Recycling nutrients in the beef supply chain through circular manuresheds: Data to assess tradeoffs

S. Spiegal[1], J.M.B. Vendramini[2], S. Bittman[3], M.L. Silveira[2], C. Gifford[4], C.A. Rotz[5], J. Ragosta[6], P.J.A. Kleinman[7]

[1] USDA-ARS, Jornada Experimental Range, Las Cruces, NM

[2] University of Florida, Range Cattle Research Experiment Station, Ona, FL

[3] Agriculture and Agri-Food Canada, Agassiz Research and Development Centre, Agassiz, BC, Canada

[4] New Mexico State University, Extension Animal Sciences and Natural Resources, Las Cruces, NM

[5] USDA-ARS, Pasture Systems and Watershed Management Research Unit, University Park, PA

[6] New Mexico State University, Jornada Experimental Range, Las Cruces, NM

[7] USDA-ARS, Soil Management and Sugar Beet Research Unit, Fort Collins, CO

Abstract

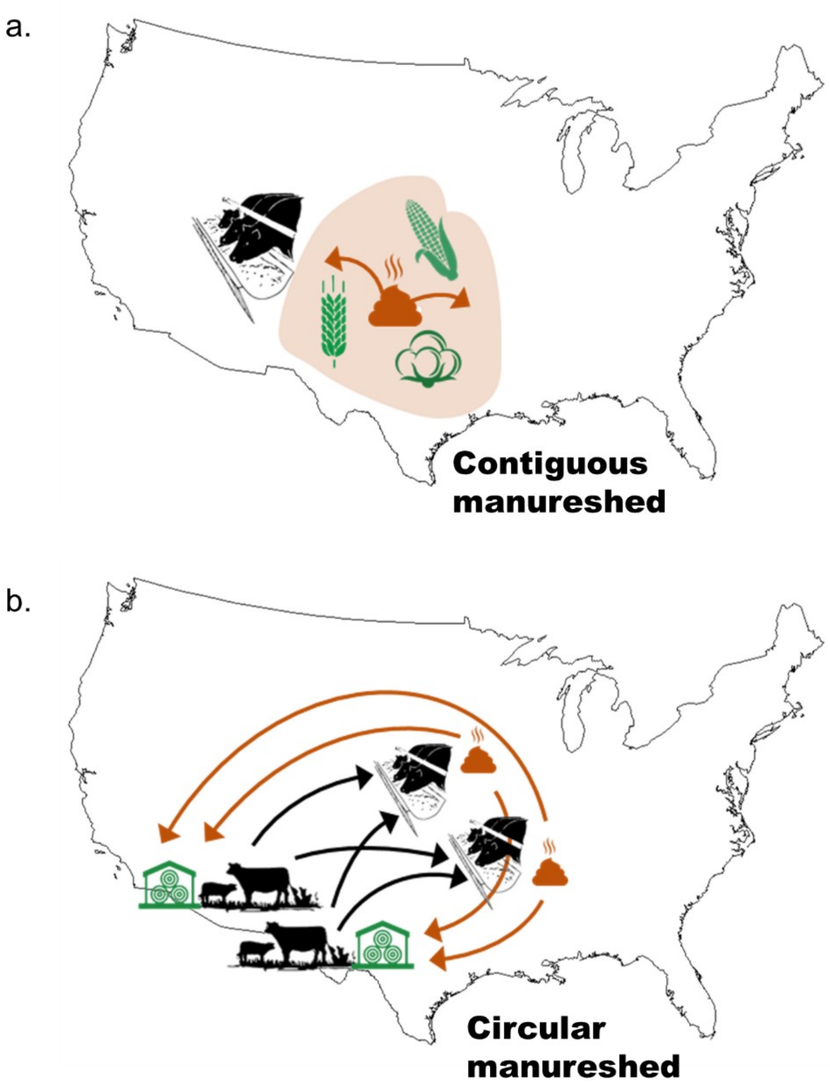
Nutrient circularity can help supply chain managers meet sustainability goals. Across the segmented beef supply chain, opportunity exists to reinforce and introduce nutrient circularity by recycling surplus manure nutrients from feedlots to feed-producing lands. We describe four datasets developed to evaluate options in U.S. and Canadian beef systems. The datasets delineate three “circular manuresheds”, each encompassing a hay-grazing landscape where beef cattle are raised on grazingland with hay grown nearby, and the distant feedlots where those cattle produce manure nutrients for potential import back to the hayfields. We selected the hay-grazing landscapes of New Mexico, USA; Florida, USA; and western Canada (the assemblage of Manitoba, Saskatchewan, Alberta, British Columbia) because of their significant grazingland production and potential to substitute feedlot manure for commercial fertilizer on hayfields. In each circular manureshed, the manure nutrients from major feedlot destinations could supply a considerable proportion of the P used by hay for grazing cattle: 34% of the P requirements in New Mexico; 36% in Florida, and 6% in western Canada. The average distance to return the resource was 647 km for New Mexico, 1884 km for Florida, and 1587 km for western Canada. These magnitudes and distances suggest that the New Mexico circular manureshed may be the most economically viable in the current agri-food system, but this reflects only part of a greater assessment of tradeoffs. The circular manureshed concept provides a platform for simultaneous consideration of competing factors for sustainability via circularity.

1. Introduction

Livestock and poultry industries are expected to support sustainability in agri-food systems by fulfilling dietary demands, protecting environmental quality, and ensuring robust smallholder livelihoods (Greenwood, 2021, Thornton, 2010). Nutrient circularity – recovering nutrients from residuals such as manures and post-harvest byproducts and reusing them for further agricultural production (Harder et al., 2021) – is a promising yet complex strategy for achieving these intertwined sustainability goals. Approaches to nutrient circularity include substituting food co-products and wastes for conventional animal feeds (e.g., van Selm et al., 2022; van Hal et al., 2019; Green-Miller et al. 2021), substituting manures or biosolids for commercial fertilizers (e.g., Metson et al., 2016; Akram et al., 2019), or both (e.g., Koppelmäki et al., 2021). Finding viable ways to achieve nutrient circularity is especially important in light of projected global scarcity of fertilizer N and P (MacDonald et al., 2012; Fixen and Johnston 2012) and fertilizer price surges (Huffstutter et al., 2022; Myers and Nigh 2021).

Nutrient circularity holds great promise in theory, but it is complicated in practice, and willing consortia need a better understanding of the spatial relationships among system components in order to operationalize it (Koppelmäki et al., 2021; van der Weil et al., 2019). The conceptual framework of the "manureshed" – the lands where surplus manure nutrients from concentrated animal feeding sites can be recycled to meet production, environmental, and socioeconomic goals – provides spatially explicit information and knowledge about where and how nutrient circularity via manure redistribution would actually work (Kleinman et al., In Review). To date, manuresheds have been designed as spatially contiguous land units: a manure hotspot is identified, and the adjacent productive agricultural lands needed to assimilate the hotspot's surplus nutrients are delineated (Figure 1a) (e.g., Saha et al., 2018; Spiegal et al., 2020b; Bryant et al., 2021). Here we modify the approach by defining a "circular manureshed" as the feed-producing lands where surplus manure nutrients from animals ingesting feed from those lands can be recycled to meet production, environmental, and socioeconomic goals (Figure 1b). Many opportunities exist for circular manureshed management in the extensive and telecoupled U.S. and Canadian beef supply chains, as the main feed inputs (hay, corn, soy, and wheat) are all viable recipients for recycling the large volumes of concentrated feedlot manure collected from feedlots (Box 1). In Figure 1b we illustrate circular manuresheds in which surplus feedlot manure is recycled onto hayfields associated with links of the beef supply chain in which cattle graze range and pasture, but the concept can also be used to recycle feedlot manure on cornfields that produce feed rations for feedlots, or to recycle poultry, swine, or dairy manures onto their respective feed farms.

Figure 1. Two types of manuresheds with examples from the U.S. beef industry: a) a spatially contiguous manureshed in which surplus manure nutrients from a beef feedlot hotspot are distributed onto any viable croplands in the vicinity, and b) a circular manureshed in which surplus manure nutrients from feedlot cattle are returned to the hay-grazing systems where those cattle originated to produce more hay.



Successful circular manuresheds require substantial initial investments to transform existing management practices, trade structures, and social networks, with coordinated and collaborative efforts beyond any one animal or feed producer (Meredith et al., 2022b; Spiegal et al., 2021; Kleinman et al., 2019; Sharara et al., 2022). Weighing tradeoffs among different types of sustainability goals (production, environmental, socioeconomic) is essential to predict returns on such investments (Harrison et al., 2021). Data about magnitudes and distances involved are needed for tradeoffs assessments. Such datasets are scarce, however, perhaps because they require a diversity of input data coupled with multidisciplinary interpretation (Godar et al., 2016; Jones et al., 2021; Basso et al., 2021; Harder et al., 2021). To help fill this knowledge gap, we developed four datasets that provide the magnitudes and distances involved in three circular manuresheds for the U.S. and Canadian beef industries, in which surplus manure nutrients from feedlots are recycled in the hayfields in landscapes where the feedlot cattle originated (Spiegal et al., 2022). We published the datasets at https://portal.edirepository.org/nis/mapbrowse?scope=knb-lter-jrn&identifier=200021001 following FAIR principles (Wilkinson et al., 2016; Supporting Information). Here we describe our rationale for selecting the components of the three circular manuresheds, the analyses used to build the datasets, the datasets' characteristics, and their potential applications for understanding tradeoffs of circular manuresheds for sustainability in the agri-food system.

2. Methods

2.1 Four datasets for three circular manuresheds

The four datasets describe three circular manuresheds for the U.S. and Canadian beef industries as of 2010-2019 (Table 1). Each circular manureshed encompasses one "hay-grazing landscape" (i.e., a large area spatially dominated by grazingland where beef cattle are raised on rangeland and/or pastureland and supplemented with hay as needed from nearby hayfields), and the many feedlots where cattle originating from the hay-grazing landscape produce manure nutrients for potential import back to the hayfields (Figure 2). In each of our circular manuresheds, the manure nutrient supply for the hayfields included feedlots *within* the administrative boundaries of the hay-grazing landscape, as well as distant feedlots where grazing cattle were exported for finishing.

We quantified flows centered on the hay-grazing landscapes of the U.S. states of New Mexico and Florida and the assemblage of four western Canadian provinces (Manitoba, Saskatchewan, Alberta, British Columbia) (Figure 3; mosaics of blue shading and tan outline within the black boundaries). We selected the three landscapes due to their similarities and differences. Beef cattle production on grazinglands are environmentally and socioeconomically important in all three hay-grazing landscapes, and they all use N and P fertilizers to produce hay for their grazing cattle (Lauriault et al., 2018; Silveira et al., 2011; Malhi et al., 2004) which could potentially be replaced by feedlot manure. The administrative boundary of the western Canada hay-grazing landscape contains a major hotspot of beef cattle feeding that can be exploited to supply the nutrient demands for hay in its hay-grazing systems, whereas New Mexico and Florida contain fewer feedlots (Figure 3). Further, New Mexico and western Canada have sizeable dairy industries that can provide another potential source of manure nutrients for hay in the hay-grazing landscape, whereas Florida does not (Dell et al., 2022; Sheppard et al., 2011). The use of dairy manure on hay is not covered here as we sought to emphasize only components of the beef industry in our circular manuresheds. Although we selected these geographies and timeframe for our analysis, our approach to data production can be reproduced to encompass different hay-grazing landscapes and different years depending on questions about nutrient circularity.

Figure 2. Schematic of the circular manuresheds described by the four datasets. Pathways of cattle vary from pasture to plate in the United States and Canada, but a central tendency entails birth to weaning in cow-calf operations, weight gains in stocker operations, achieving finishing weights in grain-based feedlots, slaughter and processing, and meat distribution and sales. Gold icons and numbers symbolize the four datasets, which provide information on the available magnitudes and necessary transport distances required to recycle nutrients from feedlots to hayfields in hay-grazing landscapes where the feedlot cattle originated (dashed arrow).

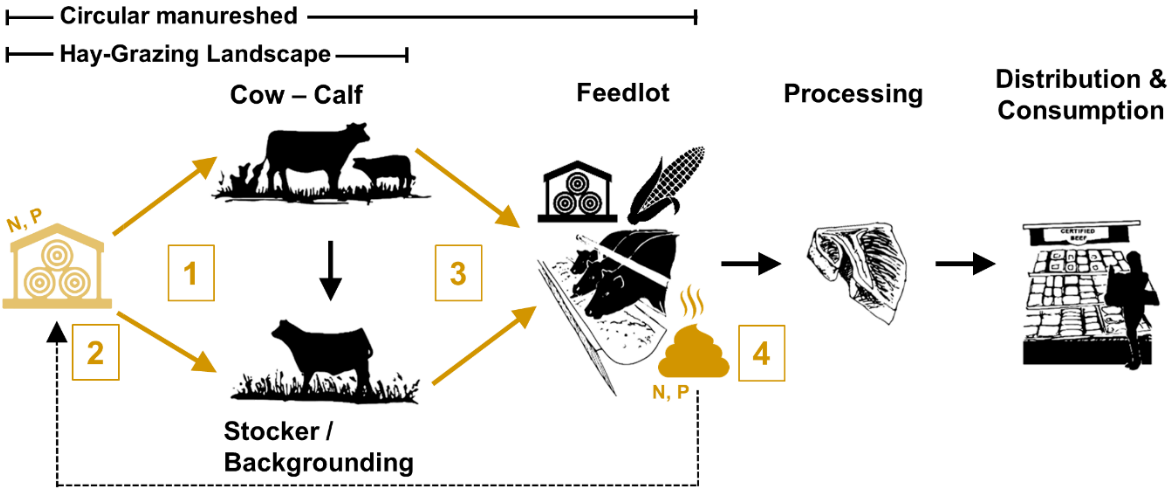


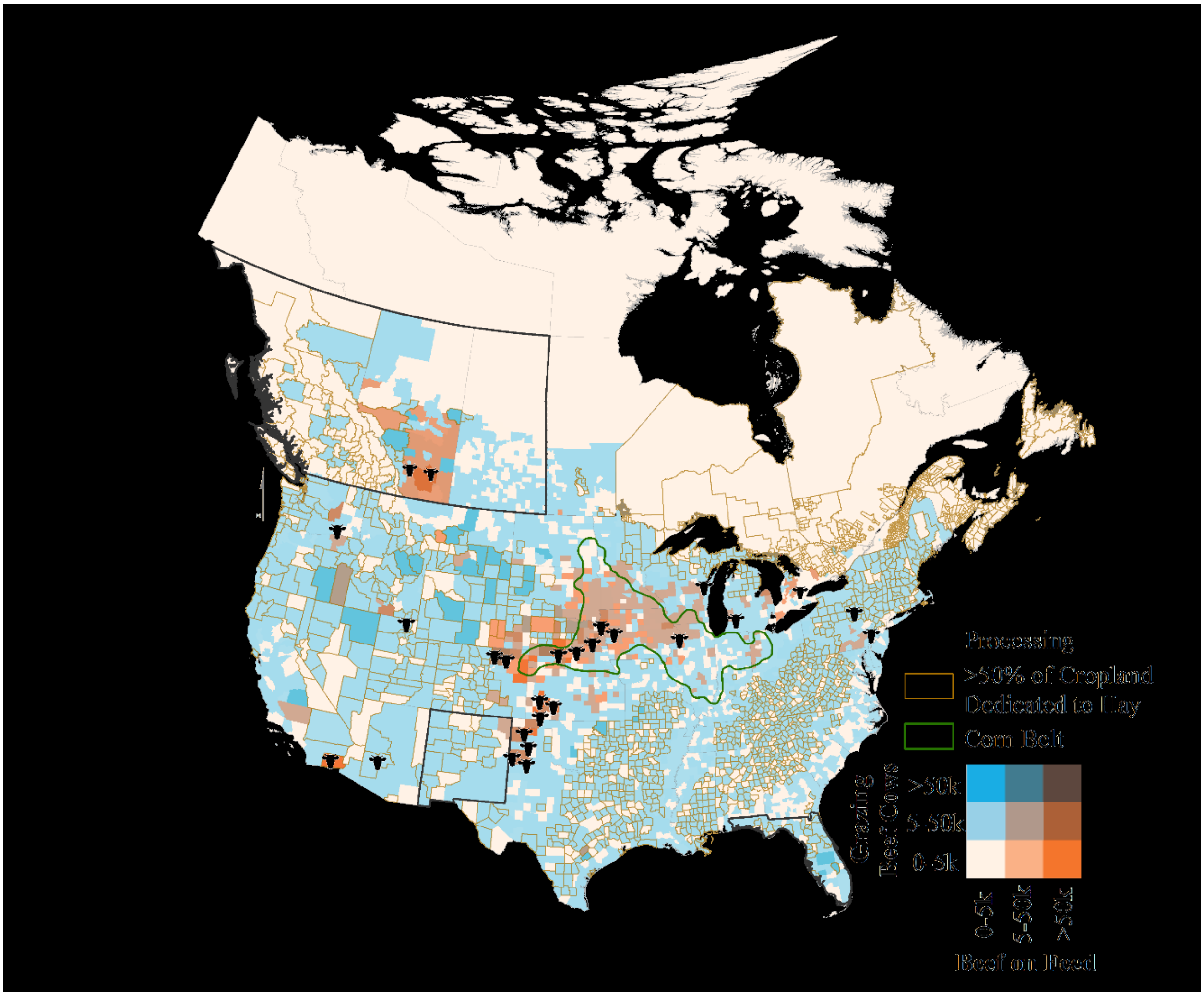
Table 1. Structure of the datasets.

Dataset	Description	Dimensions	Row structure	Years represented
Dataset 1: Hay intake by grazing cattle in three hay-grazing landscapes	Estimated amount of hay intake per cattle class per hay-grazing landscape.	16 rows, 9 columns[1]	Class of grazing cattle (6 for New Mexico, 6 for Florida, 4 for western Canada)	2019 for New Mexico and Florida; 2016 for western Canada
Dataset 2: Nutrient removal by hay fed to grazing cattle in three hay-grazing landscapes	Estimated potential N and P removed by hay produced for grazing cattle per hay-grazing landscape.	4 rows, 11 columns[1]	Hay-grazing landscape with Florida split into low quality and high quality hay	2019 for New Mexico and Florida; 2016 for western Canada
Dataset 3a: Beef cattle exports from the hay-grazing landscape of New Mexico	Number of beef cattle exported from New Mexico to U.S. counties for auction, feedlot, pasture, slaughter	8278 rows, 7 columns	New Mexico Brand Inspection origination district to US county outside of New Mexico	2014, 2015, 2016, 2017
Dataset 3b: Beef cattle exports from the hay-grazing landscape of Florida	Number of beef cattle exported from Florida to U.S. counties for breeder, dairy, feedlot, stocker	3850 rows, 7 columns	Florida origination county to US county outside of Florida	2010, 2019
Dataset 3c: Beef cattle exports from the hay-grazing landscape of western Canada	Number of cattle exported from western Canada to U.S. states for fed for slaughter, non-fed for slaughter, feeder, slaughter[2]	170 rows, 4 columns	Western Canada to U.S. state	2015, 2016, 2017, 2018, 2019
Dataset 4: Feedlot manure nutrients produced by cattle originating in three hay-grazing landscapes available for transport	Estimated manure N and P produced by cattle exported to feedlots from three hay-grazing landscapes which is available for transport back to hayfields in Dataset 2.	45 rows, 13 columns	Hay-grazing landscape to feedlot destination state or provincial assemblage	2014-2017 for New Mexico; 2010, 2019 for Florida; 2015-2019 for western Canada

[1] Coefficients for column-wise calculations vary among rows for Dataset 1 and Dataset 2. We include coefficients only in Dataset 2 for direct reference due to its large number of records. Coefficients for Datasets 2 are available in Table 2.

[2] We treat the four westernmost provinces in Canada as a cohesive "provincial assemblage" because of the structure of cattle flows data available from our Canadian source.

Figure 3. Geography of beef production in the United States and Canada. Geographic units are counties in the United States and Consolidated Census Units in Canada. Values in the squares in legend represent cattle inventory. The administrative boundaries of the three hay-grazing landscapes described in the four datasets are in black. See Supporting Materials for data sources.

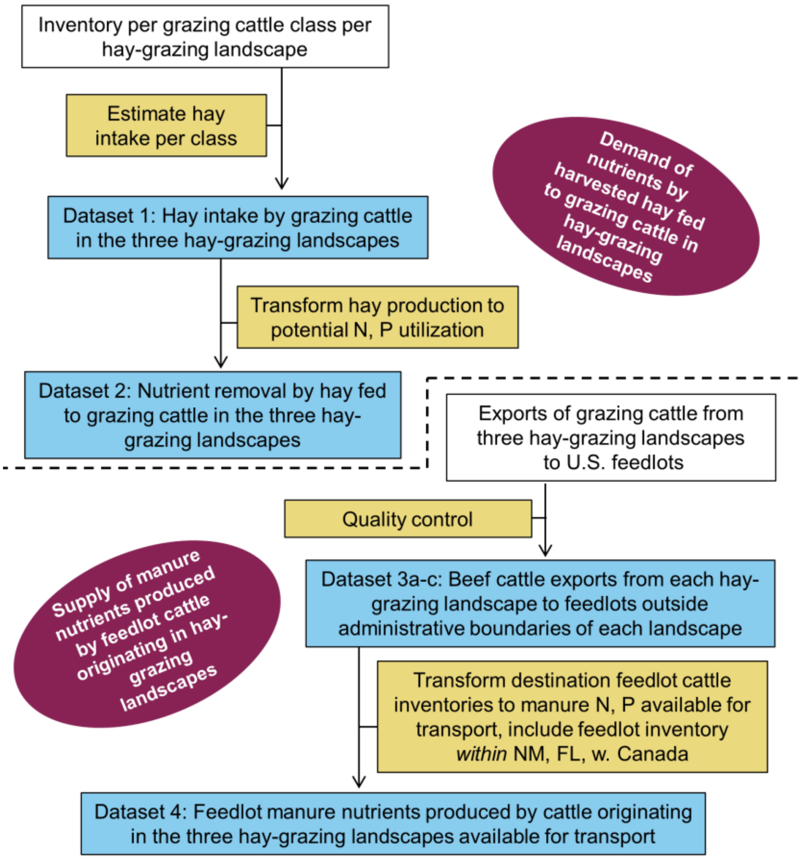


2.2 Data processing workflow

We used data from secondary sources and select equations and coefficients to develop the four datasets. Figure 4 is a summary of the data processing and analytical workflow (*sensu*

Yun and Graming 2019). Coefficients were selected to reflect reality, including the variability inherent in agricultural systems to the extent possible, but in some cases only a central tendency is reflected (discussed in Data Issues).

Figure 4. Workflow for the four datasets. Data inputs (white) with data cleaning or calculations (tan) used to derive the four datasets (blue).



2.3 Dataset 1: Hay intake by grazing cattle in three hay-grazing landscapes

Dataset 1 provides estimated average annual hay intake per class of grazing beef cattle in each hay-grazing landscape. Data inputs were the inventory per class of grazing cattle for a given year of available data: 2019 for New Mexico, 2019 for Florida, and 2016 for western Canada (USDA-NASS 2020; AAFC 2021a; AAFC 2021b). Total hay intake per class of grazing cattle (Dataset 1 “est_annual_hay_intake”), was calculated (across columns of Dataset 1) using Equation 1:

Total hay intake per class of grazing cattle (kg yr^{-1}) = Cattle inventory per class * Daily dry matter intake per class (kg/day) * Proportion of the diet that is hay * Proportion of animals receiving hay * Number of days fed hay per year (Equation 1)

We identified coefficients using literature review, an informal survey of cow-calf producers, and our local knowledge of cattle classes in each hay-grazing landscape (Supporting Information).

2.4 Dataset 2: Nutrient removal by hay fed to grazing cattle in three hay-grazing landscapes

The columns in Dataset 2 reflect a step-wise calculation that transforms the kg of hay intake (Dataset 1) to concentrations of N and P that the hay can assimilate, partitioned between alfalfa and grass hay (Table 2; details in Supporting Information). We were interested in potential nutrient uptake *before* post-harvest losses by weight occur. Accordingly, we calculated the amount of hay that must be produced to meet intake requirements *before* such losses (hay_produced), and then calculated the uptake of nutrients by that amount of hay in the remaining columns (Table 2).

Table 2. Dataset 2: Step-wise calculations (performed across columns of Dataset 2) to estimate the potential nutrient uptake by hay in each hay-grazing landscape.

	Hay produced to meet intake requirements (harvested weight)	**Alfalfa vs. grass in harvested weight**	**Dry matter conversion**	**Potential N, P removal (dry matter basis)**
	hay_produced	**alfalfa_hay, grass_hay**	**alfalfa_hay_dry, grass_hay_dry**	**alfalfa_hay_N, alfalfa_hay_P, grass_hay_N, grass_hay_P**
New Mexico	15% more than intake requirement	85% alfalfa, 15% grass	0.9	Alfalfa: 3.1% N, 0.26% P; Grass: 1.45% N, 0.22% P
Florida	30% more than intake requirement	100% grass: 50% low quality, 50% average quality[1]	0.9	Low quality grass: 1% N, 0.2% P; Average quality grass: 1.5% N, 0.3% P
Western Canada	25% more than intake requirement	25% alfalfa[2], 75% grass	0.9	Alfalfa: 3.1% N, 0.26% P; Grass: 1.45% N, 0.22% P

[1] Low quality grass has < 7% Crude Protein); average quality grass has > 7% Crude Protein.

[2] Swards categorized as alfalfa by StatsCan and in our calculations, but on the ground comprise an alfalfa-grass mix.

2.5 Dataset 3a-c: Beef cattle exports from three hay-grazing landscapes to distant feedlots

Datasets 3a, 3b, and 3c provide the number of cattle exported from the three hay-grazing landscapes to feedlots outside of New Mexico, Florida, and western Canada, respectively. These datasets were based on raw data provided by local agencies (New Mexico Livestock Board 2019; Florida Division of Animal Industry, Florida Department of Agriculture and Consumer Services, 2020; AAFC/MISB/AID/Redmeat Section, 2020). We performed extensive quality control and data aggregation before publication (Supporting Information). Table 3 summarizes the cattle categories provided by the agencies, years of data available, and inventory totals per cattle category.

Table 3. Classes, years of data, and cattle inventory per class per year of data provided in Datasets 3a-c. Values in "Total" and "Average" columns are summary statistics of available data.

		2010	2014	2015	2016	2017	2018	2019	Total	Average
Western Canada	Total Fed for Slaughter			179,061	261,784	295,224	205,850	300,983	1,242,902	248,580
	Total Feeder			261,792	163,805	104,560	171,299	159,049	860,505	172,101
	Total Non-Fed for Slaughter			19,410	32,432	18,525	23,883	25,119	119,369	23,874
	Total			460,263	458,021	418,309	401,032	485,151	2,222,776	444,555
Florida	Cattle-Breeder	1734						5449	7183	3592
	Cattle-Dairy	13,007						19,714	32,721	16,361
	Cattle-Feedlot[a]	303,057						243,774	546,831	273,416
	Cattle-Stocker[a]	123,095						110,972	234,067	117,034
	Total	440,893						379,909	820,802	410,401
New Mexico	Auction		23,663	25,777	32,420	36,446			118,306	29,577
	Feedlot		308,144	281,057	291,399	339,709			1,220,309	305,078
	Pasture		64,345	71,003	77,966	75,226			288,540	72,135
	Slaughter		47,574	48,159	56,225	34,614			186,572	46,643
	Total		443,726	425,996	458,010	485,995			1,813,727	453,432
Total		440,893	443,726	886,259	916,031	904,304	401,032	865,060	4,857,305	

[a] Partitioned by authors from “Feeder” category provided by Florida Department of Agriculture and Consumer Services

For Datasets 3a and 3b, we were able to provide records on the basis of exports from Brand Inspection District to US county (New Mexico) and exports from county to county (Dataset 3b). However, in the Canadian case, the AAFC/MISB/AID/Redmeat Section (2020) structured their data differently, with the assumption that cattle exported to the 17 western states of the contiguous United States originated in “western Canadian” (four provinces) (personal communication, Diane Blandford, Red Meat, Market and Industry Services Branch, Agriculture and Agri-Food Canada, 2020). Dataset 3c is structured on the basis of export from western Canada to U.S. state – and accordingly, records for Dataset 4 are also structured on this coarser scale.

2.6 Dataset 4: Feedlot manure nutrients produced by cattle originating in three hay-grazing landscapes available for transport

Dataset 4 contains estimates of the recoverable manure N and P available for transport back to the hayfields of the three circular manuresheds (i.e., nutrient demand available in Dataset 2). Each record (i.e., row) of Dataset 4 represents a hay-grazing landscape paired with a destination state or provincial assemblage (orig_dest). In this step of the analysis, we included cattle inventories in feedlots *within* New Mexico, Florida, and western Canada, such that each circular manureshed includes manure nutrient sources from nearby and distant feedlots (see Supporting Information for an explanation of how we estimated the inventories in feedlots within the two states and provincial assemblage).

We used a series of assumptions and coefficients from Kellogg et al. (2014) and Rotz et al. (2019) (across columns of Dataset 4) to transform the number of feedlot cattle per destination state or provincial assemblage (inventory column) into magnitude of manure N and manure P available for transport (N_available_after_feedlot_spreading_Mg, P_available_after_feedlot_spreading_Mg columns) (Table 4; Supporting Information). We deemed the nutrients as available after accounting for losses from management and handling, collection, transfer, storage, treatment, and land application at feedlots.

Table 4. Dataset 4: Step-wise calculations (performed across columns of Dataset 4) to estimate the feedlot manure nutrients available for transport back to hayfields in the three circular manuresheds.

Feedlot cattle inventory to animal unit (AU) conversion	Excreta from AUs (Mg wet weight)	Excreta that is recoverable (Mg wet weight)[1]	Nutrient content in recovered excreta (Mg)	N and P available after additional management (Mg)[2]	Manure N and P available for exported from feedlot (Mg)
animal_units	wet_manure_Mg	wet_manure_recov_Mg	N_in_wet_manure_recov_Mg, P_in_wet_manure_recov_Mg	N_after_losses_Mg, P_after_losses_Mg	N_available_after_feedlot_spreading_Mg, P_available_after_feedlot_spreading_Mg
Inventory * (days on feed/365) * (1/animals per AU). 163 days on feed for exports from New Mexico or Florida. 100 days on feed for exports from western Canada. 1.02 animals per AU	Excreta = AU*10.6 Mg	Recovered excreta = Excreta *0.75 Only destinations for which AU > 12 were included.	N content = Recovered excreta * 0.00554 P content = Recovered excreta * 0.000675	N after losses = N content * 0.4 P after losses = P content * 0.9	N after losses * 0.66 P after losses * 0.66[3]
Source: Cattle inventories in Dataset 3a-c; cattle on feed within three hay-grazing landscapes. Table 1, Equation 3 in Kellogg et al. (2014)	Source: Table 5 in Kellogg et al. (2014)	Source: Table 9 in Kellogg et al. (2014)	Source: Table 5 in Kellogg et al. (2014)	Source: Table 10 in Kellogg et al. (2014)	Source: Survey of beef feedlots in Rotz et al. 2019; Supporting Table 1

[1] Recoverable during removal from the built environment.

[2] Losses during manure collection, transfer, storage, and treatment, including nitrogen volatilization.

[3] On average, feedlots export 66% of their manure off-farm.

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Box 1: Designing circular manuresheds for a telecoupled beef supply chain

A wealth of opportunities exist for nutrient circularity in the beef supply chains of the United States and Canada. Both nations are world leaders in production on range and pasture as well as feedlots, and cattle flow from land-based systems to feedlot systems within and between the nations everyday (Greenwood 2021; Hobbs 2021).

Hay, corn, soy, and wheat are dominant feeds for beef cattle in these nations (Capper 2011; Rotz et al., 2019). All are viable recipients for recycling the large volumes of concentrated feedlot manure nutrients collected from the built environment of the feedlots (Eghball and Power 1994; Rotz et al., 2019; Wang and Sparling 1995). Currently, the export of concentrated manure from feedlots is a common, but local, endeavor in which the resource typically travels short distances – less than 16 km (10 miles) – and is applied to any crop or forage depending on local social networks, without stipulation that it must be applied in a circular fashion to cattle feeds (Figure 1a; Meredith et al., 2022a; Larney and Hao 2007).

Nutrient magnitudes and transport distances are essential types of information when expanding the status quo to systematically recycle surplus manure nutrients from beef feedlots to cattle feed lands. With regard to nutrient magnitudes, corn can typically utilize manure nutrients with greater efficiency than can alfalfa or grass hays (Kelling and Schmitt 2011; Sweeten 2002). Yet hayfields (grass and alfalfa) can serve as important manure-receiving lands in their own right, as they already fall only behind feed corn and soy as a recipient of fertilizer P across all feed crops the United States (MacDonald et al., 2012). As is the case with many crops, opportunities to fertilize hayfields with either commercial fertilizer or manure must correspond with particular times for spreading (typically between cuttings), and rates should match production expectations (e.g., Anderson 2016; Kelling and Schmitt 2011; Undersander et al. 2011; Zhang and Redfearn 2012; USDA-NRCS 2012).

Geographically, feedlots are located in most U.S. states and southern Canadian provinces, but they are concentrated in the U.S. Plains and southern Alberta (Figure 3, green outline). Similarly, corn is grown widely, but most is concentrated in the U.S. Corn Belt (Metson et al., 2016; Figure 3). On average, large U.S. feedlots import about 30% of their total corn ration from local sources outside of the Corn Belt (Meredith et al., 2022a; Denicoff et al., 2014; Drouillard 2018). Transport of manure nutrients to local cornfields could potentially minimize costs for circular manuresheds in which feedlot manure is returned to corn. Hay tends to be grown close to the grazing systems that use it to supplement cattle when needed (Rankin 2020; Havstad et al., 2018). Those hay-grazing systems are distributed very widely across both nations without major centers of concentration (blue shading with tan outline in Figure 3; USDA-NASS 2017; StatsCan 2020), translating into a diversity of opportunities for returning feedlot nutrients to hayfields associated with various phases of cattle production (e.g., Wang and Sparling 1995).

Although fundamentally important, transport distance and nutrient utilization represent just two of many competing goals when envisioning circular systems for long-term sustainability outcomes (Velasco-Muñoza et al., 2021; Harrison et al., 2021). "Telecoupling" – the notion that social-ecological systems in geographically distant places are connected via flows of information and resources so that changes in one place can affect sustainability outcomes in another place (Liu et al., 2017) – is a key consideration for U.S. and Canadian beef supply chains. In these nations, hay-grazing systems and feedlot systems are telecoupled via flows of cattle that embody nutrients from the hay-grazing systems. Returning feedlot manure nutrients to hay-grazing systems can potentially benefit feedlots, hay-grazing systems, and other component of the supply chain by a) helping to ensure a regular supply of cattle from hay-grazing systems to feedlots even during drought when hay is relied upon to supplement grazing cattle (Shrum et al., 2018; Havstad et al., 2018); b) providing a viable recipient for surplus feedlot manure nutrients managed by feedlots (Meredith et al., 2022a); and c) maintaining the non-market ecosystem services from hay-grazing systems that are increasingly valued by beef consumers (e.g., Steiner and Franzluebbers, 2009; Spiegal et al., 2020a). We focused on recycling between feedlots and hayfields foreseeing eventual societal interest in public programs that advance the cycling of nutrients between feedlots and their telecoupled land-based systems.

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3. Major characteristics of the datasets

3.1 Nutrient supply and demand and transport distances in three circular manuresheds

In each circular manureshed described by the datasets, only five feedlot destinations accounted for the vast majority of manure nutrients embodied by cattle from each hay-grazing landscape (Table 5). In the case of Florida and New Mexico, Texas was the feedlot destination that could provide the most manure nutrients back to its telecoupled hayfields. The feedlots within western Canada were the top supplier for the hay-grazing landscapes of western Canada, and Nebraska, USA was the second greatest supplier (Table 5).

Notably, the manure nutrients from those top feedlot destinations could supply a considerable proportion of the P potentially used by hay for grazing cattle in the circular manuresheds: 34% of the P in the New Mexico hay-grazing landscape; 36% the P in the Florida hay-grazing landscape, and 6% of the P in the western Canada hay-grazing landscape (Table 5; the comparatively small percentages in the Canadian case are a function of the significant nutrient demand by hay coupled with the relatively short period that beef cattle spend on feed in that area). Notably, the relatively low number of feedlot destinations could minimize logistics for returning nutrients back to the hayfields and may ultimately advance potential for circular management.

Table 5. Hay nutrient demand and feedlot manure nutrient supply in the three circular manuresheds, reported as an annual average of the 2010-2019 agri-food system. Derived from Dataset 2 and Dataset 4. The top five feedlot destinations per circular manureshed account for the majority of nutrients available to cycle back into each hay-grazing landscape, and accordingly specific nutrient supply from those destinations are reported.

Circular manureshed	**N utilization by hay fed to grazing cattle in hay-grazing landscape (Mg)[1]**	**P utilization by hay fed to grazing cattle in hay-grazing landscape (Mg)[1]**	**Feedlot destination (by state or province)**	**Manure N available from feedlot cattle from hay-grazing landscape (Mg)[2]**	**Manure P available from feedlot cattle from hay-grazing landscape (Mg)[2]**	**N demand that could be met with manure supply (%)**	**P demand that could be met with manure supply (%)**
New Mexico	13,894	1237	All (n = 22)	1645	451	12%	36%
			Top 5	1548	424	11%	34%
			Texas	1159	318		
			Kansas	172	47		
			New Mexico	90	25		
			Colorado	69	19		
			Oklahoma	58	16		
Florida	5627	1125	All (n = 5)	1496	410	27%	36%
			Top 5	1496	410	27%	36%
			Texas	700	192		
			Oklahoma	449	123		
			Kansas	232	64		
			Florida	102	28		
			Nebraska	12	3		
Western Canada	153,911	19,006	All (n = 18)	4571	1253	3%	7%
			Top 5	4494	1232	3%	6%
			Western Canada[3]	4032	1105		
			Nebraska	252	69		
			Washington	112	31		
			Colorado	63	17		

			South Dakota	34	9		

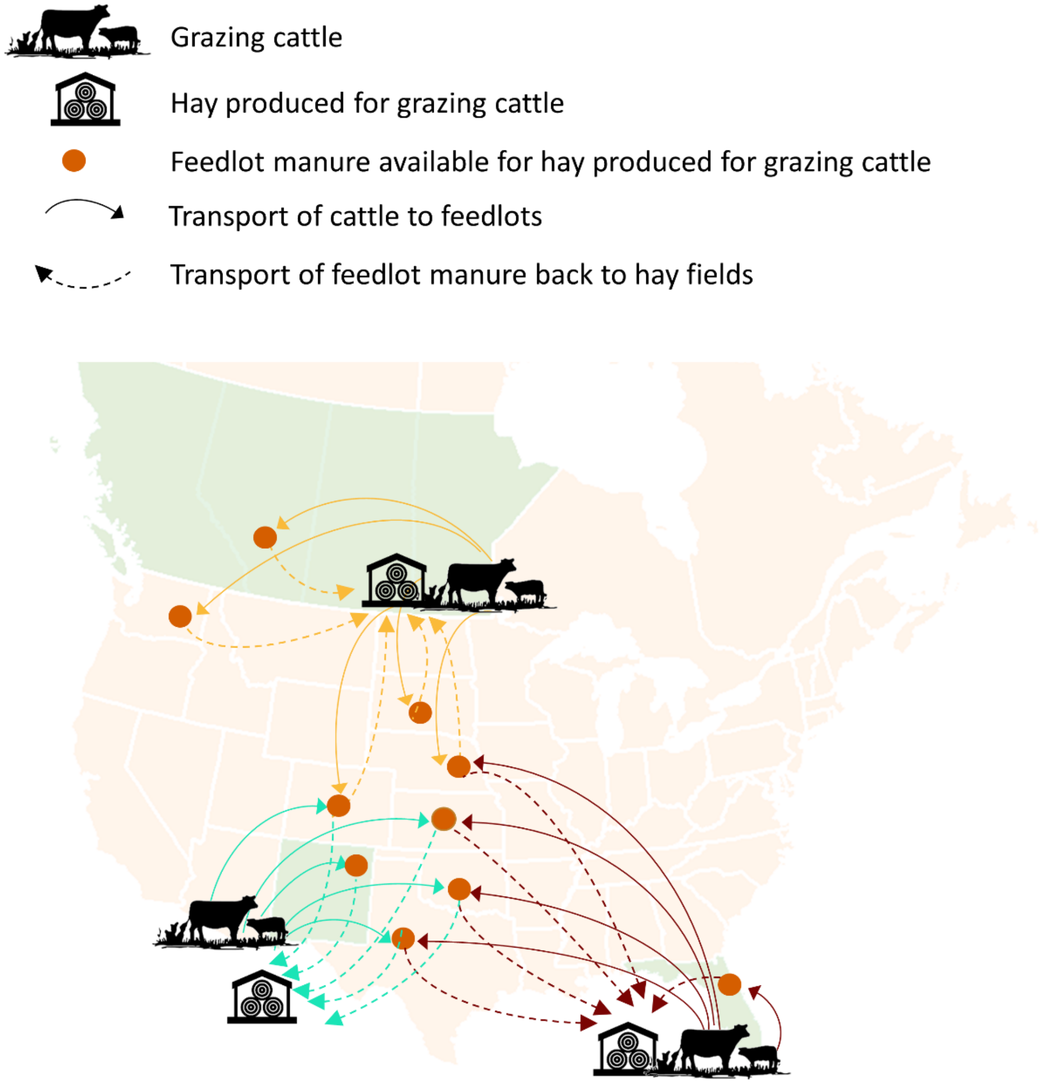
[1] Magnitude of nutrients in the hay grown for grazing cattle before post-harvest losses.

[2] After accounting for losses during collection, transfer, storage, and treatment (including volatilization and denitrification of N), and losses via land application on lands on the feedlots.

[3] Most fed cattle in western Canada are concentrated in a feedlot hotspot in southern Alberta

Figure 5 illustrates, in general terms, the distances required to transport feedlot manure back to the hay-grazing landscapes of the three circular manuresheds. Across the top five feedlot destinations per manureshed, the *average* distance for transport of the resource back to the respective hay-grazing landscapes was 647 km for the New Mexico circular manureshed, 1884 km for the Florida circular manureshed, and 1587 km for the western Canada circular manureshed. These distances were based on a simple calculation using defaults in Google Maps to calculate road distances between states, and, for the western Canada case, between Alberta and U.S. states (we used a distance of 0 km for transport from feedlots to hay-grazing systems within New Mexico, Florida, and western Canada). We encourage more sophisticated analyses that include transport distances between locations at finer scales (as in the rows of the cattle export dataset for New Mexico and Florida, Datasets 3-a), and along popular road or rail lines (e.g., Sampat et al., 2019; Yang et al., 2019).

Figure 5. Generalized distances required to transport feedlot manure back to the hay-grazing landscapes of the three circular manuresheds. Only the top 5 feedlot destinations are shown for each circular manureshed, because they account for the majority of nutrients available to cycle back into the hay-grazing landscapes.



The datasets suggest that among the three circular manuresheds, the New Mexico case may be the most economically viable in the current agri-food system. New Mexico and Florida stand to re-import a similar proportion of its P needs for hay from their telecoupled feedlots (Table 5), but the transport distances for New Mexico are shorter (Figure 5). Yet this information provides only part of the grand synthesis of important tradeoffs, which must include a broad range of factors, including fertilizer prices (which were at record highs during the construction of these datasets; Myers and Nigh 2021), demand for feedlot manure by hay and corn farms near the feedlots (e.g., Wang and Sparling 1995; Huffstutter et al., 2022), relative concentrations of other types of manure for use in the hay-grazing landscapes (e.g., Dell et al., 2022), and social license to re-import P or N back to a focal hay-grazing landscapes (e.g., Spiegal et al., 2021). The manureshed concept provides a platform to systematically weigh these considerations in a geographically-specific manner.

4. Data issues

Variability is the norm in agricultural systems, but developers of datasets like these are often not able to capture that variability due to limited data about farm-level decision-making and conditions (Capalbo et al., 2017). In our case, coefficients specific to each hay-grazing landscape were identified whenever possible, but those coefficients often represented central tendencies. For instance, for hay nutrient demand reported in Dataset 2, we selected N concentrations specific to the three hay-grazing landscapes (Table 2), but we also recognize that N concentrations can be much greater with outlying conditions of very high N content in the soil (USDA-NRCS 2012). At the same time, we used an estimate of 90% dry matter weight for both grass and alfalfa for all three regions, but forage managers may use other dry matter weights as locally appropriate (e.g., Marsalis et al., 2009).

For our dataset that reports manure N and P available for transport (Dataset 4), a primary step was transforming cattle inventory per feedlot destination into number of animal units that excrete manure on average per year (Table 4). That conversion captured variation among hay-grazing landscapes in that it was based on number of days on feed by cattle originating from each landscape (Table 4). Conversely, we treated all feedlot destinations the same in terms of estimates for the recoverability of that excreta from the built feedlot environment (25% loss of the material), and losses of nutrients during collection, transfer, storage, and treatment (60% loss of N, 10% loss of P). These loss estimates were based on national averages across great variability in capacities of feedlots to prevent nutrient losses (Kellogg et al., 2014; Sweeten 2002). We recognize that practices like composting vs. stockpiling can result in variation in manure nutrient content from 0.6% to 2.2% N and 0.3-0.9% P on a dry matter basis (Jones et al., 1995; Rotz et al., 2019; Larney et al., 2006; Supporting Table 1). These dry matter ranges are not directly compatible with our estimates as ours were calculated by wet weight (Table 4), but they illuminate the potential variability in our finding that feedlot manure P from feedlots telecoupled with the New Mexico hay-grazing landscape could be used to fulfill 34-36% of the nutrient needs of hay in that landscape.

We are not able to track the fate of some of the cattle originating from the three areas (e.g., cattle from grazinglands in New Mexico exported to out-of-state auction for further sales potentially to feedlots). Tracking their fate would help improve our knowledge of the relationships between hay nutrient demand and manure nutrient supply in our circular manuresheds.

Despite these issues, we stand by our coefficients as the best possible options for our questions about circularity in the agri-food systems of 2010-2019. Future researchers should pay keen attention to new research and knowledge about hay-grazing and feedlot systems of interest, in order to apply current and reliable coefficients to model circularity in a spatially-explicit manner.

5. Summary

Initial costs to redesign current systems to circularly manage nutrients would be significant in the current agri-food system. However, naming such barriers now can help foster new realities for the future (Basso et al., 2021). Empirical datasets such as those described here, which reliably connect patterns and processes of biophysical and socioeconomic systems in a spatially-explicit manner, are essential for advancing circularity in animal industries of modern agriculture – an imperative that is called for more and more frequently in recent years in high-profile sustainability research (e.g., Van Selm et al., 2022; Liu et al., 2017).

Despite their importance, datasets like these are rare. To our knowledge, for example, the integration of cattle flows and manure production from hay-grazing landscapes to destination feedlots is a novel contribution that is not available elsewhere. The scarcity of datasets may stem from the need for interdisciplinary collaboration to create them. We encourage dataset users and their networks to draw on multidisciplinary expertise to develop additional datasets designed to investigate prospects for circular manuresheds in agricultural supply chains. In particular, we recommend that data are developed to compare the multi-factor outcomes of circular manuresheds involving wheat, corn and hay with varying degrees of feedlot production within administrative boundaries of hay-grazing landscapes. Such analyses provide an important first step in the broader assessment of tradeoffs necessary to plan for a sustainable future fueled by nutrient circularity.

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Acknowledgements

This research was a contribution from the Long-Term Agroecosystem Research (LTAR) network. LTAR is supported by the United States Department of Agriculture. Additional support was from USDA-NIFA-AFRI grant #12726269: the Sustainable Southwest Beef Coordinated Agricultural Project. Agriculture and Agri-food Canada, the Canadian Cattlemen's Association (CANFAX), the Florida Department of Agriculture and Consumer Services, and the New Mexico Livestock Board are also gratefully acknowledged for providing data used to construct the four datasets. We are grateful the Dr. Matthew M, McIntosh for providing the artwork in Figure 1, and the map in Figure 3 provided by Dr. K. Colton Flynn. Thanks to Devon Worth for providing data on agricultural statistics from Canada. We thanks statistician Darren James, two anonymous reviewers, and journal editors whose comments helped to improve this article.