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SPECIAL SECTION: MANURESHEDS—RECONNECTING LIVESTOCK AND CROPPING SYSTEMS

Land use change and collaborative manureshed management in New Mexico

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Abstract

Agricultural communities of New Mexico regularly redistribute manure nutrients from dairies to nearby croplands to fulfill agronomic nutrient needs and protect water quality. Yet competition for water resources can result in land use change that affects these cooperative manure transfers. Focusing on three clusters of New Mexico dairy farms and their surrounding lands (three manuresheds), we calculated the magnitude of land use changes in 2008–2019 and the balance between manure nutrient supply and crop demand in 2019 to assess how past change may predict future prospects for sustainable management. The overall magnitude of change was small, with each manureshed experiencing a different complement: an exchange of cropland and rangeland in the Roosevelt manureshed (7,975 ha rangeland to cropland; 7,624 ha cropland to rangeland), a 464-ha gain in cropland but a 1,187-ha loss of "spreadable" land (cropland, rangeland, fallow) to developed land in the Doña Ana manureshed, and relatively minor changes in the Chaves manureshed. Nutrient supply and demand were mainly in balance, but a surplus of manure phosphorus (P) in the Chaves manureshed and a thin margin of P assimilation by croplands in the Roosevelt manureshed point to the need for preserving existing croplands and understanding of effects of dairy manure on shortgrass rangeland. Our assessment suggests that an ideal scenario would entail manure being generated in landscapes with portfolios of productive lands that can sustainably use the manure nutrients to minimize environmental quality concerns and agronomic tradeoffs. Coordinated, participatory, and interdisciplinary research and planning are needed.

Abbreviations: CDL, Cropland Data Layer; CRP, USDA's Conservation Reserve Program.

1 | INTRODUCTION

Redistributing manure nutrients from animal feeding sites to agricultural lands is a common practice to address concerns linked to accumulated manure and fulfill needs for nutrient inputs (MacDonald et al., 2009). In the dairying landscapes of the United States, such transport is largely a local endeavor because dairy manure's low value-to-mass ratio renders long-distance transport prohibitively expensive (Keplinger & Hauck 2006; Koelsch 2020; MacDonald et al., 2009). Cropland is the typical choice for the receiving lands in these local transfers (MacDonald et al., 2009), but in the American Southwest, rangelands cover extensive ground, making them attractive prospects for manure recycling. Yet the impacts of manure on rangelands remains an open question (Gravuer et al., 2019). At the same time, demographic and climate changes that alter water availability in the Southwest are affecting the extent and location of croplands and rangelands (Gedefaw et al., 2020; Gershunov et al., 2013; Ward et al., 2006; Zaied et al., 2020), which may affect prospects for the long-term sustainability of local manure transfer agreements involving either land use.

Responsible manure transport and recycling is paramount in the southwestern state of New Mexico, where the dairy industry and urbanization have both grown exponentially during recent decades (Cabrera & Hagevoort 2007; Ortiz et al., 2007). Incoming dairies have been located among croplands near sources of irrigation water along rivers or overlying the Ogallala Aquifer, nested in vast expanses of rangeland. As of December 2020, 148 dairy farms operated statewide, mainly clustered in seven of the state's 33 counties.

Like the industry nationwide (Powell et al., 2010), New Mexico's growing dairy industry appears to be concentrating. In 1997–2017, in the state's top dairy-producing counties, the number of farms declined while the number of cows increased (Supplement 1). Animal inventories and land bases vary among dairy farms across the state, but it is reasonable to expect that a typical farm (i.e., one that reflects the current [2019] average management among farms statewide) would raise cattle in open lot confinement, with 2,500–3,000 cows and 400–500 ha of on-farm cropland for the cows' forage ration (Joshi & Wang, 2018; USDA-NASS, 2017). According to Rotz et al. (2021), that typical farm would generate ~520,000 kg manure nitrogen (N) yr^{-1} and 64,000 kg manure phosphorus (P) yr^{-1}, of which 14% of N (~73,000 kg) and 60% of P (~38,000 kg P) would need to be exported to maintain a nutrient balance on the farm relative to crop requirements (Supplement 2). On this typical dairy farm, cropland is maintained for the forage ration for the farm's cows, whereas its grain ration is likely imported across state lines and often from significant distances (New Mexico dairy extension specialist and dairy producer, personal communications; Rotz et al., 2021).

Core Ideas

- Collaborative manureshed management requires agricultural land to utilize manure nutrients.
- In New Mexico, dairies are clustered in the state's limited cropland base.
- Losses and gains of cropland, rangeland, and developed land were observed in three manuresheds.
- Change rates are slow, but development can restrict manureshed management.

New Mexico's agricultural communities have built logistical and social structures to facilitate the redistribution of manure nutrient surpluses found at the state's dairy farms, partially motivated by environmental concerns (New Mexico dairy extension specialist and dairy producer, personal communications). Indeed, New Mexico has been a leader among top dairy-producing states in policies and practices to protect groundwater quality (Harter et al., 2014; Lazarus et al., 2010; Ogburn, 2011). Anecdotally, however, New Mexican dairy farmers have perceived a decline in options for exporting manure to nearby croplands due to cropland conversion. Even a small degree of land use conversion may have a large effect on land tenancy and the local, cooperative structures that are required for collaborative landscape management (Huntsinger & Oviedo, 2014); yet, the impacts of conversion are uncharted.

We sought to understand the degree and potential impacts of land use change in three important dairying landscapes of New Mexico to evaluate how such change may influence prospects for cooperative manure recycling among farms. We used the manureshed concept to organize our assessment because it provides a framework for understanding the opportunities, constraints, and sustainability tradeoffs related to manure transfers from manure source areas to lands that can use the manure (Saha et al., 2018; Spiegal et al., 2020). We focus on three clusters of dairy farms and the lands immediately surrounding the clusters, treating the surrounding lands as three local-scale manuresheds. In each manureshed, we quantified land use cover in 2019 and land use change in 2008–2019. We also calculated the nutrient balance between the manure supply from each dairy cluster vs. crop demand in its surrounding lands as of 2019. We discuss how different complements of land use change and nutrient balance can generate a unique set of opportunities and challenges regarding communal manureshed management. We conclude with implications of our findings for achieving the manureshed vision in New Mexico of the future.

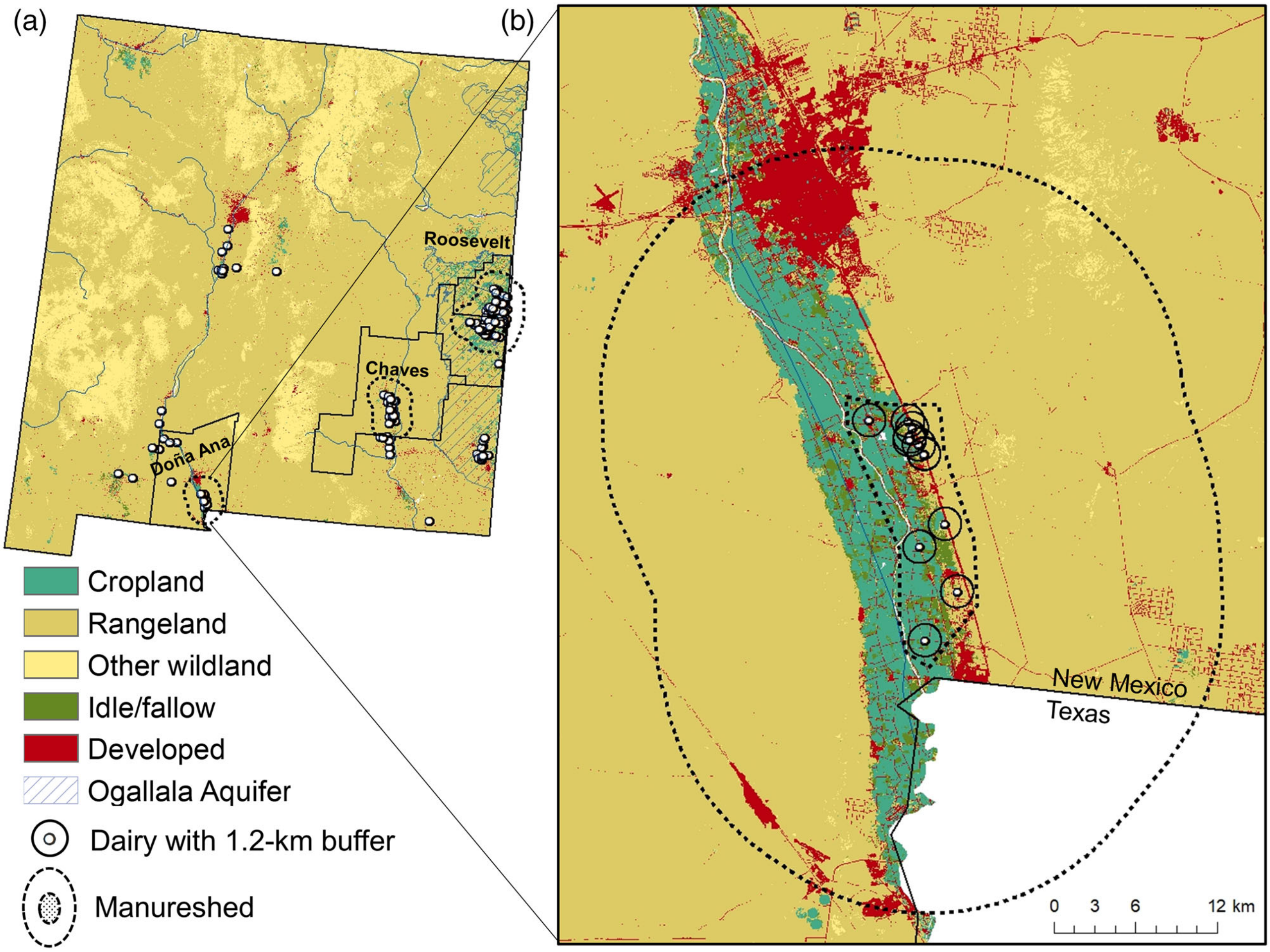

FIGURE 1 (a) Land cover in New Mexico in 2019, with three dairy manuresheds delineated in dotted lines. The four counties where the manuresheds are located are delineated in solid black lines. The Doña Ana manureshed is located in Doña Ana County and part of Texas; the Chaves manureshed is contained mainly in Chaves County; and the Roosevelt manureshed spans Curry County, Roosevelt County, and part of Texas. (b) Detail of the Doña Ana dairy cluster and surrounding manureshed

2 | MATERIALS AND METHODS

2.1 | Mapping dairy clusters and surrounding manuresheds

We first identified the locations of New Mexico's active dairies operating with groundwater discharge permits, each of which contains a plan for how the dairy operator will manage process-generated wastewater and manure solids and monitor groundwater quality (Lazarus et al., 2010). We obtained a list from the New Mexico Environment Department's website, which contained 193 records with street addresses for agricultural businesses with active discharge permits as of December 2020 (NMED, 2020). After removing the records for inactive permits and non-dairy operations, 148 records remained. We then used geocoding in the ggmaps package in R (Kahle & Wickham 2013) to join a geospatial point location (latitude, longitude) to each address provided in the list. We verified our results by looking at each point in Google Earth, checking for the presence of a dairy. Only 127 of the 148 dairies were producing milk as of December 2020 (USDA Milk Market Administrator, 2020). The remaining 21 were heifer, calf, and steer facilities, but all produced manure and therefore maintained groundwater discharge permits.

Next we calculated the distance between each pair of nearest-neighbor dairies in New Mexico's seven major dairy-producing counties (Chaves, Curry, Doña Ana, Eddy, Lea, Roosevelt, and Socorro) and calculated the average distance between nearest-neighbors in each of the counties. We selected a cluster of dairies in Chaves County, a cluster in Doña Ana County, and a cluster spanning the Curry and Roosevelt county line for further analysis; these clusters contained the largest numbers of dairies in especially close spatial proximity (Figure 1a).

We then created a 1.2-km buffer around each dairy point to represent each dairy as a 454-ha circle of land, reflecting a "typical" dairy of New Mexico (Joshi & Wang 2018; USDA-NASS, 2017; Supplement 2). We next drew "free-hand" a new polygon around each cluster of dairies as a convex hull and then created an 18-km (11.1-mile) buffer extending from each convex hull (Figure 1b). The buffer represented potential receiving lands outside of each dairy cluster (i.e., the manureshed). The buffer size of the receiving area (18 km) was selected because we have observed that this distance is within limits of typical costs of hauling solid manure from dairies, including price of diesel, labor, and vehicle use.

2.2 | Manure nutrient balance in the three manuresheds

2.2.1 | Manure nutrient supply

We calculated the manure supply from each of the three dairy clusters by extrapolating the manure N and P available for export from the "typical" New Mexico dairy farm to all dairies per dairy cluster. Animal inventories and land bases vary among dairy farms statewide, but it is reasonable to expect that a typical farm (i.e., one that reflects the current [2019] average among all of the state's farms) would support 2,500–3,000 cows and contain 400–500 ha of cropland (Joshi & Wang, 2018; USDA-NASS, 2017). We used outputs from the Integrated Farm System Model (USDA-ARS, 2020) to estimate the amount of manure nutrients available for transport off that typical farm. Seven farms, which range in size and management yet which together average 2,657 cows and 454 ha of cropland, were simulated to estimate manure N and P available for transport off of each of the seven farms after accounting for application to on-farm crops (Rotz et al., 2021; Supplement 2). Calculating the mean of that exportable manure N and P to represent conditions of the typical farm, we found that 73,293 kg manure N and 38,364 kg manure P would be in excess of on-farm crop needs and available for transport (Supplement 2). We multiplied the N and P by the number of farms per dairy cluster to estimate the total manure N and P available for transport from each cluster for current (2019) practice.

We focused only on dairy manure nutrients, instead of beef and dairy together, because dairy manure nutrients eclipse nutrients from New Mexico's fed beef industry. Looking statewide at all of New Mexico's "recoverable" manure nutrients (i.e., nutrients from manure collected from feeding operations that can be applied for other uses), the dairy industry produces the vast majority, well outweighing those produced by the handful of beef feedyards along the New Mexico–Texas border (Spiegal et al., 2020).

2.2.2 | Crop nutrient demand

Because cropland is currently the typical repository for surplus nutrients in cooperative manure management agreements in New Mexico, we explored the assimilative capacity of the croplands surrounding each dairy cluster. We did so to inform our discussion of how land use change observed in the past may predict impacts of land use change on nutrient balances and cooperative manureshed agreements in the future.

We calculated the assimilative capacity of the croplands in the buffers surrounding each cluster that intersected with New Mexico only (we did not calculate the assimilative capacity of crops in Texas in the cases of the Doña Ana and Roosevelt manuresheds). We used the extent of each crop in those lands in the Cropland Data Layer (CDL) (USDA-NASS, 2020), the crops' yield per acre reported in the 2019 New Mexico Agricultural Statistics report (USDA-NASS New Mexico Field Office, 2020), and uptake coefficients from Kellogg et al. (2014). Estimates reflected the year 2019 (Supplement 3).

2.3 | Land use change in the three manuresheds

To calculate land use dynamics in the three manuresheds, we first calculated the area of each 18-km buffer in terms of the total area and the area of the buffers that intersected with New Mexico only. Within the buffers intersecting with New Mexico, we calculated (a) the area (ha) in 2019 covered by cropland, rangeland, developed land, and idle/fallow land and (b) the area (ha) of land use change in 2008–2019 from cropland to rangeland, rangeland to cropland, and "spreadable land" to developed land (spreadable land comprised cropland, rangeland, and idle/fallow land).

Land use changes were estimated from 2008 to 2019 using the CDL (USDA-NASS, 2020). For each year, we categorized 132 classes of the CDL into six land types: cropland, rangeland, other wildland, idle/fallow, developed, and other/undefined (Bestelmeyer et al., 2015). One-way, one-time shifts from rangeland to cropland, cropland to rangeland, and "spreadable land" to developed were identified on a per-pixel basis (30-m pixels) (Lark et al., 2015). Pixels were grouped if they exhibited the same type of conversion and touched at either a side or corner, and only groups 45 pixels (~4 ha) or larger were included in calculations of converted area.

2.4 | Caveats

Our assessment depends on multiple variables and several assumptions and thus requires caveats. First, manureshed management is not a silver bullet for the wicked problems related to uneven nutrient distribution in modern agriculture. Tradeoffs must be carefully considered in each land and manure management situation. For instance, manure has qualities, such as particular N/P ratios, odor, salts, and possibly weed seeds, that can result in a low value-to-mass ratio (Kleinman et al., 2012), making hauling and spreading undesirable for certain situations. In New Mexico, the dominant crops that we consider as candidates for receiving manure in dairying landscapes include alfalfa (*Medicago sativa* L.), winter wheat (*Triticum aestivum* L.), corn (*Zea mays* L.) for silage, sorghum [*Sorghum bicolor* (L.) Moench] for grain, and cotton (*Gossypium hirsutum* L.) (USDA-NASS, 2020). Their N/P ratios are higher than the typical N/P of dairy manure (Kellogg et al., 2014), so applying manure to meet N needs can result in an over-application of P (Powell et al., 2010). Also, if spreading is conducted repeatedly on the same field or pasture, P and N can saturate the soil, leading to eutrophication and other ecological costs that can ultimately reduce the amount of land available to assimilate manure nutrients in cooperative manureshed agreements (e.g., Kleinman et al., 2012). It is also important to note tradeoffs of losing soil cover and possibly soil carbon when crop removal, with or without manure application, is not carefully managed. Nutrient management plans are designed to identify and address these concerns to enhance chances for applying manure or other nutrient sources at the right time, in the right place, and at the right rate. Careful land management planning, such as that reflected in nutrient management plans, is paramount for realizing the manureshed vision in agricultural landscapes.

Another important caveat is the many unknowns related to how spreading manure on rangelands affects rangeland ecology and productivity. Neither rangeland nor fallow land may be viable receiving lands for manure nutrients due to their innate characteristics (see "Implications of land use change" below). In certain cases, these tradeoffs may prompt researchers and planners to explore uses for surplus manure beyond land spreading, including manure to energy and composting for horticultural industries (Joshi & Wang, 2018; LPELC, 2017).

We also recognize caveats related to our quantitative analyses. First, the extrapolation of the manure nutrients available for transport from a typical dairy farm (see Supplement 2) to all farms in each cluster depends on the assumptions that all dairy farms in each cluster support a similar herd size, land base, and nutrient uptake by an on-farm cropping system. Variability is the rule in agriculture; thus, these estimates of surplus manure nutrients from each cluster should serve only as a starting point to understand the nutrient balance between dairy clusters and their surrounding croplands.

Regarding the estimate of cropland assimilative capacity in the three local manuresheds, we recognize that assimilative capacity varies with season, but our analysis covers the entire year of 2019. Moreover, we recognize that the dairies in each dairy cluster would theoretically be competing for surrounding receiving lands and that in the eastern part of the state such competition would extend among dairies and a few beef feedyards. Due to a lack of available data, we did not identify or quantitatively remove croplands and rangelands that are used to grow feed for beef cattle from the three manuresheds, although these lands would likely already be part of a manure application strategy by the few beef feedyards (Asem-Hiablie et al., 2015).

Finally, although local-scale manuresheds are the norm overall, we recognize that dairy producers maintain relationships with crop producers in locations well beyond the lands surrounding their dairies (New Mexico dairy extension specialist, personal communication). We examined land use change in surrounding lands as a starting point to enhance understanding of the possible influence of land use change on manuresheds managed on the local scale, which is currently prevalent for manure transfers nationwide (MacDonald et al., 2009).

3 | RESULTS AND DISCUSSION

3.1 | Geography of New Mexico dairy: Farm density and land use cover

Our analysis confirmed a pattern illuminated by maps of dairies and other land uses in New Mexico: most dairies across the state are located in clusters, and the clusters are located among the state's limited croplands (Figure 1a). Average distances between nearest dairy neighbors ranged from 1 km in Socorro County to 15 km in Eddy County (Socorro and Eddy county lines are not pictured in Figure 1a).

Whereas croplands represented only 1.5% of the land cover statewide as of 2019, in the immediate vicinity of the dairies, cropland represented much greater percentages: from 5% (13,301 ha) of the Chaves manureshed to 24% (70,636 ha) of the Roosevelt manureshed (Table 1). Although we calculated cover and change only within New Mexico, our analysis revealed that Texan agricultural lands are part of the Doña Ana and Roosevelt manuresheds (Figure 1b; Table 1), pointing to an opportunity for collaborative management not only across fence lines but across state lines as well.

3.2 | Manure nutrient supply vs. cropland nutrient demand

Our simulation of manure nutrient supply and demand indicates that the croplands in each of the three manuresheds could assimilate the surplus N available for transport from associated dairies by significant margins as of 2019 (Table 1). In the case of P, the croplands of the Doña Ana manureshed could assimilate the surplus nutrient, with assimilative capacity to spare. The croplands of the Roosevelt manureshed could assimilate the surplus P from its dairy cluster by only a thin margin (2.26 million kg P supply vs. 2.36 million kg

TABLE 1 Farm density per dairy cluster, land use cover and change per manureshed, and nutrient balances between dairy clusters and their surrounding manuresheds

		Chaves	Doña Ana	Roosevelt
Number and distance between dairies in cluster	number of dairies	32	12	59
	mean distance between nearest-neighbor dairies	1,729 m	1,588 m	2,902 m
Estimated manure nutrient supply from dairy cluster; cropland demand in surrounding manureshed	manure N and P available for relocation	2,345,376 kg N, 1,227,648 kg P	879,516 kg N, 460,368 kg P	4,324,287 kg N, 2,263,476 kg P
	cropland demand for N and P	3,690,219 kg N, 540,025 kg P	26,915,545 kg N, 5,236,072 kg P	12,088,939 kg N, 2,363,832 kg P
	top three crops by area in manureshed	alfalfa, barley, corn for silage	cotton, corn for silage, alfalfa[a]	winter wheat, sorghum for grain, corn for silage
Land in manureshed, 2019, ha	total area[b]	278,861 ha	166,012 ha	300,495 ha
	rangeland	245,596 ha	133,836 ha	197,096 ha
	cropland	13,301 ha	16,198 ha	70,636 ha
	developed	9,112 ha	11,043 ha	7,356 ha
Land use change in manureshed, 2008—2019, ha	rangeland to cropland	906 ha	464 ha	7,975 ha
	cropland to rangeland	350 ha	76 ha	7,624 ha
	spreadable land[c] to developed land	365 ha	1,187 ha	322 ha

[a]Pecans are a top crop in the Doña Ana manureshed but are not included in cropland assimilative capacity (see Supplement 3 for details).
[b]The area of the buffer that intersected with New Mexico. Texas covered 24,822 and 130,828 ha of the Doña Ana and Roosevelt manuresheds, respectively.
[c]Includes cropland, rangeland, and idle/fallow land.

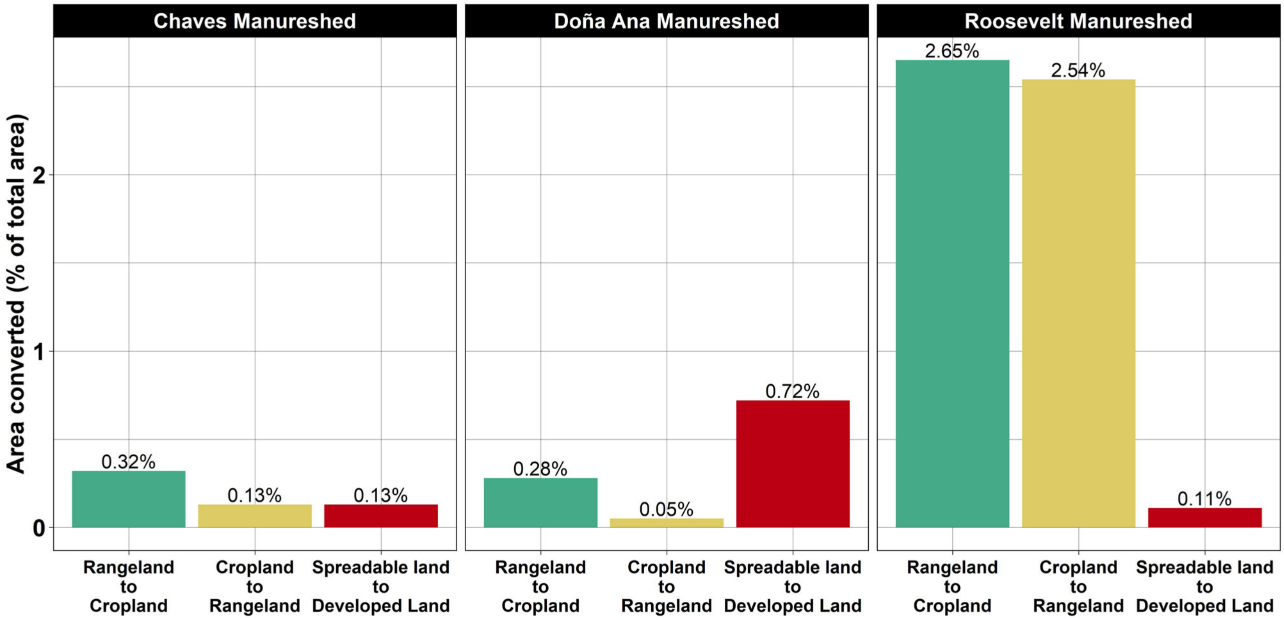

FIGURE 2 Percentage of total land area that changed in 2008–2019 in the three dairy manuresheds. See Table 1 for areas (ha) used to calculate the percentages.

P demand). The croplands in the Chaves manureshed had insufficient assimilative capacity for the P available from the Chaves dairy cluster in this analysis.

The differences in balances among the dairy clusters and surrounding manuresheds were a function of (a) primary crops per manureshed (e.g., cotton, which dominates the croplands of the Doña Ana manureshed, has a relatively high assimilative capacity for N and P) and (b) the ratio of number of dairies vs. amount of cropland per manureshed (i.e., 416 ha cropland per dairy in the Chaves case, 1,350 ha cropland per dairy in the Doña Ana case, and 1,197 ha cropland per dairy in the Roosevelt case). As noted previously, these estimates depend on many assumptions (e.g., that all dairy farms in each cluster support similar herd sizes, on-farm land bases, and nutrient uptake by on-farm cropping systems). In the case of the Roosevelt manureshed, the crops in the Texas portion of the receiving area likely provide additional assimilative capacity, rendering the margin of assimilation of P less thin; however, in this analysis the crops in Texas were not included.

Notably, a recent assessment of county-level manure "sources" and "sinks" as of 2012, which used a related but distinct approach to estimate recoverable manure nutrients in excess of cropland assimilative capacity (Spiegal et al., 2020), provided a similar picture of N and P balances. Just as the present study found that the lands surrounding the three dairy clusters could assimilate the dairy manure N from the clusters, that study found that the croplands of all four counties intersecting with the manuresheds were net sinks for manure N. That study found Chaves and Curry counties to be net sources of manure P. Our study also found the Chaves manureshed to have a manure P in excess of assimilative capacity. However, our Roosevelt manureshed, which intersects with Curry County, was in P balance (by a thin margin). We cannot directly compare nutrient balances at the manureshed scale in the present analysis vs. the county scale in Spiegal et al. (2020), illuminating the importance of scale when calculating, reporting, and interpreting nutrient balances of manure sources vs. sinks (Booth & Kucharik, 2021).

3.3 | Land use change in the three manuresheds

Each manureshed underwent each type of land use change, with the magnitude of change varying among manuresheds (Table 1). The greatest proportion of change occurred in the Roosevelt manureshed intersecting with New Mexico, where 2.65% (7,975 ha) of the total land area (300,495 ha) was converted from rangeland to cropland; conversion from cropland to rangeland closely trailed at 2.54% (7,624 ha) converted (Figure 2). These losses and gains corroborated with those recently identified for the entirety of Roosevelt County (Gedefaw et al., 2020). It is possible that both the county-wide and manureshed-scale analyses detected dynamic shifts of crop and range production in connection with USDA's Conservation Reserve Program (CRP), which tend to fluctuate with commodity prices and climate pressures (Kleinman et al., 2018). Roosevelt and Curry counties are among the top three counties for the program, with a total of 90,337 ha installed as of January 2020 (USDA-FSA, 2021b), but they are also the top two counties slated for expiration by 2021, with 38,608 ha set to expire (USDA-FSA, 2021a). Thus, the equivalent conversions between cropland and rangeland observed in this manureshed may have resulted from dynamic enrollment in and out of CRP.

In the Chaves manureshed, the change from rangeland to cropland was over twice as great as the other two types of change in the manureshed: 0.32% or 906 ha changed from rangeland to cropland vs. 0.13% from cropland to rangeland and 0.13% from spreadable land to developed land.

The Doña Ana manureshed experienced the greatest relative degree of conversion to developed land, both within the manureshed and compared with other manuresheds, at 0.72% (1,187 ha). The degree of change to developed land was likely related to the urban expansion along freeway corridors in the greater Las Cruces-El Paso area (Figure 1b) (Ward et al., 2006).

Differences among manuresheds aside, the overall magnitude of change was small, representing 2.65% or less in any case (Figure 2). Similarly low rates of change were found in southern Arizona and southern New Mexico over the same time period (Bestelmeyer et al., 2021), and the change found for the Southwest was broadly in line with nationwide rates recently presented (Lark et al., 2020; Spangler et al., 2020).

3.4 | Implications of land use changes

Overall, our analysis suggests that the manure nutrient supply and cropland demand in three local-scale manuresheds intersecting with New Mexico were largely in balance as of the year 2019 (except for the case of the Chaves manureshed, where crops were unable to assimilate the surplus manure P from the dairy cluster). Assuming cropland remains the main repository of manure nutrients in cooperative agreements, continued conversion of croplands as observed in 2008–2019 may affect this balance. Here we broadly explore some potential implications of the three types of land use change, recognizing that interdisciplinary research with explicit participation of producers, industry representatives, and key actors, such as manure brokering professionals, is needed to truly understand the causes and effects of land use change, to identify sustainability goals for the future, and to work in tandem to achieve those goals.

3.4.1 | Change to and from cropland

We found varying degrees of cropland conversion in the three manuresheds. The greatest degree of conversion to rangeland was found in the Roosevelt manureshed, and a clear signal of conversion from cropland (along with rangeland and fallow land) to development was detected in the Doña Ana landscape. Water availability is key to understanding why these lands changed in the past, their potential for change in the future, and the prospective effects of those changes on manuresheds and other management approaches designed for sustainability outcomes. The Doña Ana manureshed is located within the Upper Rio Grande Basin that extends from southern Colorado to south of El Paso, TX (Ward et al., 2006); the Chaves manureshed is situated on the Pecos River (a major tributary of the Rio Grande); and the Roosevelt manureshed is on the multi-state Ogallala Aquifer. Competition for water among agricultural, military, industrial, wildlife, and urban uses is a major issue for the Rio Grande, with allocation controlled by inter-state and international laws and with intensified competition during drought (Ward et al., 2006). Irrigation of crops has been found to contribute to the salinization of the Pecos River (Hoagstrom, 2009) and salinization and depletion of the groundwater stores of the Ogallala Aquifer (Chaudhuri & Ale, 2014).

Advocating for increases or decreases to water allocated for the forage crops that are associated with dairy production and understanding the potential statewide and regional effects such water diversion deserve a nuanced treatment that is outside of the scope of this paper. Yet, in the context of dairy manureshed management, cropland is typically the receiving land of choice in cooperative agreements that enable dairy manure recycling for multiple goals. In this sense, conversion of croplands within the lands surrounding the three dairy clusters may disrupt current nutrient balances and communal manure management systems and force producers to travel farther to find suitable land repositories for recycling. Farther hauling can increase costs, which are already increasing due to reduced access to water and other climatic impacts (Havstad et al., 2018). Managers of croplands farther afield may not be willing to accept manure, potentially exacerbating costs of manure transport agreements (Joshi & Wang, 2018). Looking ahead, cropland conservation may be an important consideration for regional planners focused on the sustainability of manureshed management, but the tradeoffs of water use and allocation in the landscapes of the Upper Rio Grande Basin, Pecos River, and Ogallala Aquifer must be considered.

3.4.2 | Change to and from rangeland

We found the overall conversion to rangeland to be minimal, except for the dynamic interplay between cropland and rangeland observed in the Roosevelt manureshed possibly linked to USDA's CRP. Rangelands provide a suite of ecosystem services valued by many segments of society, including forage for the ranching industry, biodiversity maintenance, scenic beauty, and soil carbon storage (Havstad et al., 2007). Although some contend that livestock grazing is not an optimal use for western rangelands (e.g., Beschta et al., 2013), it is worth noting here that ranching uses much less ground and surface water than does crop production on a per area basis (Ridoutt et al., 2012).

Despite the benefits they provide, rangelands are perpetually at risk of being fragmented and converted to more intensive uses with higher rates of economic return (Sayre et al., 2013). In New Mexico, most rangelands are publicly owned, but where possible, rural housing units and utility-scale solar and oil energy development can expand into rangeland areas, causing fragmentation (Alred et al., 2015; York et al., 2011). The preservation of ranching and rangelands requires thoughtful regional planning (e.g., Doña Ana County, 2010; Roosevelt Soil & Water Conservation District, 2016); however, as is the case for croplands, a fully nuanced discussion on the pros and cons of maintaining working rangelands is beyond the scope of this paper.

From the perspective of manureshed management, rangeland has intermittently been perceived by researchers as a viable option to assimilate manure nutrients in New Mexico (e.g., Cabrera et al., 2009; Joshi & Wang, 2018; Stavast et al., 2005), with the idea that spreading manure on rangeland can improve forage and/or soil properties (e.g., Cabrera et al., 2009; McFarland et al., 2007; Stavast et al., 2005). Yet in certain rangeland settings across the arid and semi-arid West, manure application has been found to adversely affect biodiversity, which is strongly valued by many stakeholders (e.g., Blumenthal et al., 2017; Gravuer et al., 2019). In addition, relatively little is known about the effects of manure on rangelands' soil properties, plant biomass production, soil greenhouse gas emission, or forage quality.

Limited research from the blue grama rangelands of the Gila National Forest, New Mexico (the study site is not included in any of the three manuresheds) found that dairy manure applied at 54 kg P ha^{-1} conserved and enhanced rangeland soil properties and their herbaceous productivity (Cabrera et al., 2009). However, rangeland is highly variable over space and time, and such experimentation must be replicated in different types of soils and vegetation, including the shrub-invaded black grama grassland of the Doña Ana manureshed and the shortgrass steppe of the Chaves and Roosevelt manuresheds (Allison & Ashcroft, 2011), before the practice can be deemed effective widely.

Even if spreading in multiple rangeland types is deemed effective for certain management targets, it is important to note that rangelands may never become a cost-effective choice for manure application because inputs such as fertilizer, irrigation, and exotic forage species plantings to improve forage productivity have almost universally been shown to be destabilizing, cost-ineffective, or both (Chen et al., 2017; McClaran & Anable, 1992). There have been few, if any, examples where attempts to increase productivity of the forage component of rangeland ecosystems by applying agronomic practices (e.g., fertilizer and irrigation) have clear cut positive cost-to-benefit ratios.

Although we did not focus explicitly on fallow land in this analysis, chances are that the land became idle due to lack of water or other management challenges. Those challenges may outweigh the potential benefits of including fallow lands in cooperative manureshed agreements. Thus, although rangeland or fallow land might appear an attractive solution to the wicked problem of nutrient imbalance in the New Mexican dairy industry, more information, and possibly improved technologies for integrating manure into drylands, are needed so that tradeoffs can be carefully weighed.

3.4.3 | Change to and from developed land

Whereas land use changes to cropland, rangeland, and fallow land result in various tradeoffs for manuresheds and the region on the whole, urbanization removes the possibilities of ecosystem service provision by any of these lands. Many ecosystem services are possible only when these lands remain intact and when farmers and ranchers are present to steward the services (Huntsinger & Oviedo, 2014).

From the perspective of manureshed management, the conversion from spreadable land to developed land may result in irreversible fragmentation of the agricultural landscapes where dairies are nested, imparting long-lasting effects on farmer-to-farmer social structures.

When weighing the tradeoffs of developing croplands into more intensive uses such as housing or retail, the well-being of communities inhabiting those developments must be considered for truly sustainable outcomes. In the three manuresheds studied here, developments would be nested in agricultural landscapes where manure is excreted and concentrated, thus potentially impacting the quality of life of new inhabitants (e.g., Deviney et al., 2021). Such considerations should be part of the overall coordinated research and planning that will enable optimal manureshed management in New Mexico.

4 | IMPLICATIONS FOR SUSTAINABLE MANURESHED MANAGEMENT IN NEW MEXICO

Although our analysis found differences in nutrient balances and past land use changes in three dairy manuresheds of New Mexico, overall, our assessment suggests that if the continuation of collaborative manure transfers is desired, then coordinated, participatory, and interdisciplinary planning is needed.

In the Chaves manureshed on the Pecos River of New Mexico, we detected minimal land use change from 2008 to 2019, along with croplands that could assimilate all of the manure

N from its cluster of dairies but not all its manure P. Although minimal land use change was detected in 2008–2019, a loss of cropland would result in further diminished assimilative capacity and the potential need for dairy producers to travel farther out of the manureshed for collaborative manure transfers. Tradeoffs of application on the shortgrass steppe of this part of New Mexico should be investigated.

In the Doña Ana manureshed on the Rio Grande, increased exurbanization could ultimately diminish the substantial degree of assimilative capacity of crops in the landscape and affect the existing social structures that enable manure transfers across farm gates.

In the Roosevelt landscape on the Ogallala Aquifer, thin margins of P assimilative capacity and dynamic change from cropland to rangeland and back again point to the need to understand more about the effects of dairy manure on the shortgrass steppe of that landscape. In the case of the Doña Ana and Roosevelt landscapes, explicit calculation of the assimilative capacity of the crops in the Texas portions of the manuresheds will help to understand the full scope of assimilation, regardless of state lines.

These three situations point to an ideal scenario for local-scale dairy manuresheds in the southwestern United States, which would entail manure being generated in areas with local portfolios of productive lands that can sustainably use the manure nutrients without contributing to environmental quality concerns (water, air, soil) or agronomic tradeoffs (Pagliari et al., 2020). Yet, as that portfolio of spreadable lands shifts over time (e.g., as receiving lands become ecologically impacted by nutrient build-up or weed seeds in manure or as neighbors become concerned over odor or environmental quality), cooperative structures will need to adapt. Given that the New Mexico dairy industry has already built dynamic, informal networks enabling the relocation of manure from dairy feeding operations to cropping systems in need, often capitalizing opportunistically on nutrient supply and demand (New Mexico dairy extension specialist and dairy producer, personal communications), the industry is well poised to use its experience to build more intentional regional plans and more formal structures. Strong market incentives and cooperative, intentional planning efforts coupled with tools that reliably connect producers are needed.

Also needed is reliable, replicated research on the effects of manures on rangeland ecology and productivity, with prioritization in the landscape of the Roosevelt and Chaves manuresheds, as well as the quantification of the minimum threshold of spreadable land needed to sustain collaborative manureshed management (e.g., Bartelt & Bland, 2007). We contend that interdisciplinary research with explicit participation of producers, industry representatives, and key actors, such as manure brokering professionals, can help fill these knowledge gaps and help New Mexico manure management advance to a sustainable future.

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AUTHOR CONTRIBUTIONS

Sheri Spiegal: Conceptualization; Data curation; Investigation; Methodology; Project administration; Writing-original draft; Writing-review & editing. Jebediah C. Williamson: Data curation; Formal analysis; Methodology; Writing-original draft; Writing-review & editing. K. Colton Flynn: Data curation; Formal analysis; Methodology; Writing-original draft; Writing-review & editing. Anthony R. Buda: Formal analysis; Investigation; Writing-original draft; Writing-review & editing. C. Alan Rotz: Data curation; Methodology; Writing-original draft; Writing-review & editing. Peter J. A. Kleinman: Conceptualization; Investigation; Writing-original draft; Writing-review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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