2.0	0.4	NS	144	2.1	26.1	116
P > F										
Site (S)		0.723	0.166	0.050	0.239	0.063	<0.001	<0.001	0.003	0.004
Landscape position (LP)		0.058	0.002	0.033	0.140	0.136	0.639	0.103	0.659	0.579
S X LP		<0.001	<0.001	0.008	<0.001	0.006	0.067	0.037	<0.001	0.018

, **, * Significant at P ≤ 0.05, 0.01 and 0.001, respectively; NS = not significant.*
† Duncan's multiple range test at the 0.05 significance level

Table 4. Selected soil characteristics (5 – 15 cm depth) of three Southwest Missouri pasture sites by landscape position.

Site	Landscape position	Soil texture Sand	Silt	Clay	pH (water)	Total org. C	EC_e	Soil P Soluble	Bray 1	Total
		%				- % -	- dS m^{-1} -	mg kg^{-1}		
Farm 1	Summit	10.3	74.9	14.8	6.1	1.5	307	1.3	64.7	611
	Shoulder	15.1	69.9	15.0	6.2	1.9	376	3.2	87.1	654
	Backslope	15.6	67.0	17.4	6.6	2.1	330	2.1	77.3	684
	Footslope	12.6	71.9	15.5	6.1	1.4	398	0.1	10.8	348
	$DMRT_{(0.05)}$†	4.5	4.4	2.2	0.4	0.3	NS	1.5	22.1	148
Farm 2	Summit	10.7	75.1	14.2	6.1	2.2	409	10.6	164.1	1034
	Shoulder	12.0	73.0	15.0	6.2	2.2	429	10.3	176.5	1185
	Backslope	11.3	73.2	15.5	6.1	2.4	494	12.6	205.7	1324
	Footslope	8.9	74.6	16.5	6.2	2.3	540	9.7	225.4	1626
	$DMRT_{(0.05)}$	1.6	NS	1.3	0.2	NS	83	NS	32.5	454
Farm 3	Summit	8.2	81.4	10.4	5.6	1.4	287	1.4	40.2	335
	Shoulder	10.3	78.7	11.0	5.4	1.5	194	1.4	36.6	423
	Backslope	13.4	72.9	13.7	5.7	1.8	267	1.1	36.9	484
	Footslope	10.2	73.2	16.6	5.9	1.6	264	0.2	22.1	432
	$DMRT_{(0.05)}$	1.9	2.8	1.9	0.4	NS	NS	NS	NS	108
P > F										
Site (S)		0.208	0.129	0.043	0.017	<0.001	<0.001	<0.001	<0.001	<0.001
Landscape position (LP)		0.067	0.043	0.031	0.290	0.008	0.036	0.658	0.658	0.407
S X LP		<0.001	<0.001	<0.001	<0.001	0.490	0.580	0.312	<0.001	0.154

, **, * Significant at P ≤ 0.05, 0.01 and 0.001, respectively; NS = not significant.*
† Duncan's multiple range test at the 0.05 significance level

Table 5. Correlation coefficients (r) between EC_a measured by different instruments and soil properties at different depths (cm) of the poultry-manure amended soils in three farms in Southwest Missouri.

EC_a by Method of Measurement	Soil Properties													
	Bray-1 P		Soluble P ($CaCl_2$)		Total P		EC_e		pH ($CaCl_2$)		Total organic C		Clay	
	0 - 5†	5 - 15	0 - 5	5 - 15	0 - 5	5 - 15	0 - 5	5 - 15	0 - 5	5 - 15	0 - 5	5 - 15	0 - 5	5 - 15
	r													
	Farm 1													
EM-38														
Horizontal	0.19	0.02	0.13	-0.11	0.11	-0.04	0.01	-0.01	0.02	0.13	0.03	-0.32*	-0.08	-0.01
Vertical	0.09	-0.21	-0.02	-0.27*	0.04	0.04	-0.02	-0.01	-0.22	-0.13	-0.24	-0.37*	-0.35*	-0.31*
Direct Contact														
Shallow	0.38***	0.05	0.24*	-0.12	0.12	0.05	-0.16	-0.11	-0.46***	-0.20	-0.18	-0.32*	-0.40**	-0.34*
Deep	0.37**	0.06	0.21	-0.17	0.07	0.06	-0.14	-0.11	-0.44***	-0.15	-0.16	-0.36*	-0.30	-0.21
	Farm 2													
EM-38														
Horizontal	0.10	0.17	0.10	0.20*	-0.07	-0.02	0.01	0.13	-0.03	-0.12	-0.18	-0.10	-0.13	-0.14
Vertical	0.12	0.14	-0.11	0.03	0.19*	0.11	-0.07	0.12	0.40***	0.34***	0.21	0.12	0.25*	0.27*
Direct Contact														
Shallow	0.08	0.03	0.18	0.05	-0.04	0.03	0.08	-0.03	-0.24**	-0.30**	-0.11	-0.14	0.02	0.06
Deep	0.08	0.03	0.14	-0.01	-0.03	0.02	0.06	0.06	-0.11	-0.24*	-0.14	-0.22	0.09	0.14
	Farm 3													
EM-38														
Horizontal	-0.01	-0.11	0.17	-0.01	-0.26*	-0.33**	0.26*	0.26*	-0.26*	-0.31**	-0.06	-0.36*	-0.32*	-0.37**
Vertical	0.12	-0.05	0.21	0.05	-0.23*	-0.36***	0.28**	0.29**	0.33**	-0.33**	0.12	-0.23	-0.46***	0.52***
Direct Contact														
Shallow	-0.01	-0.10	0.10	-0.01	-0.29**	-0.33**	0.31**	-0.16	-0.27*	-0.24*	-0.01	-0.25	-0.42**	-0.45**
Deep	-0.07	-0.12	0.07	-0.08	-0.29**	-0.31**	0.24*	-0.18	-0.20	-0.19	-0.03	-0.28*	-0.38**	-0.41**
	Over All Farms													
EM-38														
Horizontal	0.27***	0.26***	0.34***	0.20**	0.13*	0.14*	0.09	0.23***	0.10	0.35***	-0.03	-0.03	0.30***	0.30***
Vertical	0.56***	0.60***	0.46***	0.60***	0.41***	0.43***	0.47***	0.34***	0.08	0.10	0.30***	0.33***	0.02	0.05
Direct Contact														
Shallow	0.12*	0.08	0.15	0.09	0.03	0.04	0.18**	-0.02	-0.25***	-0.20***	-0.01	-0.09	-0.20*	-0.17*
Deep	0.07	0.01	0.11	-0.03	-0.01	-0.01	0.03	-0.03	-0.22***	-0.07	-0.10	-0.21**	-0.08	-0.05

, **, * Significant at $P \le 0.05$, 0.01 and 0.001, respectively; † n = 157 for each soil depth of clay and n = 275 for the 0 - 5 cm depth and n = 272 for the 5 - 15 cm depth of all other soil properties.*

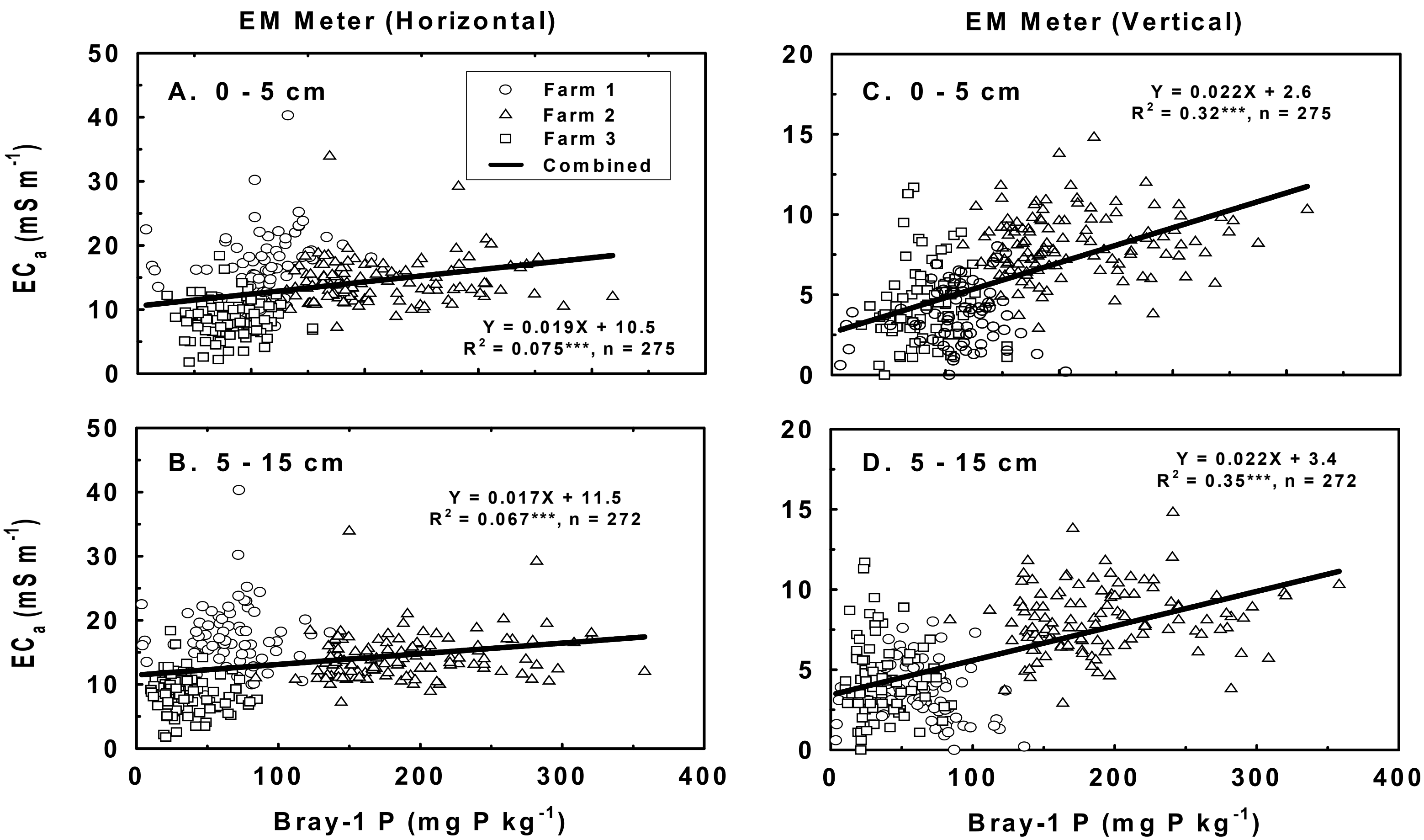

Fig. 3. Changes in soil apparent electrical conductivity (ECa) in response to a range of soil Bray-1 P over three pasture sites in southwest Missouri using the EM-38 sensor in A) the horizontal mode at the 0 - 5 cm depth, B) the horizontal mode at the 5 - 15 cm depth, C) the vertical mode at the 0 - 5 cm depth, and D) the vertical mode at the 5 - 15 cm depth

Heil and Schmidhalter [24] also observed significant variability due to texture and other soil components such as claypans and gravels. Also, potentially contributing to differences in measured EC_a between the two studies was that gravimetric soil water content was generally lower among the pasture sites over the 0 - 15 cm depth (19.9 ± 0.3 %) compared to the gravimetric soil water content of the long-term plot study (23.3 ± 1.7 %). Lower soil water content would tend to reduce overall observed EC_a measurements with both sensors and possibly cause a greater reduction in the range of EC_a, especially with the direct contact sensor since it relies on some moisture to help create tine-soil contact [19]

Soil EC_e, pH $_{(salt)}$, total organic C and clay content also significantly correlated with soil EC_a using the EM-38 sensor in the vertical mode across the three pasture sites (Table 5). The significant correlation between EC_a and EC_e for the three pasture study, which was not observed at the long-term plot study (Table 2), may be attributable to more recent poultry litter applications (i.e., ceased two years prior to sampling) and ongoing grazing of beef cattle. Higher EC_e caused by dissolved salts contained in animal manure has been cited as a reason for higher EC_a in areas receiving animal manure [27,21]. For example, [21] attributed the significant positive correlation they observed between EC_a and soil test Mehlich-3 P in a field that had received manure from confined cattle to higher soil EC_e from salts contained in the deposited manure. However, our results from the long-term plot study indicate that soil EC_a may also significantly correlate with soil test Bray-1 P even when the effects of manuring on soil EC_e has been diminished by time and weathering.

4. CONCLUSION

Soil EC_a may provide useful information for assessing variation in several forms of soil P across pasture fields in the Ozark Highlands and other regions with similar conditions that have historically received poultry litter. Our research found that soluble, soil test and total P varied significantly by pasture field and landcape position. Therefore, intensive soil sampling by landscape position would have been necessary to map this within-field spatial variability using conventional soil testing approaches. The direct contact and EM-38 sensors for measuring EC_a did not have a similar response to soil P or other soil characteristics across the study sites. This variation was attributed to several possible factors, including the proportion of coarse fragments in the soil and differences in soil water content. These factors reduce the effectiveness of obtaining reliable measurements under these soil conditions using the direct contact sensor when compared to the noncontact EM-38 sensor. This study confirms the findings of others who have observed a significant response of EC_a to animal manure applications. Our research suggests that the observed relationship between EC_a and soil P for more recent animal manure applications in these soils may be due to the effects of the animal manure on raising EC_e and for long-term historical animal manure applications on possible increases in soil CEC. However, further research under more controlled conditions may be needed to better understand the processes and factors affecting soil EC_a in response to manure applications before this technique could be used at the individual farm field level to assess spatial variation in soil P.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Schumacher JG. Water quality in the upper shoal creek basin, southwestern Missouri, 1999-2000. Water-Resources Investigations Report 01-4181. U.S. Geological Survey, Rolla, MO. 2001;60.
2. Young RE, et al. Positive approaches to phosphorus balancing in Southwest Missouri. Report #16-01. Food and Agricultural Policy Research Institute, Univ. of Missouri, Columbia, MO; 2001.
3. Mugel DN. Ground water quality and effects of poultry confined animal feeding operations on shallow ground water, Upper Shoal Creek Basin, Southwest Missouri, 2000. Water-Resources Investigations Report 02-4125. U.S. Geological Survey, Rolla, MO; 2002.
4. Sauer TJ, et al. Characterizing the surface properties of soils at varying landscape positions in the Ozark Highlands. Soil Sci. 1998;163:907-915.
5. Sauer TJ, et al. Poultry litter and grazing animal waste effects on runoff water quality. J. Environ. Qual. 1999;28:860-865.
6. Sauer TJ, Meek DW. Spatial variation of plant-available phosphorus in pastures with contrasting management. Soil Sci. Soc. Am. J. 2003;67:826-836.
7. Daniels MB, Chapman SL. Spatial distribution of soil test phosphorus in Arkansas pastures, in: W. Sabbe (Ed.), Arkansas Soil Fertility Studies 1999, Arkansas Agricultural Experiment Station, Univ. of Arkansas, Fayetteville, AR. 2000;98-103.
8. Beegle D, Sharpley AN, Graetz D. Interpreting soil test phosphorus for environmental purposes, in: J.T. Sims (Ed.), Soil testing for phosphorus: Environmental uses and implications, Southern Cooperative Series Bulletin No. 389. SERA-IEG 17 USDA-CSREES Regional Committee. 1998;31-40.
9. Sharpley AN, et al. Managing agricultural phosphorus for protection of surface waters: Issues and options. J. Environ. Qual. 1994;23:437-451.
10. Gburek WJ, Sharpley AN. Hydrologic controls on phosphorus loss from upland agricultural watersheds. J. Environ. Qual. 1998;27;267-277.
11. Lemunyon, J.L., Gilbert, R.G. (1993). Concept and need for a phosphorus assessment tool. J. Prod. Agric., 6, 483-486.
12. Sims JT, et al. Integrating soil phosphorus testing into environmentally based agricultural management practices. J. Environ. Qual. 2000;29:60-71.
13. Lory JA, et al. Feasibility and costs of phosphorus application limits on 39 U.S. swine operations. J. Environ. Qual., 2004;33:1114-1123.
14. Corwin DL, Lesch SM. Application of soil electrical conductivity to precision agriculture: Theory, principles and guidelines. Agron. J. 2003;95:455-471.
15. Kitchen NR, et al. Soil electrical conductivity as a crop productivity measure for claypan soils. J. Prod. Agric. 1999;12:607-617.

16. Sudduth KA, et al. Evaluation of a soil conductivity sensing penetrometer. Presented at the 2000 American society of agricultural engineers annual international meeting (July 9-12, 2000). Paper No. 001043. ASAE, St. Joseph, MI; 2000.
17. Johnson CK, et al. Field-scale electrical conductivity mapping for delineating soil condition. Soil Sci. Soc. Am. J. 2001;65:1829-1837.
18. Eigenberg RA, Nienaber JA. Electromagenetic induction methods applied to an abandoned manure handling site to determine nutrient buildup. J. Environ. Qual. 2003;32:1837-1843.
19. Sudduth KA, et al. Comparison of electromagnetic induction and direct sensing of soil electrical conductivity. Agron. J. 2003;95:472-482.
20. Rhoades JD. Salinity: Electrical conductivity and total dissolved solids. in: Sparks, D.L. (Ed.), Methods of soil analysis, Part 3. Chemical Methods. Soil Sci. Soc. Amer. Book Series no. 5. Soil Sci. Soc. Amer, Inc., Madison, WI. 1996:417-435.
21. Heiniger W, et al. Using soil electrical conductivity to improve nutrient management. Agron. J. 2003;95:508-519.
22. Islam MM, et al. Comparing apparent electrical conductivity measurements on a paddy field under flooded and drained conditions. Precision Agriculture. 2012;13(3):384-392.
23. Gholizadeh, et al. Relationship between apparent electrical conductivity and soil physical properties in a Malaysian paddy field. Archives of Agronomy and Soil Science. 2012;58(2):155-168.
24. Heil K, Schmidhalter U. Characterization of soil texture variability using the apparent soil electrical conductivity at a highly variable site. Computers and Geosciences. 2012;39:98-110.
25. Mastura, et al. Characterization of paddy soil compaction based on soil apparent electrical conductivity zones. African Journal of Agricultural Research. 2011;6(11): 2506-2515.
26. Aimrun W, et al. Paddy soil properties and yield characteristics based on apparent electrical conductivity zone delineation for a humid tropical rice farm. African Journal of Agricultural Research. 2011;6(23):5339-5350.
27. Eigenberg RA, et al. Electrical conductivity monitoring of soil condition and available N with animal manure and a cover crop. Agric. Ecosyst. Environ. 2001;1834,1-11.
28. Wood BH, et al. Nutrient accumulation and nitrate leaching under broiler litter amended in corn fields. Comm. Soil Plant Anal. 1996;27:2875-2894.
29. Stewart BA, Meek BD. Soluble salt considerations with waste application, in: Elliott, L.F., F.J. Stevenson (Eds.), Soils for management of organic wastes and wastewaters, Soil Sci. Soc. Am., Madison, WI. 1977;219-232.
30. Joost RE, et al. Poultry litter application to pasture grasses in Southwest Missouri, in: Southwest Missouri Center 1994 research report. College of Agric., Food and Natr. Res., University of Missouri, Mt. Vernon, MO. 1994;41-43.
31. Blake GR, Hartge KH. Bulk density, in: Klute, A. (Ed.), Methods of Soil Analysis, Part 1. Physical and Mineralogical methods, 2nd ed. American Society of Agronomy, Madison, WI. 1986;363-375.
32. McNeill JD. Rapid, accurate mapping of soil salinity by electromagnetic ground conductivity meters, in: Advances in measurements of soil physical properties: Bringing theory into practice. SSSA Spec. Publ. 30, SSSA, Madison, WI. 1992;201-229.
33. Sudduth, K.A., et al. (1999). Soil conductivity sensing on claypan soils: Comparison of electromagnetic induction and direct methods, in: P.C. Robert et al., (Eds.), Proc. 4 Intl. Conf. on Precision Agriculture, Amer. Soc Agron., Madison, WI, pp. 979-990.
34. Bray RH, Kurtz LT. Determination of total, organic, and available forms of phosphorus in soils. Soil Sci. 1945;59:39-45.

35. Murphy J, Riley, J.R. (1962). A modified single solution method for the determination of phosphate in natural waters. Anal. Chem., 27, 31-36.
36. Frank K, Beegle D, Denning J. Phosphorus, in: J.R. Brown (Ed.), Recommended chemical soil test procedures for the North Central Region, North Central Regional Research Publication No. 221, Missouri Ag Expt. Station SB 1001, Columbia, MO.1998;21-29.
37. Sommers LE, Nelson, DW. Determination of total phosphorus in soils: A rapid perchloric acid digestion procedure. Soil Sci. Soc. Amer. Proc. 1972;36:902-904.
38. Nelson DW, Sommers LE. A rapid and accurate procedure for estimation of organic carbon in soil. Proc. Indiana Acad. Sci. 1975;84:456-462.
39. Gee GW, Bauder JW. Particle-size analysis., in: Klute, A. (Ed.), Methods of Soil Analysis, Part 1, Physical and Mineralogical methods, 2nd ed., American Society of Agronomy, Madison, WI. 1986;383-411.
40. Whitney DA. Soil salinity, in: Brown, J.R. (Ed.), Recommended chemical soil test procedures for the North central region, north central regional research publication No. 221, Missouri Ag Expt. Station SB 1001, Columbia, MO. 1998:59-60.
41. SAS Institute. SAS/STAT users guide, Release 6.03 edn. Cary, NC; 1988.
42. Olsen SR, Barber SA. Effect of waste application on soil phosphorus and potassium. in:Elliott, L.F., F.J. Stevenson (Eds.), Soils for management of organic wastes and waste waters, American Society of Agronomy, Madison, WI. 1977;197-215.
43. Khaleel R, et al. Changes in soil physical properties due to organic waste applications: a review. J. Environ. Qual. 1981;10:133-141.
44. Dean JA. Lange's handbook of chemistry. McGraw-Hill, New York, NY; 1999.

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