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RESEARCH ARTICLE

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

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KEYWORDS

cropland, dairy manure, nutrient cycling, pastureland, poultry manure, swine manure

HIGHLIGHTS

- Livestock production in North America has moved to fewer farms with greater inventories.
- Land application of livestock manures is a preferred nutrient recycling strategy.
- Confined animal feeding operations have challenges to utilize livestock manure sustainably.
- Integration of livestock and cropping systems is possible on a farm or among farms.
- Nutrient balance is needed for environmental sustainability.

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GRAPHICAL ABSTRACT

ABSTRACT

Livestock production in the United States (US) and Canada is diverse, but shows a common trend in most livestock sectors toward fewer farms producing the majority of animal products despite a large number of farms still small in production scale. The migration to larger and more concentrated animal feeding operations in beef finishing and poultry, swine, and dairy production allows processors to streamline supplies to meet market demand for abundant, low-cost livestock products, whether that be for packaged meat, dairy products, or eggs. With concentration of livestock operations comes the challenge of managing manures. When sufficient land is available and nutrients are needed, livestock manure is an excellent nutrient source and land application is the preferred method of recycling this resource. However, when livestock production is constrained in a geographical area and animal densities are high, manure may become an environmental liability with potentially greater risk for runoff and leaching of nutrients, emission of odors, ammonia, and greenhouse gases, and release to the environment of pathogens and chemicals of emerging concern. Addressing these challenges now and into the future requires learning from mistakes and adopting successful approaches. We describe different levels of integration between livestock and crop producers in

New York, British Columbia, and the south-eastern US as learning opportunities to improve economic and environmental sustainability. Examples show that effective solutions should recognize (1) manure has value and is not just a cost, (2) farmers, farm advisors, extension educators, nutrient management planners, crop advisors, nutritionists, state agency personnel, regulators, and university researchers need to be active participants in development of solutions, and (3) change to a sustainable future requires a combination of government regulation and outcome-based incentives.

1 INTRODUCTION

Livestock production in North America has grown to meet the demands of an increasing human population, not only domestically, but also internationally[1]. Demand for a variety of protein-rich foods has increased. New technologies enabled by widespread use of fossil fuels have transformed agricultural industries from historically locally sufficient enterprises prior to the mid-20th century to world-wide commodity trading and shipping thereafter[2]. Refrigeration, trucking, airline transportation, marketing, trade negotiations, and automation have all helped transform agriculture over the last century. The result of larger and more efficient food processing capabilities has led to farm consolidation and growth in herd size on individual farms, which made contracting and sourcing of live animals and animal products more efficient for the meat processing industry[3,4]. Farm specialization has been a consequence of these changes.

It is important to look at trends in livestock numbers to understand the rapid changes that have transformed agriculture in North America (Fig. 1)[5]. Total number of dairy cows decreased from 19.7 million head in 1920 to 9.5 million head in 2017. Swine inventory was 59.3 million head in 1920 and rose to 72.4 million head in 2017. Beef cattle inventory was 12.6 million head in 1920 and more than doubled to 31.7 million head in 2017. Particularly rapid growth occurred in the poultry industry in the past half-century. Broiler inventory was 1.4 billion in 1959 when records were first categorized for this poultry class and grew 6-fold to 8.9 billion in 2017. In contrast, layer inventory was 359.5 million head in 1920 and remained relatively stable over the ensuing century at 368.2 million head in 2017, although the number of eggs sold has increased dramatically.

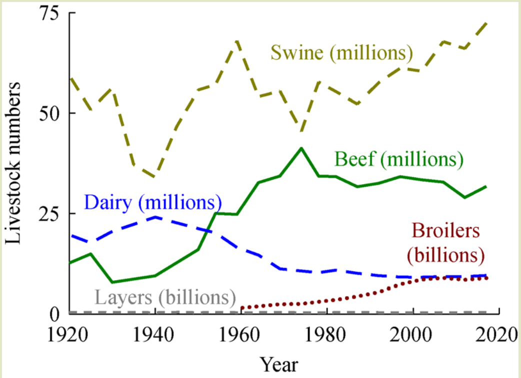

Fig. 1 Historical annual inventory of different livestock categories across the entire US. Data from USDA-National Agricultural Statistics Service[5].

Therefore, poultry and beef inventories grew the most in the US over the last century. However, the major shift that occurred during the past half-century was consolidation of greater production onto fewer farms. Beef cattle farms totaled 1.3 million in 1964 and were 0.7 million in 2017. Dairy farms totaled 4.5 million in 1920 and were only 54.6 thousand in 2017. Swine farms totaled 1.8 million in 1959 and were only 66.4 thousand in 2017. Layer farms were 2.2 million in 1959 and were only 0.2 million in 2017. Ownership of layer farms underwent consolidation to only 88.2 thousand farms in 1992, but since rebounded to a larger number of farms over the past two decades. Broiler farms were 41.7 thousand in 1959 and declined slightly to 32.7 thousand in 2017. Exponential growth in average farm inventory of dairy, swine, layers, and broilers occurred since 1960 (Fig. 2)[5].

A key outcome to consumers of the shift toward livestock consolidation on fewer farms has been more consistent quality and relatively low food prices for these nutrient-dense livestock products[6]. Food production in general, and livestock husbandry in particular, is labor intensive (i.e., physically demanding and requiring long hours) and the lifestyle of many more citizens changed along with this dramatic decline in farms across the country. Since 2000, the trajectory of agricultural production in the US stabilized at about 1% relative to gross domestic product (Fig. 3)[7].

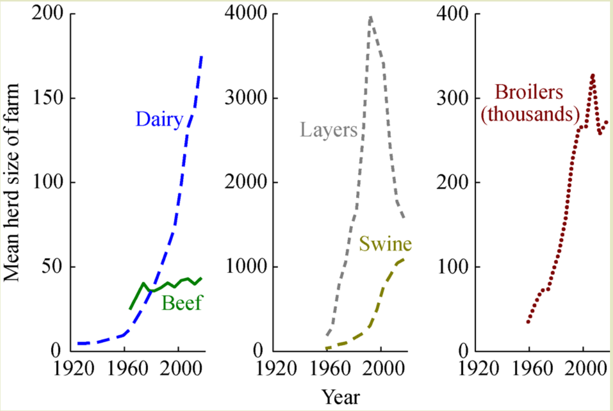

Fig. 2 Historical inventory of different livestock categories per livestock farm in the US. Data from USDA-National Agricultural Statistics Service[5].

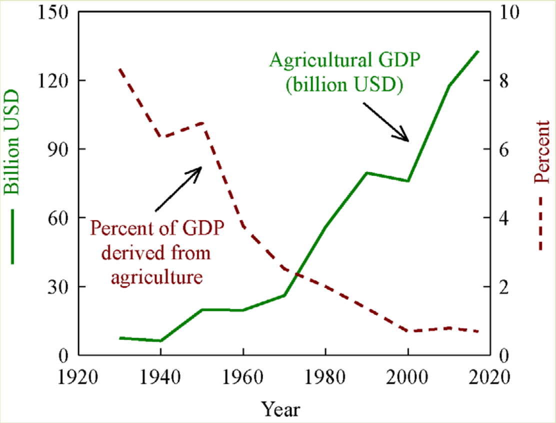

Fig. 3 Gross domestic product (GDP; billion USD) and percentage of GDP derived from agriculture during the past 100 years in the US. Data from Bureau of Economic Analysis[7].

With consolidation of livestock production within regions and on larger farms, handling of livestock manure has become a challenge. Evolving strategies are needed to cope with nutrient accumulation on high-density livestock production farms. Our objectives were to (1) describe integration between livestock and cropping systems in selected regions of North America, (2) compile a set of lessons learned from these experiences, and (3) discuss future potential for coupling of livestock and cropping systems for improved economic and environmental sustainability. We present examples of integrated livestock and crop systems from three distinct regions of North America, New York, British Columbia, and the south-eastern US. Based on ratio of mean annual precipitation and potential evapotranspiration, leaching potential was greatest in British Columbia ($1.75\ \mathrm{mm \cdot mm^{-1}}$) followed by New York ($1.51\ \mathrm{mm \cdot mm^{-1}}$) and the south-eastern US ($1.13\ \mathrm{mm \cdot mm^{-1}}$), but all three regions have relatively wet environments. Mean annual temperature was greatest in the south-eastern US (16.6°C), and considerably lower in British Columbia (9.8°C) and New York (7.7°C).

2 INTEGRATED DAIRY AND CROP PRODUCTION IN NEW YORK

According to the 2017 Census of Agriculture, New York has 33,400 farms on 2.8 Mha of land giving an average of 84 ha per farm operation[5]. Of all farmland, 1.7 Mha is cropland and 0.2 Mha is grazed pastureland. Of cropland, 42% produces forage hay, 24% produces maize (*Zea mays*) (about equally divided among maize silage and grain production), and 7% produces soybean (*Glycine max*), while the remainder of land produces vegetables, fruits, berries, greenhouse products and flowers, or other grain crops. These statistics show the importance of crop and forage production in land use in New York.

According to the 2019 State Agricultural Overview[8], the state of New York currently ranks third in milk production in the US, with about 625 thousand mature dairy cows producing 6.9 Tg of milk per year. Beef production is more limited in scope with about 105 thousand beef cattle. Goat, sheep, hog, and poultry production are not a major contribution to the state's economy so the large land area in forage and grain production mostly supplies the dairy industry.

Although there is a wide range in dairy farm sizes in New York, most of the milk is produced on operations with $\geqslant$300 cows. Most of these farms grow a significant portion of feed (mostly forages) on their own cropland and spread the majority of manure on this land, while a subset of farms export manure to neighboring farms.

2.1 Dairy and cropland integration

Farmers in New York recognize the nutrient and soil-improvement value of manure, as shown by responses to a 2010 survey[9]. Of the land operated by the 200 dairy farms in this survey, manure had been applied to 86% of the 217 ha per dairy farm in the survey. Manure was exported off the farm by 20% of dairies. Cropland farmers also recognized the benefits of manure, but they tended to place a lower monetary value on manure than dairy farmers. According to the survey, the most important reason dairy farmers did not export more manure was the belief that manure was needed to meet crop nutrient demands on their own farm. This perception reflects the relatively low livestock density of dairy farms in New York, typically ⩽ 2.4 animal units (1 animal unit = 454 kg live weight) ha^{-1}, as documented at the state level[10] and in farm-level surveys[11–14]. Low livestock density allows farms to grow up to 75% of required feed on-farm, while providing an adequate land base to spread manure at appropriate rate[11]. Therefore, most dairy farms in New York are integrated livestock and crop production systems, in which forages are grown on the farm itself but most of the feed concentrates are purchased.

2.2 Agriculture and environment regulatory system

In March 1999, the US Department of Agriculture (USDA) and the Environmental Protection Agency released the report, *Unified National Strategy for Animal Feeding Operations*, resulting from increased awareness throughout the US of the negative impact of over-application of nutrients in agriculture[15]. This report resulted in planning regulations for concentrated animal feeding operations (CAFOs) in New York, as in many other states. Currently, in New York all medium (300–699 cows) and large (⩾700 cows) dairy CAFOs are required to have a comprehensive nutrient management plan (CNMP). In this CNMP, the farmer needs to account for all on-farm nutrient sources (e.g., manure, crop rotation credits, and waste water streams) and purchased nutrients (e.g., fertilizer and manure taken in from other farms). Every year, the CNMP must document how planned management meets, but does not exceed, crop N demand on each field. Phosphorus application limits are set by the New York Phosphorus Index[16–19], a field-based assessment tool that classifies fields on regulated farms based on relative risk of P runoff into low/medium, high, or very high risk of P loss. Livestock manure and fertilizer P application are limited to N-based rates (to meet crop N needs) on fields with low and medium P index, to P-removal based rates (not exceeding annual P removal with crop harvest) on fields with high P index, and zero (no further addition) on fields classified with very high risk of P loss. All fields need to be balanced for N (N application not to exceed crop demand) with adjustment made for fields sensitive to nitrate leaching according to the New York Leaching Index[20]. The CNMP must follow Land Grant University guidelines[21] and USDA-Natural Resources Conservation Service (NRCS) 590 Nutrient Management standards[22]. Plans are developed by certified nutrient management planners, typically from private sector planning firms, but also by staff from Cornell Cooperative Extension or Soil and Water Conservation Districts. High density farms that have excess manure need to export manure or adjust animal density. Farms that violate their CAFO permit and cause water quality violations are fined by the New York State Department of Environmental Conservation.

2.3 Drivers for nutrient management improvement in New York

With regulation of medium and large CAFOs and other animal feeding operations in sensitive watersheds, improvements in nutrient management have occurred in New York. For example, fertilizer use has been drastically reduced[23,24], farm and state nutrient balances have improved over time[11,12,14,25], and annual N and P imports onto dairy farms in New York and the Upper Susquehanna Watershed (headwaters of the Chesapeake Bay Watershed) have been reduced by 20%–30% from 2004 through 2013[13]. Most improvements by dairy farms reflect reduced import of nutrients through improved feed and fertilizer management, emphasizing the importance of precision feeding, agronomic planning, and assessment of whole-farm nutrient balances. Field-based extension programs like the statewide On-Farm Starter Phosphorus Project built trust among farmers that P fertilizer could be reduced[24,26]. In partnership with farm advisors, this project illustrated to farmers on their own fields that no maize yield penalty occurred when P fertilizers were eliminated from fields classified as high or very high in soil-test P. The New York Phosphorus Index was introduced in 2001[16] and updated in 2019[18,19,23]. It was credited by planners as a driver for improvements in P balances at both farm and state levels[23,27].

2.4 Lessons learned

Ketterings[28] presented lessons learned from adaptive management approaches to achieve improvements in agriculture and the environment in New York, using examples at three levels: (1) field-level, (2) whole-farm level, and (3) regional/state level. A combination of government regulations and outcome-based management incentives using research and extension programs was most effective in obtaining greater long-term sustainability of agriculture[28]. Key factors for farm level impact were: (1) understanding stakeholder concerns and recognizing the need for improvement (ownership); (2) identifying win-win situations, if possible (feasibility); (3) deciding on effective approaches based on scientific data (research); (4) involving farmers in research (farmers as drivers of change); and most of all, (5) partnering with trusted participants (farmer, farm advisor, university researcher) along the knowledge and implementation continuum (partnership).

In New York, a strong partnership developed over the past two decades among staff at the New York State Department of Agriculture and Markets, New York State Department of Environmental Conservation, USDA-NRCS, Soil and Water Conservation Districts, Cornell Cooperative Extension, and Cornell University. This effective partnership allowed for adoption of valuable risk assessment tools (New York Phosphorus Index), implementation and further development of Land Grant University guidelines for crop management, and inclusion of adaptive management policies for regulated farms. The New York example illustrates that a regulatory approach combined with innovative, outcome-focused, people-based, on-farm research-driven, and adaptive management can be effective in achieving greater sustainability of animal agriculture over time[23]. When adopting this approach elsewhere, the value of farmers, farm advisors, extension educators, nutrient management planners, crop advisors, nutritionists, state agencies, regulators, and university researchers as active participants in the process should be recognized. The example shows that animal agriculture and cropland can be fully integrated when manure is valued as a nutrient source and soil amendment for creation of a more resilient and environmentally sound agriculture.

3 INTEGRATING POULTRY, DAIRY, AND HORTICULTURE IN SOUTHERN BRITISH COLUMBIA, CANADA

The Lower Fraser Valley (LFV) of British Columbia stretches between the communities of Hope and metro Vancouver and is bounded by coastal mountains, the Pacific Ocean (Salish Sea), and the US border. It is peri-urban with a mosaic of farmland and development with a human population of 2.5 million[29]. The LFV has highly productive land (55 thousand ha) protected for agricultural use by legislation (referred to as Agricultural Land Reserve). The dominant agricultural sectors in the LFV include livestock (mainly dairy and poultry) and horticulture (mainly small fruit, vegetables, mushrooms, and greenhouse-grown vegetables). There are about 52 thousand milking cows with additional dry cows and young stock (48 thousand) on about 25 thousand ha (60% grass and 40% maize) and about 16 million poultry (broilers, layers, turkeys, and breeders) with no associated cropland. There are also diverse smaller holdings with beef cattle, sheep, horses, specialty birds, aquaculture, and numerous small-acreage crops including grapes, hazelnuts, hops, turf, and plant nurseries. Agriculture is economically vital and provides amenities like local fresh food and other services, including food security, flood mitigation, and a visually pleasing landscape with complex edges that are hospitable for wildlife and pollinators. However, agriculture also contributes to environmental burdens, the greatest of which is nutrient excess.

3.1 Nutrient flows

Importation of N and P into the LFV occurs mostly as forages and feedstuffs for the dairy and poultry sectors (19.5 $\mathrm{Gg \cdot yr^{-1}}$ N and 4.72 $\mathrm{Gg \cdot yr^{-1}}$ P), as commercial fertilizers (4.52 $\mathrm{Gg \cdot yr^{-1}}$ N and 1.17 $\mathrm{Gg \cdot yr^{-1}}$ P), and smaller amounts as live animals, bedding, and mulches[30,31]. Most of the food produced on farmland flowed to the human ecosystem (6.7 $\mathrm{Gg \cdot yr^{-1}}$ N and 1.19 $\mathrm{Gg \cdot yr^{-1}}$ P). Nutrient imports from outside the LFV to the human ecosystem were primarily as food (9.21 $\mathrm{Gg \cdot yr^{-1}}$ N and 1.52 $\mathrm{Gg \cdot yr^{-1}}$ P), but also included commercial fertilizers, horse feed, and pet foods (1.2 $\mathrm{Gg \cdot yr^{-1}}$ N and 0.5 $\mathrm{Gg \cdot yr^{-1}}$ P). Atmospheric deposition of N as ammonia (NH_3)[32,33] and P as dust[34] are mostly from local agricultural sources, i.e., from volatilization via manure management, urea-based fertilizer applications, and livestock housing and manure storage. Some atmospheric N and P is transported from the region and may be deposited in nearby forest edges or further inland or over water[35]. Reducing nutrient imports by recycling resident nutrients is of paramount importance for the sustainability of the region.

The LFV has well-established programs for urban organic waste recycling, including composting, combustion for energy, and a few modest-sized anaerobic digesters producing renewable natural gas from urban and rural feedstocks. Small amounts of biosolids are exported to low-production rangeland, with little impact on food supply, while the remainder of urban nutrients (mainly P) are stored in soil[36] or lost to the atmosphere as NH_3, N_2O, and N_2 by volatilization (i.e., via composting, combustion, and landfills) and into water by leaching (landfills), denitrification during waste treatment and storage, and discharge from waste water treatment plants. Only a small fraction of imported nutrients is reused or returned to distant crop farms; in fact, it appears that recycling programs are more focused on recycling C than on nutrients.

3.2 Integrated manure use strategies

Reuse of livestock manures in the LFV targets N and C, but not P due to its surplus in most soils[36]. Implementation is variable due to costs and other barriers. Most dairy manure is broadcast onto grass and maize land, resulting in up to 50% of inorganic N lost as volatile NH_3, while a large fraction of organic N may not be recovered by crops and some accumulates in soil[37–39]. Despite the abundance of dairy manure slurry and nutrient-rich soils, dairy farmers continue to use commercial fertilizers to supplement their crops with both N and P. Unlike dairy farms, poultry operations import all their feed as grain from outside the region and have minimal land for manure application. The poultry industry has grown in the region due to the nearby market, good labor supply, access to national railway, and moderate year-round climate for the birds. Many poultry farms are concentrated in an area well-suited for berry production, owing to well-drained, coarse-textured soil. However, this land is perched over an unconfined aquifer flowing south to the US and used for drinking water in both countries. Berry fields need organic matter inputs, which were historically supplied via large doses of low-cost, nutrient-rich poultry manure. Leaching from these berry fields treated with poultry manure has affected nitrate levels in the aquifer[40,41].

Clearly, the berry industry needs an alternative source of organic C that does not contain large amounts of labile N. Although the supply of compost is limited and expensive, there is potentially an abundant supply of low-cost organic amendment with low labile N from nearby dairy operations, whereby solids can be removed from slurry by filtration. A study was conducted to test the potential of three types of dairy solids and local horse manure relative to municipal compost and poultry manure in terms of risk to nitrate leaching and soil P accumulation at typical high doses used for amending soil organic matter[42,43]. Dairy solids were either separated with a screw-press (with and without drying) or obtained from bed-pack barns. All products were applied at similar rates of C, but poultry manure and compost had greater N and P concentrations and lower C:N than other products (Table 1).

Soil nitrate (NO_3^-) concentration by KCl extraction peaked rapidly in the surface soil layer after application of poultry manure and to a lesser extent after application of compost (Fig. 4). Soil nitrate dissipated in the soil horizon soon after rainfall increased in the autumn[42]. Other amendments did not show elevated soil nitrate concentration above that of the control treatment, indicating they did not pose leaching risk, even at very high application rate (Table 2). Ongoing trials suggest that raspberries (*Rubus idaeus*) respond well to the low-N amendments provided that the crop is carefully treated with N fertilizer (D. Hunt, unpublished data). High manure application rates are typical of grower practice for high-value berry crops to maintain soil organic matter using a low-cost, local amendment. Manure is applied only at replanting, about every 8 years. Poultry manure had been used because it was readily available, no cost, and there were no practical alternatives. Composting manure was considered uneconomical.

Amendment with 25 Mg·ha^{-1} of dairy solids when replanting berries every 10 years loaded soil with about400 kg·ha^{-1} N and 40 kg·ha^{-1} P, or on an annual basis as about 40 kg·ha^{-1} N and 4 kg·ha^{-1} P, respectively. This is slightly less than the annual removal of N and P in the raspberry crop[44,45], although a large portion of total N is tied up by organic C, so fertilizer N is needed.

Diverting N from poultry manure away from these sandy soils should reduce nitrate loading and improve aquifer water quality[46]. An alternative use for the N-rich poultry manure could be for grass crops on nearby dairy farms that typically receive 100–200 kg·ha^{-1} N as mineral fertilizer each year. Field research has shown that livestock manures could replace a large portion of the 200 kg·ha^{-1} N typically applied to tall fescue [*Schedonorus arundinaceus* (Schreb.) Dumort.]. Yield and N uptake were greatest for broiler manure and lowest for dairy

Table 1 Chemical properties of soil amendments (dry matter basis) tested for leaching risk[42]

Property	Poultry manure	Municipal compost	Horse manure	Filtered dairy solids	Dairy bed-pack	Screw-pressed dairy solids
Dry matter (g·kg^{-1})	250	673	313	279	320	299
pH	8.8	7.0	8.3	8.7	8.7	9.2
Electrical conductivity (dS·m^{-1})	4.8	1.5	0.8	0.8	1.1	2.2
Total C (g·kg^{-1})	104	310	143	124	143	132
Total N (g·kg^{-1})	16.4	13.5	2.2	3.8	4.6	4.8
NH_4^+-N (g·kg^{-1})	7.6	2.2	0.1	0.6	0.7	0.1
C:N	6	23	65	33	31	27
Total N:NH_4^+-N	2	6	22	6	7	48
P (g·kg^{-1})	4.1	5.1	0.5	0.4	0.7	0.9
N:P	4	3	5	9	7	6

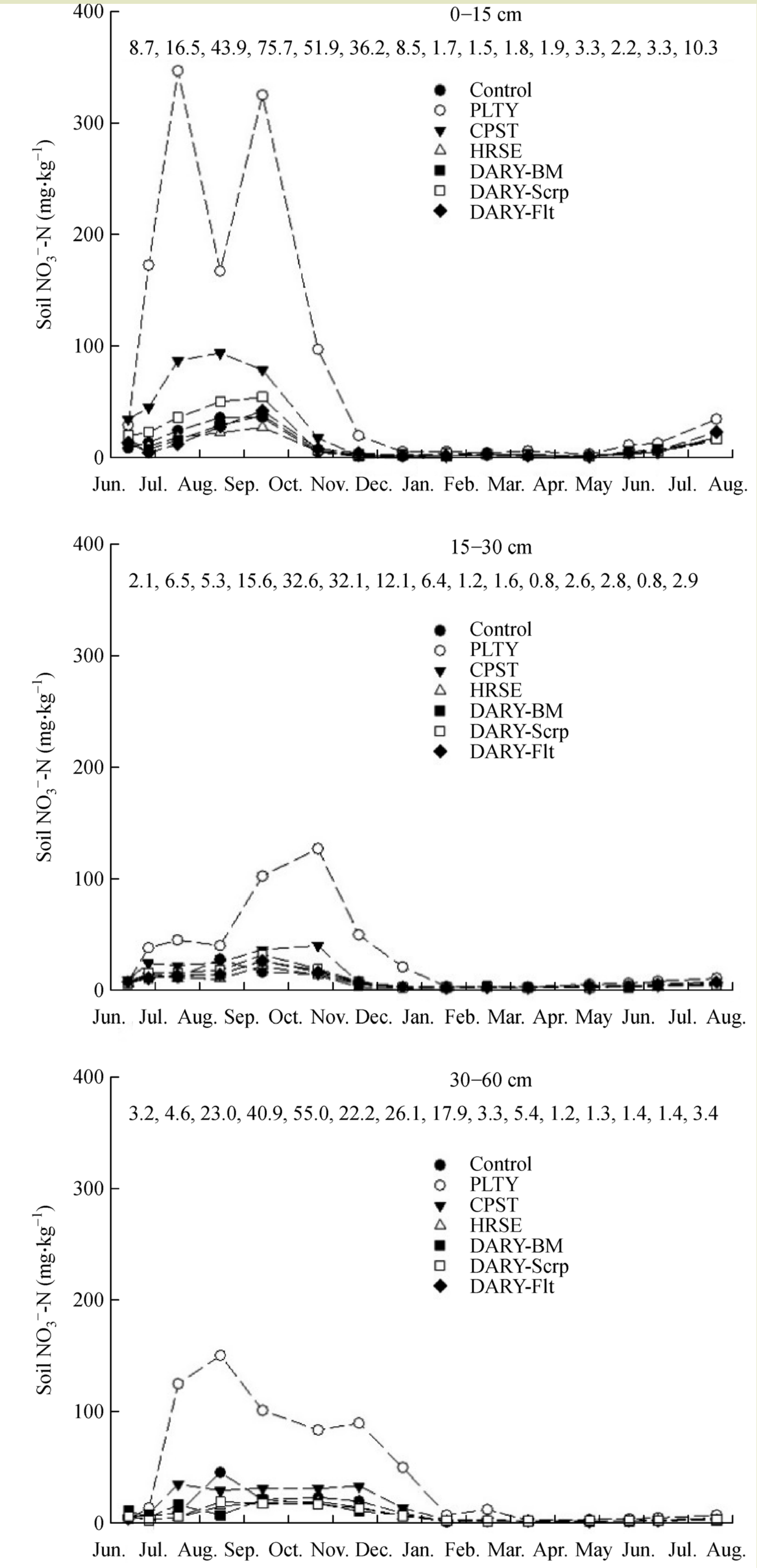

Fig. 4 Temporal changes in soil NO_3^--N concentrations (mg·kg^{-1} N) between June 2013 and August 2014 at three soil depths (Top: 0–15 cm, Middle: 15–30 cm, and Bottom: 30–60 cm) after application of organic amendments at 25 Mg·ha^{-1} DM[42]. Control is without amendment, PLTY is poultry manure amendment, CPST is municipal compost amendment, HRSE is horse manure amendment, DARY-BM is dairy bed-pack amendment, DARY-Scrp is screw-pressed dairy solids amendment, and DARY-Flt is filtered dairy solids amendment. Standard errors for each date are at the top of each panel. Data from Zhang et al.[42].

Table 2 Soil amendment application rates of dry matter, total C, total N, NH_4^+-N, and total P[42]

Amendment property	Poultry manure		Municipal compost		Horse manure		Dairy bed-pack		Screw-pressed dairy solids		Filtered dairy solids	
	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Wet application rate ($Mg\cdot ha^{-1}$)	100	200	37	74	80	160	78	156	84	168	90	180
Dry application rate ($Mg\cdot ha^{-1}$)	25	50	25	50	25	50	25	50	25	50	25	50
Total C applied ($Mg\cdot ha^{-1}$)	10.4	20.8	11.5	23.0	11.4	22.8	11.2	22.4	11.0	22.0	11.2	22.3
Total N applied ($kg\cdot ha^{-1}$)	1640	3280	501	1002	176	352	359	718	401	802	341	682
Total NH_4^+-N applied ($kg\cdot ha^{-1}$)	760	1520	82	164	8	16	55	110	8	16	54	108
Total P applied ($kg\cdot ha^{-1}$)	412	824	190	380	37	74	55	110	73	146	39	78

slurry. Broiler manure had 99% and 85% replacement value for yield and N uptake, respectively. Relatively high dry matter and N concentrations of poultry manure also make it attractive considering transportation cost.

It is important to note that an annual import of 200 $kg\cdot ha^{-1}$ N as poultry manure to dairy farms would also import about 50 $kg\cdot ha^{-1}$ P, thereby adding to P surplus on dairy farms. This surplus could be offset on farms exporting 25 $Mg\cdot ha^{-1}$ of dairy solids. Other measures for reducing P surplus on dairy farms are being investigated[47]. These include using precision injected dairy slurry or separated dairy sludge to replace starter mineral fertilizer for maize[48–50]. Also, feed imports might be reduced by improving crop production with innovative practices, such as relay cropping and deferred harvesting[42]. Some practices such as manure injection could have positive or negative side-effects on other environmental factors such as N_2O emissions.

3.3 Pilot manure trading initiative

As a next step, a pilot manure trading initiative was developed on-farm in field-scale conditions. The goal was to help farmers and policy makers better understand the applicability and operational issues associated with these strategies in high-risk nutrient environments. In November 2017, a stakeholder engagement session was held in which producers identified operational and economic concerns with manure trading. The manure trading concept involved transporting poultry manure 10–30 km to forage fields on dairy farms and hauling separated dairy solids to berry farms. Berry growers were concerned with this "different" manure source and with weed control, supply of dairy solids, and cost of solids compared to sawdust mulch. However, they were enthused with increasing organic matter using locally sourced dairy solids. Dairy producers expressed concern about being perceived as a regional solution for the poultry industry manure problem.

Dairy farmers in the LFV had already been starting to filter out solids from slurry manure, mainly to use as bedding on their own and neighboring farms. An on-farm trial was conducted to test application of dairy solids on a coarse-textured soil. The field had a newly planted crop of high-bush blueberry (*Vaccinium corymbosum* L.) cv. Calypso. In accordance with local practice for sawdust mulch, separated dairy solids were applied as a 10-cm-thick layer over the top of a 210-m-long raised bed. The product was easily applied using a single-row sawdust applicator. The farmer also applied 200 $kg\cdot ha^{-1}$ of a fertilizer blend (15-5-15 NPK) and drip-irrigation with tape laid on the soil surface. Separated dairy solids had greater water retention than sawdust. No fungal diseases were observed in the separated solids treatment. A greenhouse pot study showed no or little weed emergence in dairy separated solids, and on the farm, weeds were effectively smothered by the solids throughout the growing season. Decomposition of separated dairy solids was slow during the first growing season and fall analysis of weathered material showed N concentration of 26 $g\cdot kg^{-1}$ N (dry-matter basis). Soil pH and base saturation were similar to a sawdust-treated control bed. Plant growth measurements and overall soil fertility were not different from the control bed.

Separated dairy solids cost around 600 USD per delivered truckload compared to 300–500 USD for sawdust (Gary Telford, personal communication, from discussions with farmers). Currently, the limited supply of separated dairy solids is affecting price as farmers mainly produce the amount for their own bedding needs, with excess sold to the greenhouse industry.

The effect of poultry manure on grass production was also tested at field-scale on a dairy farm. In early spring prior to the trial, the entire field received 60 $kg\cdot ha^{-1}$ N as broadcast dairy slurry and

60 kg·ha^{-1} N of urea fertilizer. The trial began after the first grass harvest in early May with half the field treated with 60 kg·ha^{-1} N as slurry and 40 kg·ha^{-1} N as mineral fertilizer. The other half of the field received broadcast poultry manure at about 400 kg·ha^{-1} N applied at high ground speed with a vertical beater-type manure spreader to achieve the desired N rate with a uniform spread pattern. No additional N was applied to the poultry manure treatment all year, but the dairy manure treatment received 60 kg·ha^{-1} N as dairy slurry for the third and fifth cuts. Grass yield with a single application of poultry manure at 400 kg·ha^{-1} N almost matched the yield with repeated applications of slurry plus commercial N fertilizer at 540 kg·ha^{-1} N (Table 3). Soil nitrate-N with poultry manure application after the final grass harvest was 28, 21, and 15 mg·kg^{-1} NO_3-N at 0–15, 15–30, and 30–60 cm soil depths, respectively, compared to 51, 39, and 19 mg·kg^{-1} NO_3-N, respectively, for the dairy slurry field. This indicates less potential nitrate leaching with early season poultry manure application compared with ongoing applications of dairy slurry and mineral N.

3.4 Lessons learned

Change to any biological system is complex because of interactive factors and a tendency toward homeostasis. It is even more complex for intensive bio-socio-economic agricultural systems that are becoming increasingly prevalent in peri-urban regions. In this regional nutrient management initiative in the Lower Fraser Valley of British Columbia, Canada, three agricultural sectors were involved, each with contrasting needs, concerns, and perspectives. The poultry sector requires recipients for its manure; the berry sector needs a low-cost soil organic amendment that is also protective of the groundwater aquifer; and the dairy sector faces complex nutrient challenges associated with intensive production on a limited land base. Research has shown how a multi-sector approach can reduce regional nutrient surplus and potentially improve water and soil conditions, but this requires collective, yet asymmetrical action and willingness of multiple stakeholders. Most promising technologies were selected based on scientific evidence, but must be practical to all sectors, taking into account costs, policies, and changing consumer attitudes toward nutrition, organic production methods, and consumption of animal products. From a social perspective, there was a shared desire across rural and urban communities to protect agricultural land for at least three reasons: food security, supply of local fresh food, and maintaining green spaces against further development. It is evident that progress toward regional nutrient cycling initiatives will depend on active engagement of a wide range of stakeholders including farmers, consumers, researchers, and government agencies.

This project has provided farmers with accessible strategies to help them meet new environmental regulations that are being gradually introduced. However, strategies did not address all issues associated with nutrient imbalances in the region. Educational programs are addressing nutrient surpluses on farms with on-farm research and extension. A goal is to make the regional economy more circular by addressing food security, bioeconomy opportunities, landscape features, and biodiversity.

4 INTEGRATED LIVESTOCK AND CROPPING IN THE SOUTH-EASTERN US

The south-eastern US states of Alabama, Georgia, South Carolina, North Carolina, and Virginia share common features of three unique physiographic regions (Appalachian Mountains, Piedmont, and Coastal Plain). These five states occupy a total of 62.3 Mha, 6.3% of the total land area of the US. Total number of farms in the region is nearly 10% of all farms in the US (Table S1)[5]. Mean farm size among the five states is similar, ranging from low of 73 ha in Virginia to high of 95 ha in Georgia. Cattle and poultry dominate livestock production on farms in the five-state region (Table S1)[5]. Beef cattle are raised on 76.7 thousand cow-calf operations in the region with modest

Table 3 Total N application from either dairy slurry + urea or one-time application of poultry manure on forage yield on a farm in British Columbia

Cut	Total N applied with conventional approach (kg·ha^{-1})	Fresh forage yield (Mg·ha^{-1})	Total N applied with alternative approach (kg·ha^{-1})	Fresh forage yield (Mg·ha^{-1})
2	60 (dairy) + 60 (urea)	17.3	400 (poultry)	23.3
3	60 (dairy)	22.9	0	18.1
4	300 (poultry)	18.7	0	17.3
5	60 (dairy)	20.3	0	15.9
Total	540	79.2	400	74.6

herd size indicated by yearly sales of 27 to 44 calves per farm (Table S2)[5]. The number of farmers raising laying hens is 23.3 thousand and the number of farmers raising meat chickens is 7.7 thousand. There are 7.1 thousand swine producers in the region, and 2.4 thousand farms are in North Carolina alone.

Pastureland occupies 23% of farmland area in the region, while cropland occupies 44% and woodland occupies 28% (Table S3)[5]. Pastures are stocked primarily with beef cattle at an average of 1.3 head ha^{-1}. The combined land area for pasture and cropland allows for plentiful opportunities to spread livestock manures. Water and air quality issues can be compromised when the mass of ruminant excreta is combined with manure application from non-ruminant livestock species in the region.

Manure produced by poultry is typically applied to both pastureland and cropland, and in some cases to a small fraction of newly established woodland. The quantity of manure produced by poultry varies from 60 to 80 $g \cdot kg^{-1} \cdot d^{-1}$ bodyweight, and this excretion rate is of similar magnitude for other livestock species (Table S4)[51]. Broiler chickens have high N excretion, like that of dairy, due to the high protein diet to achieve rapid growth. Broiler manure is also rich in P due to supplements to enhance growth rate and bone development. Further descriptions of livestock sectors in the south-eastern US are in Tables S1–S4 and Figs. S1–S6.

4.1 Livestock manure utilization in the south-eastern US

All livestock manures in the region are utilized, either (1) on the same farm from which they were produced, (2) sold to neighboring farms as a nutrient source, or (3) sold to a non-agricultural sector for various uses, such as to create compost with other organic substrates, concentrated into pelletized organic fertilizers, or pyrolyzed for energy and production of biochar. Since each farm has some independence in decision-making toward compliance with water quality regulations (e.g., in the case of CAFOs) or to meet family-farm functionality, a wide spectrum of possibilities exists. Poultry and swine are the most concentrated livestock operations in the region, and most likely to have excess manure issues.

The impact of utilizing livestock manures on cropland was investigated in on-farm research trials in the region. Goals of this evaluation were to (1) assess how livestock manures affected soil physical, chemical, and biological properties and processes, (2) compare relative maize grain yield production with and without manure application, and (3) compare maize yield response to supplemental inorganic N fertilizer application with and without manure application. While results of these trials were published previously[51,52], the specific focus here was on the contrast between commercial maize fields that routinely received livestock manures paired with maize fields that did not have a history of manure amendment (Table 4). Brief description of methods can be found in Supplementary materials.

4.1.1 Effect of manure application on soil properties

Paired analysis of fields with and without livestock manure indicates that some soil properties were positively affected by recent manure inputs and other soil properties were not (Table 5). It is noteworthy that livestock manure inputs included the diversity of livestock manure applications in the region. Fields were compared as with and without livestock manure only, as there were too few observations within sub-categories of physiographic region, soil type, and type and rate of livestock manure to make more detailed comparisons.

Fields with a history of livestock manure application had significantly lower soil bulk density than paired fields without

Table 4 Characteristics of on-farm maize production trials conducted in three physiographic regions of North Carolina and Virginia from 2015 to 2018[51,52]

Physiographic region	Number of trials	Soil types	Type and rate of animal manure
Coastal Plain	3	Loamy sand, very fine sandy loam	Poultry manure (1.6–2.2 $Mg \cdot ha^{-1} \cdot yr^{-1}$) Swine slurry (180 $m^3 \cdot ha^{-1}$)
Piedmont	26	Sandy loam, fine sandy loam, loam, silt loam, sandy clay loam, silty clay loam, clay loam	Municipal biosolids (2.2 $Mg \cdot ha^{-1} \cdot yr^{-1}$) Cattle bedpack (5–16 $Mg \cdot ha^{-1} \cdot yr^{-1}$) Poultry manure (3.1–9.4 $Mg \cdot ha^{-1} \cdot yr^{-1}$)
Appalachian Mountains	13	Sandy loam, loam, silt loam, clay loam	Cattle bedpack (10–16 $Mg \cdot ha^{-1} \cdot yr^{-1}$) Dairy slurry (50–60 $m^3 \cdot ha^{-1}$) Poultry manure (3.1–9.0 $Mg \cdot ha^{-1} \cdot yr^{-1}$)

Table 5 Responses of soil properties and processes (0–20-cm depth) to paired-field analysis of with and without livestock manure amendment[51,52]

Soil property	Coefficient of variation	Without manure	Significance	With manure
Physical properties				
Sand ($g \cdot kg^{-1}$)	32	369	NS	369
Clay ($g \cdot kg^{-1}$)	28	286	NS	274
Bulk density ($Mg \cdot m^{-3}$)	9	1.38	*	1.32
Sieved density ($Mg \cdot m^{-3}$)	8	1.05	NS	1.05
Chemical properties				
pH ($-\log[H^+]$)	8	6.2	NS	6.2
Cation exchange capacity ($cmol_c \cdot kg^{-1}$)	33	8.8	†	10.1
Base saturation (%)	10	83	NS	85
Residual inorganic N ($mg \cdot kg^{-1}$)	61	11	†	15
Residual soil ammonium-N ($mg \cdot kg^{-1}$)	45	8	NS	9
Residual soil nitrate-N ($mg \cdot kg^{-1}$)	145	3	NS	6
Mehlich-III extractable P ($g \cdot m^{-3}$)	101	115	*	185
Mehlich-III extractable K ($g \cdot m^{-3}$)	53	142	***	213
Mehlich-III extractable Ca ($g \cdot m^{-3}$)	44	1145	†	1357
Mehlich-III extractable Mg ($g \cdot m^{-3}$)	38	188	NS	195
Mehlich-III extractable S ($g \cdot m^{-3}$)	55	19	†	23
Mehlich-III extractable Mn ($g \cdot m^{-3}$)	60	105	NS	101
Mehlich-III extractable Cu ($g \cdot m^{-3}$)	49	3.7	**	4.9
Mehlich-III extractable Zn ($g \cdot m^{-3}$)	76	6	***	12
Biological properties				
Surface residue C ($kg \cdot ha^{-1}$)	64	1297	***	3410
Surface residue N ($kg \cdot ha^{-1}$)	56	54	***	147
Total organic C ($g \cdot kg^{-1}$)	34	14.6	*	17.3
Total soil N ($g \cdot kg^{-1}$)	37	1.24	**	1.55
Particulate organic C ($g \cdot kg^{-1}$)	35	2.8	**	3.7
Particulate organic N ($g \cdot kg^{-1}$)	39	0.18	***	0.24
Soil microbial biomass C ($mg \cdot kg^{-1}$)	31	582	**	735
C mineralization in 24 d ($mg \cdot kg^{-1}$)	31	414	***	574
Net N mineralization in 24 d ($mg \cdot kg^{-1}$)	38	50	**	66
Soil-test biological activity in 3 d ($mg \cdot kg^{-1}$)	30	171	***	219

Note: Means are from 42 pairs of fields across three physiographic regions in the south-eastern US. †, *, **, and *** indicate significance at $p \leqslant 0.10$, $p \leqslant 0.05$, $p \leqslant 0.01$, and $p \leqslant 0.001$, respectively.

manure application (Table 5). Therefore, manure application in combination with no-till management created a more porous soil surface condition. Density of soil determined after uniform sieving was not affected by manure application.

Soil chemical properties were variable in response to livestock manure amendment (Table 5). Several properties were not different with or without manure amendment, including pH, base saturation, residual soil ammonium, residual soil nitrate, and extractable Mg and Mn. Cation exchange capacity, residual inorganic N, and extractable Ca and S tended to be greater in fields with manure than fields without manure. Extractable P, K, Cu, and Zn were significantly greater in fields with manure than those without manure. Therefore, relative changes in soil properties ranged from not significantly different (19%±36% difference) to marginally significant (23%±8% difference) to strongly significant (61%±25% difference).

Soil organic C and N fractions were determined as measures of biological properties (Table 5). All soil C and N fractions were significantly greater in fields with than without livestock manure. Relative difference was 29%±6% among fractions in soil. Relative difference in surface residue C and N contents was 168±5%. Nutrients contained in livestock manures contributed to overall soil fertility status, mostly in soil C and N fractions but also in several chemical properties. Nitrogen export in harvested grain products is often very high and N inputs from livestock manures can help restore soil fertility. The value of livestock manures as N source is widely recognized and field application rates of manure are often based on N content[53]. With repeated applications over time, concerns grow over the increasing levels of P in soil, since this nutrient can also contribute to water quality issues[54,55]. Extractable P in soil becomes unbalanced with repeated manure inputs based solely on N content, because the P input of some livestock manures exceeds the P export from many grain-cropping systems[56].

Soil microbial biomass and activity were fostered to a much greater degree in fields with livestock manures (Table 5). These biological components are necessary to release N from manures via mineralization. Manure-amended soils had 32% greater N mineralization capacity than fields without manure. Previous research has shown that the relatively rapid analysis time of soil-test biological activity can be a good indicator of soil N availability from mineralization[57], and this simple soil-testing tool may help better manage N in cropland fields as well as in pastures[58,59].

4.1.2 Effect of manure application on crop yield response

Maize grain yield response to supplementary inorganic N application during mid-vegetative stage (i.e., sidedressing) was tested on fields with and without manure. When supplementary inorganic N was withheld at sidedressing time, those fields with livestock manure tended to yield greater than fields without livestock manure (Table 6). Magnitude of maize yield response to supplementary N was much lower in fields with livestock manure than without. At the first unit of supplemental N, maize yield response to inorganic N was much lower in fields with manure than without, indicating a greater reserve of inherent soil fertility when livestock manure was applied. As well, the inorganic N factor per unit of grain production (i.e. quantity of inorganic N needed to produce each Mg of grain, a measure of fertilizer nutrient use efficiency) was significantly lower in fields with manure than without. This effect occurred at all cost-to-value thresholds, i.e. the marginal return of grain required to offset the marginal cost of N fertilizer. Cost-to-value threshold is an important determinant of economic viability of supplementary N application, because of the nonlinear yield response to N availability. As cost of N fertilizer increases with static grain price, the quantity of N required to maximize profit will be lower. Similarly, if grain price declines with static N fertilizer price, then the quantity of N required to maximize profit will be lower.

4.2 Lessons learned

A large diversity of farms exists in the south-eastern US with

Table 6 Maize grain yield response characteristics to supplemental inorganic N in fields with and without animal manure application[51,52]

Yield response characteristic	Coefficient of variation	Without animal manure	Significance	With animal manure
Grain yield without supplementary inorganic N at sidedress ($Mg \cdot ha^{-1}$)	69	8.3	†	11.2
Maximum grain yield with full inorganic N input ($Mg \cdot ha^{-1}$)	63	11.0	NS	12.3
Yield response at first instance of inorganic N (kg grain kg^{-1} N)	123	34	***	10
Nitrogen factor at low cost-to-value threshold (kg N Mg^{-1} grain)	94	12.6	***	4.6
Nitrogen factor at medium cost-to-value threshold (kg N Mg^{-1} grain)	127	8.3	***	2.5
Nitrogen factor at high cost-to-value threshold (kg N Mg^{-1} grain)	157	5.1	***	1.0

Note: Mean values are from 42 pairs of fields across three physiographic regions in the south-eastern US. †, *, **, and *** indicate significance at $p \leqslant 0.10$, $p \leqslant 0.05$, $p \leqslant 0.01$, and $p \leqslant 0.001$, respectively. Low, medium, and high cost-to-value thresholds were set at 5, 10, and 20 kg grain kg^{-1} N.

both small and large livestock enterprises. Broiler chicken production has expanded rapidly in recent decades and fortunately it has grown in areas with significant pastureland available to receive this manure. Accumulation of P in soil has helped overcome general deficiency of P in weathered soils (i.e., Ultisols) throughout the region, but application rate has also exceeded sustainable thresholds with repeated application in some areas. Research continues to explore manure application rate, timing, and placement issues in sensitive areas of landscapes. Swine production has dramatically changed over the decades with only a relatively small number of farms in a few Coastal Plain counties in North Carolina producing the vast majority of pork. However, there is an increasing burden of excess manure with CAFOs that can threaten water quality, particularly with vulnerability of heavy rainfall from hurricanes prevalent in the region. Cropping systems with high nutrient extraction will need to be developed in these areas. Beef cattle inventory in the region has remained stable over time and is associated with sufficient pasture to receive excreta directly from grazing livestock.

In on-farm research trials in the south-eastern US, manure application to maize fields resulted in net N fertilizer value of 37–60 $\mathrm{kg \cdot ha^{-1}}$ N, based on different cost-to-value threshold scenarios. On-farm trials indicate that greater testing of soil biological activity could be used in the future to isolate if and how much available N deficit occurs on specific fields. Therefore, these on-farm trials gave ample evidence that livestock manure application to cropland in the region was providing:

(1) Economic benefit in substitution of purchased N inputs and avoidance of other costly nutrient inputs of P, K, secondary nutrients, and micronutrients.

(2) Ecological benefit in storage of C and N in soil, and concomitant benefits to soil health and functioning of microbial communities.

As with all agronomic practices, there will be an optimum level of inputs to match outputs, so the type, timing, placement, and rate of livestock manure inputs need to be considered for each region and its natural resource concerns. Further development of soil testing and partnership among agricultural sectors will be needed. Over-application of livestock manures to land can lead to serious environmental impacts that eventually harm economic conditions for individual farms. Storage of manure and essentially not utilizing it as a resource on regional lands surrounding livestock facilities is also a liability that does not benefit the whole of agriculture in the long-term. Balancing the needs and concerns of agriculture and its surrounding communities must be considered for long-term success.

5 SUMMARY AND CONCLUSIONS

Livestock production in North America is diverse in geographical and ecological settings, production styles and components, level of integration with other parts of the farming enterprise, and how successfully they meet societal requirements to balance production, profitability, and environmental goals. Long-term sustainability is being challenged by shifting emphases of society, and by changing climatic conditions. A general tendency is for a small fraction of farms within poultry, swine, and dairy sectors to produce most food products, despite a large number of small- and medium-sized farms with an important social role. In the past, livestock manure was commonly returned to farmland as a scarce and valued nutrient source. With the rise of concentrated animal feeding operations during the past few decades, environmental quality can become threatened when insufficient land is available to utilize concentrated sources of manure. We present examples of crop-livestock integration in three distinct regions of North America: New York, British Columbia, and the south-eastern US.

New York is one of the leading states in the US for dairy production. Large quantities of manure are produced and a combination of regulation and partnerships among farmers, land-grant university, local extension, and various governmental and non-governmental organizations has renewed recognition of the value of livestock manure to balance nutrient demands of annual and perennial crops. Better use of nutrients on farms has greatly increased nutrient use efficiency in the headwaters of the Chesapeake Bay watershed. The Lower Fraser Valley in British Columbia, Canada has a mild climate ideal for both agricultural operations and suburbanization. Sandy soils combined with large inputs of poultry manure and abundant precipitation have threatened groundwater quality. A win-win strategy for soil health and environmental quality was described to instead fertilize forage production fields with poultry manure and supply these feedstuffs to dairy, while using separated dairy manure solids as a high-C amendment to small-fruit production fields. In the south-eastern US with abundant poultry and swine production, livestock manure application continues to benefit crop production by improving soil organic matter and available soil N along with better soil health conditions. Inorganic fertilizer inputs can be reduced knowing the value of livestock manure to crop yield responses.

In all three regions, the key lesson learned is that by valuing livestock manure as a resource with known nutrient contents and as an organic C source to improve soil health, agronomically appropriate land application rates can distribute livestock manure onto the landscape in an ecologically sustainable manner. Cropland can serve as a receiving body for livestock manure, but also benefit as a local resource to produce grains and feedstuffs vital for livestock. It is only when concentrated animal feeding operations do not have plans to utilize nutrients in ecologically and environmentally appropriate manners does the natural cycle of crop and livestock production become broken. These examples in three contrasting regions of North America offer encouragement for greater integration of crop and livestock production at different levels of the agricultural enterprise. We suggest lessons can be learned from these examples, but that further innovations for ecologically, economically, and socially acceptable approaches to crop-livestock integration be explored in the unique conditions of different regions.

Supplementary materials

The online version of this article at https://doi.org/10.15302/J-FASE-2020365 contains supplementary materials (Tables S1–S4; Figs. S1–S5).

Compliance with ethics guidelines

Alan Franzluebbers, Derek Hunt, Gary Telford, Shabtai Bittman, and Quirine Ketterings declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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