Supplementary materials

INTEGRATED CROP-LIVESTOCK SYSTEMS: LESSONS FROM NEW YORK, BRITISH COLUMBIA, AND THE SOUTH-EASTERN UNITED STATES

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METHODS FOR EVALUATION OF LIVESTOCK MANURE APPLIED IN THE SOUTH-EASTERN US

A total of 42 fields had received some sort of livestock manure in the year of evaluation, and often in previous years of the rotation as well (Table 4 in the text). Each of these manured fields was paired with another field in relative proximity having similar soil textural class (total of 84 fields in pair-wise comparison). Most fields were managed with no tillage (78 of 84 fields). There was a diversity of cropping sequences including 40 fields with soybean as previous crop, 27 fields with maize as previous crop, and 17 fields with either cotton (*Gossypium hirsutum*), hay, sunflower (*Helianthus annuus*), or wheat (*Triticum aestivum*) as previous crop.

Soil was sampled at a depth of 0–10 and 10–20 cm in each field and the weighted mean based on bulk density was computed for the 0–20-cm depth. In each field, 6–8 cores (4-cm diameter) were collected from a 5 m × 30 m area and this was repeated four times in each field. Mean values across in-field replicates were computed and used as values in this survey across multiple fields. Multiple, supplementary rates of inorganic N fertilizer rates were applied to test each field for sufficiency of N supplied by N mineralization from soil and manure inputs. Most yield estimates were from hand harvest (3 m^2) of trials having small plots (4.5 m × 7.5 m) within a field or from the same hand harvest strategy from multiple locations within field-length strips of N fertilizer treatments.

Table S1 Characteristics of most numerous livestock operations in the five-state subset of the south-eastern US

State	Total farmland area/Mha	Number of farms (thousands)					
		All farms	Beef cows	Dairy cows	Swine	Layer hens	Broiler chickens
Alabama	3.47	40.6	20.0	0.4	1.1	3.8	2.0
Georgia	4.03	42.4	14.9	0.6	1.1	4.7	2.1
South Carolina	1.92	24.8	6.9	0.2	1.0	3.5	0.6
North Carolina	3.41	46.4	16.4	0.5	2.4	5.5	2.0
Virginia	3.16	43.2	18.5	1.0	1.5	5.7	1.1
% of US total in region	4.4	9.7	10.5	5.0	10.6	10.0	23.6

Note: Data from USDA-NASS[1].

Table S2 Livestock sold per year in the five-state subset of the south-eastern US

State	Cattle and calves		Hogs and pigs		Broiler chickens	
	Total (thousands)	Number per farm	Total (thousands)	Number per farm	Total (millions)	Number per farm (thousands)
Alabama	595	34	241	285	1108	549
Georgia	506	38	574	707	1381	656
South Carolina	158	29	536	730	241	428
North Carolina	377	27	35,800	16,690	833	425
Virginia	826	44	664	534	262	242
% of US total	3.5		16.1		43.0	

Note: Data from USDA-NASS[1].

Table S3 Total land use by sector and average by individual farm in the 5-state subset of the south-eastern US

State	Pastureland		Cropland		Woodland	
	Total/Mha	Hectare per farm	Total/Mha	Hectare per farm	Total/Mha	Hectare per farm
Alabama	1.11	37	1.14	46	1.,07	65
Georgia	0.75	28	1.77	64	1.31	66
South Carolina	0.32	22	0.82	50	0.68	54
North Carolina	0.52	19	2.02	59	0.72	33
Virginia	1.05	34	1.25	39	0.74	36
% of US total	2.1		9.2		23.7	

Note: Farms may not have all three land use combinations, so areas per farm in different land uses cannot be summed. Data from USDA-NASS[1].

Table S4 Daily manure production and N and P concentrations as affected by livestock species Unit: $g \cdot kg^{-1}$

Livestock type	Total mass	Nitrogen	Phosphorus
Beef cow on high-forage diet	59	0.31	0.11
Lactating dairy cow	80	0.45	0.07
Growing pig	63	0.42	0.16
Laying hen	61	0.83	0.31
Broiler chicken	80	1.10	0.34

Note: Data summarized by USDA-NRCS[2].

Chicken production in the region is for both meat (broilers) and eggs (layers). Broiler production has become streamlined through genetics, housing environmental management, and feed rations. Market live-weight more than doubled from 1.1 kg in 1925 to 2.8 kg in 2018. Production days have been reduced more than half from 112 days in 1925 to 48 days since 1990. Feed requirements (i.e., feed efficiency) have been reduced more than half from 4.7 kg feed kg^{-1} live-weight in 1925 to 1.8 kg feed kg^{-1} live-weight in 2018. Bird mortality has been reduced from 18% in 1925 to a relatively stable rate of about 5% since 1970. Reduced production time has led to around 6 flock cycles (or cohorts) each year[3].

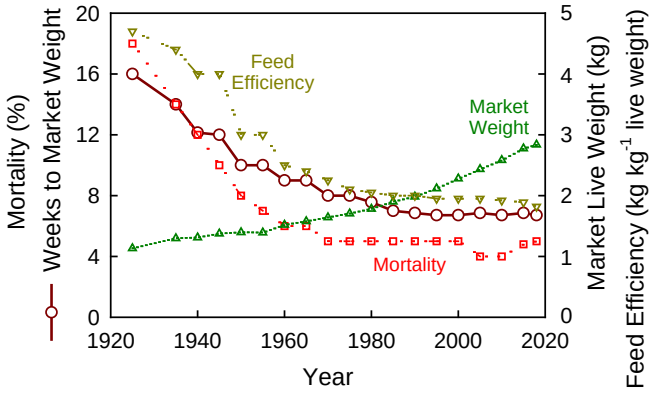

Fig. S1 Historical poultry production characteristics in the US as documented by the National Chicken Council[4,5].

In 2017, farms producing broilers were bi-modal in distribution from many small-scale producers (< 2 thousand birds sold yr^{-1}) on one end, few with moderate production, and increasingly more farms with large-scale production (> 200 thousand birds sold yr^{-1}) on the other end (Fig. S2(a)). As an example of the concentration of broiler production, data from Franklin County in the Piedmont of Georgia (ranked first in broiler production in Georgia in 2017) showed similar numbers of farms over time, but with increasingly greater production on each farm (Fig. S2(b)). In 2017, there were 144 farms reporting broiler production in Franklin County and 1 farm had production of 60-100 thousand birds, 6 farms had 100-200 thousand birds, 50 farms had 200-500 thousand birds, and 87 farms had > 500 thousand birds sold to the market. Mean market delivery per farm was 598.8 thousand birds in 2017. It can be inferred that four to six flocks per year were produced on these farms. These county level data illustrate the large increase in broiler production from a particular group of farms over the past 50 years, as well as the shift in production from relatively small-scale operations to large-scale operations (Fig. S2(c)).

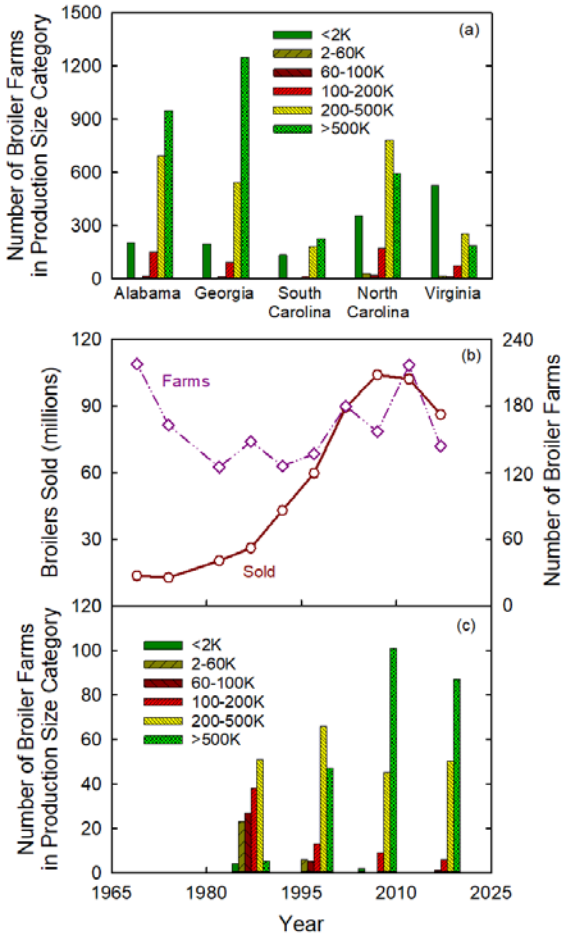

Fig. S2 Number of farms in each state sorted by broiler production output in 2017 (a), number of broilers sold and number of farms in Franklin County, Georgia (b), and number of broiler farms in Franklin County, Georgia by production category in 1987, 1997, 2007, and 2017 (c). Data from USDA-NASS[1].

Most farms producing eggs from laying hens in the region have small flocks. A total of 19.0 thousand farms had flocks of < 50 hens. Assuming a normal distribution, nearly 500 thousand layers were present in these small-scale operations. However, 46.4 million laying hens in the region were from moderately large flocks of 10-50 thousand on 891 farms throughout the region. Thus, most farms have small flocks, but a small minority of farms produce most of the eggs. It is likely that the small flocks are predominantly free-ranging chickens roaming the farmyard with random excretion patterns and occasional removal of manure from the chicken coop to be applied to a vegetable garden or around the farmstead. However, large volumes of manure must be

removed from the large confined laying houses. Concentrations of N and P are relatively high in laying hen manure, so spreading on non-legume cropland and pastureland is ideal.

Layer farms in the region were mostly with small flocks, but there were also farms with larger flocks, particularly in Alabama, Georgia, and North Carolina (Fig. S3(a)). As an example of concentration of laying hen production, data from Dekalb County in Alabama (ranked first in laying hen inventory in Alabama in 2017) were assembled in Fig. S3(b). In 2017, there was a bi-modal distribution of number of farms among different size categories. Many small-holder flocks existed, hardly any small industrial sized flocks, several dozen medium-sized flocks, and no large-sized production facilities. The historical trend was for some farms with very small flocks to get larger from the 1960s to the 1980s, but there was a resurgence of small farms with egg layers after the turn of the 21st century. Dekalb County also has a diversity of agricultural production, ranking first in Alabama in swine and broiler sales. The county ranks fourth in the state in cattle and calves sales and eighth in dairy sales.

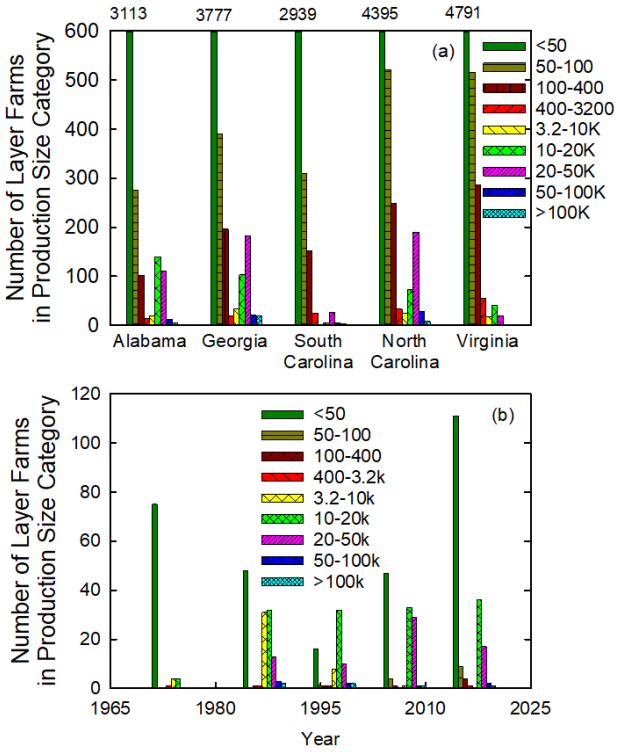

Fig. S3 Number of farms in each state sorted by laying hen inventory in 2017 (a) and number of laying hen inventory by production category in Dekalb County, Alabama in 1974, 1987, 1997, 2007, and 2017 (b). Data from USDA-NASS[1].

Swine production on southern farms has been a tradition for generations. Some reflection of that is the large number of farms still selling < 25 hogs per farm per year[1]. However, swine production has become concentrated in the Coastal Plain physiography of the five-state region, particularly in North Carolina. Number of swine-producing farms in North Carolina (2.4 thousand) far exceeds that of other states in the region (Table S1), as well as total production (35.8 million sold) due to large confinement facilities on individual farms (Table S2). In these CAFOs, swine slurry is often pumped into a settling lagoon, and semi-clarified water is then delivered to nearby cropland or pastureland as nutrient-containing irrigation water.

Most farms in the region with swine have small inventories, except for North Carolina (Fig. S4(a)). As an example of the expansion and development of the swine industry in North Carolina, data from Duplin County NC are summarized in Fig. S4(b,c). Prior to the 1990s, a more evenly distributed number of farms occurred across a diversity of production-size categories. Since then, a rapid movement occurred toward several hundred farms producing almost all swine in the county. A correction in number of viable swine producers occurred around 2009 due to the H1N1 pandemic, the global recession, and reduced consumption of pork[6].

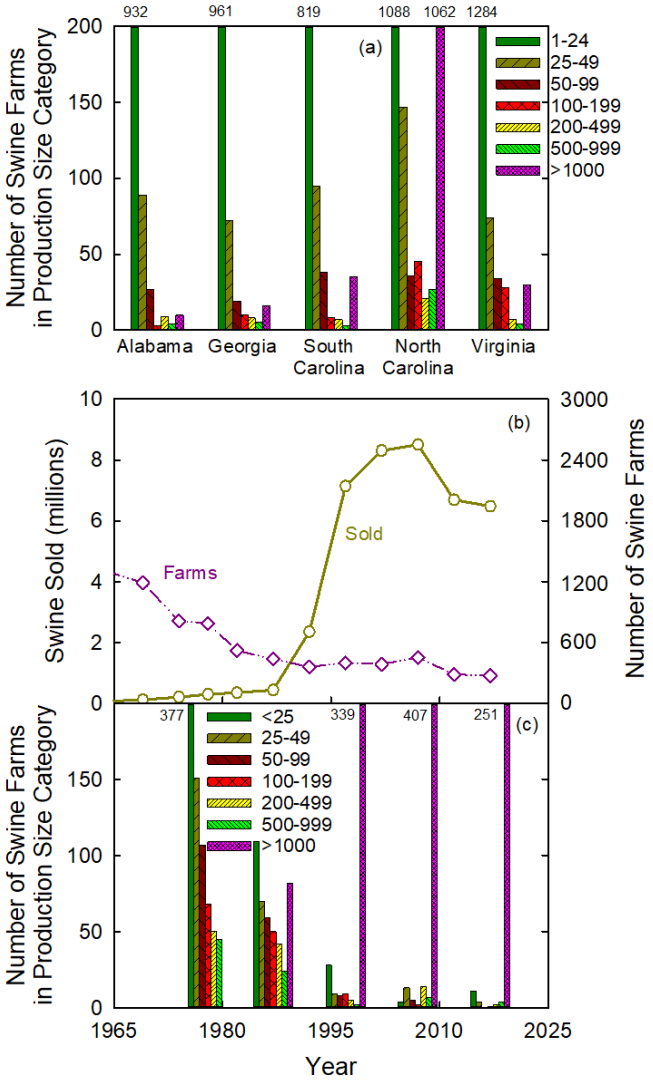

Fig. S4 Number of swine farms in each state sorted by hog inventory in 2017 (a), number of swine sold and number of swine farms in Duplin County, North Carolina (b), and number of swine farms in Duplin County, North Carolina by production category in 1977, 1987, 1997, 2007, and 2017 (c). Data from USDA-NASS[1].

Milk production in the south-eastern US is a relatively small fraction of US production (2.5% of total milk sales and 5.0% of dairy cow inventory). Dairy production in the region is relatively uniform by inventory, although Virginia has the greatest inventory at 1048 head. Contemporary farms feed total mixed ration, although there is a resurgence of some grazing-based dairies. There are many farms in each state that have small dairy herds. Across these states, 58% of all dairies have herds of < 10 head and 22% have herds > 100 head.

Most farms in the region with dairy have small inventories, except for Virginia (Fig. S5(a)). Rockingham County in the Shenandoah Valley of the Appalachian Mountain region is the leading milk producer in Virginia. It is also the leading producer in the state of broilers and eggs and ranks third in cattle and calf sales and fourth in production of sheep and goats. Overall, farmers in Rockingham County lead the state in sales of livestock products. An historical view of dairy farms in the county is shown in Fig. S5(b,c). Changes in the dairy sector of the county were gradual compared with changes in the poultry and swine sectors. There was a gradual decline in dairy farms and increasing herd size from middle-sized operations moving into the large-sized category around the turn of the 21st century (Fig. S5(c)).

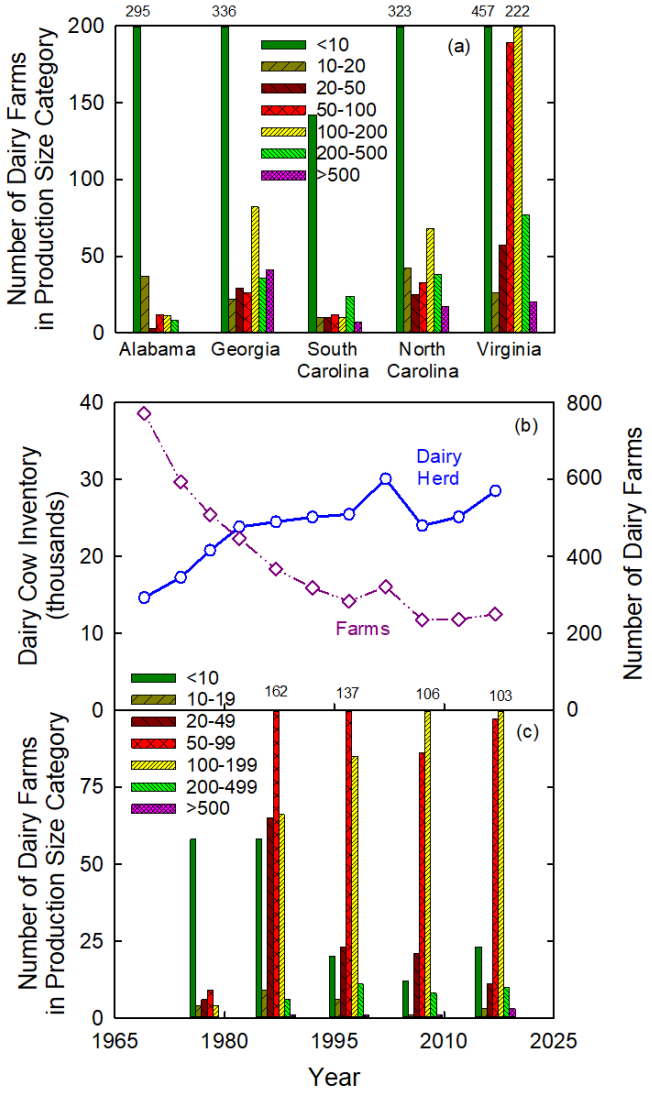

Fig. S5 Number of farms in each state sorted by dairy cow inventory category in 2017 (a), number of dairy cows and number of dairy farms in Rockingham County, Virginia (b), and number of dairy farms in Rockingham County, Virginia by production category in 1978, 1987, 1997, 2007, and 2017 (c). Data from USDA-NASS[1].

Beef cattle herds are distributed throughout each of the five states in the region. Most beef farms in the region have < 50 head, like those across the US. Beef producers tend to have low financial risk, so change in herd size is minimal. Since most beef cattle graze perennial pastures in the region, there is relatively low operating cost if stocking rate is set moderately to avoid degradation of swards. Cattle inventory has been the most stable of all livestock industries in the region. Most calves produced in the five-state region are shipped to feedlots in other parts of the country, primarily the Great Plains region where the majority of cattle are fed to market weight.

Beef cattle farms are prevalent in all five states of the region, and most operations have < 100 head per farm (Fig. S6(a)). Anderson County in South Carolina serves as an example of changes in beef cattle farms, numbers, and herd size over the past 50 years (Fig. S6(b,c)). Number of farms has been relatively stable over time. However, economic disruptions like the energy crisis in the 1970s and the recession from 2007 to 2009 resulted in significant farm losses. Cattle herd numbers tend to rebound with time after such events. Beef herd size has been relatively stable over time in Anderson County and herd size reflects that of the region (Fig. S6(c)).

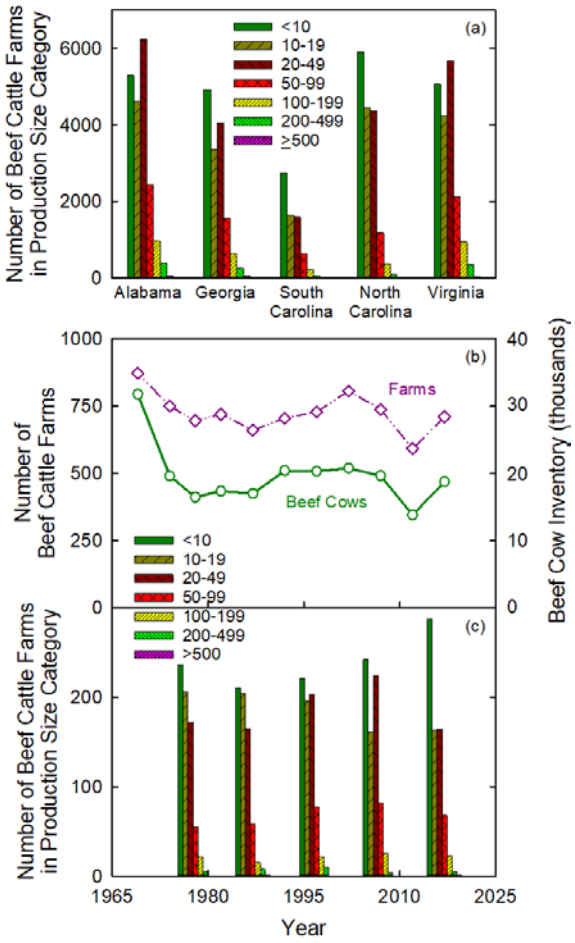

Fig. S6 Number of beef cattle farms in each state sorted by cow inventory in 2017 (a), number of beef cattle farms and beef cattle inventory in in Anderson County, South Carolina (b), and number of beef cattle farms by production category in in 1978, 1987, 1997, 2007, and 2017. Data from USDA-NASS[1].

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