Received: 30 September 2021 | Accepted: 22 March 2022 | Published online: 25 April 2022

DOI: 10.1002/jeq2.20351

Journal of Environmental Quality

DATASET ARTICLE

P-FLUX: A phosphorus budget dataset spanning diverse agricultural production systems in the United States and Canada

M. R. Williams[1] | **P. Welikhe**[1,2] | **J. Bos**[1] | **K. King**[3] | **M. Akland**[4] | **D. Augustine**[5] | **C. Baffaut**[6] | **E.G. Beck**[7] | **A. Bierer**[8] | **D.D. Bosch**[9] | **E. Boughton**[10] | **C. Brandani**[11] | **E. Brooks**[12] | **A. Buda**[13] | **M. Cavigelli**[14] | **J. Faulkner**[15] | **G. Feyereisen**[16] | **A. Fortuna**[17] | **J. Gamble**[16] | **B. Hanrahan**[3] | **M. Hussain**[18] | **M. Kohmann**[19] | **J. Kovar**[20] | **B. Lee**[4] | **A. Leytem**[8] | **M. Liebig**[21] | **D. Line**[24] | **M. Macrae**[22] | **T. Moorman**[20] | **D. Moriasi**[17] | **N. Nelson**[23] | **A. Ortega-Pieck**[12] | **D. Osmond**[24] | **O. Pisani**[9] | **J. Ragosta**[25] | **M. Reba**[26] | **A. Saha**[10] | **J. Sanchez**[19] | **M. Silveira**[19] | **D. Smith**[27] | **S. Spiegal**[25] | **H. Swain**[10] | **J. Unrine**[4] | **P. Webb**[28] | **K. White**[14] | **H. Wilson**[29] | **L. Yasarer**[30]

[1]National Soil Erosion Research Laboratory, USDA-ARS, West Lafayette, IN, USA

[2]Dep. of Agronomy, Purdue Univ., West Lafayette, IN, USA

[3]Soil Drainage Research Unit, USDA-ARS, Columbus, OH, USA

[4]Dep. of Plant and Soil Sciences, Univ. of Kentucky, Lexington, KY, USA

[5]Rangeland Resources Research Unit, USDA-ARS, Fort Collins, CO, USA

[6]Cropping Systems and Water Quality Research Unit, USDA-ARS, Columbia, MO, USA

[7]Kentucky Geological Survey, Univ. of Kentucky, Henderson, KY, USA

[8]Northwest Irrigation and Soils Research Lab, USDA-ARS, Kimberly, ID, USA

[9]Southeast Watershed Research Laboratory, USDA-ARS, Tifton, GA, USA

[10]Buck Island Ranch, Archbold Biological Station, Lake Placid, FL, USA

[11]Dep. of Animal and Range Science, New Mexico State Univ., Las Cruces, NM, USA

[12]Dep. of Soil and Water Resources, Univ. of Idaho, Moscow, ID, USA

[13] Systems and Watershed Management Research Unit, USDA-ARS, University Park, PA, USA

[14]Sustainable Agricultural Systems Laboratory, USDA-ARS, Beltsville, MD, USA

[15]Dep. of Plant and Soil Science, Univ. of Vermont, Burlington, VT, USA

[16]Soil and Water Management Unit, USDA-ARS, St. Paul, MN, USA

[17]Grazinglands Research Laboratory, USDA-ARS, El Reno, OK, USA

[18]W.K. Kellogg Biological Station, Michigan State Univ., Hickory Corners, MI, USA

[19]Range Cattle Research and Education Center, Univ. of Florida, Ona, FL, USA

[20]Agroecosystems Management Research, USDA-ARS, Ames, IA, USA

[21]Northern Great Plains Research Laboratory, USDA-ARS, Mandan, ND, USA

[22]Dep. of Geography and Environmental Management, Univ. of Waterloo, Waterloo, ON, Canada

Abbreviations: LTAR, Long-term Agroecosystem Research.

[23]Dep. of Agronomy, Kansas State Univ., Manhattan, KS, USA
[24]Dep. of Crop and Soil Sciences, North Carolina State Univ., Raleigh, NC, USA
[25]USDA-ARS, Jornada Experimental Range, Las Cruces, NM, USA
[26]USDA-ARS, Delta Water Management Research Unit, Arkansas State Univ., Jonesboro, AR, USA
[27]Grassland, Soil and Water Research Laboratory, USDA-ARS, Temple, TX, USA
[28]Dep. of Crop, Soil, and Environmental Sciences, Univ. of Arkansas, Fayetteville, AR, USA
[29] Science and Technology Branch, Brandon Research and Development Centre, Agriculture and Agri-Food Canada, Brandon, MB, Canada
[30]National Sedimentation Laboratory, USDA-ARS, Oxford, MS, USA

Correspondence
M. R. Williams, USDA-ARS National Soil Erosion Research Laboratory, 275 S. Russell St., West Lafayette, IN 47907, USA.
Email: mark.williams2@usda.gov

Assigned to Associate Editor Jaehak Jeong.

Abstract
Quantifying spatial and temporal fluxes of phosphorus (P) within and among agricultural production systems is critical for sustaining agricultural production while minimizing environmental impacts. To better understand P fluxes in agricultural landscapes, P-FLUX, a detailed and harmonized dataset of P inputs, outputs, and budgets, as well as estimated uncertainties for each P flux and budget, was developed. Data were collected from 24 research sites and 61 production systems through the Long-term Agroecosystem Research (LTAR) network and partner organizations spanning 22 U.S. states and 2 Canadian provinces. The objectives of this paper are to (a) present and provide a description of the P-FLUX dataset, (b) provide summary analyses of the agricultural production systems included in the dataset and the variability in P inputs and outputs across systems, and (c) provide details for accessing the dataset, dataset limitations, and an example of future use. P-FLUX includes information on select site characteristics (area, soil series), crop rotation, P inputs (P application rate, source, timing, placement, P in irrigation water, atmospheric deposition), P outputs (crop removal, hydrologic losses), P budgets (agronomic budget, overall budget), uncertainties associated with each flux and budget, and data sources. Phosphorus fluxes and budgets vary across agricultural production systems and are useful resources to improve P use efficiency and develop management strategies to mitigate environmental impacts of agricultural systems. P-FLUX is available for download through the USDA Ag Data Commons (https://doi.org/10.15482/USDA.ADC/1523365).

1 | INTRODUCTION

Accelerating global demand for agricultural products combined with the need to conserve natural resources has resulted in calls for sustainable intensification—that is, increasing production while minimizing environmental impact (Kleinman et al., 2018; Spiegal et al., 2018). Sustainable intensification requires scalable strategies that efficiently invest resources and mitigate trade-offs produced when simultaneously working toward both production and environmental objectives. The use and management of phosphorus (P) is the epitome of a sustainable intensification challenge given its widespread use in agricultural production (Sharpley et al., 2018), its likely future scarcity (Van Vuuren et al., 2010), and environmental concerns associated with excess P delivered to surface waters (Bennett et al., 2001; Elser et al., 2007). Improving our understanding of the spatial and temporal fluxes of P within and among agricultural production systems and quantifying the effects of management practices on P cycling are critical needs for addressing this challenge.

Numerous studies have quantified P fluxes in cropland (Baker & Richards, 2002; Bos et al., 2021; Hanrahan et al., 2019; Lanyon et al., 2006; Ma et al., 2011; MacDonald et al., 2011), rangeland, and pasture systems (Obour et al., 2011; Rothwell et al., 2020; Sattari et al., 2016; Swain et al., 2007; Vendramini et al., 2007) across varying spatial and temporal scales. Accounting for P inputs (e.g., fertilizer application) and outputs (e.g., crop removal) to a defined system over a fixed time period is useful for determining P budgets. Phosphorus budgets can help identify P surpluses or deficits, provide insight into P cycling processes, and quantify P use efficiency (Zhang et al., 2020). However, comparing nutrient fluxes and budgets among studies can be difficult due to variability in the conceptual model used for completing the budget (Oenema et al., 2003). Depending on the conceptual model (e.g., Soil–Plant, Animal–Plant–Soil, Agro–Food, Landscape, and variants within each; Li et al., 2019), the flux components used for completing the budget can vary along with the level of detail captured by the budget. Agriculture is also diverse, spanning gradients in scale, climate, physiography, ecology, economics, and culture (Zhang et al., 2007). Differences in spatial and temporal boundaries further complicate the comparison of nutrient budgets and nutrient use efficiencies among agricultural production systems (Oenema et al., 2003; Zhang et al., 2020).

The USDA Long-term Agroecosystem Research (LTAR) network was designed to rectify the difficulties often associated with multisite comparisons and seeks to develop a national roadmap for the sustainable intensification of agricultural production in the face of a diverse range of agricultural stressors and expectations (Kleinman et al., 2018). Through empirical experimentation and coordinated observation, the LTAR network enables cross-site comparison, as well as integration of findings at broader spatial and temporal scales. The network is currently represented by 18 locations representing approximately 49% of cereal production, 30% of forage production, and 32% of livestock production in the United States (Kleinman et al., 2018). Partnerships with universities and other research organizations have further broadened the scope and relevance of the LTAR network in the United States and internationally (Walbridge & Shafer, 2011). Many LTAR locations and partners have a long tradition of measuring water and nutrient fluxes at field and watershed scales (Kleinman et al., 2018). The network is therefore uniquely poised for characterizing P fluxes, P use efficiency, and P budgets across diverse agroecosystems and for providing the data (Kaplan et al., 2017) and inferences needed to inform both local and national P management strategies.

Through collaboration among LTAR network locations ($n = 15$) and with partner research organizations in the United States and Canada ($n = 9$), including those in the USDA Conservation Effects Assessment Project (CEAP) and the Agriculture and Agri-Food Canada Living Laboratories Initiative, the P-FLUX dataset was developed. P-FLUX is a harmonized dataset of P fluxes (inputs and outputs) and budgets, as well as estimated uncertainties for each flux and budget, for 61 diverse production systems. The objectives of this paper are (a) to present and provide a description of the P-FLUX dataset, (b) to provide summary analyses of the agricultural production systems included in the dataset and the variability in P inputs and outputs across systems, and (c) to provide details for accessing P-FLUX, dataset limitations, and example future uses.

Core Ideas

- Assessing P fluxes and budgets is critical for sustainable agricultural intensification.
- P fluxes and budgets were determined for 61 production systems in the USA and Canada.
- P inputs, outputs, and budgets were highly variable across production systems.
- A detailed and harmonized dataset of P fluxes/budgets and uncertainties was developed.
- Data are available as comma-separated (.csv) files through the USDA Ag Data Commons.

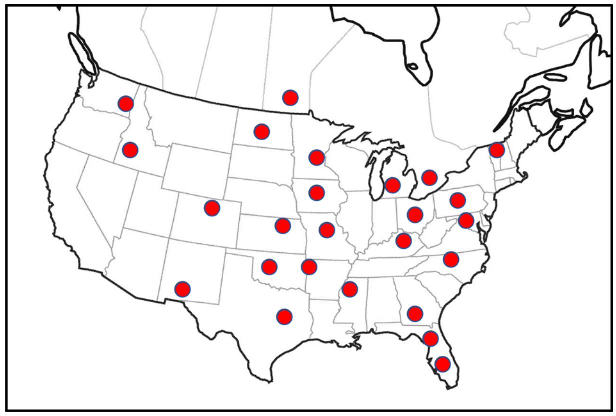

FIGURE 1 Map of research locations in the United States and Canada that contributed to the P-FLUX dataset. Note: Points reflect the general location of the main research institution and not the specific research sites included in the dataset

2 | DATASET DESCRIPTION

2.1 | Geographic extent and production systems

The P-FLUX dataset spans 22 U.S. states and 2 Canadian provinces, with latitudes ranging from Florida, USA (27°24′39.75″ N) to Manitoba, Canada (49°53′42.27″ N) and longitudes from Vermont, USA (73°12′43.56″ W) to Washington, USA (117°10′54.12″ W) (Figure 1). Each of the 24 locations contributed data from one or more production systems ($n = 61$) that were representative of common agricultural practices for their respective region. Production systems are classified as either (a) cropland with grain, root, or fiber crops ($n = 42$); (b) cropland with harvested forage ($n = 6$); (c) mixed ($n = 6$); (d) rangeland ($n = 5$); or (e) bioenergy ($n = 2$). Crop rotations vary from 1 yr (i.e., continuous cropping) to 10 yr (Table 1). The most common crops include

TABLE 1 Locations and production systems included in the P-FLUX dataset. If a production system is represented more than once within a given state or province, then the number (n) of systems is indicated in parentheses

State or province	Production system
Arkansas, USA	Continuous cotton
	Cotton–corn
	Pasture; grazed tall fescue
	Pasture; hayed and grazed tall fescue ($n = 2$)
Colorado, USA	Rangeland
Florida, USA	Rangeland ($n = 2$)
Georgia, USA	Cotton–peanut ($n = 2$)
	Sorghum–peanut–cotton
Idaho, USA	Wheat–potato–barley–sugar beet ($n = 2$)
	Continuous corn
	Continuous corn; with triticale cover crop
	Corn–barley–alfalfa–alfalfa–alfalfa ($n = 2$)
Iowa, USA	Corn–soybean ($n = 2$)
	Corn–soybean; with cereal rye cover crop
Kansas, USA	Corn–soybean
Kentucky, USA	Corn–soybean ($n = 2$)
Manitoba, Canada	Canola–soybean–wheat
	Wheat–canola
	Wheat–hemp
	Organic small grains with flexible rotation
Maryland, USA	Corn–soybean–wheat & soybean; with rye cover crop ($n = 2$)
	Corn–soybean; with rye and vetch cover crop
	Corn–soybean–wheat; with rye and vetch cover crop
	Corn–soybean–wheat–alfalfa–alfalfa–alfalfa
Michigan, USA	Continuous corn
	Hybrid poplar
	Switchgrass
Minnesota, USA	Corn silage–alfalfa
Mississippi, USA	Continuous cotton
	Continuous soybean
Missouri, USA	Corn–soybean
New Mexico, USA	Rangeland
North Carolina, USA	Pasture and continuous corn
	Pasture
	Corn–wheat–soybean
North Dakota, USA	Spring wheat–corn–soybean
	Spring wheat–corn–soybean; with cover crop
Ohio, USA	Corn–soybean ($n = 2$)
	Corn–soybean–wheat
Oklahoma, USA	Continuous wheat ($n = 2$)
	Rangeland
Ontario, Canada	Soybean–soybean–corn
	Corn–soybean–wheat ($n = 2$)
Pennsylvania, USA	Corn–corn–corn–corn–corn–corn–corn–alfalfa–alfalfa–alfalfa ($n = 2$)
Texas, USA	Corn–corn–wheat ($n = 3$)
Vermont, USA	Corn silage–hay
Washington, USA	Spring wheat–garbanzo–winter wheat

corn (*Zea mays* L.; $n = 35$), soybean [*Glycine max* (L.) Merr.; $n = 23$], and wheat (*Triticum aestivum* L.; $n = 21$). The dataset also includes other general site information (e.g., area and soil series).

2.2 | Phosphorus fluxes and management

For each agricultural production system, research locations completed a P budget data form providing detailed information on P fluxes. Research locations provided management information including P application (source, timing, placement, rate) and crop removal for each crop within the rotation. For example, in a production system with a 2-yr rotation of corn and soybean, the mean and standard deviation for P application rate and crop removal were reported for both corn and soybean (Table 2). In cases where separate P budget data forms from the same location were completed for replicate plots with similar production systems (i.e., similar field and nutrient management practices), data were averaged to create one representative dataset for the system since P fluxes and budgets were nearly identical. Data on hydrologic losses (i.e., surface runoff and subsurface drainage), P applied via irrigation, and atmospheric deposition were reported on a calendar year because these measurements are typically not available for each specific crop within a rotation (Table 2). All data provided from research locations were assumed to be representative of current agricultural practices and climate common to the region where the data were collected, and data are not specific to particular years or time period.

If data on one or more P flux component were not measured by the research location, data were estimated whenever possible. Data for atmospheric deposition and hydrologic losses were estimated using literature values from studies

TABLE 2 Example data from a corn–soybean rotation in Ohio, USA

Variable	Data
Site name	Eastern Corn Belt LTAR
State/Country	Ohio, USA
Area (ha)	13
Soil series (USDA)	Hoytville clay loam
Length of crop rotation (yr)	2
Crop rotation	Corn–soybean
Cover crop	No
Irrigation	No
Subsurface drainage	Yes
Type of tillage	No-till
P source	Inorganic
P application timing	Spring/Fall
P application placement	Broadcast
Avg. P application rate (kg P ha^{-1} yr^{-1})	
Corn	17.20 ± 24.32[a]
Soybean	0.00 ± 0.00
Information source	Measured
Reference	Farm records
Avg. P removed by crop (kg P ha^{-1} yr^{-1})	
Corn	26.00 ± 2.83
Soybean	22.00 ± 2.83
Information source	Measured yield, literature
Reference	IPNI (2014)
Avg. atmospheric P deposition (kg P ha^{-1} yr^{-1})	
Corn–soybean	0.14 ± 0.10
Information source	Literature
Reference	Baker & Richards (2002)
Avg. surface runoff total P losses (kg P ha^{-1} yr^{-1})	
Corn–soybean	0.00 ± 0.00
Information source	Measured
Reference	Hanrahan et al. (2019)
Avg. subsurface drainage total P losses (kg P ha^{-1} yr^{-1})	
Corn–soybean	0.42 ± 0.17
Information source	Measured
Reference	Hanrahan et al. (2019)

[a]Mean ± SD.

carried out in nearby sites or regions (i.e., state or province) and similar P management practices (for hydrologic losses). Crop removal was estimated, if needed, by multiplying average crop yield by a crop P removal factor obtained from the literature (e.g., IPNI, 2014). If a site did not have data on crop yield, yield was estimated using recent agricultural census data (USDA National Agricultural Statistics Service; https://www.nass.usda.gov). For P flux components without estimates of variability, the standard deviation was assumed to be 25% of the corresponding component value, similar to the approach used by Baffaut et al. (2020) to assign uncertainties to water budget components whose uncertainty was not quantified. Each P flux for all production systems is classified within the dataset based on the data source as either (a) measured data, (b) estimated data from similar sites or derived from literature values, (c) professional judgment, or (d) model results. Full citations are included in the dataset when flux components were estimated.

2.3 | Phosphorus budgets

Phosphorus budgets were calculated for each production system, whereby P inputs included application rate, atmospheric deposition, and irrigation water, and P outputs included crop removal and hydrologic losses. Agronomic P budgets (ΔP_{agro}) were determined using the soil surface approach accounting for the main P fluxes crossing the soil surface layer (i.e., excluding hydrologic losses; Soil–Plant conceptual model; Li et al., 2019; Oenema et al., 2003). Inputs were summed (Equation 1) and total input uncertainty (U_{input}) was calculated by combining individual input uncertainties (i.e., standard deviations; Equation 2). Subsequently, ΔP_{agro} with its uncertainty ($U_{\Delta Pagro}$) was determined using Equation 3.

$$\sum \text{Input} = P_{application} + P_{atmosphere} + P_{irrigation} \tag{1}$$

$$U_{input} = \sqrt{U^2_{P_{application}} + U^2_{P_{atmosphere}} + U^2_{P_{irrigation}}} \tag{2}$$

$$\Delta P_{agro} = \sum \text{Input} - P_{crop} \pm \sqrt{U^2_{Input} + U^2_{Pcrop\_removal}} \tag{3}$$

Hydrologic losses from a production system were summed (Equation 4) and the total uncertainty calculated by combining the uncertainties of individual components (Equation 5). Overall P budgets ($\Delta P_{overall}$; Agronomic budget − hydrologic losses) with its uncertainty was subsequently determined (Equation 6).

$$P_{hydrologic} = P_{surface} + P_{subsurface} \tag{4}$$

$$U_{P_{hydrologic}} = \sqrt{U^2_{P_{surface}} + U^2_{P_{subsurface}}} \tag{5}$$

$$\Delta P_{overall} = \Delta P_{agro} - \sum P_{hydrologic} + \sqrt{U^2_{Pagro} + U^2_{Phydrologic}} \tag{6}$$

TABLE 3 Descriptive statistics for average annual P inputs, outputs, agronomic P budgets, and overall P budgets for production systems

Variables	n	Min.	25th percentile	Median	Mean	75th percentile	Max.
		kg ha^{-1}					
Inputs							
$P_{application}$	61	0.0	9.7	24.9	42.6	35.1	387.1
$P_{atmosphere}$	61	0.0	0.3	0.4	0.4	0.6	1.9
$P_{irrigation}$	61	0.0	0.0	0.0	0.0	0.0	0.1
Outputs							
$P_{crop\_removal}$	60	0.0	10.2	21.7	21.0	28.7	70.8
$P_{hydrologic}$	51[a]	0.0	0.3	0.6	1.4	2.0	10.4
Budgets[b]							
Agronomic	61	−26.4	−3.2	3.4	22.4	17.3	345.4
Overall	51	−32.7	−2.6	3.2	21.6	16.5	340.6

[a]Total P (n = 46); dissolved reactive P (n = 5).

[b]Agronomic = $P_{application} + P_{atmosphere} + P_{irrigation} - P_{crop\_removal}$; Overall = Agronomic − $P_{hydrologic}$.

For production systems with more than one crop in the rotation, annual average P inputs, outputs, ΔP_{agro}, and $\Delta P_{overall}$ were calculated. Consistent with previous studies, positive budgets indicate an increase in P storage and negative budgets indicate a decrease in P storage, after accounting for all inputs and outputs. Averaging and uncertainty propagation was accomplished using the errors function in the R package errors, which uses first-order Taylor series method for uncertainty propagation (R Core Team, 2017; Ucar et al., 2018). Descriptive statistical analysis for P fluxes and budgets was performed using conventional univariate statistics functions in the R package Hmisc (Harrel, 2021).

3 | DATASET OVERVIEW

3.1 | Phosphorus inputs

Across production systems, P application was the largest input ranging from 0.0 to 387.1 kg ha^{-1} (mean = 42.6 ± 77.5 kg ha^{-1} yr^{-1}; Table 3, Figure 2). Systems receiving P were typically cropland, with inorganic P (n = 33), organic P (i.e., manure; n = 19), and mixed P (i.e., both inorganic and organic P; n = 3) as the source of applied P. Six production systems did not receive any P applications. Phosphorus application rate tended to be greater in systems receiving organic P (median = 55.7 kg ha^{-1} yr^{-1}; mean = 140.3 ± 156.2 kg ha^{-1} yr^{-1}) compared with inorganic P (median = 20.3 kg ha^{-1} yr^{-1}; mean = 19.5 ± 10.1 kg ha^{-1} yr^{-1}). Application timing occurred in the spring (April–June; n = 19), summer (July–September; n = 2), fall (October–December; n = 16), and winter (January–March; n = 1). The remaining systems (n = 17) had mixed application timing (i.e., application timing varied each rotation year). Phosphorus was surface broadcast (n = 26), incorporated with tillage (n = 15), injected (n = 7), or mixed placement (n = 7).

Irrigation occurred in 25% (n = 15) of production systems, with irrigation water adding P in only two systems. Only one of the two systems had measured or estimated values for inputs resulting from irrigation equaling 0.1 kg ha^{-1} yr^{-1} (Table 3, Figure 2). Atmospheric deposition was generally estimated using literature values. Across production systems, atmospheric deposition ranged from 0.01 to 1.9 kg ha^{-1} yr^{-1}, with a median of 0.4 kg ha^{-1} yr^{-1} (mean = 0.4 ± 0.3 kg ha^{-1} yr^{-1}; Table 3, Figure 2).

3.2 | Phosphorus outputs

Production systems ranged from one crop in the rotation (e.g., continuous corn) to greater than three crops in the rotation (Table 1). Crops were harvested in 57 of the 61 systems, with measured data (n = 26) and values estimated from the literature (n = 31) as primary data sources. Crop removal ranged from 0 (i.e., no crop harvested) to 70.8 kg ha^{-1} across sites with a median of 21.6 kg ha^{-1} (mean = 20.6 ± 14.6 kg ha^{-1}; Table 3, Figure 2). For the most common crops—corn, soybean, and wheat—median crop removal was 31.5 kg ha^{-1} (mean = 28.6 ± 10.9 kg ha^{-1}), 18.8 kg ha^{-1} (mean = 17.3 ± 5.9 kg ha^{-1}), and 12.7 kg ha^{-1} (mean = 15.3 ± 11.6 kg ha^{-1}), respectively.

Hydrologic losses were expected to occur in 60 of 61 production systems, with data either measured (n = 43), estimated from the literature (n = 8), or no data reported (n = 9). Of the systems with hydrologic data, most were reported as total P load (n = 46), whereas others were reported as only dissolved reactive P load (n = 5). Phosphorus losses were reported as both surface runoff (n = 44) and subsurface

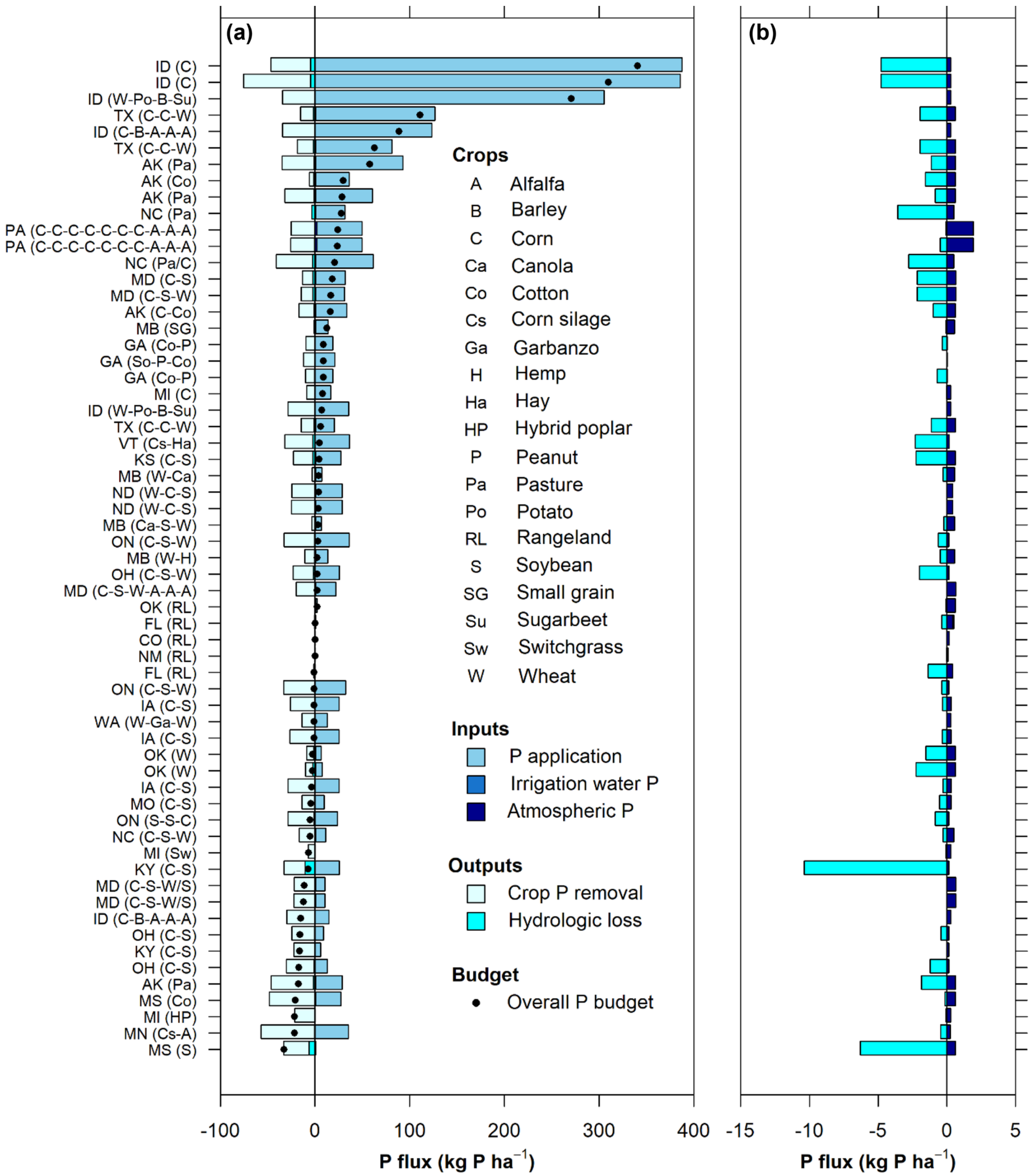

FIGURE 2 Phosphorus fluxes and budgets for 61 production systems in the P-FLUX dataset. (a) Average annual inputs (P application rate, irrigation water P, and atmospheric P deposition), outputs (crop P removal, hydrologic losses), and overall P budgets. For visualization, the production systems are ranked from largest (top of figure) to smallest (bottom of figure) overall P budget. The production systems are identified on the *y*-axis as the state/province abbreviation followed by the crop type(s) in parentheses. (b) Detailed depiction of atmospheric P deposition, irrigation water P, and hydrologic losses for each of the production systems

tile drainage ($n = 22$). Hydrologic loss varied from 0.0 to 10.4 kg ha^{-1} yr^{-1}, with a median P loss of 0.8 kg ha^{-1} yr^{-1} (mean = 1.5 ± 1.9 kg ha^{-1} yr^{-1}; summary statistics reported herein include both dissolved reactive [$n = 5$] and total P [$n = 46$]) (Table 3, Figure 2). When present, subsurface drainage was a significant pathway for P loss, contributing >50% of the total hydrologic losses in some cases. For sites with subsurface hydrologic losses, median surface runoff losses were 0.3 kg ha^{-1} yr^{-1}, while median subsurface losses were 0.4 kg ha^{-1} yr^{-1}. For sites with only surface hydrolgoic losses, runoff was also an important P output (Figure 2).

3.3 | Agronomic and overall phosphorus budgets

Agronomic and overall P budgets were variable across production systems (Table 3; Figure 2). Agronomic budgets ranged from −26.4 to 345.4 kg ha^{-1} yr^{-1}, with a median of 3.4 kg ha^{-1} yr^{-1} (mean = 22.4 ± 70.6 kg ha^{-1} yr^{-1}). Phosphorus inputs exceed outputs for 39 systems, indicating an increase in agronomic P, whereas inputs were less than outputs for 22 systems, indicating a decrease in agronomic P. Overall budgets ranged from −32.7 to 340.6 kg ha^{-1} yr^{-1} and had a median of 3.2 kg ha^{-1} yr^{-1} (mean = 21.6 ± 69.7 kg ha^{-1} yr^{-1}).

4 | DATA AVAILABILITY AND FUTURE USE

4.1 | Data availability

P-FLUX data are available for download as comma-separated (.csv) files through the USDA Ag Data Commons (https://doi.org/10.15482/USDA.ADC/1523365). All LTAR data products are in the public domain and may be freely copied, distributed, edited, remixed, and built upon, with the expectation that publications, models, and data products that make use of the dataset should include proper acknowledgement, including citing datasets, in a similar way to citing a journal article. The LTAR network data sharing principles and guidelines (Kaplan et al., 2020) accompanies the P-FLUX dataset on the Ag Data Commons website.

4.2 | Data limitations

While P-FLUX is a detailed dataset of P fluxes and budgets from diverse agricultural production systems in the United States and Canada, it is important to note several limitations and areas where the dataset could be improved. The P-FLUX dataset is viewed as a living dataset, whereby as the LTAR network continues to grow and new data are collected, the P-FLUX dataset can also evolve, update, and improve. The current dataset comprises P fluxes derived from various data sources (measured, estimated from literature sources, etc.), which adds uncertainty to calculated budgets. Although P-FLUX captures this uncertainty, additional data collection will undoubtedly improve flux and budget estimates. Similarly, data within P-FLUX are average fluxes and budgets under typical management and representaive climatic conditions; therefore, data are not specifically tied to a particular calender year or time periods within the database. Including annual data rather than averages, adding time periods of data collection, and including accompanying climatic data (e.g., precipitation) would enhance the utility of the dataset, especially for assessing the effects of climate change, for example, on agricultural management and P loss.

The inputs, outputs, and budgets in the P-FLUX dataset are based on a Soil–Plant conceptual model (Li et al., 2019) and, as a result, do not account for animal components (e.g., animal feed as an input; animal products as outputs). The animal component can represent a significant contribution to fluxes and budgets in livestock-oriented systems (e.g., Rothwell et al., 2020; Swain et al., 2007), especially for the rangeland systems included in the dataset. P-FLUX, therefore, may be missing important factors for these livestock systems that would contribute to P management, budgets, and loss that would be captured with other conceptual models (e.g., Animal–Plant–Soil; Li et al., 2019). The P-FLUX dataset also does not contain information on soil P concentration. Inclusion of soil test P data was outside of the initial scope of database development (i.e., characterization of fluxes and budgets) but would be a useful metric to include as the database evolves to enhance exploration of relationships among fluxes and budgets.

4.3 | Data use

The P-FLUX dataset can be used to characterize P fluxes and budgets (and their uncertainty) across agricultural production systems given its consistent conceptual model and calculation methods. It serves as a valuable resource for future studies examining spatial and temporal fluxes of P within and among agricultural production systems and determining the effect of management practices on P cycling. The P-FLUX dataset can also serve to help constrain inputs to numerical models such as the Soil and Water Assessment Tool (SWAT) and provide benchmarks for model outputs related to crop productivity and water quality. As a publicly available database, it has the potential to be expanded, updated, and improved for further uses by the LTAR network and scientific community.

Here, we briefly highlight one of many potential examples of how P-FLUX data could be used in future studies. Data on P management practices (e.g., P rate, source, timing, and placement) were compared to hydrologic losses (surface + subsurface) from production systems (Figure 3). Preliminary results show that P losses increased with increasing application rate and that production systems with P applied as either organic or mixed (combination of inorganic and organic P) sources tended to have greater losses compared to production systems with no application or inorganic P sources (Figure 3a and 3c). Phosphorus broadcast on the soil surface and incorporated with tillage generally had greater losses compared to no P applied and injected P (Figure 3b). Phosphorus applied

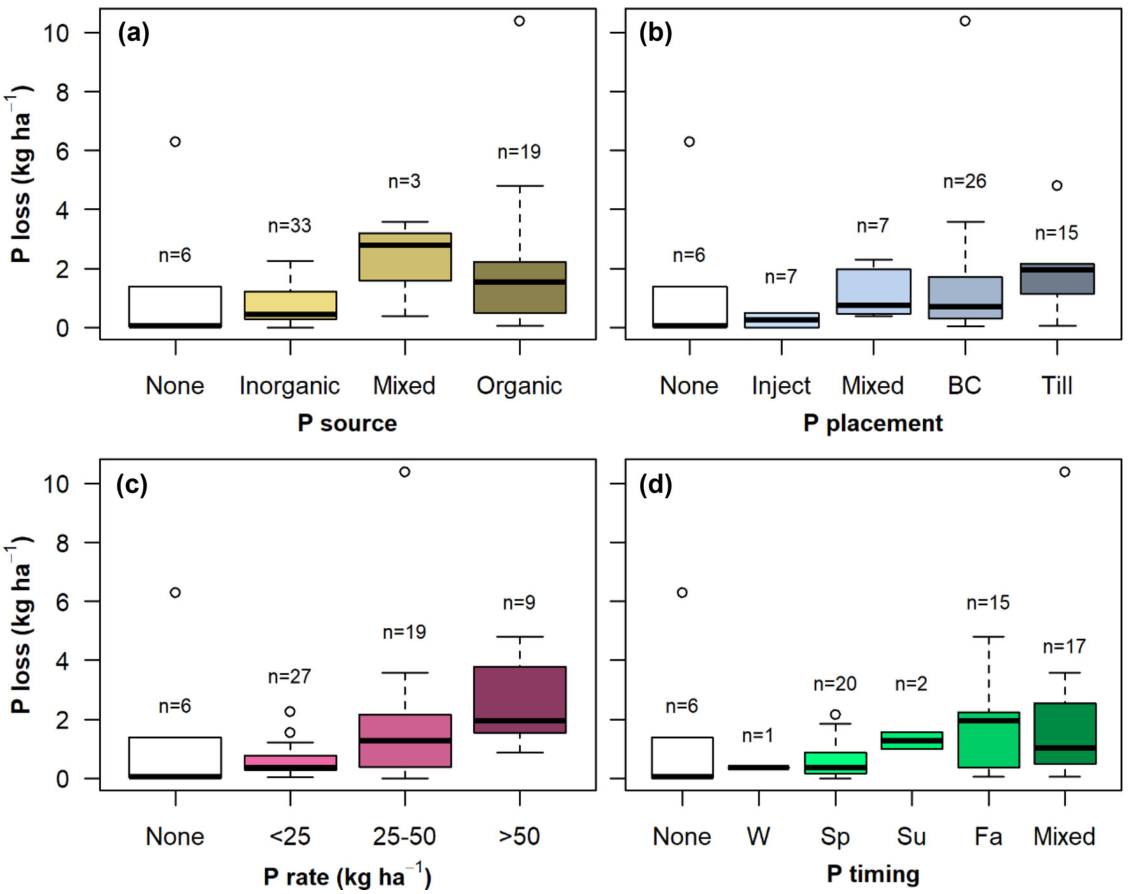

FIGURE 3 Hydrologic P losses from production systems by (a) source, (b) placement, (c) application rate, and (d) application timing. For all panels, “None” refers to systems where no P was applied and “Mixed” refers to a combination of management practices (e.g., combination of inorganic P and organic P was applied). In panel (b), “BC” refers to broadcast application and “Till” refers to incorporation with tillage. In panel (d), “W,” “Sp,” “Su,” and “Fa” refer to winter, spring, summer, and fall, respectively. Preliminary results on source, placement, and timing in this example do not account for differences in application rates or soil nutrient levels among the various management categories

in the fall also tended to result in greater loss compared with other seasons (Figure 3d). It should be noted that preliminary results on source, placement, and timing in this example do not account for differences in application rates or soil nutrient levels among the various management categories.

5 | CONCLUSION

P-FLUX is a detailed dataset of P fluxes and budgets that facilitates comparison of data across diverse agricultural production systems in the United States and Canada through consistent reporting and calculation methods. P-FLUX data are publically available for download as comma-separated (.csv) files through the USDA Ag Data Commons (https://doi.org/10.15482/USDA.ADC/1523365). Multi-location datasets such as P-FLUX are needed to address complex local-, regional-, and national-scale P management challenges, improve P use efficiency, and inform implementation of management strategies to mitigate P losses to surface waters. The P-FLUX dataset has the potential to increase understanding of P fate and transport through further data analyses and modeling approaches including the example highlighted previously. The dataset also can serve as a framework for collecting similar data from additional production systems for further comparison or can be expanded to include other data and analytes measured in agroecosystems such as nitrogen and carbon fluxes.

ACKNOWLEDGMENTS

The authors would like to thank the technicians and support staff across contributing sites for their efforts in collecting, analyzing, and compiling the data used in the study. This work is a contribution of the Long-term Agroecosystem Research (LTAR) network. LTAR is supported by the U.S. Department of Agriculture. The U.S. Department of Agriculture prohibits discrimination in all its programs and activities on the basis of race, color, national origin, age, disability, and where applicable, sex, marital status, familial status, parental status,

religion, sexual orientation, genetic information, political beliefs, reprisal, or because all or part of an individual's income is derived from any public assistance program. (Not all prohibited bases apply to all programs.) USDA is an equal opportunity provider and employer. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

AUTHOR CONTRIBUTIONS

M. Williams: Conceptualization; Formal analysis; Writing – original draft; Writing – review & editing. P. Welikhe: Conceptualization; Data curation; Methodology; Writing – review & editing. J. Bos: Data curation; Writing – original draft; Writing – review & editing. K. King: Writing – original draft; Writing – review & editing. M. Akland: Resources; Writing – review & editing. D. Augustine: Resources; Writing – review & editing. C. Baffaut: Resources; Writing – review & editing. E.G. Beck: Resources; Writing – review & editing. A. Bierer: Resources; Writing – review & editing. D.D. Bosch: Resources; Writing – review & editing. E. Boughton: Resources; Writing – review & editing. C. Brandani: Resources; Writing – review & editing. E. Brooks: Resources; Writing – review & editing. A. Buda: Resources; Writing – review & editing. M. Cavigelli: Resources; Writing – review & editing. J. Faulkner: Resources; Writing – review & editing. G. Feyereisen: Resources; Writing – review & editing. A. Fortuna: Resources; Writing – review & editing. J. Gamble: Resources; Writing – review & editing. B. Hanrahan: Resources; Writing – review & editing. M. Hussain: Resources; Writing – review & editing. M. Kohmann: Resources; Writing – review & editing. J. Kovar: Resources; Writing – review & editing. B. Lee: Resources; Writing – review & editing. A. Leytem: Resources; Writing – review & editing. M. Liebig: Resources; Writing – review & editing. D. Line: Resources; Writing – review & editing. M. Macrae: Resources; Writing – review & editing. T. Moorman: Resources; Writing – review & editing. D. Moriasi: Resources; Writing – review & editing. N. Nelson: Resources; Writing – review & editing. A. Ortega-Pieck: Resources; Writing – review & editing. D. Osmond: Resources; Writing – review & editing. O. Pisani: Resources; Writing – review & editing. J. Ragosta: Resources; Writing – review & editing. M. Reba: Resources; Writing – review & editing. A. Saha: Resources; Writing – review & editing. J. Sanchez: Resources; Writing – review & editing. M. Silveira: Resources; Writing – review & editing. D. Smith: Resources; Writing – review & editing. S. Spiegal: Resources; Writing – review & editing. H. Swain: Resources; Writing – review & editing. J. Unrine: Resources; Writing – review & editing. P. Webb: Resources; Writing – review & editing. K. White: Resources; Writing – review & editing. H. Wilson: Resources; Writing – review & editing. L. Yasarer: Resources; Writing – review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

C. Baffaut https://orcid.org/0000-0001-7840-1953
E.G. Beck https://orcid.org/0000-0001-6900-7858
A. Bierer https://orcid.org/0000-0001-9966-797X
D.D. Bosch https://orcid.org/0000-0001-9021-8705
E. Brooks https://orcid.org/0000-0002-6921-4870
G. Feyereisen https://orcid.org/0000-0003-2785-4594
M. Liebig https://orcid.org/0000-0002-2716-3665
M. Macrae https://orcid.org/0000-0003-3296-3103
T. Moorman https://orcid.org/0000-0001-7409-0609
A. Ortega-Pieck https://orcid.org/0000-0001-5371-4240
J. Ragosta https://orcid.org/0000-0002-6117-4771
M. Reba https://orcid.org/0000-0001-6830-0438
M. Silveira https://orcid.org/0000-0003-2166-3156
D. Smith https://orcid.org/0000-0002-7194-5787
S. Spiegal https://orcid.org/0000-0002-5489-9512
H. Wilson https://orcid.org/0000-0002-6611-9501

REFERENCES

Baffaut, C., Baker, J. M., Biederman, J. A., Bosch, D. D., Brooks, E. S., Buda, A. R., Demaria, E. M., Elias, E. H., Flerchinger, G. N., Goodrich, D. C., Hamilton, S. K., Hardegree, S. P., Harmel, R. D., Hoover, D. L., King, K. W., Kleinman, P. J., Liebig, M. A., McCarty, G. W., Moglen, G. E., … Yasarer, L. M. W. (2020). Comparative analysis of water budgets across the U.S. long-term agroecosystem research network. *Journal of Hydrology*, *588*, 125021. https://doi.org/10.1016/j.jhydrol.2020.125021

Baker, D. B., & Richards, R. P. (2002). Phosphorus budgets and riverine phosphorus export in northwestern Ohio watersheds. *Journal of Environmental Quality*, *31*, 96–108. https://doi.org/10.2134/jeq2002.9600

Bennett, E. M., Carpenter, S. R., & Caraco, N. F. (2001). Human impact on erodable phosphorus and eutrophication: A global perspective. *Bioscience*, *51*, 227–234. https://doi.org/10.1641/0006-3568(2001)051%5b0227:HIOEPA%5d2.0.CO;2

Bos, J., Williams, M., Smith, D., Armstrong, S., & Harmel, D. (2021). Long-term effect of poultry litter application on phosphorus balances and runoff losses. *Journal of Environmental Quality*, *50*, 639–652. https://doi.org/10.1002/jeq2.20219

Elser, J. J., Bracken, M. E. S., Cleland, E. E., Gruner, D. S., Harpole, W. S., Hillebrand, H., Ngai, J. T., Seabloom, E. W., Shurin, J. B., & Smith, J. E. (2007). Global analysis of nitrogen and phosphorous limitation of primary producers in freshwater, marine, and terrestrial ecosystems. *Ecology Letters*, *10*, 1135–1142. https://doi.org/10.1111/j.1461-0248.2007.01113.x

Hanrahan, B. R., King, K. W., Williams, M. R., Duncan, E. W., Pease, L. A., & LaBarge, G. A. (2019). Nutrient balances influence hydrologic losses of nitrogen and phosphorus across agricultural fields in northwestern Ohio. *Nutrient Cycling in Agroecosystems*, *113*, 231–245. https://doi.org/10.1007/s10705-019-09981-4

Harrel, F. E. (2021). Package 'Hmisc'. Cran.Rstudio.Com. https://hbiostat.org/R/Hmisc/

International Plant Nutrition Institute (IPNI). (2014). *IPNI estimates of nutrient uptake and removal*. http://www.ipni.net/article/IPNI-3296

Kaplan, N. E., Armendariz, G. A., Arthur, D. K., Carter, J., Derner, J. D., Heilman, P., Kleinman, P. J. A., Nash, P., Sadler, E. J., & Vandenberg, B. (2017). *An "information ecosystem" to meet the data management requirements of the Long-term Agroecosystem Research (LTAR) network*. https://my.usgs.gov/confluence/pages/viewpage.action?pageId=570077009

Kaplan, N., Arthur, D. K., & Coffin, A. (2020). *Long-term Agroecosystem Research (LTAR) network data sharing principles and guidelines* (Version 1.0). https://ltar.ars.usda.gov/wp-content/uploads/2020/05/LTAR_DataSharing_PrincGuide_v1_0.pdf

Kleinman, P. J. A., Spiegal, S., Rigby, J. R., Goslee, S. C., Baker, J. M., Bestelmeyer, B. T., Boughton, R. K., Bryant, R. B., Cavigelli, M. A., Derner, J. D., Duncan, E. W., Goodrich, D. C., Huggins, D. R., King, K. W., Liebig, M. A., Locke, M. A., Mirsky, S. B., Moglen, G. E., Moorman, T. B., … Walthall, C. L. (2018). Advancing the sustainability of US agriculture through long-term research. *Journal of Environmental Quality*, *47*, 1412–1425. https://doi.org/10.2134/jeq2018.05.0171

Lanyon, L. E., Arrington, K. E., Abdalla, C. W., & Beegle, D. B. (2006). Phosphorus budgets for Pennsylvania cropland: 1939 to 2002. *Journal of Soil and Water Conservation*, *61*, 51–58.

Li, T., Zhang, X., Davidson, E., Dou, Z., Zhang, W., & Zhang, F. (2019). A hierarchical framework for unpacking the nitrogen challenge. *Earth and Space Science Open Archive*, https://doi.org/10.1002/essoar.10501085.1

Ma, W., Ma, L., Li, J., Wang, F., Sisák, I., & Zhang, F. (2011). Phosphorus flows and use efficiencies in production and consumption of wheat, rice, and maize in China. *Chemosphere*, *84*, 814–821. https://doi.org/10.1016/j.chemosphere.2011.04.055

MacDonald, G. K., Bennett, E. M., Potter, P. A., & Ramankutty, N. (2011). Agronomic phosphorus imbalances across the world's croplands. *Proceedings of the National Academy of Sciences of the United States of America*, *108*, 3086–3091. https://doi.org/10.1073/pnas.1010808108

Obour, A. K., Silveira, M. L., Vendramini, J. M. B., Jawitz, J. W., O'Connor, G. A., & Sollenberger, L. E. (2011). A phosphorus budget for bahiagrass pastures growing on a typical Florida Spodosol. *Agronomy Journal*, *103*, 611–616. https://doi.org/10.2134/agronj2010.0372

Oenema, O., Kros, H., & De Vries, W. (2003). Approaches and uncertainties in nutrient budgets: Implications for nutrient management and environmental policies. *European Journal of Agronomy*, *20*, 3–16. https://doi.org/10.1016/S1161-0301(03)00067-4

R Core Team. (2017). *R: A language and environment for statistical computing (3.4)*. R Foundation for Statistical Computing. https://www.r-project.org/

Rothwell, S. A., Doody, D. G., Johnston, C., Forber, K. J., Cencic, O., Rechberger, H., & Withers, P. J. A. (2020). Phosphorus stocks and flows in an intensive livestock dominated food system. *Resources, Conservation and Recycling*, *163*, 105065. https://doi.org/10.1016/j.resconrec.2020.105065

Sattari, S. Z., Bouwman, A. F., Martinez Rodríguez, R., Beusen, A. H. W., & Van Ittersum, M. K. (2016). Negative global phosphorus budgets challenge sustainable intensification of grasslands. *Nature Communications*, *7*, 1–12. https://doi.org/10.1038/ncomms10696

Sharpley, A. N., Jarvie, H., Flaten, D., & Kleinman, P. (2018). Celebrating the 350th anniversary of phosphorus discovery: A conundrum of deficiency and excess. *Journal of Environmental Quality*, *47*, 774–777. https://doi.org/10.2134/jeq2018.05.0170

Spiegal, S., Bestelmeyer, B. T., Archer, D. W., Augustine, D. J., Boughton, E. H., Boughton, R. K., Cavigelli, M. A., Clark, P. E., Derner, J. D., Duncan, E. W., Hapeman, C. J., Harmel, R. D., Heilman, P., Holly, M. A., Huggins, D. R., King, K., Kleinman, P. J. A., Liebig, M. A., Locke, M. A., … Walthall, C. L. (2018). Evaluating strategies for sustainable intensification of US agriculture through the Long-Term Agroecosystem Research network. *Environmental Research Letters*, *13*, 034031. https://doi.org/10.1088/1748-9326/aaa779

Swain, H. M., Bohlen, P. J., Campbell, K. L., Lollis, L. O., & Steinman, A. D. (2007). Integrated ecological and economic analysis of ranch management systems: An example from south central Florida. *Rangeland Ecology & Management*, *60*, 1–11. https://doi.org/10.2111/05-071R1.1

Ucar, I., Pebesma, E., & Azcorra, A. (2018). Measurement errors in R. *The R Journal*, *10*, 549–557. https://doi.org/10.32614/RJ-2018-075

Van Vuuren, D. P., Bouwman, A. F., & Beusen, A. H. W. (2010). Phosphorus demand for the 1970–2100 period: A scenario analysis of resource depletion. *Global Environmental Change*, *20*, 428–439. https://doi.org/10.1016/j.gloenvcha.2010.04.004

Vendramini, J. M. B., Silveira, M. L. A., Dubeux, J. C. B. Jr., & Sollenberger, L. E. (2007). Environmental impacts and nutrient recycling on pastures grazed by cattle. *Revista Brasileira de Zootecnia*, *36*, 139–149. https://doi.org/10.1590/S1516-35982007001000015

Walbridge, M. R., & Shafer, S. R. (2011). A long-term agroecosystem research (LTAR) network for agriculture. In *Proceedings of the Fourth Inter-agency Conference on Research in the Watersheds, Fairbanks, AK, 26–30 Sept. 2011*. https://www.ars.usda.gov/ARSUserFiles/np211/LTAR%20Walbridge%20and%20Shafer%202011%20Paper.pdf

Zhang, W., Ricketts, T. H., Kremen, C., Carney, K., & Swinton, S. M. (2007). Ecosystem services and dis-services to agriculture. *Ecological Economics*, *64*, 253–260. https://doi.org/10.1016/j.ecolecon.2007.02.024

Zhang, X., Davidson, E. A., Zou, T., Lassaletta, L., Quan, Z., Li, T., & Zhang, W. (2020). Quantifying nutrient budgets for sustainable nutrient management. *Global Biogeochemical Cycles*, *34*, e2018GB006060. https://doi.org/10.1029/2018GB006060

How to cite this article: Williams, M. R., Welikhe, P., Bos, J., King, K., Akland, M., Augustine, D., Baffaut, C., Beck, E. G., Bierer, A., Bosch, D. D., Boughton, E., Brandani, C., Brooks, E., Buda, A., Cavigelli, M., Faulkner, J., Feyereisen, G., Fortuna, A., Gamble, J., Hanrahan, B., … Yasarer, L. (2022). P-FLUX: A phosphorus budget dataset spanning diverse agricultural production systems in the United States and Canada. *Journal of Environmental Quality*, *51*, 451–461. https://doi.org/10.1002/jeq2.20351