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Crop-specific manure nitrogen and phosphorus management in US croplands from 1970 to 2025

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Abstract Manure is the largest organic nitrogen (N) and phosphorus (P) input to US cropland, but existing long-term data products often estimate manure from broad livestock classes that overlook herd structure and do not resolve crop-specific management. This masks two linked processes that matter for nutrient budgets and loss-risk assessments: livestock-based top-down demographic change in manure production and agronomic-surveyed bottom-up variation in timing, method, and treated-area intensity of manure application. Here, we reconstructed a spatially explicit manure N and P management dataset for the contiguous United States by combining an age-group manure production framework, county livestock distributions, state-level crop-specific manure management surveys, treated-area information, and crop distribution maps. The management product reports county-level crop-specific manure N and P use rates on treated area and on all cropland for 1970-2025. Age-group manure production increased from 4.7 to 7.4 Tg N yr^{-1} and from 0.73 to 1.3 Tg P yr^{-1} between 1970 and 2021, then declined to 7.0 Tg N yr^{-1} and 1.2 Tg P yr^{-1} by 2025. The crop-use application component increased from 0.79 to 1.4 Tg N yr^{-1} and from 0.25 to 0.53 Tg P yr^{-1} between 1970 and 2025 (county-crop allocation for corn, soybean, winter wheat, spring wheat, cotton, sorghum, rice, barley, durum wheat, other crops, and cropland pasture), after peaking around 2021-2022. Cross-dataset comparison shows that, among existing national data products, this top-down and bottom-up reconciliation is consistent to the bottom-up crop-management constraints while placing manure N near the lower range of existing products and substantially reducing manure P relative to broad livestock classes estimates. This dataset supports crop-specific nutrient budgets, gridded crop and water-quality modeling, and management-resolved assessments of manure N and P loss risk.

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1. Introduction

Animal manure is a major pathway through which livestock production returns nitrogen (N), phosphorus (P), carbon, and micronutrients to agricultural soils. In the United States (US), manure supplies a large organic nutrient pool that can substitute for mineral fertilizer, maintain soil organic matter, and connect livestock and cropping systems (Bouwman et al., 2013; Bian et al., 2021; Falcone, 2021; Wang et al., 2026). This recycling benefit depends on whether manure nutrients reach crops at agronomically useful rates. When livestock production becomes spatially concentrated, local manure supply can exceed nearby crop demand, creating N loss pathways through ammonia volatilization, nitrous oxide emissions, and nitrate leaching, and P loss pathways through runoff, erosion, and legacy soil accumulation (Yang et al., 2016; Stackpoole et al., 2019). Resolving where manure N and P are produced, where they are applied, and how they are managed is therefore essential for nutrient budgets and for models of agricultural water-quality and greenhouse-gas impacts.

Spatially explicit manure N and P datasets are essential to evaluate regional manure nutrient recycling, especially the redistribution of manure nutrients from livestock-intensive source areas to cropland areas where manure can substitute for synthetic fertilizer (Spiegal et al., 2020). This spatial mismatch exposes the core data challenge for manure accounting: livestock-based top-down manure production totals are critical to close county nutrient budgets, whereas survey-based bottom-up crop management information is crucial to identify where manure can realistically substitute for mineral fertilizer and where nutrients loss risks are concentrated.

Existing US manure products have provided valuable long-term estimates, but they often separate production from management. The synthetic N fertilizer dataset of Cao et al. (2018) provides a useful precedent, showing that nutrient-input products are more useful for biogeochemical and water-quality modeling when they resolve application rate, timing, and fertilizer type rather than annual totals alone. Top-down products multiply county livestock inventories by broad animal-category excretion coefficients and recoverability factors, then distribute manure over agricultural land (Yang et al., 2016; Bian et al., 2021; Falcone, 2021). These estimates preserve broad national and regional patterns, but broad categories can suppress changes in age group, body weight, feed intake, and production stage. Bottom-up survey data provide the missing crop-management perspective: the USDA Economic Research Service (ERS) Agricultural Resource Management Survey reports crop-specific manure treated area, application rate, timing, and method for major field crops (USDA-ERS, 2024), and recent ERS synthesis shows that manure reaches only a small fraction of US cropland, with strong differences among crops (Lim et al., 2023). Used alone, however, these survey data are incomplete in space and time and are not closed to a national manure mass balance. A long-term manure management product must therefore reconcile top-down recoverable manure N and P supply with bottom-up crop-specific management, while keeping production, recoverability, crop allocation, treated-area percentage, application rate, timing, and method conceptually separate.

These constraints also make management attributes, not only annual nutrient totals, central to a useful manure dataset. Farmers and advisors value manure for crop fertility and soil benefits, but recent stakeholder evidence identifies transportation and application cost, air-quality concerns, and timing constraints as major barriers to manure use (Erickson et al., 2025). Thus, a spatial manure product that resolves only production and annual application insufficiently show where recycling is agronomically plausible or where losses are likely to be amplified by crop, season, and placement choices. Linking crop-specific application rates with timing and method therefore provides the management context needed to connect manure supply, crop nutrient demand, and environmental risk.

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To address this need, we reconstructed a spatially explicit manure N and P management dataset for the contiguous United States (CONUS). The dataset reconciles a top-down age-group production constraint, available for 1960-2025 from USDA-NASS Quick Stats and Census of Agriculture records, with bottom-up crop-specific application and rate products available for 1970-2025 from USDA-ERS ARMS, USDA-COA treated-area records, county crop-area tables, annual 4 km total N and P all-cropland rate rasters for 1970-2021, and state-by-crop timing and method fractions for 1970–2019. Our objectives were to (1) update broad-category county manure totals with an age-group-based production framework that resolves livestock class, body size, and production stage; (2) reconcile these county totals with state-level crop-specific survey information on application rate, timing, and method; and (3) map annual total crop-specific manure N and P application to 4 km cropland while retaining timing and method as state-by-crop management fractions. We used the dataset to quantify national N and P trends, identify crop and regional hotspots, compare our estimates with existing manure products, and evaluate the management settings that shape manure nutrient recycling and loss risk.

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2. Methods

We developed annual manure N and P production for CONUS counties from 1960 to 2025 using an age-group framework with dynamic animal-specific coefficients. We then reconstructed state-level crop-specific manure application rates, timing, and method from survey-based bottom-up sources and reconciled the county recoverable manure N and P supply with application rate layers for 1970-2025. By downscaling state crop-specific management patterns to counties, converting treated-area rates to all-cropland rates, and spatializing the annual all-cropland N and P rates to 4 km cropland maps while retaining timing and method as state-by-crop fractions, we produced a management-resolved manure N and P dataset that keeps production, recoverable supply, crop-use application, and management attributes conceptually joint. Figure 1 outlines the workflow of the manure management database development process.

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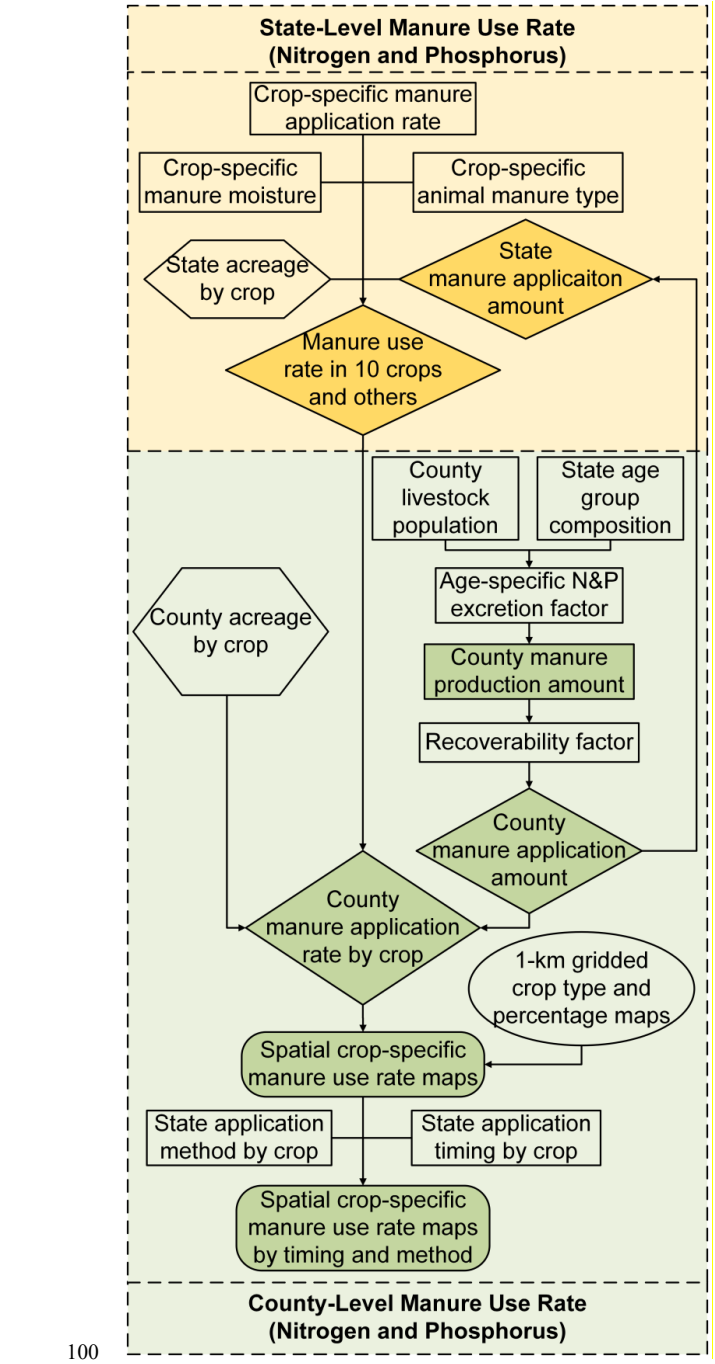


Figure 1. Workflow for reconstructing manure N and P production and crop-use management data. Livestock inventories and age-specific manure coefficients define county manure production, whereas crop management surveys and crop-area data constrain county crop allocation. The framework produces four distinct outputs: annual county manure N and P production (1960-2025), annual county crop-specific application (1970-2025), state-by-crop timing and method fractions for 1970-2019, and 4 km annual total N and P all-cropland rate layers (1970-2021).

2.1 Manure N and P production and recovery

We developed an age-group-based framework to estimate annual manure N and P excretions for counties in the CONUS from 1960 to 2025. In contrast to approaches based on aggregated livestock totals, this

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method explicitly represents livestock age and production classes, thereby accounting for differences in manure nutrient excretion among animal groups. Annual livestock population data at state and county levels were compiled primarily from USDA-NASS Quick Stats, the USDA Census of Agriculture, and related NASS survey products (USDA-NASS, 2026). The animal-specific age composition were supplemented by NASS survey records at state level. This age-group structure was allocated to county animal populations under the assumption that counties within the same state share the same age-group composition. For benchmark years with direct age-group observations (1960, 1964, 1969, 1974, 1978, 1982, 1987, 1992, 1997, 2002, 2007, 2012, 2017, and 2022,), age-group inventories were used directly. For non-benchmark years, annual age-group populations were reconstructed by linearly interpolating the ratio of each age group to its corresponding species total between adjacent benchmark observations and then rescaling the interpolated series to reported annual species totals. County species totals were subsequently aligned to the corresponding state species totals. This closure preserved real county FIPS records for spatialization and kept the county-summed national production total numerically consistent with the state-level age-group total.

Annual manure N and P production for each livestock age group was calculated as the product of animal population and class-age-specific excretion coefficient (Table S1 in the Supplement). Separate coefficients were assigned for N and P to reflect differences in animal body size, feeding regime, and production stage across livestock classes. County-level manure N and P totals were then derived by summing across all livestock groups within each state and year. This bottom-up age-group procedure links manure nutrient generation directly to livestock demographic structure and provides a more process-based production constraint than methods applying a single coefficient to broad livestock categories.

Because manure nutrients are lost during collection, storage, and transportation, only a fraction of the manure produced is ultimately recoverable for land application. We estimated recoverable manure N and P using county-level recoverability coefficients from the Nutrient Use Geographic Information System (NuGIS; https://www.nutrienttools.org/getting-started/nutrient-use-gis/) for 1987-2016. NuGIS annualized the coefficients reported by Kellogg et al. (2014) through linear interpolation. For years outside the NuGIS period, we extended the coefficients to 1970 and 2025 by holding the 1987 and 2016 values constant for earlier and later years, respectively.

2.2 Total manure N and P application

Total manure N and P application was defined as the recovered manure nutrient supply allocated to land rather than the total manure produced by livestock. For each county and year, recovered manure N and P from the age-group production framework provided the mass-balance constraint for land application. These totals were subsequently partitioned among cropland, cropland pasture, and permanent pasture using assimilative-capacity constraints, and the cropland component was further distributed to crop-specific treated-area and all-cropland rate products. This separation keeps livestock production, recoverability, and land-use allocation as distinct steps in the dataset.

2.2.1 Manure-treated area and percentage of treated area (PTA)

We reconstructed county-level acreages receiving manure applications for ten crop categories and two pasture classes from 1970 to 2022 by harmonizing USDA Census of Agriculture county treated-area records, Kellogg and Moffitt pasture treated-area estimates, USDA-ERS ARMS crop-management survey data, and county crop-area tables. The ten crop categories include nine named major crops (corn, soybean, winter wheat, spring wheat, cotton, sorghum, rice, barley, and durum wheat) plus other crops; the two pasture classes are cropland pasture and permanent pasture. USDA-COA (2024) reported manure-treated acreage on agricultural land, including cropland and pasture, for each county in 2002, 2007, 2012, 2017, and 2022. We calculated percentage of treated area (PTA) relative to total agricultural land for each

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154 county and gap-filled unavailable years by linear interpolation; for years before 2002, each county
155 retained its 2002 PTA. Annual county treated area was obtained by multiplying PTA by agricultural land
156 area for 1970–2022. For 2022–2025, the 2021 county-crop treated-area structure was carried forward and
157 scaled to updated county production constraints, so the extension should be interpreted as a production-
158 constrained continuation rather than newly observed management. Based on the total treated cropland
159 area, crop-specific planted area, and state-level crop PTA, we estimated county-level treated area for each
160 crop category using Eq. 1.

161 $$\text{Treated Area}_i = \frac{\text{PTA}_i \times \text{Area}_i}{\sum_1^{10} \text{PTA}_i \times \text{Area}_i} \times Total\ \text{Treated Area} \quad (1)$$

162 where $a_{c,i,t}$ is the county treated area receiving manure for crop i in county c and year t, $p_{s,i,t}$ is the state-
163 level crop PTA, $A_{c,i,t}$ is planted area, $A_{c,t}$ is the total county cropland area receiving manure, and i denotes
164 one of the ten crop categories.

165 **2.2.2 Assimilative-capacity allocation (AC) of manure N and P to cropland and pasture**

166 Recovered manure N and P were allocated to cropland, cropland pasture, and permanent pasture using
167 assimilative capacity (AC). AC represents the amount of manure nutrients that can be applied to available
168 land without building up soil nutrient levels over time (Kellogg and Moffitt, 2011). Based on AC values
169 for cropland, cropland pasture, and permanent pasture from Kellogg and Moffitt (2011) (Table S2 in the
170 Supplement), we calculated total manure N and P application for each land-use class within each county
171 using Eq. 2.

172 $$\text{Manure Nutrient}_i = \frac{\text{AC}_i \times \text{PTA}_i \times \text{Area}_i}{\sum_1^3 \text{AC}_i \times \text{PTA}_i \times \text{Area}_i} \times \text{Manure Nutrient Recovered} \quad (2)$$

173 where $m_{l,c,t}$ is manure N or P application amount for land-use class l in county c and year t (g N yr^{-1} or g
174 P yr^{-1}), $ac_{l,c,t}$ is assimilative capacity, $p_{l,c,t}$ is PTA, $A_{l,c,t}$ is area, $M_{c,t}$ is recovered manure N or P supply in
175 the county (g N yr^{-1} or g P yr^{-1}), and l denotes cropland, cropland pasture, or permanent pasture.

176 **2.2.3 State-level crop-specific manure N and P application rate, timing, and method**

177 The USDA Economic Research Service Agricultural Resource Management Survey (ARMS; USDA-
178 ERS, 2024) provides crop-specific manure management information at the state level for 1996–2013
179 (Table S3 in the Supplement). We estimated manure N and P use rates for nine major crops in each
180 available state from the reported manure mass application rate, animal sources of manure (beef, dairy,
181 hogs, poultry, and other animals), and manure moisture status (lagoon liquid, slurry liquid, and semi-dry
182 or dry). Because N and P content differ across animal types and moisture levels, we applied animal- and
183 moisture-resolved N and P content coefficients (Joern and Brichford, 1993). For crops with incomplete
184 survey coverage, we assumed the crop-specific application rate followed the inter-annual variation of the
185 corresponding state-average rate, computed by dividing the county-level cropland manure application
186 amount from Sect. 2.4 by total state cropland area. We then gap-filled missing years from 1970 to 2021
187 using one-way interpolation (Eq. 3) when only one bracketing year was available and distance-weighted
188 interpolation (Eq. 4) when both bracketing years were available. The rate products were extended to 2025
189 by carrying forward the 2021 county-crop structure and scaling to updated county and state application
190 constraints. Because these rates apply to treated cropland, we also computed equivalent state-average
191 rates on all cropland by multiplying treated-cropland percentages by the corresponding treated-area rate.

192 $$\text{Interpolated rate}_{i+k} = \frac{\text{Referenced rate}_{i+k}}{\text{Referenced rate}_i} \times \text{Raw rate}_i \quad (3)$$

193 $$\text{Interpolated rate}_{i+k} = \frac{\text{Referenced rate}_{i+k} \times \text{Raw rate}_i}{\text{Referenced rate}_i} \times \frac{k-i}{j-i} + \frac{\text{Referenced rate}_{i+k} \times \text{Raw rate}_i}{\text{Referenced rate}_j} \times \frac{j-k}{j-i} \quad (4)$$

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where x_k is the missing rate in year k, x_b and x_e are the beginning and ending bracketing observations, r_k is the complete reference series used to preserve inter-annual variation, and k denotes the missing year within the gap.

In parallel with manure application rate, ARMS reports application timing and method as percentages of treated area. Timing categories include fall application before the next planting season, spring application before planting, and application after planting. Method categories include broadcast without incorporation, broadcast with incorporation, injection, and sprinkler or irrigation-based application. The fraction of each timing and method was calculated by dividing the treated area of each operation by the summed treated area of all operations. Missing timing and method fractions were gap-filled via linear interpolation to produce the available state-by-crop management series for 1970-2019. We retained these state-by-crop fractions as management attributes and used them to calculate treated-area-weighted state-level timing and method rates.

2.3 County-level manure N and P application rates

County-level manure N and P rates for cropland pasture and permanent pasture were calculated by dividing the land-use-specific manure application amount by the corresponding pasture area. Historical pasture rates were reconstructed through 2021 where the pasture-area and rate-pipeline inputs were available, and the pasture rate layers were then extended to 2025 under the same post-2021 production-constrained rescaling used for the county-crop application products.

County-crop manure N and P rates were reconstructed by reconciling county cropland manure application amounts from Sect. 2.1 with state-level crop-specific manure rates from Sect. 2.2. The historical county-crop treated-area and all-cropland rate layers were first built from the available survey and crop-area inputs; the 2022-2025 layers were then extended by preserving the 2021 crop allocation pattern and rescaling to updated county application totals. Assuming that relative crop-rate ratios within counties follow their state-level patterns, we downscaled state crop rates to county crop rates using Eq. 5.

$$\text{Nutrient use rate}_i^{\text{ct}} = \frac{\text{Nutrient application}_{\text{ct}}}{\sum_{j=1}^{10} \text{Nutrient use rate}_j^{\text{st}} \times \text{Area}_j^{\text{ct}}} \times \text{Nutrient use rate}_i^{\text{st}} \quad (5)$$

where $r_{c,i,t}$ is the manure N or P use rate for crop i in county c and year t, $M_{c,t}$ is county manure N or P application amount for cropland, $r_{s,j,t}$ is the state crop rate for crop j, $A_{c,j,t}$ is county planted area for crop j, and the crop set includes the nine named major crops plus other crops.

2.4 Gridding annual total manure rates and mapping state-level management

We spatialized the annual total all-cropland county-by-crop manure N and P rates for 1970-2021 by combining county-crop rate products with annual crop distribution maps and aggregating the resulting layers to 4 km rate rasters. For each year, county-level crop-specific rates were assigned to cropland pixels for the corresponding crop type and then aggregated to gridded manure N and P application layers for total cropland. Application timing and method were retained as state-by-crop fractions rather than gridded products.

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3. Results

3.1 National and county patterns of manure production

The age-group production estimates increased from 4.7 Tg N yr^{-1} and 0.73 Tg P yr^{-1} in 1970 to 7.4 Tg N yr^{-1} and 1.3 Tg P yr^{-1} in 2021, before declining to 7.0 Tg N yr^{-1} and 1.2 Tg P yr^{-1} by 2025 (Table S4 in the Supplement). These totals describe nutrients generated by livestock before recoverability and allocation to cropland.

National manure N and P production were concentrated in cattle and poultry, with the balance shifting toward poultry over time (Table S4 in the Supplement). Cattle remained the largest source, but its share declined from 77 % of manure N production and 63 % of manure P production in 1970 to 66 % and 48 %, respectively, in 2025. Over the same period, poultry manure production increased from 0.44 to 1.6 Tg N yr^{-1} and from 0.13 to 0.47 Tg P yr^{-1}, raising its contribution from 9 % to 23 % of national manure N and from 17 % to 39 % of national manure P. Hogs contributed 0.64 Tg N yr^{-1} and 0.15 Tg P yr^{-1} in 2025, whereas sheep and horses together accounted for less than 3 % of national manure N and P production. This shift of livestock-group contributions explains why the age-group framework changes manure P totals more strongly than manure N totals: national manure P depends strongly on the poultry-cattle composition, not only on total animal numbers.

County-level manure N production remained concentrated in livestock-intensive parts of California, the High Plains, the Midwest, and eastern dairy and poultry regions from 1970 to 2024 (Fig. 2). High-production counties persisted within these regions, while the recent years show stronger production in parts of the High Plains and western livestock regions. The spatial pattern therefore combines persistent regional concentrations with changes in the magnitude of county nutrient supply.

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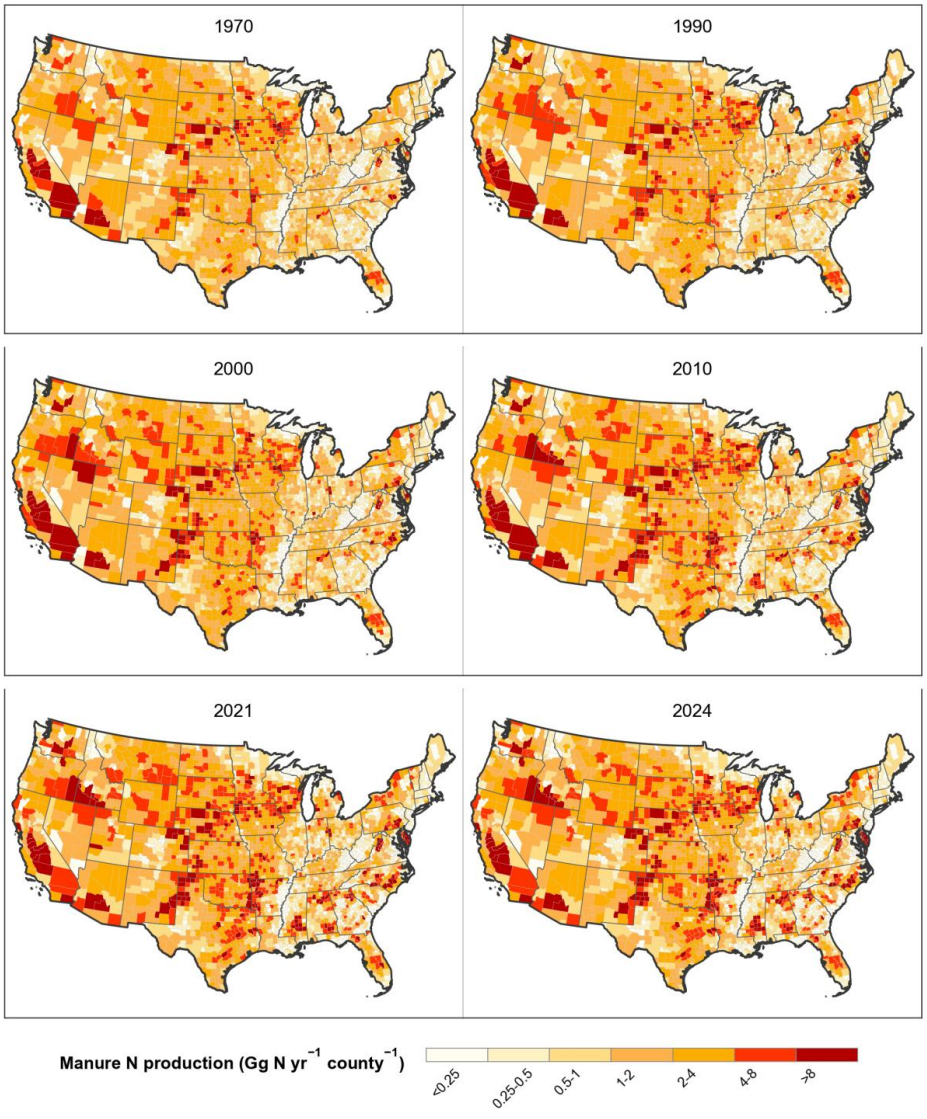


Figure 2. County-level manure nitrogen (N) production across the contiguous United States in 1970, 1990, 2000, 2010, 2021, and 2024 (left to right, top to bottom). Values are annual county totals (Gg N yr^{-1} county^{-1}) from the age-group production framework. White counties have no mapped production value. County totals are not normalized by land area.

Manure P production shared many of the county hotspots in the N maps, including California and the central livestock-producing regions, with additional concentrations across the Midwest and eastern poultry and dairy regions (Fig. 3). The growing national poultry contribution to P production provides context for these regional differences (Table S4 in the Supplement). Both maps report county totals rather than production per unit land area or cropland application rates; they locate livestock nutrient sources without identifying the fields that receive manure.

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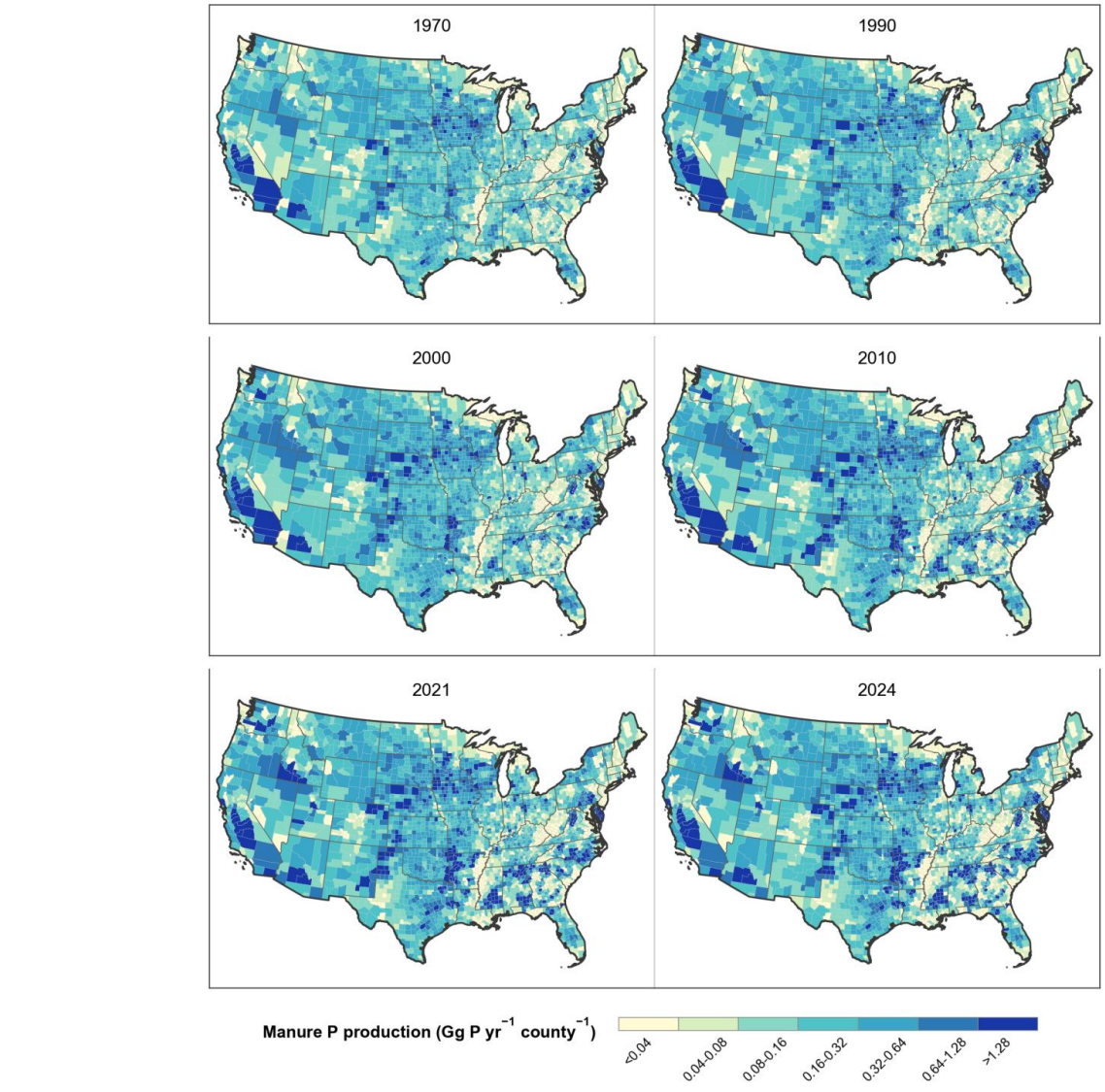


Figure 3. County-level manure phosphorus (P) production across the contiguous United States in 1970, 1990, 2000, 2010, 2021, and 2024 (left to right, top to bottom). Values are annual county totals (Gg P yr^{-1} county^{-1}) from the age-group production framework. County totals are not normalized by land area.

3.2 National manure N and P application

The crop-use application component, defined here as cropland plus cropland pasture entering the county-crop allocation pipeline, rose from 0.79 Tg N yr^{-1} in 1970 to 1.4 Tg N yr^{-1} in 2025, an increase of 78 % (Fig. 4a). Manure P application increased from 0.25 to 0.53 Tg P yr^{-1} over the same period, an increase of 109 %. The highest national crop-use application totals occurred around 2021-2022 after rapid increases after 2000, whereas both the production constraint and the extended application component weakened slightly in the most recent years.

Crop-specific N application rates differed sharply between treated-area and all-cropland conventions (Fig. 4b, c, d). In 2020, winter wheat had the highest treated-area N rate among the major crops (37 g N m^{-2} yr^{-1}), followed by cotton (26 g N m^{-2} yr^{-1}), sorghum (22 g N m^{-2} yr^{-1}), barley (20 g N m^{-2} yr^{-1}), and corn

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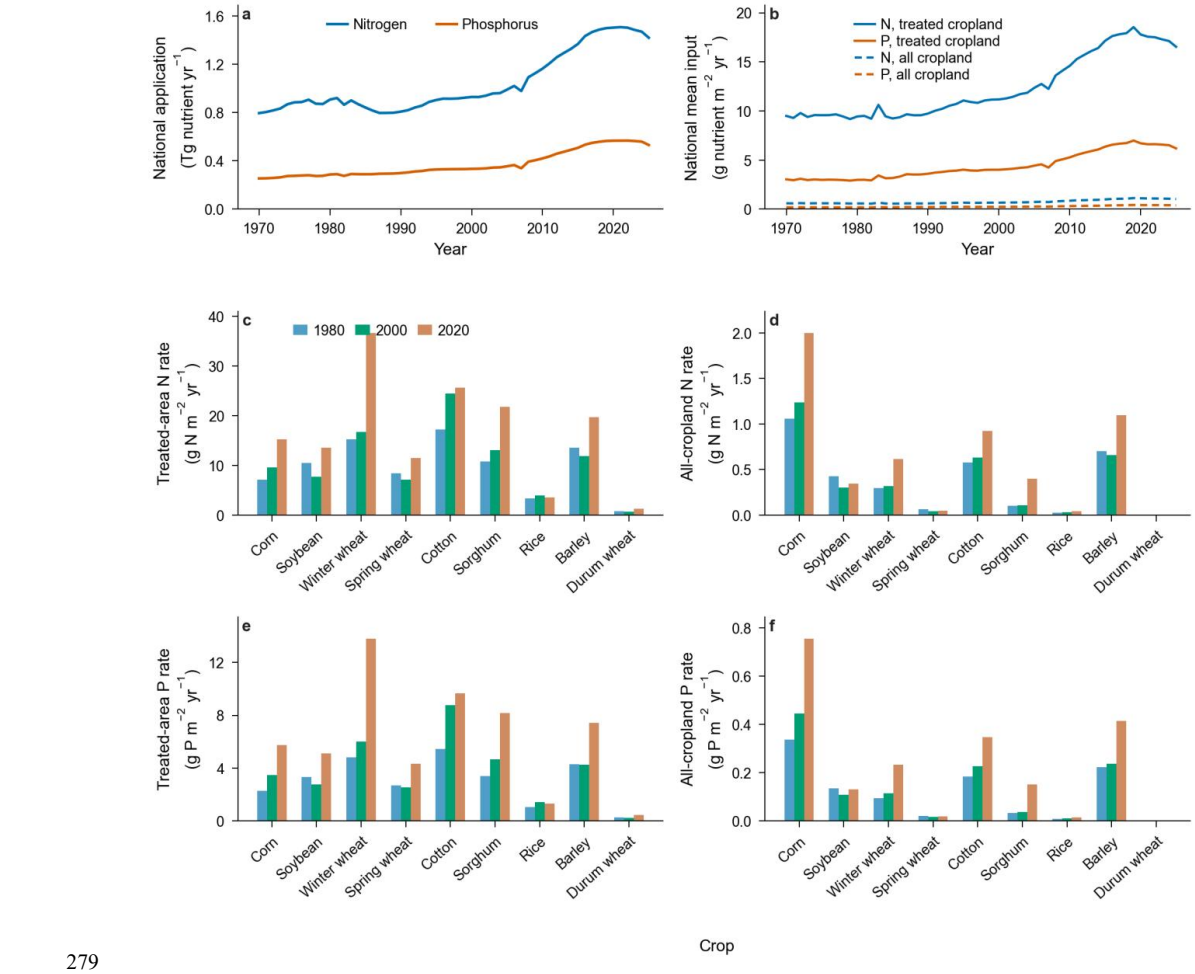


Figure 4. National manure N and P application trends and crop-specific application rates in US cropland systems from 1970 to 2025. (a) National totals of manure N and P application in the crop-use application component (Tg nutrient yr^{-1}). (b) National mean N and P application rates on treated cropland and all cropland (g nutrient m^{-2} yr^{-1}). (c, e) Crop-specific N and P rates on treated area and (d, f) corresponding rates averaged across all cropland for 1980, 2000, and 2020. National rates were area-weighted from county-by-crop estimates.

3.3 Spatial patterns of manure N and P application

Manure N application was spatially concentrated rather than uniformly distributed across CONUS cropland (Fig. 5). For the selected panel years from 1970 to 2019, high-rate areas persisted in livestock- and feed-crop-intensive regions, especially across parts of the Midwest, the Great Plains, and the eastern dairy and mixed-farming regions. These maps use the all-cropland rates and show that national increases in manure N use were expressed as both intensified rates within existing hotspot regions and expansion of moderate-rate areas in counties where manure-producing livestock and manure-receiving cropland overlap. Manure P showed a broadly similar spatial footprint but lower absolute rates than N (Fig. 6). The

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most intensive P inputs appeared in regions where county manure generation, crop area, and treated-area allocation converged.

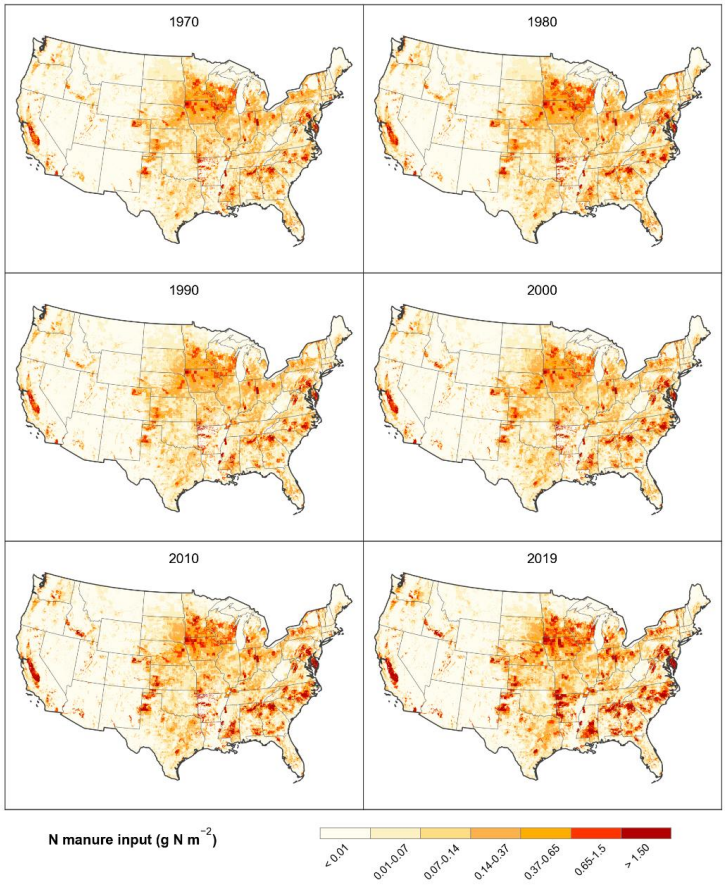


Figure 5. Spatial distribution of manure N application rates across US cropland for six representative years from 1970 to 2019. County-by-crop manure N all-cropland rates were spatialized to a 4 km grid using annual crop distribution maps. Rates are expressed as g N m^{-2} yr^{-1}. White areas indicate cells with no cropland manure application.

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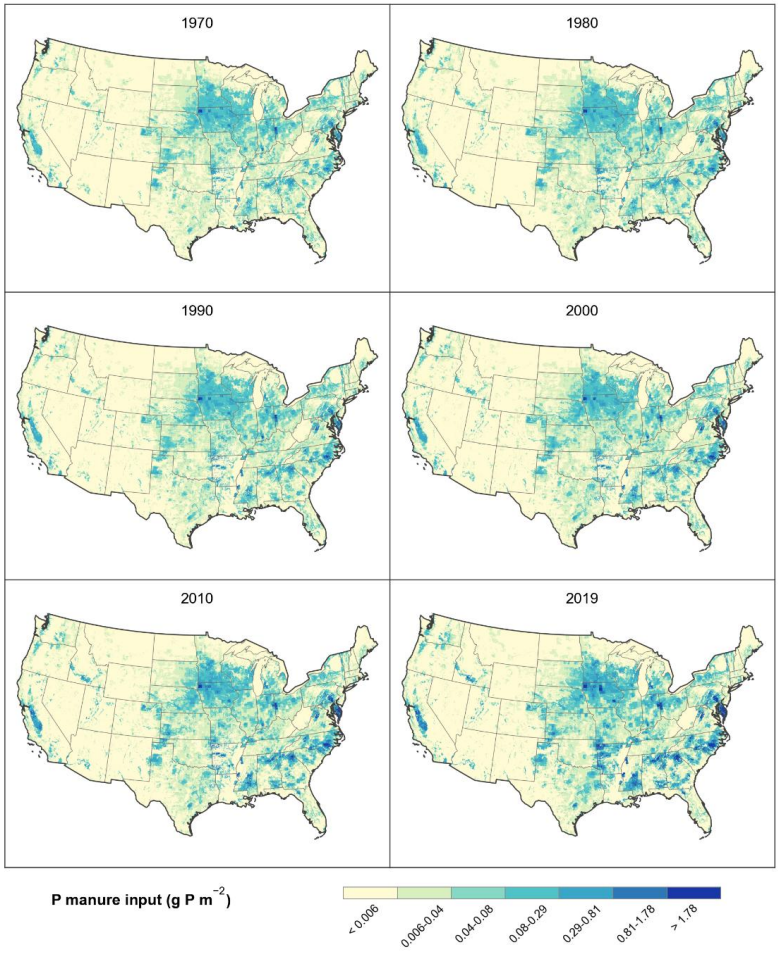


Figure 6. Spatial distribution of manure P application rates across US cropland for six representative years from 1970 to 2019. County-by-crop manure P all-cropland rates were spatialized to a 4 km grid using annual crop distribution maps. Rates are expressed as g P m^{-2} yr^{-1}. White areas indicate cells with no cropland manure application.

3.4 Crop contributions to manure nutrient inputs by state

State-by-crop time series revealed large regional differences in the crop composition of manure N inputs (Fig. 7). In Corn Belt and Lake States, corn dominated the manure N stack because it combined large crop area with increasing treated-area rates after 2000. In contrast, western and Great Plains states showed more mixed contributions from wheat, barley, sorghum, and other crops. The black state-total line and crop stacks also show where bottom-up crop-rate products required top-down consistency constraints to avoid exceeding county-level recoverable manure N supply.

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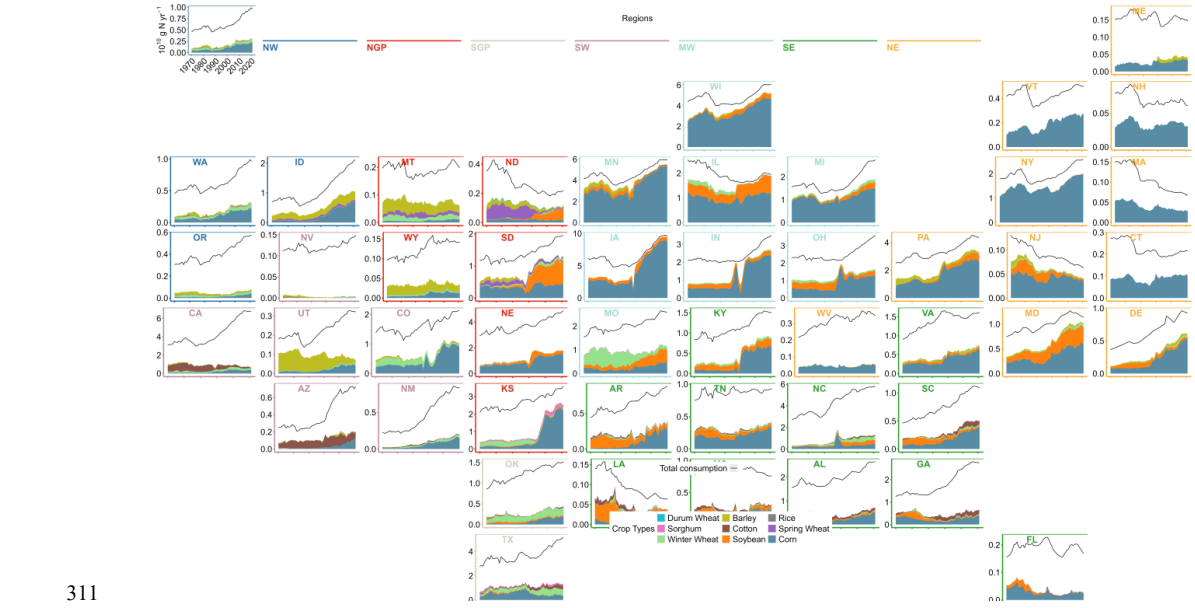


Figure 7. State-level time series of manure N inputs by nine major crops from 1970 to 2021 in the contiguous United States. Stacked areas show crop contributions, and the black line shows the state total. Each state tile uses an independent y-axis scale; values are scaled by 10^{10} g N yr^{-1}.

The corresponding P stacks had the same state-by-crop structure but a smaller nutrient magnitude (Fig. 8). P inputs were especially concentrated in states where manure-generating livestock production and manure-treated cropland were spatially coupled. The comparison between N and P stacks indicates that manure management cannot be inferred from N alone: differences in N/P ratios and the age-group manure generation framework had a greater influence on P totals than N totals.

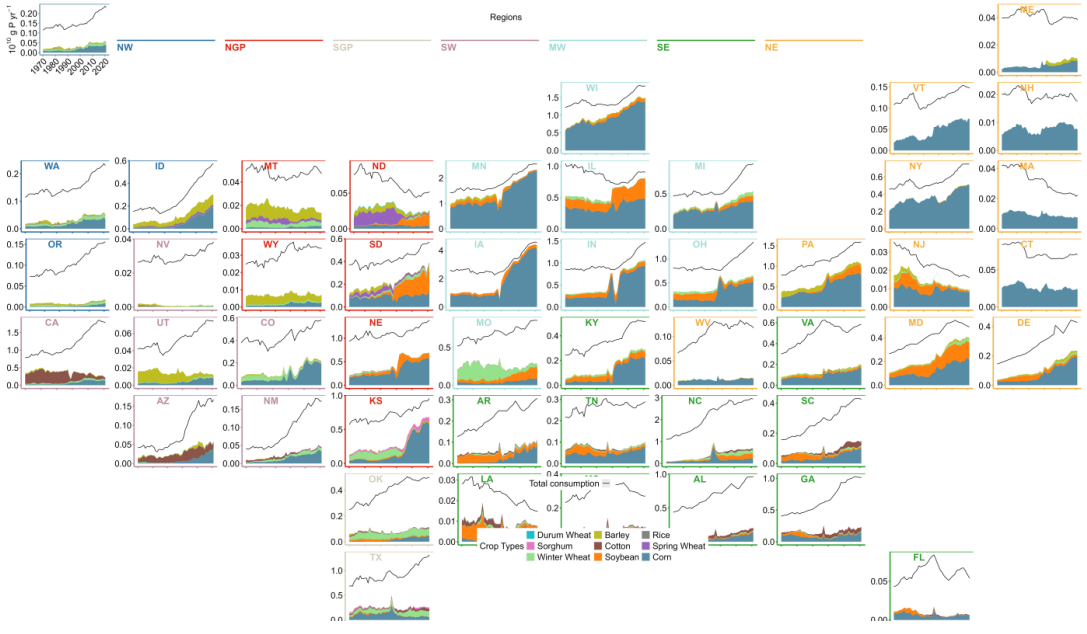


Figure 8. State-level time series of manure P inputs by nine major crops from 1970 to 2021 in the contiguous United States. Stacked areas show crop contributions, and the black line shows the state total. Each state tile uses an independent y-axis scale; values are scaled by 10^{10} g P yr^{-1}.

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3.5 Manure application timing and method

Application timing differed strongly among crops (Fig. 9). Pre-planting applications dominated most crop systems. In 2019, spring-before-planting application accounted for about 50 % of corn manure application and 61 % of cotton manure application, while fall application dominated soybean (64 %), winter wheat (77 %), spring wheat (100 %), durum wheat (100 %), and barley (70 %) in the state-crop timing data. After-planting application was generally small and was most visible for barley and a few localized systems. These patterns indicate that a large share of manure nutrients is applied before peak crop nutrient demand.

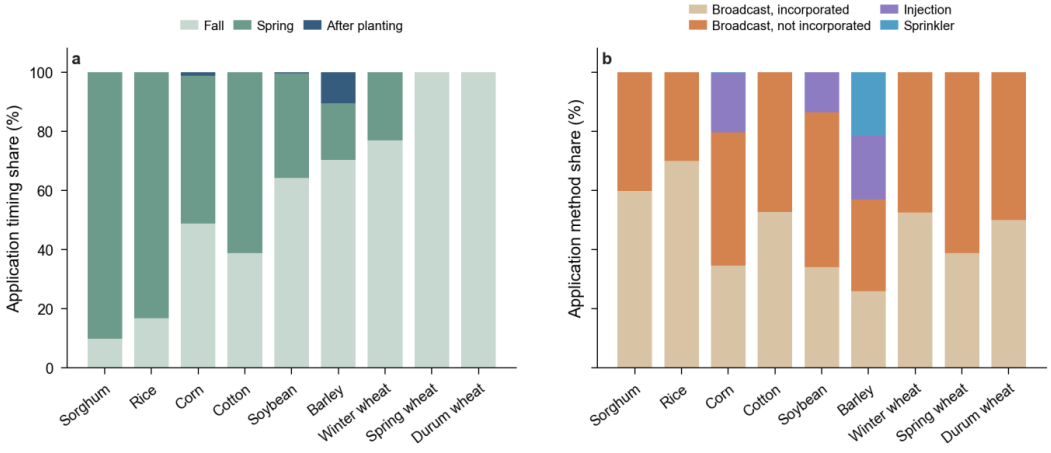


Figure 9. Crop-specific shares of manure application timing and method for major US crops in 2019. (a) Timing categories are fall application in the previous year, spring application before planting, and application after planting. (b) Method categories are broadcast with incorporation, broadcast without incorporation, injection, and sprinkler or irrigation-based application. Bars show unweighted means of state-level treated-area fractions for each crop, normalized to sum to 100 % within each crop.

The treated-area-weighted state-level N timing maps for 2019 showed that fall and spring manure inputs were concentrated in the same manure-use regions identified in the annual N and P maps (Fig. 10), with paired N and P timing maps provided in Figs. S1 and S2. Fall application was prominent in parts of the Midwest, Great Plains, and Northwest, while spring-before-planting application was more broadly distributed across crop-producing regions. After-planting inputs were smaller and occurred in fewer states, producing a much weaker national pattern than the two pre-planting categories.

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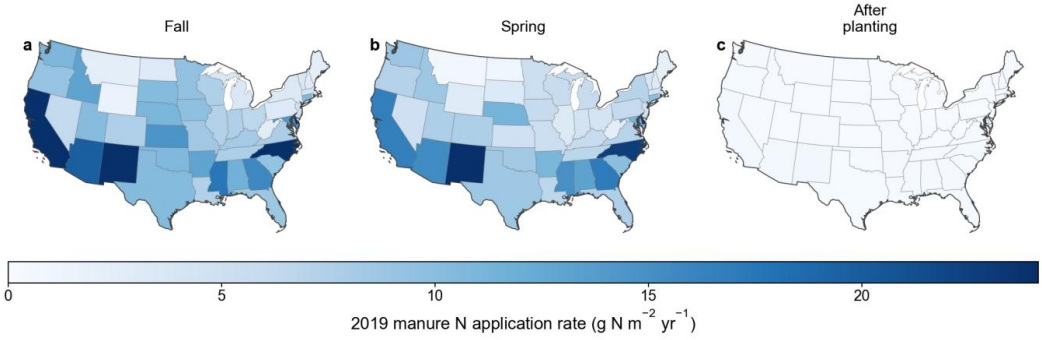


Figure 10. Treated-area-weighted state-level manure N application rates for three application-timing categories across the contiguous United States in 2019. Timing categories include fall application in the previous year (FAL), spring application before planting (SPR), and application after planting (AFP). Rates were calculated from uncapped state-by-crop treated-area rates, county-crop treated area, and state-by-crop timing fractions.

Application method also varied by crop and region (Fig. 11; Figs. S3 and S4 in the Supplement). Broadcast without incorporation was the most popular method for corn and soybean in 2019, accounting for about 45% and 52% of application, respectively. Broadcast with incorporation dominated cotton, sorghum, rice, and winter wheat, while injection and sprinkler-based application were smaller components and were concentrated in specific crops and regions. The state-level method maps show that high manure-rate states often coincide with broadcast application, a combination that can increase nutrient-loss risk when manure is applied before planting or without incorporation.

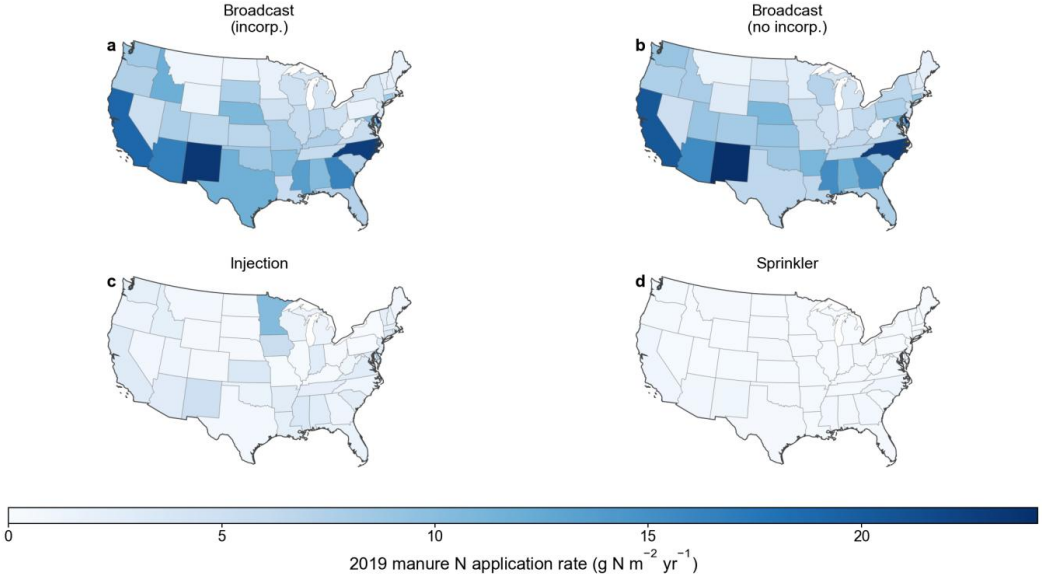


Figure 11. Treated-area-weighted state-level manure N application rates for four application methods across the contiguous United States in 2019. Method categories include broadcast without incorporation (BNI), broadcast with incorporation (BWI), injection (INJ), and sprinkler or irrigation-based application (SPR). Rates were calculated from uncapped state-by-crop treated-area rates, county-crop treated area, and state-by-crop method fractions.

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4. Discussion

4.1 Improvements from the age-group-based manure framework

The cross-dataset comparison clarifies that the age-group framework mainly changes the top-down manure production constraint, while the downstream crop-allocation structure remains anchored to bottom-up survey evidence (Fig. 12). This combination makes the present dataset the alignment of the compared national products to the bottom-up crop-management constraints while preserving county-level mass balance. Our updated age-group manure N production increased from 4.7 Tg N yr^{-1} in 1970 to 7.4 Tg N yr^{-1} in 2021, placing it near the lower range of existing national products, before declining to 7.0 Tg N yr^{-1} by 2025. The difference is much larger for P: our estimate increased from 0.73 to 1.3 Tg P yr^{-1} between 1970 and 2021 and then declined to 1.2 Tg P yr^{-1} by 2025, whereas broad-category products commonly estimate more than 1.6 Tg P yr^{-1} in the 1970s and about 2.0 Tg P yr^{-1} in the late 2010s. Historical national manure datasets likewise differ in their treatment of livestock categories, nutrient production, and application, so comparison with Bian et al. (2021), Yang et al. (2016), and Falcone (2021) is most informative for evaluating the production constraint rather than assuming equivalence among generated, recoverable, and applied nutrients. The comparison therefore supports the central correction in this dataset: livestock demographic structure has a stronger effect on manure P than on manure N, and the recent production extension shows that manure nutrient supply did not continue increasing after the early 2020s.

This N-P asymmetry arises because fixed livestock-category coefficients impose a stable nutrient ratio on animals whose body size, production stage, and feeding regime changed substantially over the study period. For N, the age-group update lowers national production relative to legacy products but preserves the broad upward trend after the 1990s. For P, the same update contracts the production constraint more strongly, because broad N/P ratios overstate P excretion for several livestock classes. The result is not simply a lower curve; it changes the interpretation of manure P surplus, especially in livestock-intensive counties where previous products could propagate high P totals into crop application rates.

The production and application panels should be read as different fluxes. Production represents the county manure generated by the age-group livestock framework, whereas application represents the cropland, including cropland-pasture, component used by the county-crop allocation pipeline. Application is therefore smaller than production because not all generated manure is recoverable, allocated to cropland, or retained inside the crop-specific product. This distinction is consistent with recent national manure-recycling frameworks that separately define generated manure, recoverable nutrients, current cropland application, and crop nutrient demand (Wang et al., 2026). In 2025, the consistency-constrained crop-use application total was 1.4 Tg N and 0.53 Tg P, compared with 7.0 Tg N and 1.2 Tg P in the production constraint. This reconciliation step closes the residual mismatch between bottom-up crop survey rates and age-group county totals while preserving the relative crop ranking from the survey-based management layer, conceptually paralleling the top-down/bottom-up reconciliation used for synthetic P by Cao et al. (2024).

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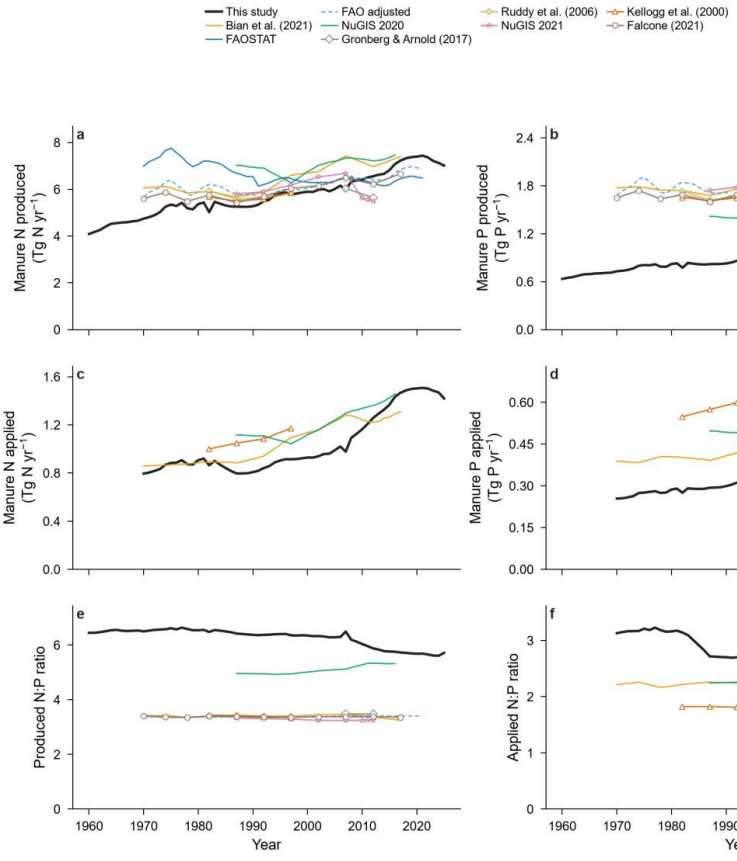


Figure 12. Comparison of manure N and P production and application estimates across national data products. The black line highlights this study, calculated from the county age-group mainline outputs. Panels show (a) manure N production, (b) manure P production, (c) manure N application, (d) manure P application, (e) the N:P ratio of production, and (f) the N:P ratio of application. External products include Bian et al. (2021), FAOSTAT (2024), NuGIS (The Fertilizer Institute, 2020), Gronberg and Arnold (2017), Ruddy et al. (2006), Kellogg et al. (2000a, b), and Falcone (2021).

4.2 Implications for manure nutrient recycling and spatial hotspots

The trajectory of manure N and P inputs from 1970 to 2025 mirrors the long-term reorganization of CONUS livestock geography (Falcone et al., 2018). Total cropland manure N and P use increased by 78 % and 109 %, respectively, over the study period, but the increase was unevenly distributed across regions and crops. The Midwest and the eastern dairy belt remained persistent hotspots throughout the record, while the Northern Great Plains and parts of the Southeast intensified after the early 1990s as confined-feeding operations expanded. The resulting separation between livestock nutrient sources and receiving cropland is a structural constraint on redistribution because manure is costly to transport relative to its nutrient content, particularly where livestock production is geographically concentrated (MacDonald et al., 2009; Lim et al., 2023). The decline-and-recovery pattern visible in the late 1980s coincides with the farm crisis and the wave of livestock consolidation (MacDonald et al., 2009).

The spatial reorganization of manure inputs has implications that synthetic-fertilizer datasets cannot capture on their own. Cao et al. (2024) showed that synthetic P hotspots have shifted toward the Midwest and the Great Plains since 1980, tracking corn-soybean expansion. The manure P hotspots reported here overlap with this pattern in feed-grain regions but additionally identify concentrated dairy and poultry

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geographies in the eastern US, where manure rather than mineral fertilizer dominates P inputs. The crop-stack decomposition further shows that corn alone explains a large fraction of the late-period rise in manure N use in many Corn Belt and Lake States - a consequence of its combination of large planted area, rising treated-area fractions, and increasing per-area rates after 2000 - whereas wheat, barley, sorghum, and pasture govern manure inputs in the western and Great Plains states. Regional redistribution can in principle connect livestock nutrient sources with crop nutrient demand, but county source-sink mismatches and transport and management constraints limit how completely local surpluses can be redirected to receiving cropland (Spiegal et al., 2020; Powers et al., 2019). These cross-crop differences mean that nutrient-management policies anchored only to county manure totals would misidentify the cropping systems most exposed to manure-driven nutrient loading.

Separating treated-area rates from all-cropland rates clarifies how manure recycling is represented spatially. In 2020, corn received a treated-area manure N rate of 15 g N m^{-2} yr^{-1} but only 2.0 g N m^{-2} yr^{-1} when averaged across all cropland; winter wheat received 37 g N m^{-2} yr^{-1} on treated area but a much lower rate when spread over its full planted footprint. The difference between these two conventions explains why national-average manure inputs can appear modest while loading rates on the subset of treated cropland are much higher. Because the gridded product allocates these rates rather than observing individual receiving fields, the treated-area values should not be interpreted as direct field-level measurements. This gap is the manure analogue of the fertilized-versus-all-cropland divergence highlighted for synthetic P by Cao et al. (2024) and motivates reporting both conventions for downstream model applications and nutrient budget assessments.

4.3 Timing and method as loss-risk controls

Manure nutrient inputs do not reach the soil as a single undifferentiated annual flux: application timing and method determine how much of the applied N and P is available to the next crop and how much is exposed to volatilization, runoff, erosion, and leaching pathways (Cao et al., 2018; Stackpoole et al., 2019). Pre-planting applications dominated most major crops in the present dataset. In 2019, fall application accounted for the majority of manure inputs to soybean (64 %), winter wheat (77 %), spring wheat (100 %), durum wheat (100 %), and barley (70 %), while spring-before-planting application dominated corn (50 %) and cotton (61 %). This timing structure overlaps with the synthetic-P pre-planting pattern reported by Cao et al. (2024) for the same crops and regions, indicating that manure and mineral nutrient pulses can enter soils during the same pre-uptake period. Loss risk nevertheless depends on the interaction between timing, incorporation, soil condition, and hydrologic events rather than timing alone; snowmelt studies, for example, show that manure timing and tillage can strongly alter nutrient export (Bhandari et al., 2021). Where these timings coincide with intense rainfall, snowmelt, or saturated soils, the potential for dissolved-P transport and nitrate loss can increase (Algoazany et al., 2007; Bhandari et al., 2021).

Application method further conditions the magnitude of these losses. Broadcast without incorporation was the dominant method for corn (45%) and soybean (52%) in 2019, and a similarly broadcast-heavy pattern was reported for synthetic P on these crops by Cao et al. (2024). Because surface placement leaves nutrients more directly exposed to runoff pathways, the combination of broadcasting and vulnerable hydrologic periods is relevant to loss risk, although the resulting losses cannot be inferred directly from the allocated management shares alone (Bhandari et al., 2021; Algoazany et al., 2007). Non-broadcast methods such as injection and banded placement were concentrated in dairy regions of the Northeast and the Lake States and in wheat and barley systems of the Northern Great Plains, consistent with regional differences in manure-management systems and operational constraints (Lim et al., 2023). The convergence of pre-planting timing and surface broadcasting on corn and soybean across the Midwest therefore indicates where management configurations associated with greater nutrient-loss susceptibility

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are most prevalent in this dataset, rather than demonstrating realized field-scale losses, and overlaps with regions where contemporary and legacy agricultural P contribute to water-quality impairment (Stackpoole et al., 2019).

By delivering state-by-crop timing and method fractions for 1970-2019 alongside annual 4 km total N and P all-cropland rates, the dataset supports management-specific scenario analysis without implying sub-state observations of timing or method. Model users can apply or aggregate these fractions according to the spatial support and assumptions of their application. This information complements the synthetic-fertilizer management layers of Cao et al. (2018, 2024) and supports evaluation of total reactive N and P loading while preserving the distinction between gridded annual rates and state-level management attributes.

4.4 Limitations and future improvements

Several limitations remain because the dataset reconciles production, recoverability, land allocation, and crop management from sources that differ in spatial support, survey coverage, and process representation. (1) County manure availability depends on recoverability coefficients and assumptions about collection, storage, treatment, transport, and on- versus off-farm application. Large operations routinely move manure between farms, and diet changes such as phytase adoption can alter manure P content (MacDonald et al., 2009), so recovered nutrient does not always equal locally applied nutrient at the county level. Recent national assessments similarly distinguish manure production, recoverable manure, current application, and crop demand, emphasizing that these quantities represent different stages of the recycling pathway (Wang et al., 2026). (2) The framework allocates manure using county land capacity, crop area, treated-area fractions, and state-level crop management patterns, but it does not observe the exact fields receiving manure; all-cropland gridded rates should therefore be interpreted as spatially distributed inputs for budgeting and modeling rather than as field-level observations. (3) Timing and method fractions are constant within each state-crop-year and so mask within-state variation driven by farm size, livestock proximity, manure form, soil conditions, and weather-driven field access, a limitation also acknowledged by Cao et al. (2024) for synthetic P. (4) P estimates retain uncertainty in livestock-specific N/P relationships; age-group resolution reduces this bias relative to broad categories, but additional manure composition data would further constrain P estimates. These uncertainties affect local rates and management attribution, and the 2022-2025 application and rate extension should be interpreted as production-constrained continuation rather than newly observed management. They do not overturn the main conclusion that age-group livestock structure lowers the production constraint, especially for P, while the survey-based crop layer controls the spatial and crop-specific allocation of applied manure.

5. Conclusion

We developed a spatially explicit manure N and P management dataset for US cropland systems by replacing legacy broad-category manure generation with an age-group-based framework and reconciling the resulting county totals with crop-specific manure management data. The dataset separates a top-down manure production constraint, updated to 2025, from crop-use application and rate layers extended to 1970-2025. National crop-use manure application rose from 0.79 to 1.4 Tg N yr^{-1} and from 0.25 to 0.53 Tg P yr^{-1} between 1970 and 2025, while production reached 7.4 Tg N yr^{-1} and 1.3 Tg P yr^{-1} in 2021 before declining to 7.0 Tg N yr^{-1} and 1.2 Tg P yr^{-1} by 2025. These inputs remained concentrated in crop and livestock production hotspots rather than evenly distributed across all cropland. Cross-dataset comparison shows that the age-group framework produces moderate reductions in manure N and much stronger reductions in manure P relative to broad-category products, while preserving the downstream crop-management structure. By separating production, crop allocation, treated-area rates, all-cropland

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rates, timing, and method, the dataset provides a basis for evaluating manure nutrient recycling, crop-specific nutrient loading, and management-related N and P loss risks across the contiguous United States.

Data availability

The dataset comprises annual county manure N and P production and application for 1960-2025, county-by-crop treated-area and all-cropland application rate products for 1970-2025, annual 4 km total cropland N and P all-cropland rate rasters for 1970-2021, and state-by-crop timing and method fractions for 1970-2019. Datasets used in this study are available at https://doi.org/10.6084/m9.figshare.34325817 (Cao et al., 2026).

Supplement

The supplement related to this article is available.

Author contribution

CL, PC, and BY conceptualized the paper and developed the methodology. PC and BY reconstructed the dataset. PC and BY prepared the paper with contributions from CL.

Competing interests

At least one of the (co-)authors is a member of the editorial board of Earth System Science Data.

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