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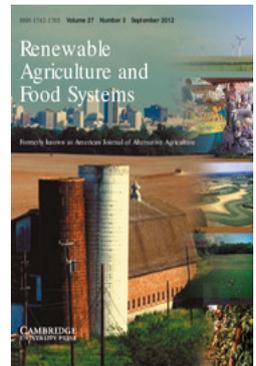
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Soil fertility and crop growth under poultry/crop integration

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Research Paper

Abstract

Innovative sources of soil fertility are of utmost importance to growers in light of rising fertilizer costs and environmental concerns. Integrating livestock and crop production is one channel by which agricultural practitioners can enhance soil fertility. For this research, soil fertility was analyzed in pastured poultry/crop agroecosystems to determine whether free-ranging birds and pasture could be used to replace or supplement non-manure-based fertilizers. Soils from adjacent cropped areas were compared to plots with a recent history of pastured poultry use on two farms, and crop plants were grown in each type of soil in a replicated greenhouse experiment. Spatial variation in soil fertility was also assessed relative to location of poultry coops. Pastured poultry plots had elevated soil total C, total N, $\text{NH}_4^+\text{-N}$, $\text{NO}_3^-\text{-N}$, Olsen P, exchangeable K, organic matter, cation exchange capacity and electrical conductivity relative to the control of typically managed organic farm soils without pastured animal inputs. These soil fertility changes conferred greater biomass and height to sunflowers and beans grown in these soils relative to control soils for most treatments. Results suggest that pastured poultry can effectively fertilize soil for certain crops but that a need exists for more research into (1) phosphorus management and (2) ensuring a spatially uniform distribution of manure.

Key words: crop/livestock systems, integrated agriculture, manure, pasture

Introduction

As the price of conventional fertilizer soars and interest in alternative sources of crop fertilizer grows¹, there is an increasing demand for on-farm sources of soil fertility². Integrating livestock and crop production is one channel by which agricultural practitioners can enhance soil fertility using on-farm resources of animal manure and pasture plants^{3–5}. Farmer interest in utilizing pasture-raised chickens (*Gallus gallus domesticus*), in particular, to improve soil fertility and enhance crop performance has grown in recent years, as has consumer demand for pastured poultry products^{6–8}. In pastured production, poultry live outdoors and consume pasture plants and grain^{9,10}. Relatively few peer-reviewed articles have been published regarding soil fertility and crop growth under pastured poultry management, yet inferences about the role of poultry on soil fertility can be made from the substantial literature on the fertilizer content values of poultry manure and litter^{1,11–13}.

Poultry manure and litter are known effective plant fertilizers. Various estimates give the nutrient concentrations of poultry manure at an average of 5.1% nitrogen (N), 1.9% phosphorus (P) and 2.6% potassium (K)^{14–16}.

Many field studies suggest that poultry manure and/or litter application to crop soils can enhance chemical, biological and physical quality, and plant growth. Sainju et al.¹¹ found broiler litter increased soil carbon (C) and N sequestration in intensive cropping systems at a depth of 0–10 cm. Adeli et al.¹ reported that broiler litter application to cropping systems linearly increased extractable soil P, K, soil cation exchange capacity and soil total C at 0–15 cm in a 3-year study. Land application of poultry litter has also been found comparable to inorganic fertilizer for supplying soil P and increasing forage yield¹⁷.

Poultry manure and litter have been widely studied because the poultry industry generates high quantities that are frequently applied to crop or pasture fields^{11,18}. Less is known about the effect of utilizing live birds for soil fertilization. Manure deposited by live birds is surface-applied and not tractor-incorporated; although Kratz et al.¹⁹ reported that fecal N and P inputs by free-ranging birds corresponded with increased soil N and P levels. Studies such as these suggest that integrating live poultry into crop agroecosystems may effect significant changes to soil fertility and yield.

The objectives of this study were to: (1) determine whether soil from poultry pasture (PPAS) enhanced soil

fertility in comparison with typical organic non-animal based management (control); and (2) identify whether crops grown in soil from PPAS fields achieved equivalent growth parameters as crops grown in control soils. These effects were assessed for two agroecosystems: (1) a mixed annual/berry system where crops were planted subsequent to removal of birds from pasture; and (2) an orchard setting where birds were temporally and spatially integrated with crop production.

Methods

Study region and experiments conducted

Research was conducted between 2009 and 2011 in the Central Coast region of California at two working farms. The region is characterized by a nearly year-round agricultural growing season with a mild Mediterranean climate. The rainy, cooler season is from November to April, and the dry, warm season is from May to October. Three assessments were conducted: for objective 1, soil fertility parameters were compared from adjacent plots on two farms, and spatial variation in soil fertility was assessed relative to location of poultry coops. For objective 2, crop plants were grown in a replicated greenhouse experiment using soils from plots with a recent history of pastured poultry and soils from adjacent cropped areas without a history of pastured poultry.

Site selection

This research was conducted on working farms, making site selection a critical aspect of experimental design. The advantage of agroecological studies based on working farms is that they reflect real-world farming conditions and generate data based on actual management practices. The disadvantage is a reduced ability to replicate treatments and choose ideal controls. In choosing sites for this research, we sought farms with management practices representative of integrated pastured poultry/crop production. Field histories and farmer interviews were used to determine that there were no *a priori* reasons for poultry placement related to soil fertility and that plots were similar enough to deduce whether differences were due to the presence or absence of poultry and pasture. Two farms were selected that met all requirements. At each farm we established two adjacent plots, one with a history of crop production and one with a history of pastured poultry. Adjacent plots had similar cropping histories and identical soil types and slopes.

Research sites

Farm A was used as an exemplar of PPAS in a mixed annual/berry agroecosystem. Soil is a Lockwood series (fine-loamy, mixed, Thermic and Pachic Argixerolls). Texture of the topsoil is clay (sand: 28.4%, silt: 28.4% and

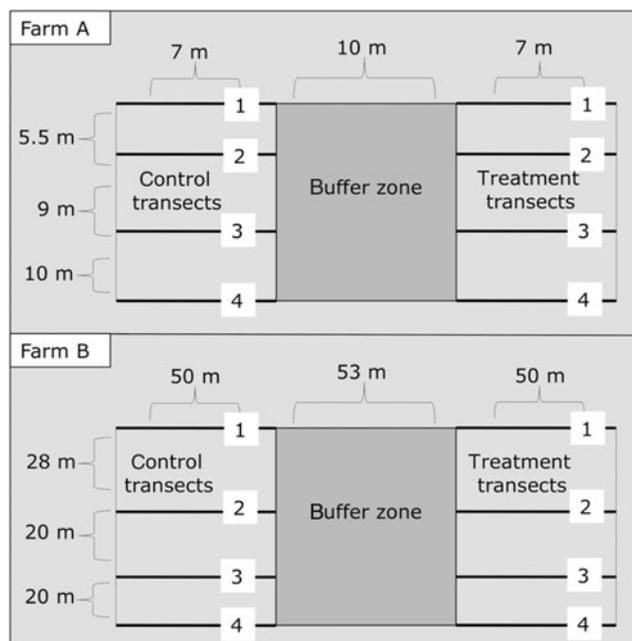


Figure 1. Experimental design of soil fertility study showing transects (bold lines), distance between transects, and buffer zones at both sites.

clay: 43.2%). At this site, hens were the integrated animals, and plots were alternately dedicated to crop and pasture production. Plot sizes were 24.5m × 7m (Fig. 1).

At this site, the pasture plot had a 2-year history of poultry grazing (2470 birds per ha). Pasture fields were seeded with fescue (*Festuca arundinacea*), orchardgrass (*Dactylis glomerata*), ryegrass (*Lolium* spp.), clover (*Trifolium* spp.) and trefoil (*Lotus corniculatus*), and intermittently ranged by hens for 2 years before being converted back to crop production. Prior to pasture, the treatment field was planted with popcorn (*Zea mays averta*) in 2007 and pumpkins (*Cucurbita* spp.) in 2006. During crop sequences, plots were planted with cover crops [bell beans (*Vicia faba*), purple vetch (*Vicia benghalensis*), peas (*Pisum sativum*) and oats (*Avena sativa*)] during the winter season. While managed as pasture, overhead irrigation was used, and during crop rotations, drip irrigation was employed.

The control field had a 2-year history of wheat (*Triticum* sp.) and popcorn (*Zea mays averta*) during the time the treatment field was planted as pasture and grazed by poultry. Previously, the control field was planted with wheat in 2007 and popcorn in 2006. Winter cover crops, as described above, were planted into these crop rotations. Compost and lime were added to all crop sequences biennially, both at a rate of 2.4Mg ha⁻¹. Both fields were converted to strawberry (*Fragaria* sp.) production subsequent to the first day of data collection. During strawberry cultivation, winter cover crops were not utilized.

Farm B was used as an exemplar of PPAS in an orchard system. Soil is a Sorrento series (fine-loamy, mixed, Thermic and Calcic Haploxerolls). Texture of the topsoil is sandy clay loam (sand: 51.4%, silt: 26.4%, and clay: 22.2%). At this site, meat chickens were integrated into a portion of walnut (*Juglans regia*) orchard on pasture seeded as above. Plot size was 68 m × 50 m (Fig. 1). An equally sized section of the orchard with no prior history of poultry was used as the control, and both plots had equivalent walnut tree density (100 trees per ha). Chickens grazed the PPAS orchard from April to September annually for the previous 7 years (2470 birds per ha). The control orchard had no history of poultry and was planted with the same cover crop mix described above. No other amendments were added to either plot. Both plots were irrigated on the same schedule, receiving water three times per year for 12 h.

Data collection for soil fertility

This assessment was conducted from 2009 to 2011. Using a stratified composite sampling design²⁰, eight composite samples per plot were gathered. Each composite sample was composed of 15 thoroughly combined sub-samples. Samples were gathered from two depths (0–15 and 15–30 cm) along eight permanent transects per site in two plots (Fig. 1), and sub-samples of each composite sample were used for analysis. Field history and farmer interviews were obtained to determine that no *a priori* reasons existed for delineation of field margins (e.g., soil-type differences or productivity), and transects were placed so that the distance between transects was greater than the distance between treatments to rule out stochastic spatial variation. At Farm A, transects were not true replicates because the treatment field was grazed by a single flock of hens, meaning that all data collected represent the effect of one flock. For this reason, we present data from this site as repeated measures. At Farm B, transects were true replicates because meat chickens were housed in discrete pens, and each transect represents the effect of a distinct flock. Data from this site are presented as means across time.

Inorganic N was measured four times per year ($n = 256$)²¹, analyzed for ammonium–nitrogen ($\text{NH}_4^+\text{-N}$) and nitrate–nitrogen ($\text{NO}_3^-\text{-N}$) on a flow injection analyzer (Lachat QuikChem 8000, Milwaukee, WI)²² at the University of California, Santa Cruz (UCSC). Total C and total N were measured twice yearly ($n = 64$) and assessed on the VarioMAX CNS analyzer (Elementar, Mt. Laurel, NJ)²³ at UCSC. Calcic properties of Farm B soils were limited to >50 cm depth, making inorganic C removal from soils prior to total C analysis unnecessary because sample soils were collected from surface depth increments of 0–15 and 15–30 cm. Soil electrical conductivity²⁴ was determined twice yearly ($n = 31$, missing one sample, topsoil only) as a saturated paste using a conductivity meter (Denver Instrument, Model 250) at

UCSC. Extractable sodium bicarbonate P (Olsen P), exchangeable K (ex. K), pH (saturated paste), cation exchange capacity and soil organic matter as determined by weight loss-on-ignition were assessed four times per year ($n = 128$)²⁵ at A&L Laboratories (Modesto, CA).

In a sub-study conducted in February 2010, spatial variation in soil fertility was assessed for the coop-based system at Farm A. Hens, unlike the meat chickens at Farm B, ranged within their fields during the day, frequently seeking shelter under the coop. This study was conducted to determine whether soil fertility values changed with distance from the coop. Samples were taken every 4 m on four 16-m transects at two coops ($n = 20$). Soil samples were collected from a depth of 0–15 cm and analyzed for inorganic N, Olsen P, ex. K, pH, cation exchange capacity and organic matter, using the methods described above.

Greenhouse trial

To address the question of crop growth response to PPAS independent of farmer management, a series of greenhouse experiments were conducted using soil from PPAS and control plots. From each plot, five gallons of topsoil (0–15 cm depth) were collected from 20 random sub-samples. Soil was then air-dried, mixed well and crushed to approximately 2 mm diameter aggregates. Two bean seeds (*Phaseolus vulgaris* L. var. Hystyle) were planted on November 5, 2009 with Farm A soil and thinned to one shoot on November 11, 2009 ($n = 33$). In the same manner, sunflowers (*Helianthus annuus* L.) were planted on April 23, 2010 with soil from Farms A and B and thinned on April 29, 2010 ($n = 174$). Containers were arranged in a random formation, misted daily and grown at daytime temperatures of 22.8–23.9°C for 30 days in the UCSC greenhouse. At 30 days from seeding, plants were clipped at the soil level and measured for height. Plants were then oven-dried at 60°C for 36 h and the biomass weighed.

Data analysis

True replication of treatment within site at Farm A was not viable due to the scale of the treatment, and management practices between the two farms differed too greatly to warrant statistical comparison across farms. Instead, we present results as two distinct case studies. Two-tailed Student's *t*-tests were conducted for most data analysis with the exception of the spatial variation study, where simple linear regressions were used to determine the effect of distance from coop on soil fertility parameters. JMP, version 8 was used for all statistical tests²⁶ with the alpha level set at 0.05. The following data with non-normal distributions were transformed to meet assumptions of normality: \log_{10} of total C at Farm A (15–30 cm) and Farm B (both depths); total N at Farm B (15–30 cm); $\text{NH}_4^+\text{-N}$ at Farm A (15–30 cm) and Farm B (both depths); $\text{NO}_3^-\text{-N}$ for all tests; Olsen P at Farm A (0–15 cm) and Farm B (both depths); ex. K at Farm B (15–30 cm); and

Table 1. Farm A soil fertility results for the 0–15 cm depth except where indicated.

Parameter	Days since birds removed	Mean PPAS	Mean control	df	t-stat.	P-value	dir.
pH	0	6.90 (0.09)	6.55 (0.09)	5.98	2.78	0.0320*	+
	98	7.18 (0.05)	6.88 (0.09)	4.72	3.06	0.0302*	+
	181	7.03 (0.05)	6.85 (0.05)	5.99	2.53	0.0500*	+
	384	7.25 (0.12)	7.30 (0.16)	5.57	0.25	0.8096	0
Total C (g kg ⁻¹)	0	47.50 (1.28)	47.24 (1.23)	5.99	0.15	0.8889	0
Total N (g kg ⁻¹)	0	4.13 (0.04)	3.96 (0.04)	5.89	3.01	0.0241*	+
	441	4.16 (0.04)	4.04 (0.06)	4.95	1.58	0.1750	0
NH ₄ ⁺ -N (mg kg ⁻¹)	0	3.30 (1.20)	2.29 (0.41)	3.68	0.80	0.4713	0
	51	2.28 (0.61)	1.41 (0.15)	3.39	1.39	0.2500	0
	98	3.87 (0.35)	2.49 (0.24)	5.29	3.29	0.0200*	+
	147	2.20 (0.09)	2.27 (0.41)	3.23	0.15	0.8894	0
NH ₄ ⁺ -N (mg kg ⁻¹) (15–30 cm)	0	3.40 (0.78)	2.23 (0.21)	3.81	1.36	0.2500	0
	51	2.38 (0.55)	0.90 (0.11)	4.85	3.50	0.0182*	+
	98	4.60 (1.08)	3.47 (1.47)	4.83	1.04	0.3478	0
NO ₃ ⁻ -N (mg kg ⁻¹)	0	32.00 (7.81)	15.55 (1.60)	3.97	2.36	0.0778	0
NO ₃ ⁻ -N (mg kg ⁻¹) (15–30 cm)	0	26.91 (9.70)	15.67 (1.96)	3.16	0.04	0.9674	0
	51	40.60 (6.69)	20.74 (2.21)	5.11	3.23	0.0211*	+
	98	11.58 (1.23)	24.20 (0.99)	3.85	6.50	0.0033*	-
	147	32.37 (5.27)	39.89 (6.26)	5.99	0.83	0.4385	0
Olsen P (mg kg ⁻¹)	0	29.90 (3.63)	24.25 (8.08)	4.21	1.02	0.3617	0
Ex. K (mg kg ⁻¹)	0	552.25 (22.09)	561.53 (21.95)	6.00	0.30	0.7759	0
Organic matter (g kg ⁻¹)	0	62.50 (0.87)	58.50 (0.96)	5.94	3.10	0.0214*	+
	98	62.00 (0.58)	63.00 (1.41)	3.97	0.65	0.5487	0
Cation exchange capacity (cmol kg ⁻¹)	0	25.10 (0.48)	26.15 (0.42)	5.91	1.65	0.1512	0
Electrical conductivity (dS m ⁻¹)	0	0.72 (0.03)	0.50 (0.05)	4.87	8.57	0.0004*	+
	98	0.53 (0.04)	0.52 (0.06)	4.79	0.43	0.6885	0

Figures in parentheses are standard errors.

Results are shown from time zero until the sampling date after which all differences were neutral.

'dir.' indicates direction of change for significant results of PPAS relative to the control.

* indicates statistically significant differences.

organic matter at Farm B (15–30 cm). For the spatial variation data, NH₄⁺-N, NO₃⁻-N and Olsen P were log₁₀ transformed, and ex. K data were square root transformed. However, original means and standard errors are reported and graphically displayed hereafter for ease of interpretation.

Results

Effects on soil fertility

At Farm A, PPAS plots had elevated soil pH, total N, organic matter and electrical conductivity levels relative to the control at a depth of 0–15 cm at day 0, the day birds were removed from pasture and pre-conversion to strawberries (Table 1). Subsequent to removal of birds from pasture and conversion to strawberries, pH values remained significantly higher. Soil inorganic N differences were statistically significant for NH₄⁺-N at 98 days after conversion at the 0–15 cm depth and at 51 days for the 15–30 cm depth. Soil NO₃⁻-N differences differed significantly at 51 and 98 days after conversion at the 15–30 cm depth. No other significant differences were found at the 15–30 cm depth.

At Farm B, PPAS plots had decreased soil pH and elevated total C, total N, NH₄⁺-N, NO₃⁻-N, Olsen P, ex. K, organic matter, cation exchange capacity and electrical conductivity levels relative to the control (Table 2). These results were consistent at the 15–30 cm depth with the exception of soil organic matter.

Spatial variation in soil fertility results

Certain soil fertility parameters varied strongly along spatial gradients within PPAS fields where free-ranging hens lived. Regression analysis showed that soil NH₄⁺-N, NO₃⁻-N, Olsen P and ex. K all significantly decreased with distance from coop at a depth of 0–15 cm (Fig. 2). Soil pH, organic matter and cation exchange capacity were unaffected. Correlations of the following parameters and distance from coop were significant: NH₄⁺-N ($r^2 = 0.42$, $F_{1,18} = 13.27$, $P = 0.0019$); NO₃⁻-N ($r^2 = 0.79$, $F_{1,18} = 68.28$, $P < 0.0001$); Olsen P ($r^2 = 0.06$, $F_{1,18} = 1.15$, $P < 0.0001$); ex. K ($r^2 = 0.33$, $F_{1,18} = 8.88$, $P = 0.008$).

Greenhouse trial

PPAS soil improved crop growth relative to the control for both biomass and plant height, showing a neutral effect

Table 2. Farm B soil fertility results.

Parameter	Soil depth (cm)	Mean PPAS	Mean control	df	<i>t</i> -stat.	<i>P</i> -value	dir.
pH	0–15	6.99 (0.06)	7.36 (0.05)	27.59	4.96	<0.0001*	–
	15–30	7.10 (0.06)	7.43 (0.05)	27.66	4.48	0.0001*	–
Total C (g kg ⁻¹)	0–15	16.07 (0.90)	11.26 (0.25)	7.48	5.35	0.0009*	+
	15–30	22.7 (6.73)	7.86 (0.33)	6.28	3.22	0.0169*	+
Total N (g kg ⁻¹)	0–15	1.54 (0.10)	1.05 (0.00)	6.01	5.06	0.0023*	+
	15–30	1.96 (0.52)	0.76 (0.03)	6.31	3.24	0.0164*	+
NH ₄ ⁺ -N (mg kg ⁻¹)	0–15	4.97 (1.48)	1.24 (0.17)	51.76	4.32	<0.0001*	+
	15–30	2.65 (0.57)	0.86 (0.16)	52.98	4.25	<0.0001*	+
NO ₃ ⁻ -N (mg kg ⁻¹)	0–15	18.70 (3.04)	12.69 (2.70)	60.47	2.27	0.0267*	+
	15–30	15.14 (2.18)	9.73 (1.68)	58.36	2.40	0.0198*	+
Olsen P (mg kg ⁻¹)	0–15	60.33 (5.14)	25.03 (2.38)	28.98	6.91	<0.0001*	+
	15–30	44.72 (4.40)	13.81 (0.99)	28.33	10.11	<0.0001*	+
Ex. K (mg kg ⁻¹)	0–15	542.17 (17.21)	311.57 (12.57)	26.00	10.82	<0.0001*	+
	15–30	391.5 (28.4)	224.53 (11.37)	23.98	6.13	<0.0001*	+
Organic matter (g kg ⁻¹)	0–15	28.60 (1.14)	22.63 (1.02)	28.42	3.90	0.0003*	+
	15–30	22.53 (1.65)	19.44 (1.59)	28.22	1.70	0.0995	0
Cation exchange capacity (cmol kg ⁻¹)	0–15	18.39 (0.22)	16.08 (0.50)	20.54	4.27	0.0004*	+
	15–30	17.71 (0.62)	15.63 (0.34)	21.78	2.94	0.0076*	+
Electrical conductivity (dSm ⁻¹)	0–15	0.52 (0.04)	0.35 (0.02)	9.95	3.75	0.0038*	+

Figures in parentheses are standard errors.

'dir.' indicates direction of change for significant results of PPAS relative to the control.

* indicates statistically significant differences.

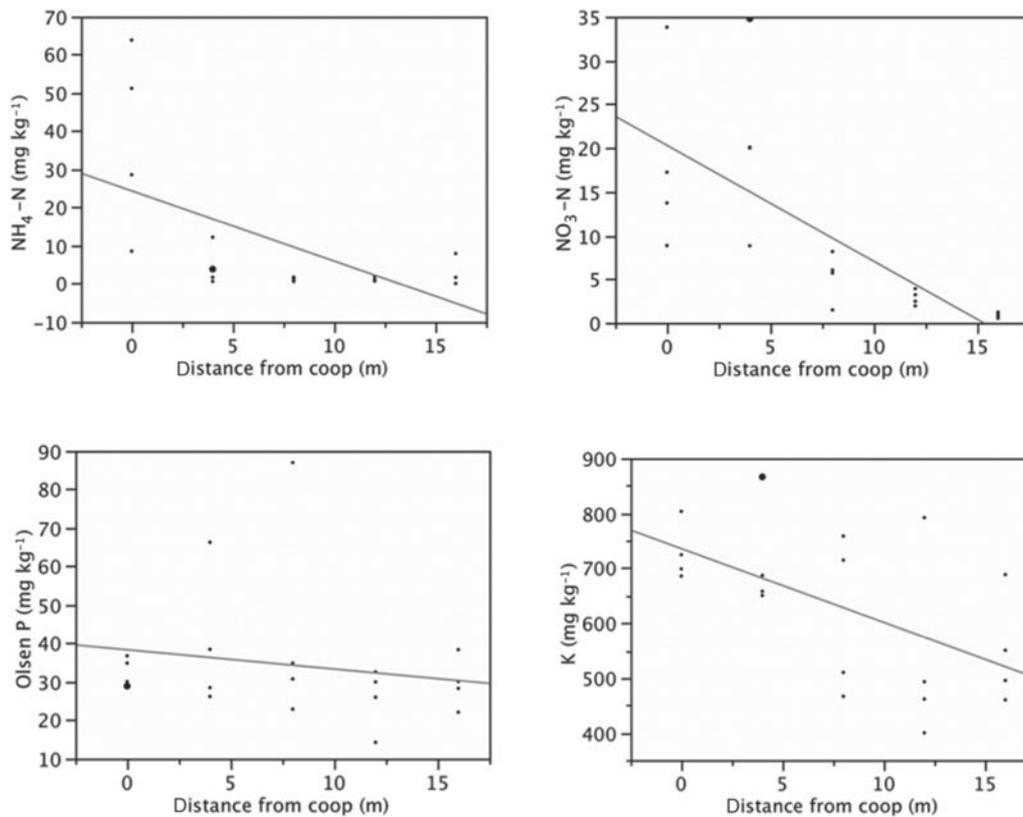


Figure 2. Regressions of soil ammonium–nitrogen (NH₄⁺-N), nitrate–nitrogen (NO₃⁻-N), extractable sodium bicarbonate P (Olsen P) and exchangeable K (ex. K) showing significant correlations to distance from coop.

only for sunflower biomass at one site. PPAS soil enhanced average bean biomass by a factor of 1.48 in Farm A soil (Fig. 3, $t(30.48)=3.31$, $P=0.0024$; Farm B soil not tested). Biomass results for sunflowers varied

by farm. At Farm A, PPAS soil enhanced average sunflower biomass by a factor of 1.08 (Fig. 4, $t(54.94)=3.56$, $P=0.0008$). At Farm B, there was no significant difference in average biomass between plants

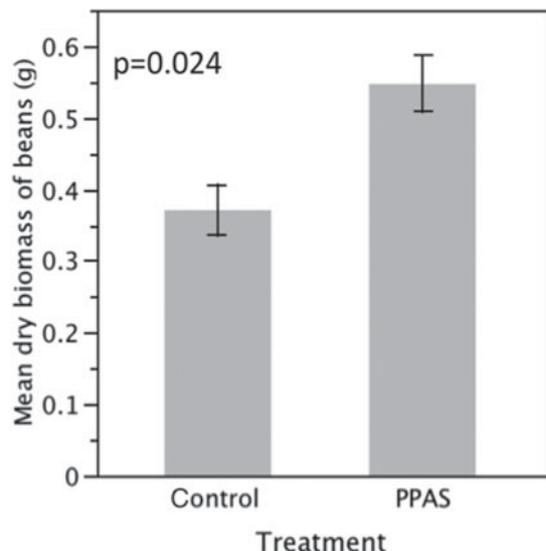


Figure 3. Biomass (grams/plant) of beans grown in soils from the control and PPAS with standard errors.

grown in PPAS and control soils (Fig. 4, $t(49.28) = 1.51$, $P = 0.1373$). PPAS soil enhanced sunflower height relative to the control group by a factor of 1.11 at Farm A (Fig. 5, $t(57.92) = 2.09$, $P = 0.041$) and by a factor of 1.06 at Farm B (Fig. 5, $t(108.17) = 2.30$, $P = 0.023$).

Discussion

PPAS plots had elevated soil fertility parameters of soil total C, total N, $\text{NH}_4^+\text{-N}$, $\text{NO}_3^-\text{-N}$, Olsen P, ex. K, organic matter and cation exchange capacity levels relative to the control. These changes conferred greater biomass and height to plants grown in these soils in the greenhouse in most cases. Some of these soil fertility parameters varied along spatial gradients within the PPAS fields where free-ranging hens lived. PPAS plots had highly increased soil Olsen P levels relative to the control at Farm B, with implications for environmental contamination of adjacent waterways. These results suggest that, despite the fact that in pasture-based systems manure is applied gradually by poultry rather than as a one-time mechanically incorporated application, PPAS does significantly affect soil fertility for multiple parameters, although it is not clear whether this effect is due to poultry manure or pasture plants.

Soil pH was raised relative to the control at Farm A, which is consistent with other studies of the effect of poultry manure and litter on soil acidity^{1,27,28}. Hen poultry manure tends to increase soil pH because poultry feed contains calcium carbonate (CaCO_3) as an additive²⁹. Feeds designated for hens contain more CaCO_3 than meat chicken feed to aid in shell production. Contrary to this phenomenon, manure in general can have a soil acidifying effect; when NH_4^+ is converted to NO_3^- and H^+ ions are released to the soil, pH is lowered³⁰.

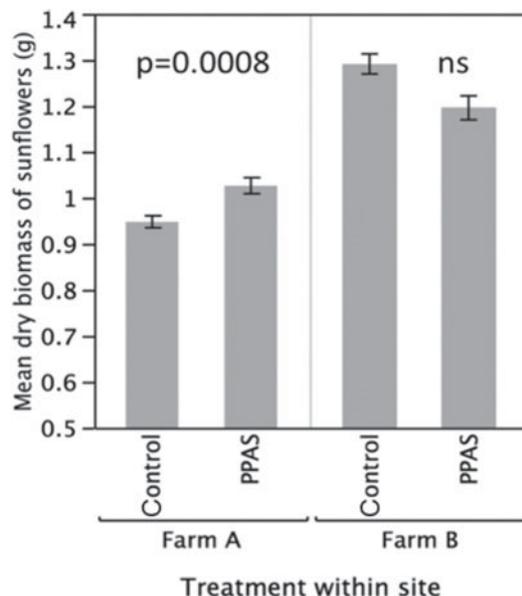


Figure 4. Biomass of sunflowers (grams/plant) grown in soils from the control and PPAS within farm with standard errors.

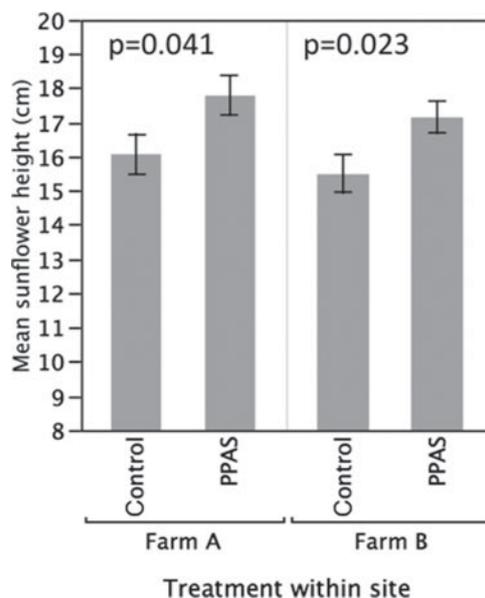


Figure 5. Height of sunflowers (cm/plant) grown in soils from the control and PPAS within farm with standard errors.

At Farm B, PPAS decreased soil pH. At this site, meat chickens were the integrated animal, which means that substantially less CaCO_3 was present in the feed, and the liming effect of the feed was apparently not greater than the acidifying effect of the manure. Also having an effect on soil pH at these sites was the buffering capacity of the soil, as determined by cation exchange capacity. At Farm A, soil cation exchange capacity was higher than Farm B soil cation exchange capacity, meaning that more CaCO_3 would be required to increase the pH of the soil than at Farm B. With hen feed containing more CaCO_3 than meat chicken feed, this effect was achieved. These

inorganic C additions were likely minor sources of increased total C measured in PPAS soils. Rather, soil total C increases are attributed largely to significant increases in organic matter.

PPAS plots showed elevated soil total C relative to the control at Farm B, the site with a 7-year history of PPAS. Similarly, other studies of manure have found a relationship between long-term manure applications and soil total C increase^{1,31}. Soil total N was also increased by PPAS at both sites. Total N in poultry manure comprised 40–70% uric acid ($C_5H_4N_4O_3$), which is readily converted to ammonia (NH_3) in soil^{19,32}. NH_3 is then either subject to volatilization or conversion to NH_4^+ , depending on soil pH, and eventually NO_3^- by nitrification. NH_4^+ -N and NO_3^- -N were increased in PPAS plots at both sites. Soil ex. K was also enhanced in PPAS plots at Farm B.

In addition to these chemical changes, soil organic matter was raised relative to the control in PPAS plots at the 0–15 cm depth for both sites. High soil organic matter is associated with high soil nutrient-holding capacity, low penetration resistance and a biologically active soil ecosystem^{13,33,34}. Soil cation exchange capacity was also raised in PPAS plots relative to the control at Farm B but not Farm A, which is explained by the soil type of each site. Farm B had a sandy clay loam with 22% clay content, while Farm A had a clay soil with 43% clay content. At Farm A, the control soil had a substantially higher cation exchange capacity than the control Farm B, which is consistent with cation exchange properties of clay. At Farm B, PPAS plots has significantly elevated soil organic matter levels, which would lead to an increase in measurable cation exchange capacity for a soil not dominated by clay. Soil electrical conductivity was also increased in PPAS plots at both sites, although not beyond established threshold values for salt-sensitive crops³⁵.

Soil P levels were highly increased in PPAS plots relative to the control at Farm B. Phosphate is an additive to poultry feed, and excessive P accumulation associated with the use of poultry manure as a crop fertilizer is a well-known phenomenon^{36–38}. Crops utilize approximately six times more N than P, yet N:P ratios are typically closer to 1:1 or 2:1 in manure³⁷. Growers often apply manure to meet crop growth goals or N levels, resulting in P excess. Excessive soil P is lost primarily to overland runoff of P-enriched sediment and manure particles³⁹. Loss of P to adjacent waterways can lead to eutrophication⁴⁰. Whether soil P levels associated with pastured poultry pose an environmental risk is unique to each farm, as chemical and hydrological factors determine P retention and movement⁴¹. However, suggested threshold values of soil Olsen P for environmental quality are approximately 30–40 mg kg⁻¹^{42,43}. Farm B levels exceeded this threshold for the PPAS treatment, and Farm A levels were close to the lower bound of this threshold in the PPAS treatment. Growers should be aware of this issue and conduct regular soil tests. When soil P reaches unacceptable levels for local conditions, birds should be relocated.

Finally, another issue of concern was the spatial variation in soil NH_4^+ -N, NO_3^- -N, Olsen P and ex. K within PPAS fields where free-ranging hens lived. Hens tend to spend more time near or in the coop than toward the field margins, with the obvious result that they deposit more manure near the coop. Kratz et al.¹⁹ found similar hot spots in free-range meat chicken runs. This issue can be ameliorated with more frequent relocation of portable coops. Research is required to determine how often coops should be moved to maximize nutrient deposition.

The relevance of these values to plant growth and yield depends on the type of crop grown with or subsequent to PPAS. In the case of this study, PPAS levels were at least as effective as the input methods growers were using for control soil preparation as shown by the growth results in the greenhouse trial. At the study sites reported on in this paper, the equivalent quantity of dry manure applied to a plot was approximately 8.4 Mg ha⁻¹ yr⁻¹ for layers and 10.9 Mg ha⁻¹ yr⁻¹ for broilers. Studies using comparable application rates have found that 10 Mg ha⁻¹ of dry poultry manure resulted in higher N uptake by barley than inorganic N fertilizer alone at comparable rates of inorganic N application⁴⁴; a litter application rate of 3.7 Mg ha⁻¹ produced lint yields equivalent to maximum achievable with inorganic fertilizer, while 8.7 Mg ha⁻¹ maximized lint yield¹²; and litter application for cotton at a rate of 6.7 Mg ha⁻¹ maximized plant N utilization, while at rates of 10.1 and 13.4 Mg ha⁻¹, bulk density was improved relative to inorganic N treated soils¹.

Conclusions and future research

Innovative sources of soil fertility enhancement are of utmost importance to growers in light of rising fertilizer costs and environmental concerns. This study demonstrates the utility of pastured poultry as a technique for soil fertility enhancement on intensively managed organic farms. We found increased levels of soil total C, total N, NH_4^+ -N, NO_3^- -N, ex. K, organic matter and cation exchange capacity in PPAS plots. These soil fertility changes conferred greater biomass and height to sunflowers and beans grown in these soils. This management practice is not without drawbacks, however, and future research is necessary to mitigate nutrient management issues.

Particular attention is needed regarding soil N and P dynamics. This study suggests that 7 years of PPAS leads to excessively high Olsen P levels (Farm B). Research should be directed at (1) determining the amount of time birds should be withheld from a field before reintroducing a pasture rotation; and/or (2) a stocking density that optimizes soil P levels. At optimal P levels, N levels will likely be inadequate. To add more N, leguminous winter cover crops could be used. N-scavenging cover crops could also be used to minimize N loss and to recycle

inorganic N. Radish (*Raphanus sativus*), mustard (*Brassica hirta* and *Brassica alba*), phacelia (*Phacelia tanacetifolia*), rye (*Secale cereale*) and annual ryegrass (*Lolium multiflorum*) are all known nitrogen scavengers^{45,46} that could function to recycle N from poultry manure. Finally, altering supplements added to poultry feed may impact water-soluble soil P levels and is an area of ongoing research⁴⁷. Movement of birds within a field also needs to be researched in order to optimize nutrient management. Hot spots can be addressed by determining how long a coop can remain in one location before leading to excessive nutrient accumulations.

Investigations into nutrient management and hot spots are imminent needs of future research that will directly impact management. Additional areas of research will serve to elucidate mechanism, adding to a theoretical understanding of integrated crop/livestock systems, and potentially influencing management. This research does not distinguish between the roles of manure and pasture plants in determining soil fertility changes. Although poultry manure undoubtedly determines certain soil-quality changes in pastured poultry/crop systems, pasture plants are also likely to play a role. Maintaining a field with a pasture mix of grass and legumes is functionally similar to cultivating a cover crop⁴⁸, and the effects of cover crops on nutrient cycling, organic matter and physical soil quality are well known^{2,49}. Additionally, pasture is tilled less frequently than crop fields, potentially leading to decreased erosion and higher carbon storage^{50,51}. In order to develop a mechanistic understanding of the relative contribution of manure versus pasture plants on soil quality, further research utilizing chicken enclosures is necessary.

Integrating pastured livestock with crop production is an emerging phenomenon on the Central Coast of California. Our study demonstrates that integrated pastured poultry systems appear to be an effective practice for managing soil fertility and crop growth. When managed with care, integrated pastured poultry/crop agroecosystems have the potential to contribute to the sustainable production of food via recycling of manure, bolstering of soil fertility and reduction of purchased fertility inputs.

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