Crop-specific Management History of Phosphorus Fertilizer Input (CMH-P) in the Croplands of United States: Reconciliation of Top-down and Bottom-up data Sources

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Abstract

Understanding and assessing the spatiotemporal patterns in crop-specific phosphorus (P) fertilizer management is crucial for promoting crop yield and mitigating environmental problems. The existing P fertilizer dataset, derived from sales data, depicts an average application rate on total cropland at the county level but overlooks cross-crop variations. Conversely, the survey-based dataset offers crop-specific application details at the state level yet lacks inter-state variability. By reconciling these two datasets, we developed long-term gridded maps to characterize crop-specific P fertilizer application rates, timing, and methods across the contiguous US at a resolution of 4 km × 4 km from 1850 to 2022. We found that P fertilizer application rate on fertilized area in the US increased from 0.9 g P m^{-2} yr^{-1} in 1940 to 1.9 g P m^{-2} yr^{-1} in 2022, with substantial variations among crops. However, approximately 40% of cropland nationwide has remained unfertilized in the recent decade. The hotspots for P fertilizer use have shifted from the southeastern and eastern US to the Midwest and the Great Plains over the past century, reflecting changes in cropland area, crop choices, and P fertilizer use across different crops. Pre-planting (fall and spring) and broadcast application are prevalent among corn, soybean, and cotton in the Midwest and the Southeast, indicating a high P loss risk in these regions. In contrast, wheat and barley in the Great Plains receive the most intensive P fertilizer at planting and via non-broadcast application. The P fertilizer management dataset developed in this study can advance our comprehension in agricultural P budget and

facilitate the refinement in P fertilizer best management practices to optimize crop yield and reduce P loss. Datasets are available at https://doi.org/10.5281/zenodo.10700822 (Cao et al., 2024).

1 Introduction

Phosphorus (P) is fundamental for life on Earth, serving as a crucial component of genetic material, cellular membranes, and adenosine triphosphate for energy storage. The application of P has facilitated unprecedented increases in food, feed, fiber, and fuel production, and is one of the cornerstones of modern agriculture (Tilman et al., 2002). Before the 19th century, the major P sources for agricultural land were animal and human excreta, along with slaughterhouse by-products (Cordell et al., 2009; Bouwman et al., 2013). Starting around the mid-to-late 19th century, the production of mineral P fertilizers from phosphate rock grew rapidly after the mid-20th century (Lu and Tian, 2017). The application of mineral P fertilizer increased from 1.0 Tg P yr^{-1} to 1.7 Tg P yr^{-1} from 1960 to 2017 in the US (Samreen, 2019), rectifying the P deficiency of soils. However, P application was found to exceed the crops needs by up to 50% in many regions across the US (Glibert, 2020; Sabo et al., 2021). A substantial part of surplus P, defined as the difference between input and removal by crops, can be lost through soluble P in runoff and subsurface flow, and particulate P in soil erosion. These losses can accumulate along transport pathways such as soils, riparian areas, streams, and wetlands, leading to long-term impacts on P loading (Sharpley et al., 2013; Stackpoole et al., 2019). Increased P loading has contributed to the harmful algal blooms and large hypoxia zones, which degrade aquatic ecosystems and harm coastal economies by destroying habitats, disrupting the food web, and damaging tourism and fisheries. To improve P use efficiency in agriculture and mitigate the environmental impacts of excessive P, it is essential to understand the spatial distribution and temporal dynamics of P fertilizer use.

Developing a contemporary P fertilizer dataset is challenging due to incomplete data from multiple sources and the lack of information on crop-specific applications. Previous studies have developed historical county-level P fertilizer consumption in the US from 1945 to 2017, following a top-down approach that relies on state-level fertilizer sales data and county-level fertilizer expenditure data (Alexander and Smith, 1990; Falcone, 2021; Brakebill and Gronberg, 2017). In these studies, the average P fertilizer application was estimated by dividing the consumption by the total cropland area within each county. These top-down P fertilizer databases utilize a single value for average P fertilizer use, overlooking cross-crop variations. Additionally, the percentage of fertilized area relative to the total planting area varies significantly among different crops (USDA-ERS, 2019). As not all planting areas are fertilized, distributing total P fertilizer application on the total planting area has underestimated the actual application rate in the fertilized fields. Characterizing the spatial and temporal heterogeneity of crop-specific P fertilizer application rate due to different P demands across crop types can offer deeper insights into P use efficiency, budget trajectories, and P loading analysis (Sabo et al., 2021; Stackpoole et al., 2019; Swaney and Howarth, 2019). P fertilizer management practices, such as application timing and method, also differ among crop types and are crucial for optimal nutrient management. For example, over 30% of rice fields in the US received injected P fertilizer, whereas around 40% of corn fields received broadcasting P fertilizer (USDA-ERS, 2024), implying high potential P loss by runoff and erosion from corn fields. A bottom-up approach, based on crop-specific P fertilizer application rates and management practices on the treated areas, can help to improve the performance of models and develop P fertilizer conserving strategies. However, to the best of our knowledge, there is a lack of comprehensive bottom-up databases that provide long-term, spatially explicit, crop-specific P fertilizer management data across the US.

By combining the top-down (total P consumption and average P application rate) and bottom-up (crop-specific P application rate) data sets, we developed a spatially explicit time-series database to characterize agricultural P fertilizer application rate, timing, and method in the contiguous US (CONUS) at 4 km resolution from 1850 to 2022. The main objectives of this study are 1) to characterize the spatiotemporal patterns of P fertilizer application rates across the US over the last 170 years by considering P fertilizer management differences among crops; 2) to investigate the spatial patterns of P fertilizer application timing and method.

2 Methods

We reconstructed the annual state-level crop-specific P fertilizer (hereafter referred to as P) application rate from 1850 to 2022 using the same methodology in Cao et al. (2018) by integrating and gap-filling multiple sources. Subsequently, the crop-specific P fertilizer application rate was adjusted to match the state-level total P consumption. Using the same approach in Zhang et al. (2021), we further downscaled the application rate to county-level during 1930-2022 based on county-level P consumption and cropland acreage of each crop type (Ye et al., 2024). We split the annual P application rate generated above into four application timings and three application methods according to the statewide crop-specific survey data during the study period. The datasets of crop-specific P fertilizer management (application rate, timing, and method) generated above were then spatialized into gridded maps based on annual time-series maps of crop area and type at the spatial resolution of 1 km × 1 km across the CONUS (Ye et al., 2024) (Fig. 1).

2.1 Historical P fertilizer use rate reconstruction

2.1.1 P fertilizer consumption

We obtained the historical P consumption from 1850 to 2022 for the CONUS by harmonizing the national P consumption data from Mehring et al. (1957) for 1850-1951, USDA (1971) for 1952-1959, USDA-ERS (2019) for 1960-2015, and FAO (2021) for 2016-2022.

We integrated the annual state-level P consumption from multiple sources that cover different periods during 1930-2016 (Table S1). We gap-filled the unavailable state-level P consumption data for the periods pre-1930 and 2017-2022 by one-way interpolation (Eq. 1) using the national P consumption generated above as a reference. Whereas the periods 1970-1975 and 1978-1987 were gap-filled by distance-weighted interpolation (Eq. 2). The state-level P consumption generated above includes all crops, cropland pasture, permanent pasture, and non-farm land (Table S2). By harmonizing and linearly interpolating the ratio of P consumption of these lands to total consumption from multi-sources, we calculated the P consumption of croplands, cropland pasture, permanent pasture, and non-farm from 1850 to 2022 in each state respectively (See supplementary material for details). We calculated the state-level P application rate of cropland by dividing the P fertilizer consumption of cropland by the total cropland area of each state.

Based on state fertilizer sales data provided by AAPFCO (2022) and county-level fertilizer expenditure data from the USDA Census, the county-level P consumption was estimated every 5 years from 1969 to 2017 with 1987-2016 annually interpolated (Falcone, 2021; NuGIS, 2022). The missing years were interpolated by Equation (2) during the periods of 1970-1986 and 2013-2016, and by Equation (1) after 2017 using the state-level P consumption generated above as reference. The state shares of different lands were applied to estimate the P consumption of these lands in each county.

$$\text{Interpolated } data_{i+k} = \frac{Referenced\ trend_{i+k}}{Referenced\ trend_i} \times Raw\ data_i, \quad (1)$$

$$\text{Interpolated } data_{i+k} = \frac{\text{Referenced trend}_{i+k} \times Raw\ data_i}{Referenced\ trend_i} \times \frac{k-i}{j-i} + \frac{\text{Referenced trend}_{i+k} \times Raw\ data_j}{Referenced\ trend_j} \times \frac{j-k}{j-i}, \quad (2)$$

Where $Raw\ data$ is the raw data that contains missing values, $Referenced\ trend$ is the complete data from which the inter-annual variations that raw data can refer to, i and j are the beginning and ending year of the gap, $i + k$ is the kth missing year. Equation 1 was used when the beginning or ending year is unavailable, whereas Equation 2 was used when both years are available.

2.1.2 Referenced state-level crop-specific P application rate

The national P application rates of 9 major crop types, including corn, soybean, winter wheat, spring wheat, cotton, sorghum, rice, barley, and durum wheat, from 1927 to 2022 were obtained by integrating multiple data sources (Table S4). In contrast to the state-level P application rate generated in section 2.1.1, reflecting the inter-annual variation of each state, the national crop-specific P application rate characterizes the variation of each crop at the national scale. We gap-filled the national crop-specific P application rate for the period of 1850-2022 by using state-level P application rates as a reference. For the period before 1927, when national crop-specific P application rates were unavailable, Equation (1) was used to retrieve the P application rate of each crop. For the period from 1927 to 2022, the cubic spline interpolation method was used to gap-fill P application rates when raw data were missing in less than 3 consecutive years. While Equation (2) was applied in gap-filling when missing data were found in more than 3 consecutive years.

Four regression models, quadratic, cubic, exponential, and logarithmic functions, were built between the interpolated national crop-specific P application rates and raw state-level crop-specific P application rates of 9 crops from 1954 to 2022. The best-fit model was used to adjust the national crop-specific P application rates (Cao et al., 2018). Finally, the interpolated national crop-specific P application rates from 1850 to 1953 with no adjustment and from 1954 to 2022 with adjustment jointly served as the referenced state-level crop-specific P application rate trend.

2.1.3 State- and county-level crop-specific P application rates

We obtained the state-level crop-specific P application rates of 9 crops from 1954 to 2022 from the same data sources as national crop-specific P application rates (Table S4). This includes the information of P application rates in the fertilized croplands and percentage of fertilized croplands. Due to the lack of information to identify the fertilized cropland spatially, the P application rates were adjusted by multiplying use rates with fertilized cropland percentage. For winter wheat, spring wheat, and durum wheat, only the total P consumption of these three wheat types was available at the state level for the period of 1954-1989. The wheat types planted in each state were determined based on the Agricultural Chemical Use Survey (USDA-NASS, 2021). We calculated the fractions of P consumption for each wheat type to the total P consumption of all wheat types in each state in 1990. This fraction was used to estimate the P consumption of each wheat type for the period of 1954-1989. The P application rate of each wheat type was then calculated as P consumption divided by the planting area of the corresponding wheat type.

For the period from 1850 to 1953, the state-level P application rates of 9 crops were gap-filled by Eq. (1) using the referenced P application rate generated in section 2.1.2. Whereas Eq. (2) and the cubic spline method were used to gap-fill the missing years between 1954 and 2022 for missing years over or less 3 consecutive years, respectively. The P consumption of cropland pasture calculated in section 2.1.1 was divided by the area in each state to generate the cropland pasture P application rate. The P consumption of all other crops in each state was calculated by subtracting the P consumption of 9 crops, cropland pasture, permanent pasture, and non-farm from state total P consumption. The P use rate of "Other Crops" was generated by dividing the P consumption by the area of Other Crops. Due to the mismatch between state total P consumption from top-down sales data and crop-specific P consumption from the bottom-up survey, the summed P consumption of 9 major crops exceeds the state total P amount in some states (Fig. S1), resulting in a negative rate of Other Crops. We adjusted the crop-specific application rates of major crops to match the state total P consumption by assuming that total P consumption data from top-down source is more reliable. First, we reconstructed the positive application rates of Other Crops in each state. If the 10-year moving average of the positive application rates of the Other Crops was available, we used it to replace the negative rates of the Other Crops. Otherwise, if the moving average was unavailable, we interpolated the gaps using the area-weighted mean of Other Crops across all states within the corresponding region as the reference trend. The selection of Eq. (1) and Eq. (2) for interpolation depends on the availability of the beginning and ending year of the gap. After excluding the P fertilizer consumption of cropland pasture, Other Crops, permanent pasture, and non-farm uses from the state total P consumption, we used the remaining total consumption to scale the crop-specific P fertilizer application rates for major crops. Specifically, for certain crops that exhibit abnormal change trends in some states due to inadequate survey data (e.g., corn in Illinois), we manually adjusted the rates for these crops to align with the differences (Fig. S2).

By assuming the relative ratio of P application rate among crop types in counties follow their state-level patterns in the same year, the crop-specific P application rate generated above was downscaled from state level to county level using Eq. (3) from 1970 to 2022. The P consumption of each crop within a given county was calculated by multiplying the state-level P application rate by the planting acreage. A scaler was then calculated by dividing the county total P consumption by the summation of P consumption of all crop types to adjust the state-level P use rates for each crop within this county.

$$P\ rate_i^{ct} = \frac{P\ cons_{ct}}{\sum_{j=1}^{11} P\ rate_j^{st} \times Area_j^{ct}} \times P\ rate_i^{st} \qquad (3)$$

where $P\ rate_i^{ct}$ is the P application rate of crop type *i* in a given county, $P\ cons_{ct}$ is annual county P consumption, $P\ rate_j^{st}$ is the P application rate of crop type *j* in state *st*, $Area_j^{ct}$ is county-level planting area of crop type *j*, crops include 9 crops aforementioned, cropland pasture, and Other Crops.

2.2 P fertilizer application timing

By using the same approach as Cao et al. (2018), we estimated the P use at four application timings: fall (previous year), spring (before planting), at planting, and after planting of 9 major crops in each state from 1996 to 2013 from a statewide survey by USDA-ERS (2021) (Table S5). The raw data includes crop-specific P fertilizer application rates and percentages of the fertilized cropland for each of the 4 timings in each state. We calculated the P fertilizer consumption at each timing by multiplying the application rate with the area percentage and total cropland area. The fraction of the P fertilizer consumption at each timing was used to split the annual P fertilizer application rate generated in Sect. 2.1 into 4 application timings. The years before 1996 and after 2013 were assumed to adopt the same application timing strategy of years 1996 and 2013, respectively. We linearly interpolated the fractions of missing years between 1996 and 2013. The average application timing fraction based on the fraction of the abovementioned 8 major crops (excluding winter wheat), peanuts, and oats was used for cropland pasture and Other Crops.

2.3 P fertilizer application method

USDA-ERS (2021) reported the percentages of fertilized cropland by 5 P application methods for each crop during 1996-2013 based on a statewide survey (Table S5). For the years before 1996 and after 2013, we assume farmers adopt the same application method strategy of years 1996 and 2013, respectively. Due to the low adoption rate of the two mixed methods (Mixed method with incorporation and Mixed method without incorporation, $< 5\%$), we regrouped all 5 methods into 3 types: No Broadcast (e.g., chisel, knifed in, and banded in), Incorporation (Broadcast with incorporation and Mixed method with incorporation), and No Incorporation (Broadcast without incorporation and Mixed method without incorporation). We calculated the fraction of fertilized cropland by each method to total fertilized cropland to split the annual P application rate into 3 application methods. The average application method fraction of 8 major crops (excluding winter wheat), peanuts, and oats was used for cropland pasture and other crops.

2.4 Developing gridded maps for characterizing P fertilizer management history

To characterize the variation in spatial P fertilizer management information, we assigned the state-level (1850-1929) and county-level (1930-2021) crop-specific P fertilizer management data generated above to 1 km × 1 km gridded maps based on historical crop type distribution maps of the CONUS from 1850 to 2022 developed by Ye et al. (2024). It is worth noting that the P fertilizer management information remains consistent for the same crop within a given county but varies across crops, while 1-km annual crop type and area maps help add spatial heterogeneity of P fertilizer input within a county. The crop type distribution maps were developed using satellite images and imputed county-level planting area of each crop type from the USDA-National Agricultural Statistics Service (2022). We timed the gridded P application rate with crop density maps to convert the unit of P use rate from g P per cropland area to g P per land area. The crop density maps were reconstructed by integrating various sources of inventory and satellite data, representing the percentage of cropland within each pixel. More details about the land cover maps can be found in Ye et al. (2024). We then resampled the P fertilizer management maps a 4 km × 4 km resolution for display purposes. To examine the regional discrepancy of P fertilizer management in the study area, we partitioned the CONUS into 7 regions according to the US-FNCA (2022), including the Northwest (NW), the Southwest (SW), the Northern Great Plains (NGP), the Southern Great Plains (SGP), the Midwest (MW), the Northeast (NE), and the Southeast (SE).

3 Results

3.1 Magnitude and spatiotemporal patterns of P fertilizer uses

The amount of total P consumption in the US kept a moderate increase trend from 0.002 Tg P yr^{-1} in 1850 to 0.3 Tg P yr^{-1} in 1930, followed by a rapid rise to 2.2 Tg P yr^{-1} by 1980. After a swift fall to 1.6 Tg P $^{-1}$ in 1987, P consumption experienced large inter-annual fluctuations, reaching 1.7 Tg P $^{-1}$ in 2022 (Fig. 2a). In 1980, corn was the primary consumer of P fertilizer use (43% of national consumption), followed by Other Crops (17%), soybean (11%), and winter wheat (10%). Conversely, other crop types accounted for less than 10% of total use. In 2022, corn remained the dominant P fertilizer consumer (37%). However, the shares of Other Crops and soybean increased to 23% and 19% in 2022, respectively, while the shares of other crops diminished or remained stagnant (Fig. 2b & Fig S3). The P application rate on fertilized areas rapidly increased from 0.9 g P m^{-2} yr^{-1} in 1940 to 2.5 g P m^{-2} yr^{-1} in 1979, then declined to 1.9 g P m^{-2} yr^{-1} in 2022. In contrast, the P application rate on all cropland gradually increased from a low level of 0.3 g P m^{-2} yr^{-1} in 1940, reaching its peak at 1.2 g P m^{-2} yr^{-1} in 1979 and leveling off to 1.1 g P m^{-2} yr^{-1} in 2022. It exhibited a smaller range of fluctuations over time. Correspondingly, a dramatic elevation in P application rate was found among various crops from 1940 to 1980, with increments ranging from 0.5 g P m^{-2} yr^{-1} in durum wheat to 2.4 g P m^{-2} yr^{-1} in corn (Fig. 2c). From 1980 to 2020, large decreases in application rates were found in corn, winter wheat, sorghum, and cropland pasture, while large increases were found in spring wheat, rice, and durum wheat. As an increasing proportion of total cropland received P fertilizer from 1940 to 2022, the gap between P fertilizer use rate that on all cropland and on fertilized area has been narrowing for most crops except for soybean and cropland pasture.

Geospatially, as the P fertilizer consumption declined in the southeastern and eastern US and increased in the Midwest and the Northern Great Plains since 1900, the hotspot of P use has shifted correspondingly (Fig. 3-4). Low application rates (< 0.4 g P m^{-2} yr^{-1}) were common in the eastern US before 1940. The application rates in the Midwest and west coast showed remarkable increases to above 1.0 g P m^{-2} yr^{-1} by 1980. After 2000, the east of the Northern Great Plains and the Midwest became the US hotspots, displaying the most intensive P fertilizer use.

The P use in the Midwest and the Northern Great Plains is dominated by the nine major crops, whereas in other regions, like the Northwest, Southwest, and Northeast, Other Crops account for a considerable share of P use (Fig. 4). Owing to their wide cultivation, corn and soybean are the primary recipients of P nationwide in the most recent decade (the 2020s). The intense P fertilizer use is concentrated in the Midwest and the Northern Great Plains for corn (> 0.8 g P m^{-2} yr^{-1}) and for soybean (0.5-1.2 g P m^{-2} yr^{-1}) (Fig. 5). In comparison, the P uses of the rest seven major crops are mainly distributed in different regions. Low-level of application rate (< 0.5 g P m^{-2} yr^{-1}) is applied to cotton in the Southeast and the Southern Great Plains. Sorghum is planted mainly in the Southern Great Plains with application rate < 0.2 g P m^{-2} yr^{-1}. Rice is highly concentrated along the rice-belt and part of California with a relatively high application rate (0.5-0.8 g P m^{-2} yr^{-1}). P fertilizer applied to barley, spring wheat, and durum wheat is distributed in the Northern Great Plains at a moderate rate (0.3-0.8 g P m^{-2} yr^{-1}). Winter wheat has a wider spatial distribution with a low application rate, except for some regions in Kansas, Oklahoma, and Montana (0.3-0.5 g P m^{-2} yr^{-1}).

3.2 Patterns of P fertilizer application timings

Nationwide, corn, soybean, and cotton producers favor fall and spring applications before planting. Conversely, producers of all three wheats and barley apply a large portion of annual P fertilizer at planting (Fig. 6). The timing of P application varies significantly across the CONUS (Fig. S4). Fall application prevails in the Midwest and the Southern Great Plains (> 40%), especially in Iowa (> 60%) and Illinois (> 50%) (Fig. S4a). Relatively high portions of P fertilizer, up to 20%, are also applied in fall in the Southeast, the eastern Northern Great Plains, and the Northwest. In comparison, P applied in spring before planting dominates across the nation, especially in the east of the US (Fig. S4b). Intense P application (> 50%) at planting is prevalent in the Northeast, the Northwest, and both the north part of the Northern Great Plains and the Southern Great Plains (Fig. S4c). Application after planting is the least popular application timing (< 20%) in the nation, which mainly occurs in the Southern Great Plains, the Southeast, and some other states (e.g., Michigan, Nebraska, and Washington) (Fig. S4d). In contrast to the wider distribution of different timing ratios, the hotspots of P application rate for 4 timings were found in the Midwest, the Great Plains, and the rice-belt due to generally low application rate in other regions (Fig.

7). Intense P fertilizer was applied in the fall in the Midwest (> 0.6 g P m^{-2}) (Fig. 7a), particularly in Iowa and Illinois. Spring application was concentrated in the corn-belt and rice belt with rates greater than 0.5 g P m^{-2} (Fig. 7b). Farmers in the Northern Great Plains, Kansas, Indiana, and Wisconsin favored application at planting (Fig. 7c). After planting applications were minimal (< 0.2 g P m^{-2}) in the rice-belt and Nebraska (Fig. 7d).

3.3 Patterns of P fertilizer application methods

Nationally, broadcast application is popular among corn, soybean, cotton, and rice. In contrast, the non-broadcast method (e.g., injection and side-dress) dominates among three wheat types, sorghum, and barley (Fig. 6). The adoption of the P application method differs substantially among regions (Fig. S5). Non-broadcast is predominantly used in Wisconsin, Michigan, the Great Plains, and the Northwest (Fig. S5a). Broadcast with incorporation is widespread in the CONUS. However, the adoption rate is relatively low (< 40 %) in most of the region (Fig. S5b). In comparison, high P application by broadcast without incorporation (> 50%) is mainly distributed in the Midwest and the Southeast (Fig. S5c). Due to the intense use of P fertilizer in the corn-belt and rice-belt, the hotspots of P application rate (> 0.6 g P m^{-2}) for 3 methods were found in various regions within these two belts (Fig. 8). Non-broadcast application is prevalent in the Northern Great Plains, Kansas, and Minnesota (Fig. 8a). Intense application of P fertilizer via broadcast with incorporation was observed in Minnesota and Illinois (Fig. 8b). The corn-belt and rice-belt received most of their P fertilizer through broadcast without incorporation (Fig. 8c).

4 Discussion

4.1 Adjustments and improvements in state-level crop-specific P application rate

The national total P consumption obtained from the gap-filled bottom-up data in this study, summed from all major crops, cropland pasture, permanent pasture, and non-farm use, aligns well with diverse top-down data sources both in magnitude and inter-annual variations (Fig. S6). However, the bottom-up source displays a larger P consumption of certain crops in certain states (e.g., corn in Illinois), contributing to the divergences between these two approaches, notably after 2010 (Fig. S1&S2). These overestimations may be caused by distorted crop-specific P application rate and/or fertilized area percentage, derived from an inadequate survey pool. By modifying the surveyed crop-specific P application rate at the state level, we matched the state total P consumption between bottom-up and top-down approaches (Fig. 4). Despite the bottom-up source offering insights into cross-crop variations of P application rate, it overlooks the inter-state variability. Based on the total P consumption and crop-specific planting area in each county, we scaled the P application rate of each crop from state level to county level, which portrays greater variability across counties. Particularly, the ranges are wider for corn, soybean, winter wheat, sorghum, and barley (0-6 g P m^{-2} yr^{-1}) than those for spring wheat, cotton, rice, durum, cropland pasture, and Other Crops (Fig. 9). In addition, downscaling state-level P application rate to the county level augments the clarity of the geospatial pattern (Fig. 10). Top-down sources calculated average P use rate in each county by dividing the total P consumption by all cropland areas, yielding in a uniform value within each county but contrasting patterns across counties (Fig. 10a, d, g). Conversely, our map based on bottom-up sources at the state level detailed spatial heterogeneity in intensive agricultural regions, highlighting the cross-crop differences in P fertilizer use (Fig. 10b, e, h). By combining these two sources, our map characterizes spatial variability across counties and crop types (Fig. 10c, f, j). It highlights the region with intense P use, indicated by the top-down source, but also differentiates P application rates among crops within each county, indicated by the bottom-up source. This is particularly evident in the southern part of Missouri and the boundary between Minnesota and Dakotas (Fig. 10c&j). Accurate information on fertilizer management is essential for improving agricultural sustainability (Dhillon et al., 2017). Different crops have distinct P needs, and tailoring P use based on these needs can enhance the efficiency of P fertilizer utilization, maximizing crop yield while mitigating environmental impacts (Sabo et al., 2021). Moreover, detailed information on crop-specific P fertilizer management is important for assessing P losses attributed to runoff, erosion, and leaching, contributing to the development of agricultural policies (Daloğlu et al., 2012). Given the significance of crop-specific information, we advocate for the incorporation of cross-crop variations into the development of P fertilizer datasets.

4.2 Temporal and spatial dynamics of P fertilizer management

Concurrent with the historical changes in US cropland since 1850, P use has experienced different stages of change similar to nitrogen fertilizer use (Cao et al., 2018), influenced by various factors. From 1850 to 1940, the primary crops, corn, cotton, and winter wheat, were mainly concentrated in the eastern US. The constrained production of phosphate rock and low demand by limited crop productivity contributed to the low level of P consumption and application rate. As cropland expanded to the Midwest and the Great Plains from 1940 to 1980, the consumption of P fertilizer peaked after a sharp increase, driven by the rising application rate and percentage of fertilized area across various crops (Fig. 2-5). The major contributors to P consumption during this period were corn in the Midwest and spring wheat and winter wheat in the Great Plains. Following a brief decline in the 1980s due to improved fertilizer use efficiency, increased use of animal manure, and farm crisis (Scholz et al., 2013; Bouwman et al., 2017; Zhang et al., 2018), P consumption has stabilized with annual fluctuations primarily caused by changes in grain demand and fertilizer prices (US-EPA, 2024). Throughout this period, P consumption continued to decline in the eastern US while increasing or leveling off in other regions, driven by the continued expansion of corn and soybean at the expense of other crops (Fig. 2-5). Another possible contributing factor to the decline in P consumption is that the generous high-rate P application over a half-century has raised soil P level so much that it made it possible to have lower application and still meet crop demands (Sabo et al., 2021; Bian et al., 2022).

In the past decade, the average percentage of P fertilized area in the US was around 60% (including cropland and pasture), notably lower than that for nitrogen fertilizer. (Fig. S7). The percentage of fertilized area varies among crops, ranging from 42% for soybean to 89% for spring wheat. Estimating P use efficiency and P losses in agricultural systems highly relies on the precise application rate of P fertilizer (Solangi et al., 2023). It is noteworthy that, when we develop the environmental assessments that are sensitive to P fertilizer application rates, the results might be biased without considering the fertilized area percentage, especially for the crops with lower fertilized area percentages, such as soybean, cotton, and sorghum.

Despite the application of P fertilizer after planting is strongly recommended for improving P fertilizer use efficiency and minimizing P losses to the environment, this application timing remains the least popular choice for major crops in the US. Notably, rice in the US rice belt, sorghum in the Southern Great Plains, and cotton along the southwest coast were major contributors to post-planting applications. In contrast, both fall and spring applications before planting, leaving P susceptible to loss (King et al., 2018), have been widely adopted across multiple crops in the CONUS due to lower fertilizer prices, the availability of labor, and the ease of operating equipment (Carver et al., 2022). Winter wheat in the Southern Great Plain and the Northwest received over 40% of its annual P fertilizer in the fall, potentially contributing to boosting yield. However, corn and soybean farmers in the Midwest, cotton farmers in the Southwest and north of Texas, and sorghum farmers in the Southern Great Plains favor fall application, implying a high potential risk for P loss (Nelson et al., 2023; Yuan et al., 2013). Except for winter wheat, spring wheat, and durum wheat, all other crops receive more than a quarter of their annual P fertilizer in spring before application. Despite being closer to the planting date, the P fertilizer applied during early spring may be prone to loss via runoff, erosion, and leaching during intense rainfall (Williams and King, 2020; Algoazany et al., 2007). Application at planting is more prevalent among winter wheat and spring wheat in the Southern Great Plains and the Northern Great Plains, respectively.

Non-broadcast application is commonly found for winter wheat, durum wheat, and barley in the Northwest and Northern Great Plains, and for spring wheat, cotton, and sorghum in the Southern Great Plains. In addition, corn farmers in Wisconsin, Michigan, and the Northeast apply most of their annual P fertilizer using the non-broadcast method. The non-broadcast has been considered as a more conservative management to prevent P loss (Carver et al., 2022; Smith et al., 2016). However, broadcasting, including post-incorporation and non-incorporation, remains widespread across the US, particularly in the Midwest (hotspot for P fertilizer use) and the Southeast.

4.3 Uncertainty

The uncertainties of this database are mainly from several aspects: (1) The reconstructed P fertilizer management data extends back to 1850. However, compared to the national P use information, finer scale sources at the state- and county-level are only available from the 1930s onwards. Due to absence of earlier data, we interpolated the state-level P fertilizer consumption use back to 1850 by assuming they have the consistent interannual variations with the national data. This approach to addressing the temporal gaps may introduce larger uncertainties in the state-level temporal trajectories before the 1930s; (2) Limited information on P use in cropland pasture and permanent pasture at finer temporal and spatial resolution, contributing to uncertain estimates for Other Crops; (3) Adjustments were made on crop-specific P fertilizer use rates at the state level to reconcile top-down and bottom-up data sources. However, the paucity of detailed crop-specific information may introduce biases in our adjustments made for certain crops; (4) The composition of the Other Crops differs across states. All crop types under Other Crops within each state receive equal P application rate, which may bias the application rate for some crop types; (5) Due to the lack of finer spatial resolution information, we assumed the crop-specific P application timing and method are identical within each state. However, the spatial heterogeneity of application timing and method may be overlooked. Therefore, a finer resolution of spatial and temporal survey capturing crop-specific P application rate, timing, and method will be invaluable for enhancing our understanding of the spatiotemporal patterns of P fertilizer management information in the US; (6) Due to the lack of information on where croplands are fertilized, we assumed all the croplands in each state were fertilized but at a lower rate by multiplying the rates in the fertilized cropland with the percentage of fertilized cropland. This could lead to underestimation of P fertilizer use rate in fertilized areas and overestimation in non-fertilized area, especially when the state-level fertilized cropland percentage is low.

5 Data availability

The P fertilizer management dataset is publicly available via ZENODO at https://doi.org/10.5281/zenodo.10700822 (Cao et al., 2024).

6 Conclusion

By harmonizing various data sources, we reconstructed a long-term spatially explicit P fertilizer management dataset at 4 km ×4 km resolution from 1850 to 2022 in the CONUS. We discussed the divergence between top-down (total P consumption) and bottom-up (crop-specific P fertilizer use) data sources, underscoring the necessity to improve crop-specific management information in future surveys. The newly developed dataset, leveraging the strengths of both data sources, highlights cross-crop variabilities in the long-term use of P fertilizer among counties. The results reveal a substantial increase in P fertilizer consumption and application rate from 1850 to 2022, notably during 1940-1980. However, the magnitude and long-term changing trend differed significantly across crop types. It is worth noting that approximately 40% of cropland in the US does not receive P fertilizer inputs. Since 1850, the hotspots of P fertilizer use have shifted from the southeastern and eastern US to the Midwest and the Great Plains, driven by changes in cropland distribution and P fertilizer application rate across different crop types. Additionally, P fertilizer application timing and method vary substantially across crop types and regions. Corn, soybean, and cotton in the Midwest and the Southeast receive over 60% of their annual P fertilizer at pre-planting and through broadcasting. Conversely, winter wheat, spring wheat, durum wheat, and barley in the Great Plains and the Northwest predominantly receive their annual P fertilizer at- and post-planting, and via non-broadcasting. Promoting efficient P fertilizer management, encompassing the proper application rate, timing, and method, is essential for enhancing P use efficiency and thus contributes to economic, social, and environmental sustainability and profitability.

Author contributions

CL, PC, and BY conceptualized the paper and developed the methodology. PC and BY reconstructed the dataset. PC and BY prepared the manuscript with contributions from all the co-authors.

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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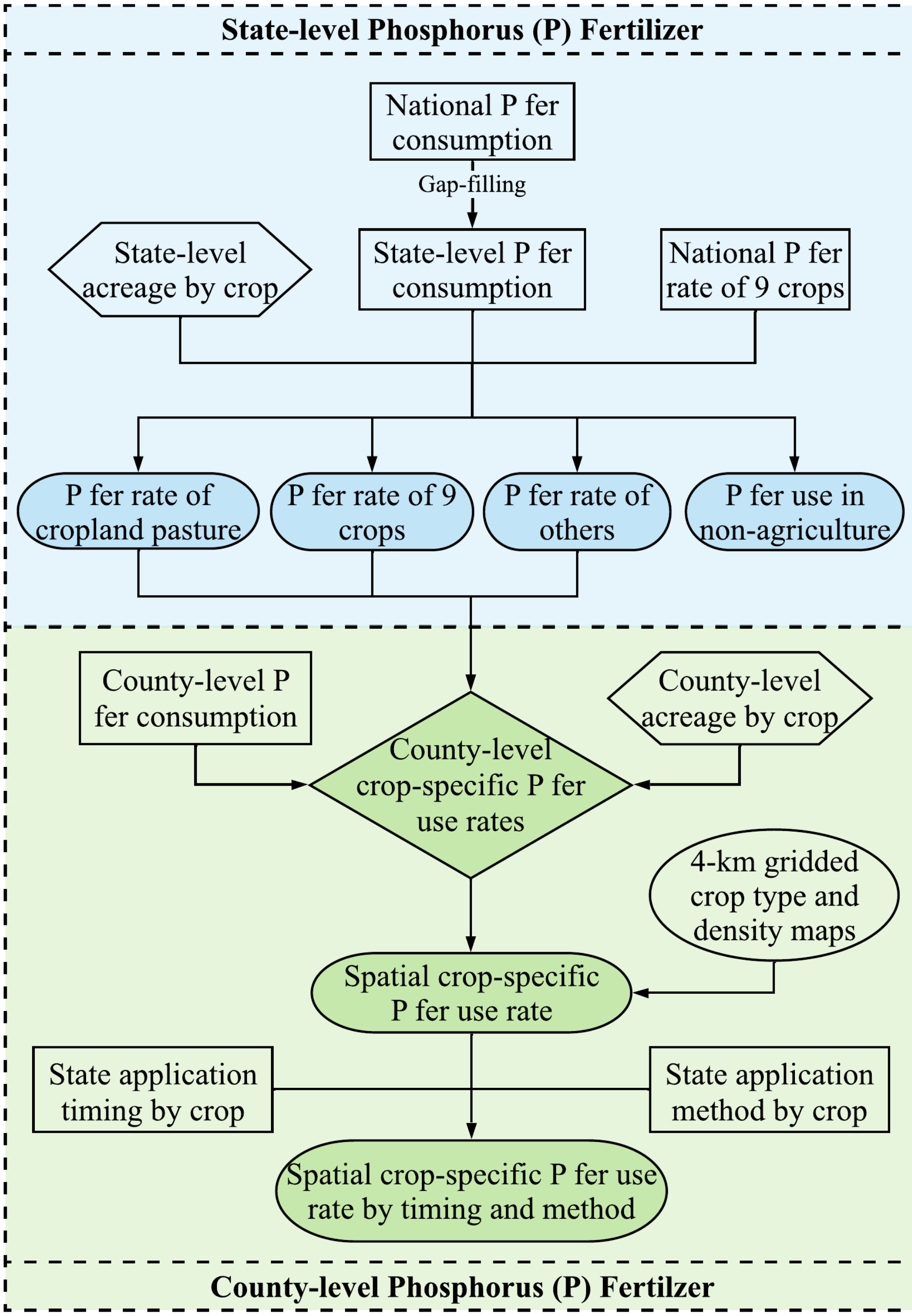

Figure 1. Diagram for P fertilizer management dataset development. The upper blue box represents the development of state-level crop-specific P fertilizer application rate based on the bottom-up dataset. The lower green box represents the development of county-level P fertilizer application rate development by reconciling the top-down and bottom-up dataset.

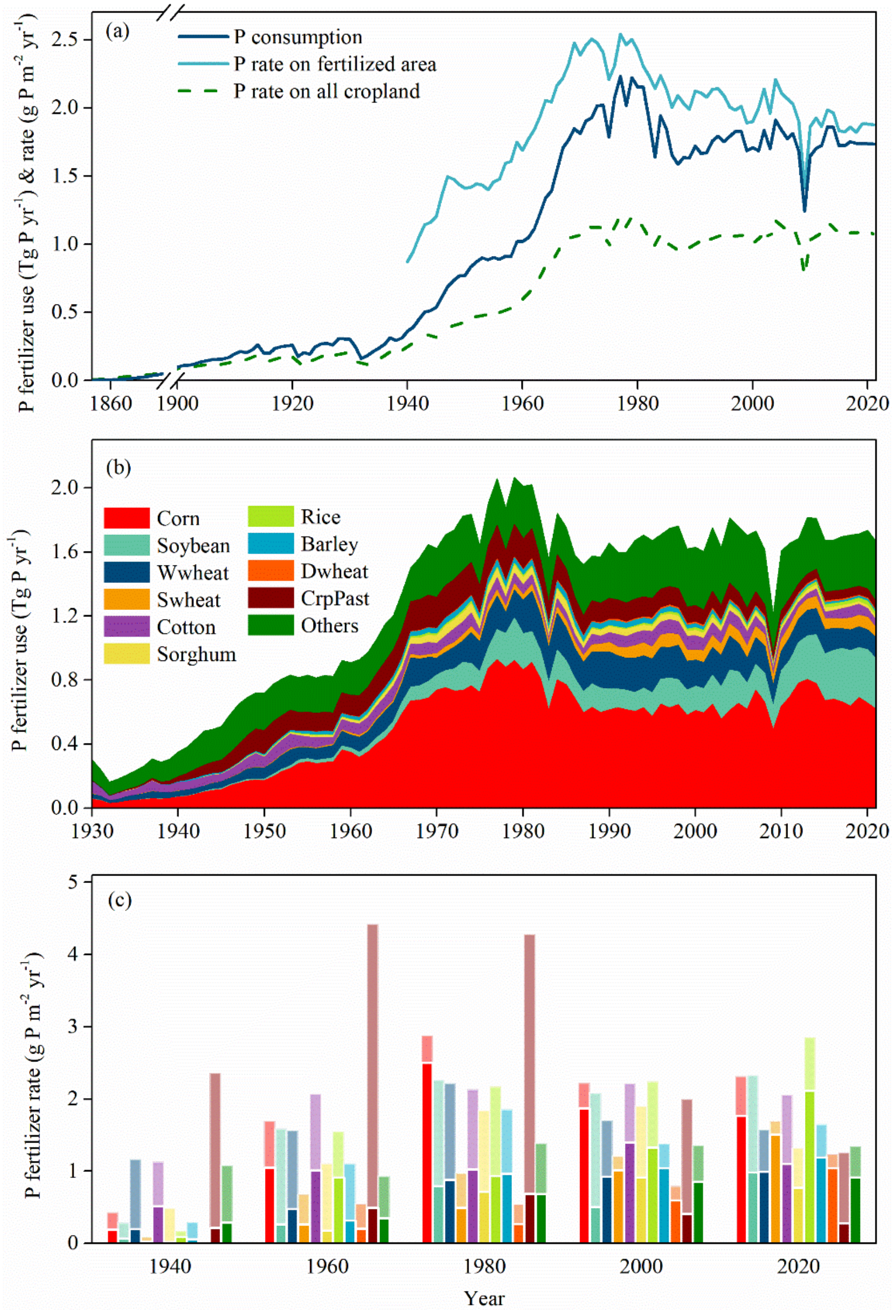

Figure 2. Time-series of P fertilizer consumption and average application rates for all crops (a), and P fertilizer consumption (b) and application rates (c) for 11 specific crops in the contiguous US. All cropland is the total planting area, while the fertilized area is the proportion of the cropland that receives P fertilizer. In panel (c), light-colored bars denote the application rate on fertilized area and dark-colored bars show the modified application rate with the assumption that the county-level P fertilizer consumption was distributed on all the croplands. Both start from zero on the y-axis.

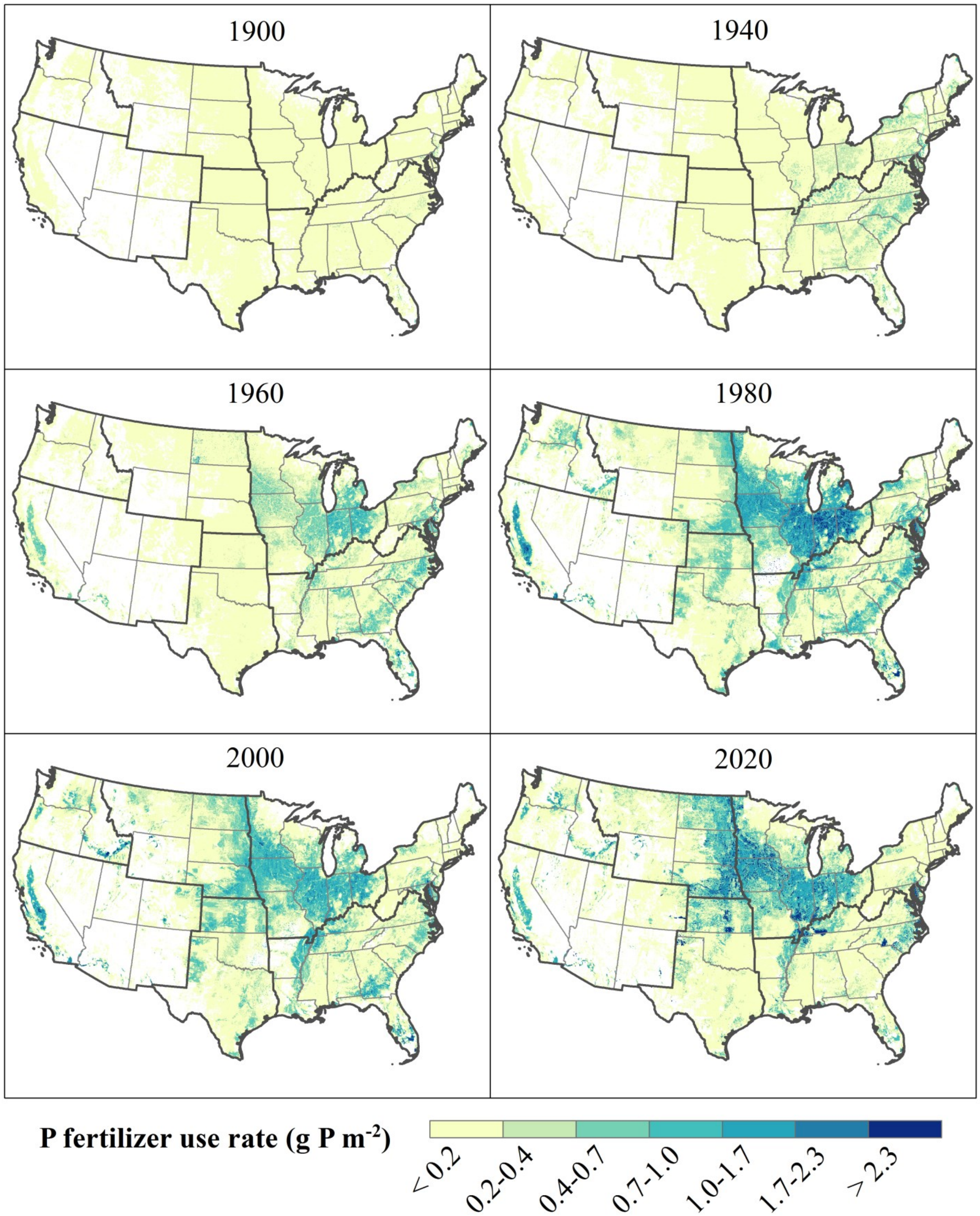

Figure 3. Spatial distribution of P fertilizer application rates in the 1990s, 1940s, 1960s, 1980s, 2000s, and 2020s in the contiguous US at a resolution of 4-km x 4-km, with regions framed as NW (Northwest), NGP (Northern Great Plains), SGP (Southern Great Plains), SW (Southwest), MW (Midwest), SE

(Southeast), and NE (Northeast). The maps generated for 1900, 1940, and 1960 relied on state-level crop-specific data. Subsequent maps, post-1960, utilized county-level crop-specific data. The values on the map represent the P fertilizer use rate on all land areas and can be converted to P fertilizer use rate on per unit cropland area by lining up with our crop type and area database (Ye et al., 2024)

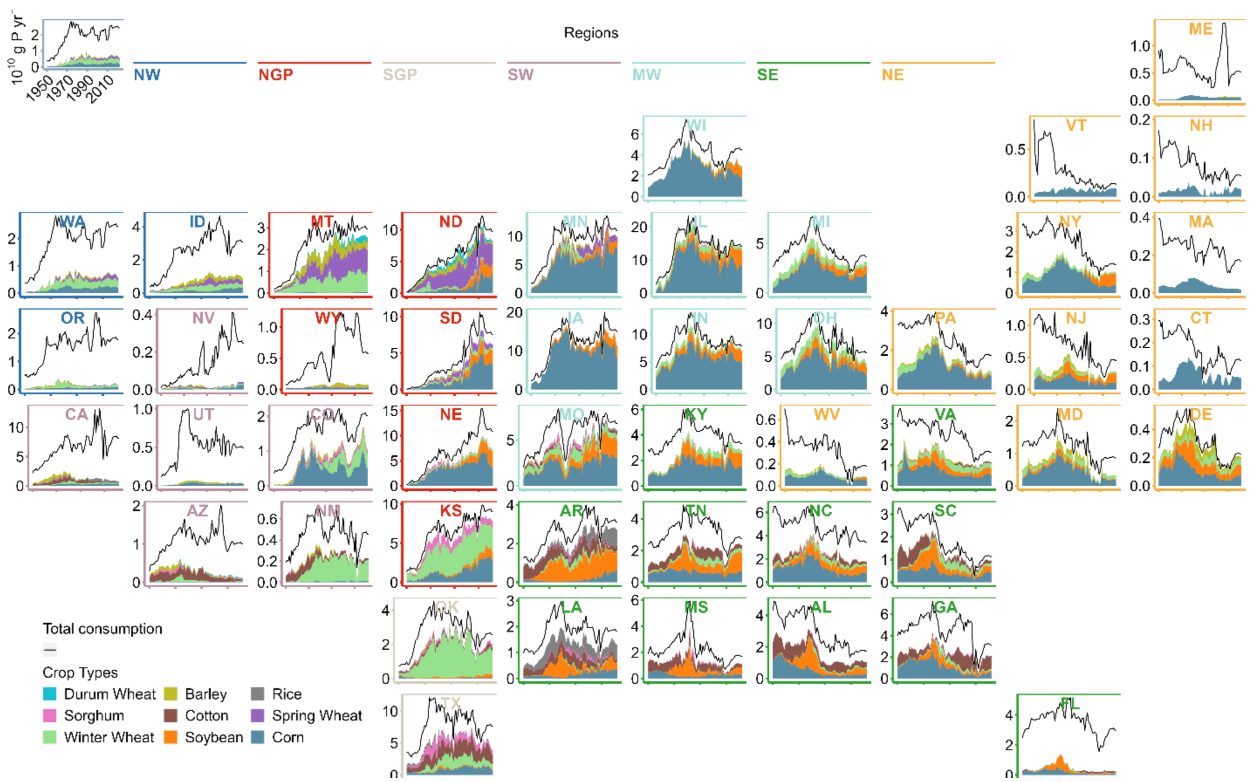

Figure 4. Time-series of P fertilizer consumption by each state and 9 major crops from 1950 to 2022 in the contiguous US. The top-left figure illustrates the scales of x-axis and y-axis. The solid black line in each subplot represents total P fertilizer consumption, and the stacked area represents P fertilizer consumption by different crops. NW is the Northwest, NGP is the Northern Great Plains, SGP is the Southern Great Plains, SW is the Southwest, MW is the Midwest, SE is the Southeast, NE is the Northeast.

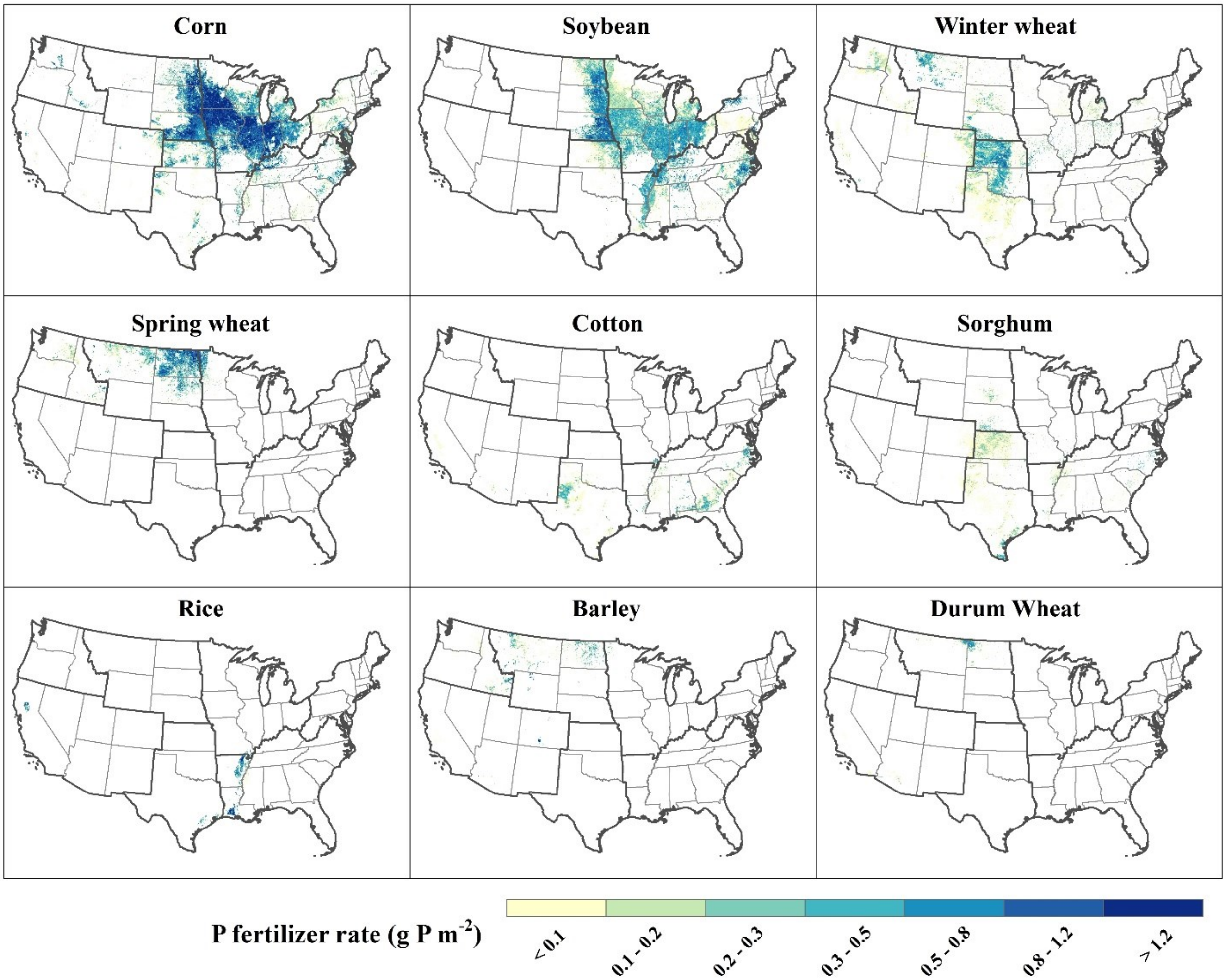

Figure 5. Spatial distribution of P fertilizer application rates for 9 major crops in 2020 at 4-km x 4-km resolution, with regions framed as NW (Northwest), NGP (Northern Great Plains), SGP (Southern Great Plains), SW (Southwest), MW (Midwest), SE (Southeast), and NE (Northeast). The values on the map represent the P fertilizer use rate on all land areas and can be converted to P fertilizer use rate on per unit cropland area by lining up with our crop type and area database (Ye et al., 2024)

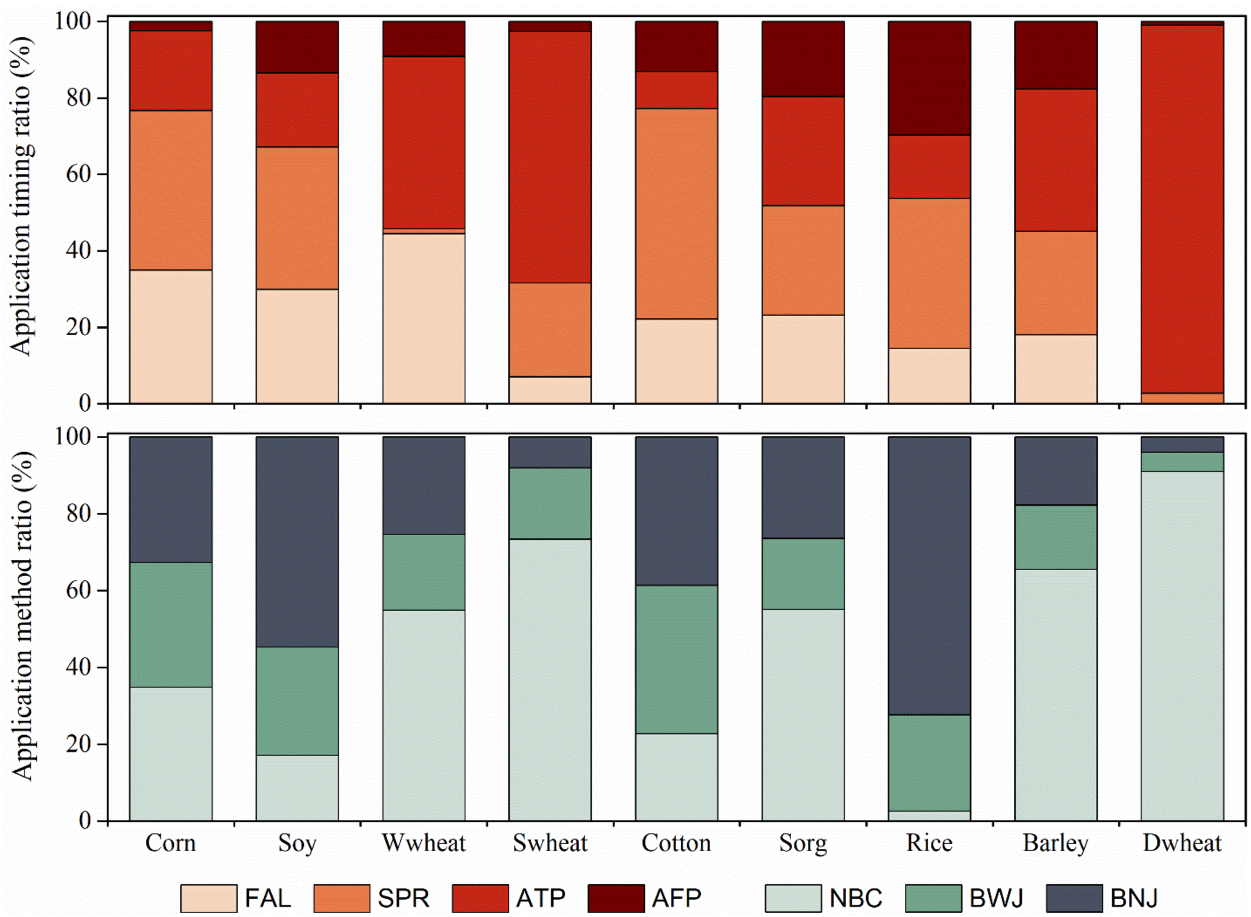

Figure 6. The share of each application timing and method for 9 major crops in the US. FAL is fall application in previous year. SPR is spring application before planting. ATP is application at planting. AFP is application after planting. NBC is non-broadcast. BWJ is broadcast with injection, which is mix or inject after broadcast. BNJ is broadcast with no injection.

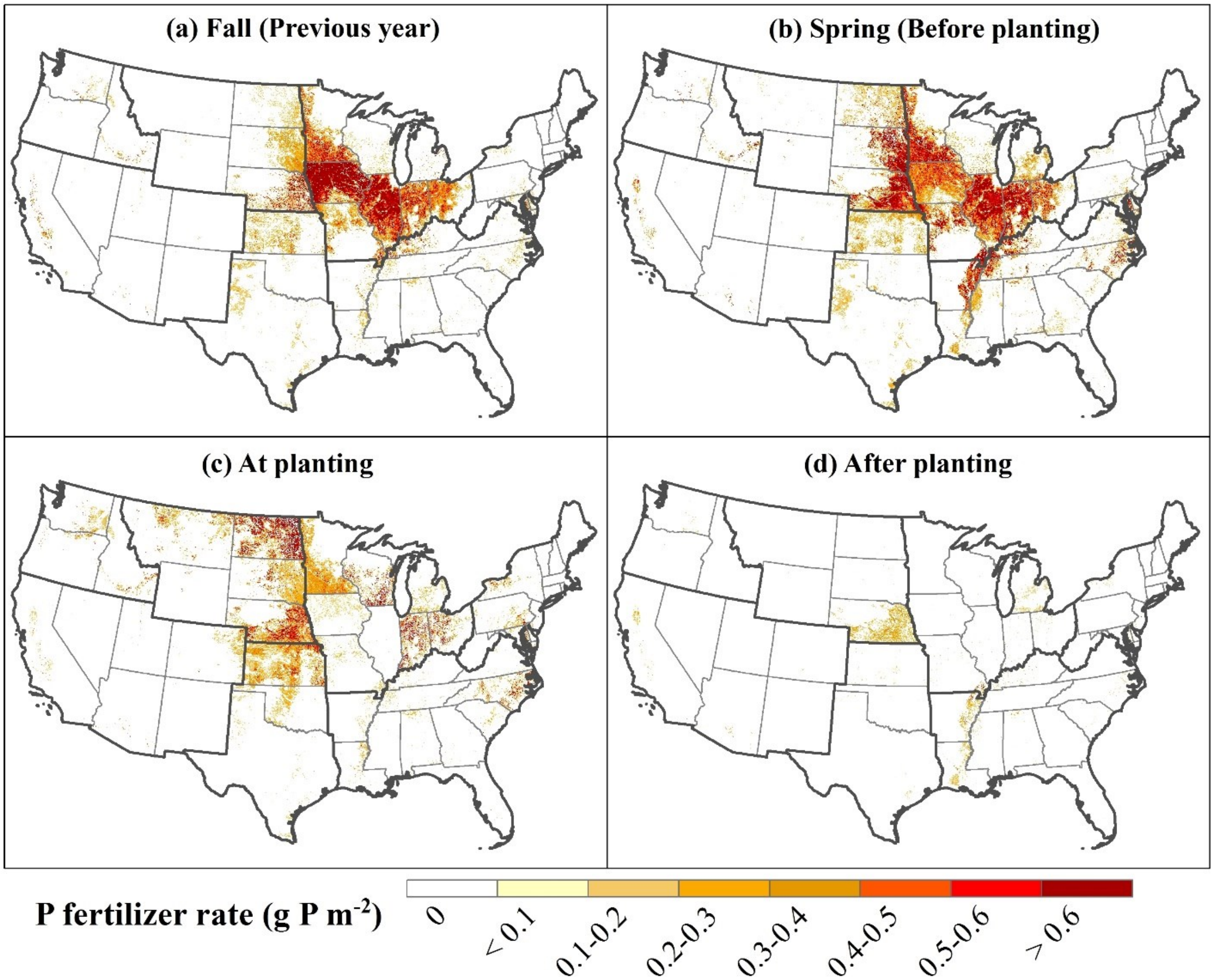

Figure 7. Spatial distribution of P fertilizer application rates at four application timings across the contiguous US in 2020.

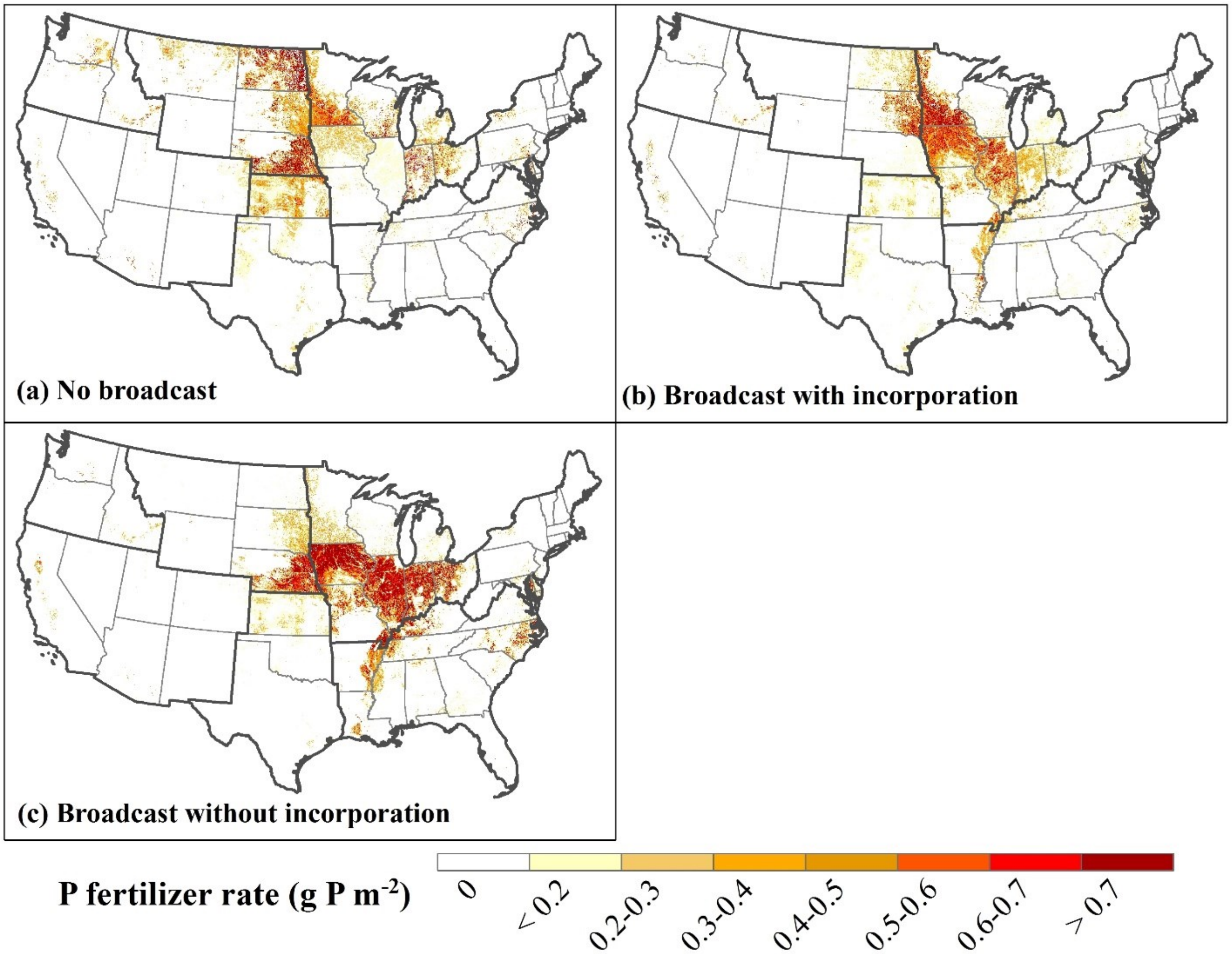

Figure 8. Spatial distribution of P fertilizer application rates in three application methods across the contiguous US in 2020.

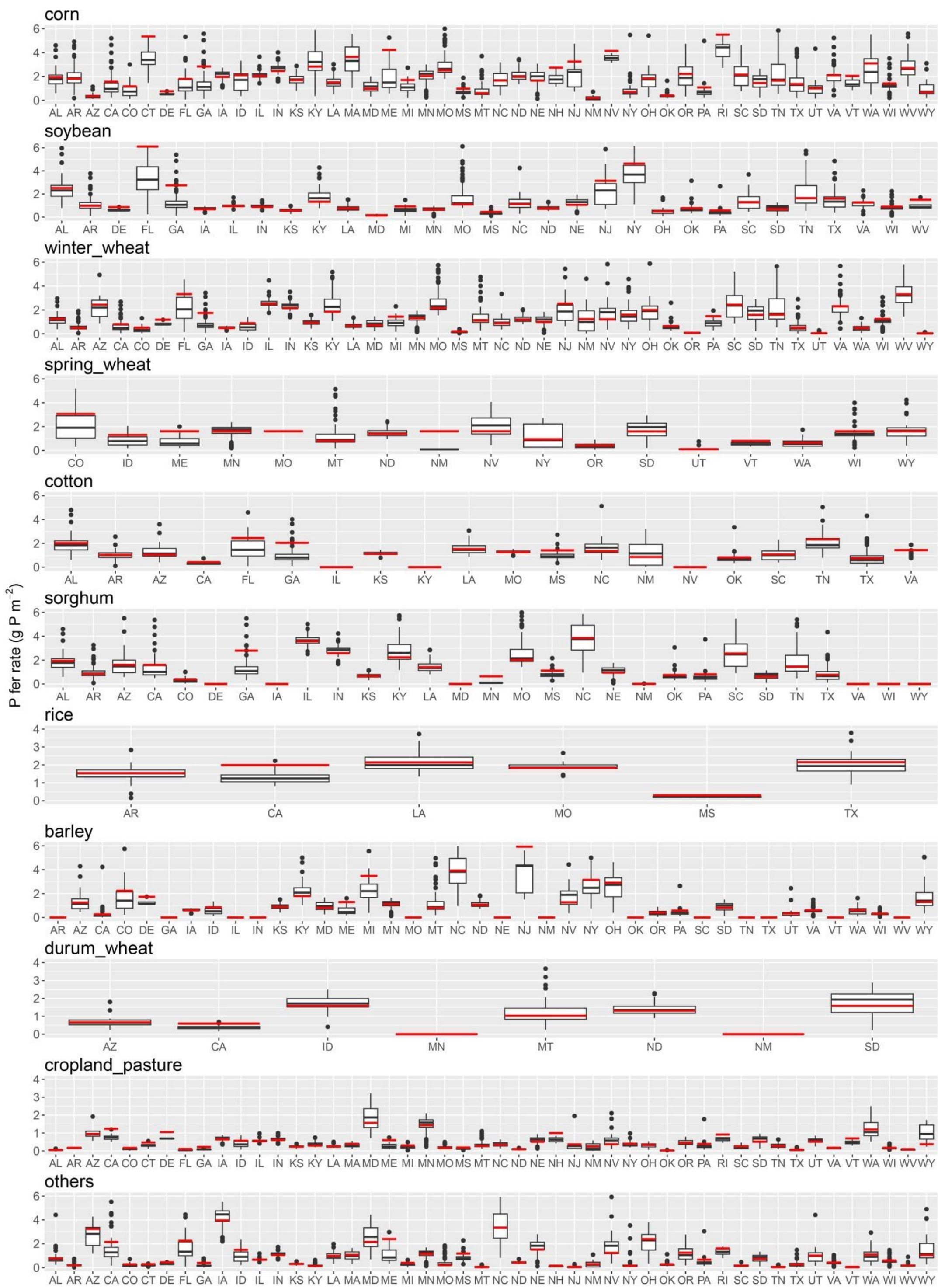

Figure 9. Comparison between state-level (red line) and county-level average (black boxplot) crop-specific P fertilizer application rate in primary crop-planting states in 2015. The red line indicates the state-level P fertilizer application rate. The box plot shows the distribution of county-level P fertilizer application rate (dots are outliers).

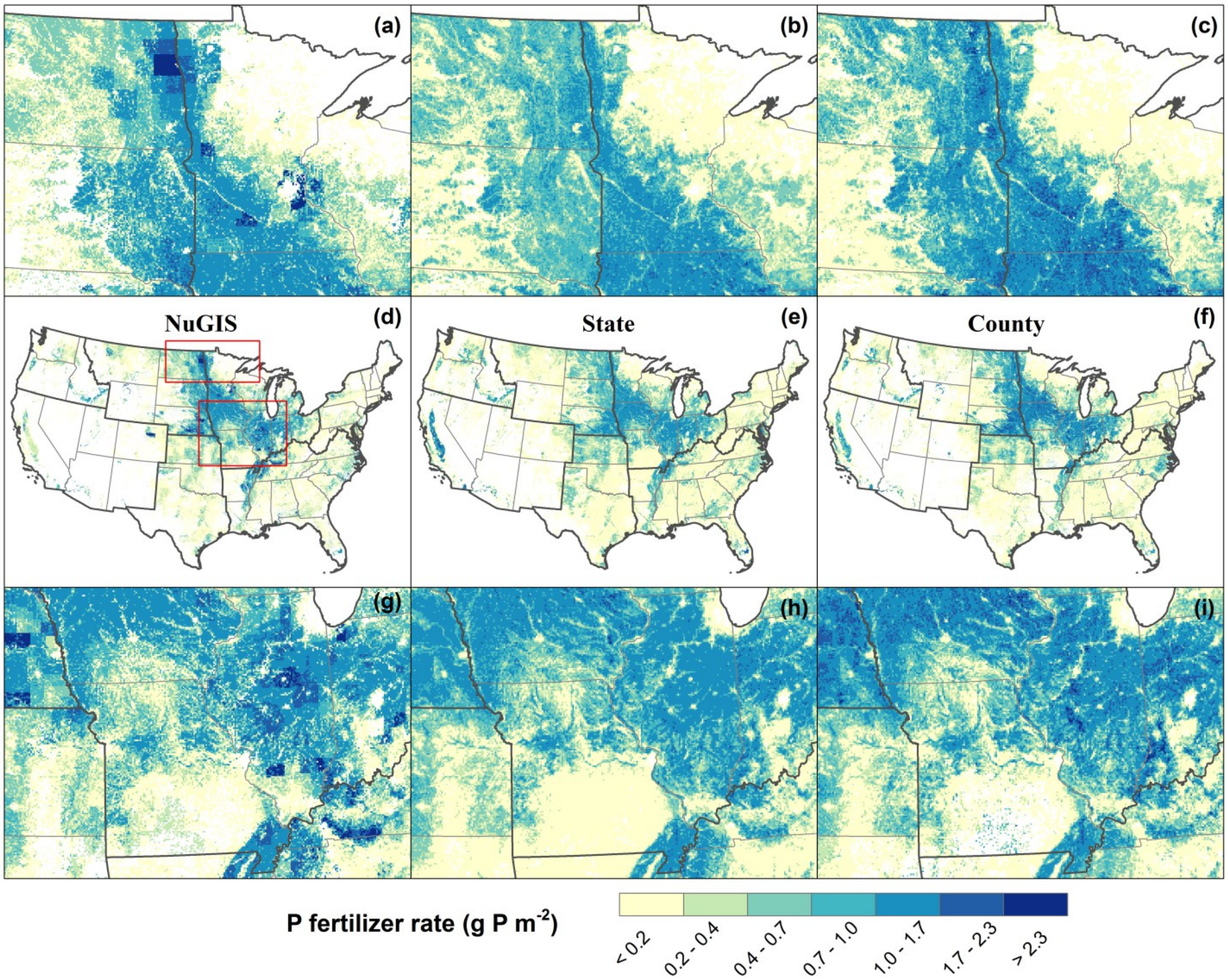

Figure 10. Comparison of spatial distribution of P fertilizer application rate in the contiguous US in 2016. NuGIS (a, d, g) represents the average application rate derived from county-level sales data. State (b, d, h) and county (c, f, i) data used for plotting represent the crop-specific P fertilizer application rate at state- and county-level developed in this study, respectively. To make it comparable, the same cropland map was used to mask out the cropland extent for NuGIS. Two red boxes in Fig d were zoomed in to demonstrate more details in the top and bottom panels.