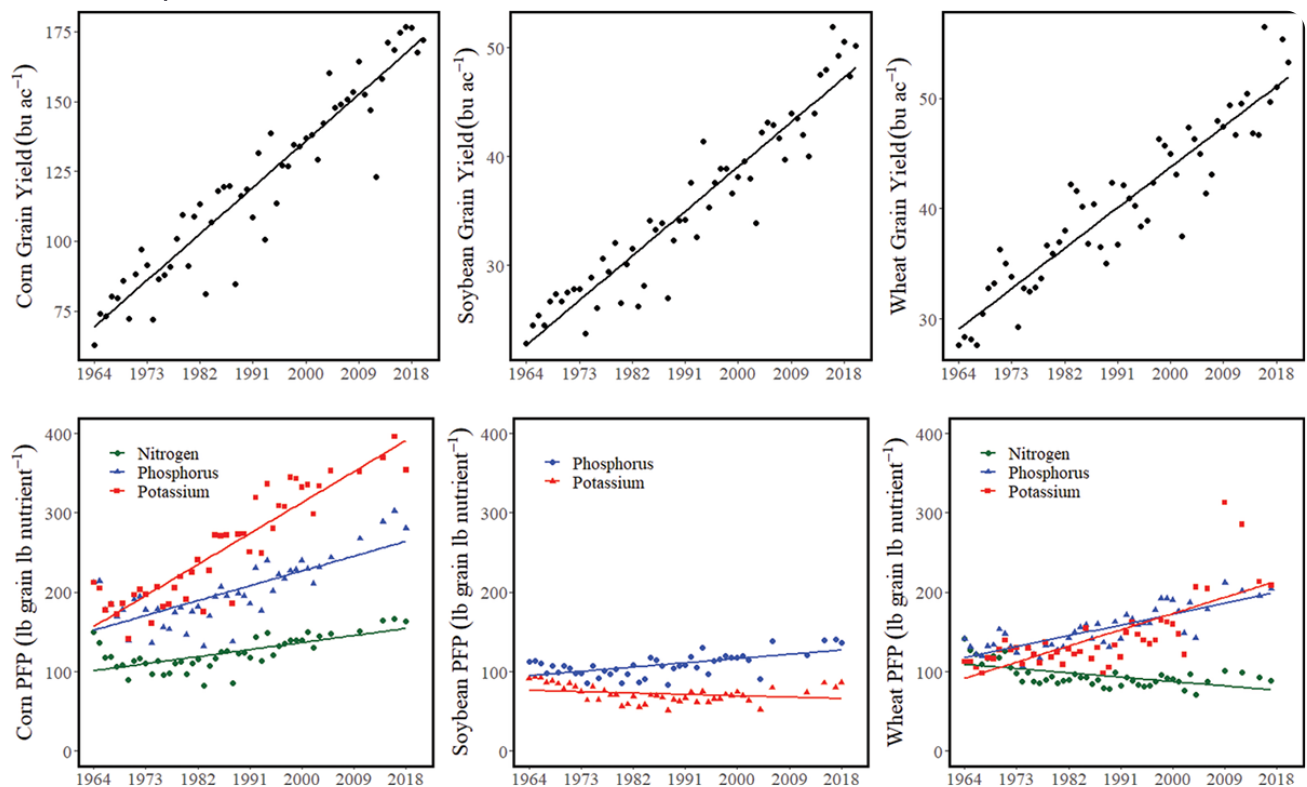




Nutrient use efficiency—A metric to inform 4R nutrient stewardship

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March 10, 2021



An increasing frequency of environmental stresses on crop yields, concern of air and water quality, and financial pressure all warrant the need for a focus on nutrient use efficiency (NUE). For the values to be meaningful at the farm level, a relationship between management decisions and NUE should be identified. The status and trend of NUE in U.S. cropping systems will be discussed to provide a baseline understanding of where we are with the use of this metric and where measuring NUE is beneficial.

This article is [part of a series](#) from The Fertilizer Institute, highlighting some of the latest 4R research.

Abbreviations

- | | |
|--------------|-------------------------------|
| • NUE | • nutrient use efficiency |
| • PFP | • partial factor productivity |
| • PNB | • partial nutrient balance |

Farmers are faced with concurrent demands of improving productivity and use of resources such as crop nutrients. An increasing frequency of environmental stresses on crop yields, concern of air and water quality, and financial pressure all warrant the need for a focus on nutrient use efficiency (NUE). Defined simply, NUE describes the

capacity for a system to convert inputs to outputs in relation to the nutrient status (system-wide surplus or deficit) of the system or crop. Nutrient use efficiency can advise research questions or be used as a performance metric, but for the values to be meaningful at the farm level, a relationship between management decisions and NUE should be identified. Components of 4R nutrient stewardship—the right source, rate, timing, and placement of nutrients—all have an important role in efficient use of nutrients on the farm. The status and trend of NUE in U.S. cropping systems will be discussed to provide a baseline understanding of where we are with the use of this metric and where measuring NUE is beneficial.

NUE Definitions and Applications

Various expressions and methods of estimating NUE have been used by agronomists and scientists (Dobermann, [2005](#)). Many NUE definitions (conceptual or arithmetic) exist as a function of the question being posed. For example, if you are interested in solely the relationship between nutrients in and harvest biomass out of the field, then simply using pounds of grain harvested per pounds of nutrient applied is sufficient. However, if you want to know the efficiency of a single nitrogen application at increasing yield, then NUE should be expressed as the difference between fertilized and unfertilized crop yield per unit of nitrogen applied. The requirement of data (or treatments in the field) will also depend on which NUE term is used and what facet of the cropping system you wish to examine.

This article and discussion will focus on three metrics of efficient nutrient use that can inform the agronomic performance of cropping systems and indicate propensities for accumulation or deficit of nutrients in farm fields. Table [1](#) lists the three terms highlighted here and used in the context of NUE. Mass balance simply refers the nutrients entering the system minus the nutrients leaving the system (or field) with

harvest and is expressed as a nutrient balance per acre. Partial factor productivity (PFP) is a ratio of harvested yield to unit of nutrient applied. Values of PFP are expressed as mass of harvested grain (or biomass) divided by the unit of nutrient applied. Finally, partial nutrient balance (PNB) is a ratio of nutrients removed with harvest to nutrients applied. The form of nutrients applied can be either fertilizer, recoverable manure nutrients, or biological N fixation of legumes (as is the case for PNB calculated in this article).

Table 1. Terms, descriptions, and units used to discuss nutrient use efficiency

Term	Description	Unit
Mass balance	Balance = (nutrients applied) – (harvest removal of nutrients)	lb nutrient ac ⁻¹
Partial factor productivity (PFP)	PFP = (lb grain harvested) / (lb nutrient applied)	lb grain lb nutrient ⁻¹
Partial nutrient balance (PNB)	PNB = (lb harvest removal) / (lb applied nutrient)	lb removed lb applied ⁻¹

Though the terms listed in Table 1 can be applied to each nutrient, ranges of NUE values differ greatly by nutrient. The behavior of nutrients in cropping systems will inherently affect the potential use efficiency and range of NUE values that are observed. Other publications have detailed crop and geographical differences of NUE values for specific nutrients (Baligar et al., 2001; Dobermann, 2007; Fixen et al., 2015). This article will focus on trends within the U.S. for a few major crops that consume a large portion of the applied nitrogen (N), phosphorus (P), and potassium (K) in the country.

The PNB and mass balance data discussed here represent an ongoing effort to estimate and investigate nutrient use dynamics within the U.S. using the Nutrient Use Geographic Information System (NuGIS). This system is managed and supported by a collaboration among PAQ Interactive (Monticello, IL), Plant Nutrition Canada (Guelph, ON), The Fertilizer Institute (Arlington, VA), and the Foundation for Agronomic Research (Arlington, VA); inception of NuGIS was undertaken by the International Plant Nutrition Institute.

U.S. Nutrient Use Efficiency

Annual variability of NUE can be driven by many environmental factors. Ultimately, NUE determination is an artifact of the available data, area of interest, and period of time. Partly for these reasons, national assessments of NUE as PFP should be considered in the context of crop yield trends. Corn, soybean, and wheat yields have increased linearly from 1964 to 2018 (Figure 1). Though annual variation exists, the general trend of greater crop yields over time indicates both increased rates of nutrient removal with harvested grain and a more rapid reduction of nutrient balances (applications minus removal).

From 1964 to 2018, PFP of N, P, and K increased for corn grain production in the U.S. (Figure 1). In 1964, the national average was 1 lb of N, P_2O_5 , and K_2O resulting in 150, 213, and 213 lb corn grain, respectively. Over time, this has fluctuated, yet still increased to arrive at 164, 281, and 354 lb of corn grain produced from 1 lb of N, P_2O_5 , and K_2O , respectively. Though N, P, and K PFP increased, the magnitude of increase per year (sloped of the corn K PFP line) was greater for K over the 54-year period.

Mean U.S. soybean yield increased from 22.8 bu ac⁻¹ in 1964 to 50.6 bu ac⁻¹ in 2018. Partial factor productivity of P in soybean increased from 113 lb grain lb P₂O₅⁻¹ in 1964 to 136 lb grain lb P₂O₅⁻¹ in 2018; however, K PFP has remained relatively consistent to slightly declining. Challenges in K management for major soybean-producing areas have garnished recent attention and point to a need to better understand K uptake and use of soybean. Wheat grain yield increased 23.4 bu ac⁻¹ from 1964 to 2018 with a corresponding increase in P and K PFP for the same time. Nitrogen PFP of wheat shown in Figure 1 shows a slight decline in values from 142 lb grain lb N⁻¹ in 1964 to 88 lb grain lb N⁻¹ in 2018.

To compliment NUE assessment methods like PFP, investigating the mass balance of a system indicates the pounds of nutrients remaining in the system after both applications and crop removal of nutrients. Mass balance of N, P, and K in pounds of nutrients per acre for the U.S. from 1987 to 2016 is shown in Figure 2. These values represent nutrient inputs (fertilizer, manure, and biological N fixation) and crop removal with harvest of 21 specific crops that are considered within NuGIS. Clear trends of nutrient mass balance for N, P, and K are easily seen in Figure 2 with considerable difference between each nutrient. While N balance trends remained fairly consistent

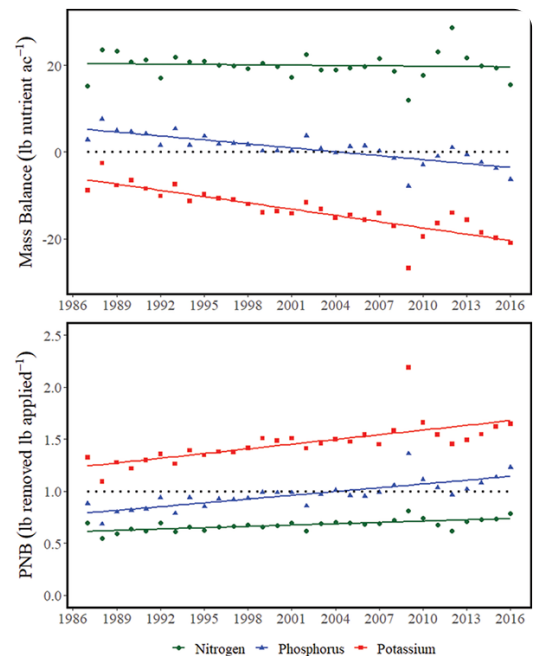


Figure 2, Mass balance (lb nutrient cropland acre⁻¹) and partial nutrient balance (PNB) of nitrogen, phosphorus (P₂O₅), and potassium (K₂O) for the U.S. from 1987–2016. Dotted lines represent neutral values indicating equivalent amounts of nutrient removed with harvested biomass and inputs (fertilizer, recoverable manure nutrients, and biological nitrogen fixation) (NuGIS, 2021).

(with visible annual variation), both P and K balances have continually decreased from 1987 to 2016. These trends may raise some questions as to a “mining effect” occurring of P and K from cropland acres within the U.S. Certainly greater P and K are being removed with harvested biomass than is being applied in the form of fertilizer or manure, yet to completely comprehend the nutrient status of a given production field, analysis of soil test P and K would be required. An important takeaway from patterns such as these for immobile nutrients is that crop removal can have a very large influence on the nutrient balance, and thus frequent and comprehensive soil-testing programs should be employed to monitor available nutrient concentrations.

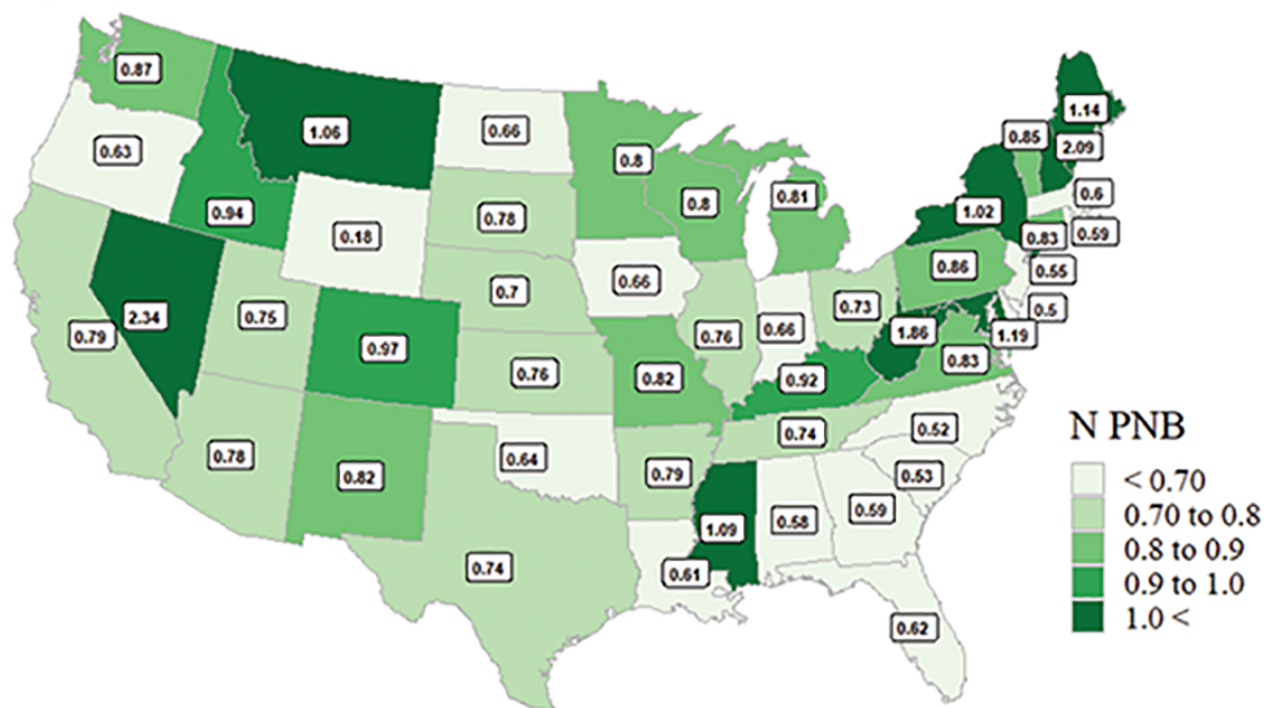
Influential economic and environmental events can easily be seen within these trends. For example, global economic stress in 2009 and drought conditions in 2012 clearly affected mass balance values in those specific years shown in Figure 2. The lower pane shows the PNB (or removal to use ratio) for N, P, and K from 1987 to 2016 in the U.S. Values above 1.0 (dotted line in Figure 2) indicate greater amounts of nutrients leaving cropland production systems, whereas values below 1.0, indicate a surplus or accumulation of nutrients in the system. Partial nutrient balance can be thought of a mirrored image to mass balance, as greater values indicate a more negative mass balance; and so similar trends can be seen for the PNB of N, P, and K as mass balance. Nitrogen PNB has increased slightly from 0.69 in 1987 to 0.78 lb N removed lb N applied⁻¹. Interestingly, P has transitioned from being in surplus in cropland production systems in 1987 (0.87 lb P₂O₅ removed lb applied⁻¹) to greater removal than application in 2016 (1.23 lb P₂O₅ removed lb applied⁻¹) and has consistently shown PNB values above 1.0 after 2008 (Figure 2.). Potassium PNB has increased by 0.32 lb K₂O removed lb applied⁻¹ from the 1987 value to 1.66 lb K₂O removed lb applied⁻¹ in 2016. These baseline national values are useful in the overarching discussion of U.S. crop production system performance, but variation between region, or state is

considerable. Next let's turn our attention to state- and watershed-scale NUE and discuss spatial variability within the U.S.

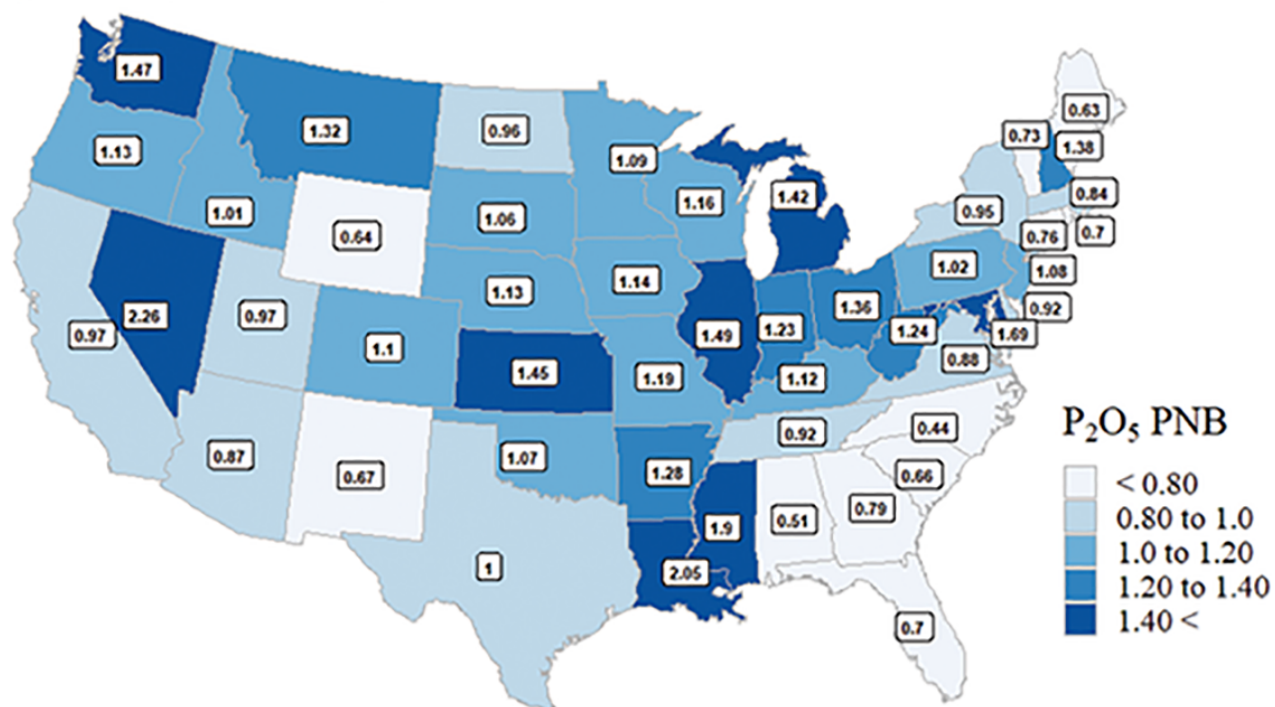
Regional Focus and Interpretations

Regionality of NUE values is influenced by many local environmental and management factors. Additionally, NUE will inherently vary by crop, as mentioned earlier. Partial nutrient balance of N, P, and K is shown by U.S. state in Figure 3, and values represent the annual mean of 2013 to 2016. Darker colors indicate larger PNB values or greater removal of nutrients than those entering cropland systems as fertilizer, recoverable manure nutrients, or biological N fixation of legumes. Because of these variables that are considered, regional effects of the degree of fertilizer use, livestock production, and leguminous crops being grown will differ. As with any spatial interpretation of data, local knowledge and expertise can inform why specific NUE trends are seen and the underlying reasoning behind them. For example, regions with greater native soil nutrients may exhibit higher NUE values due to lower applications needed to achieve an economically optimum yield response.

Nitrogen (2013-2016)



Phosphorus (2013-2016)



Potassium (2013-2016)

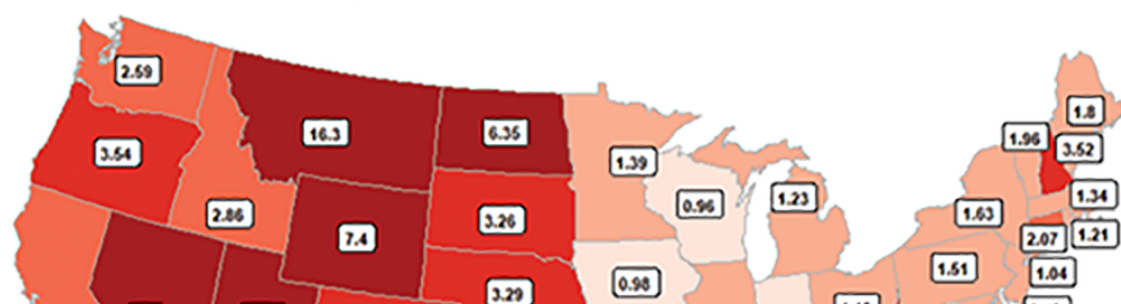
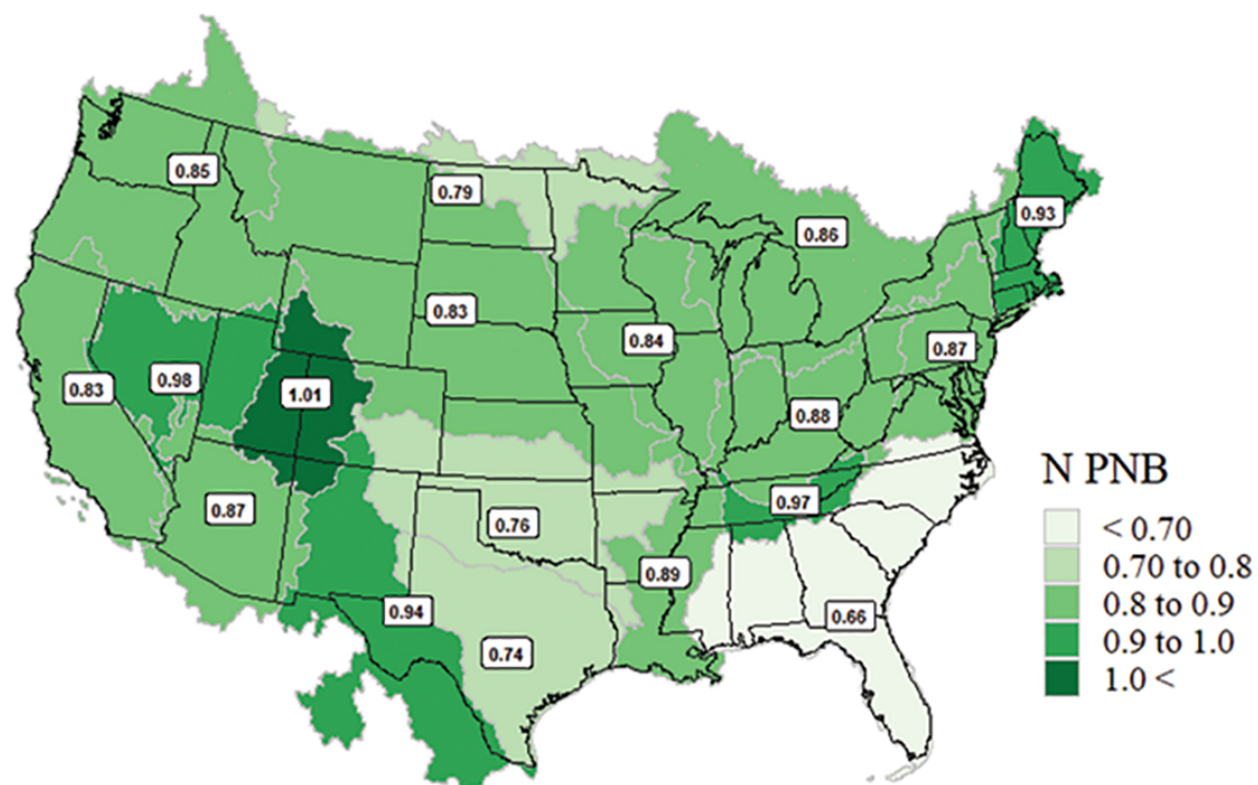
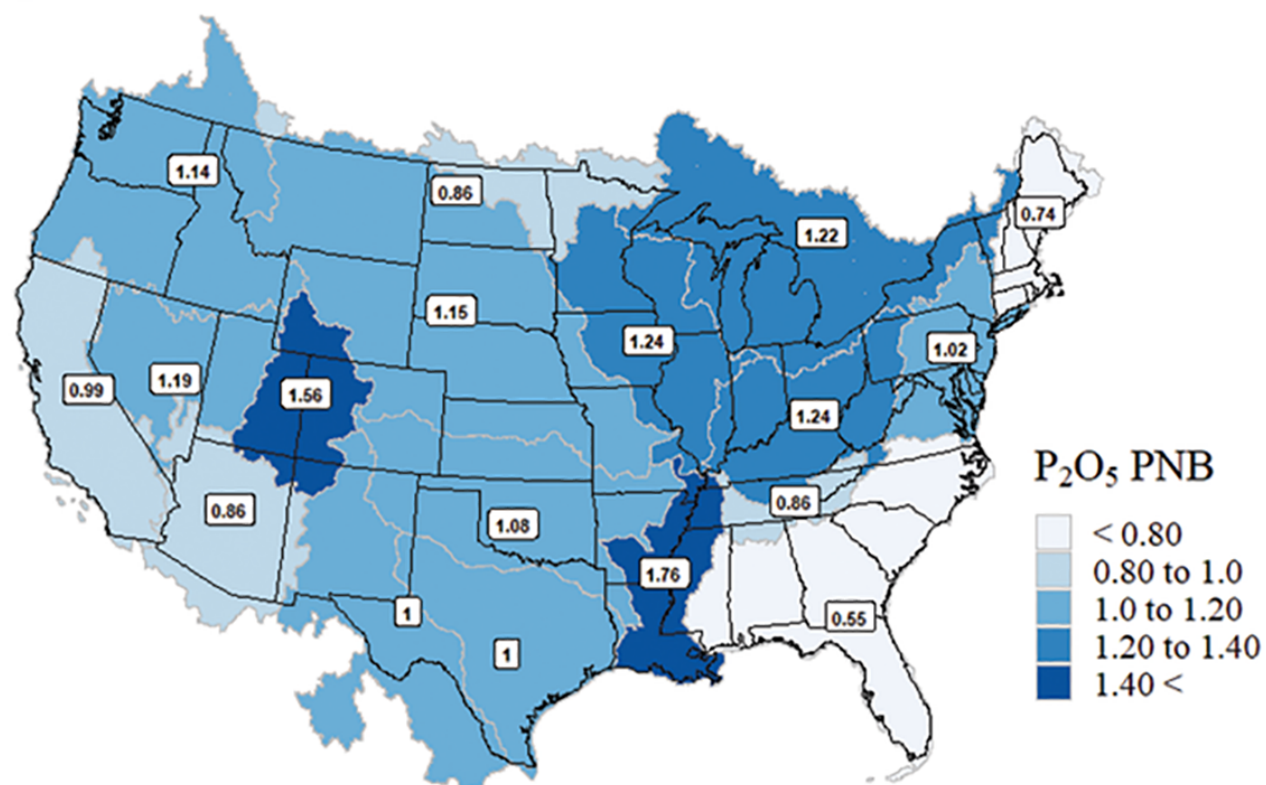


Figure 3, Nitrogen, phosphorus, and potassium mean partial nutrient balance (PNB) from 2013 to 2016 for each U.S. state (NuGIS, [2021](#)). Partial nutrient balance is calculated by dividing the amount of nutrients removed with harvest by those applied to cropland. Source of nutrients considered were fertilizer, manure, and biological N fixation of legumes.

Nitrogen (2013-2016)



Phosphorus (2013-2016)

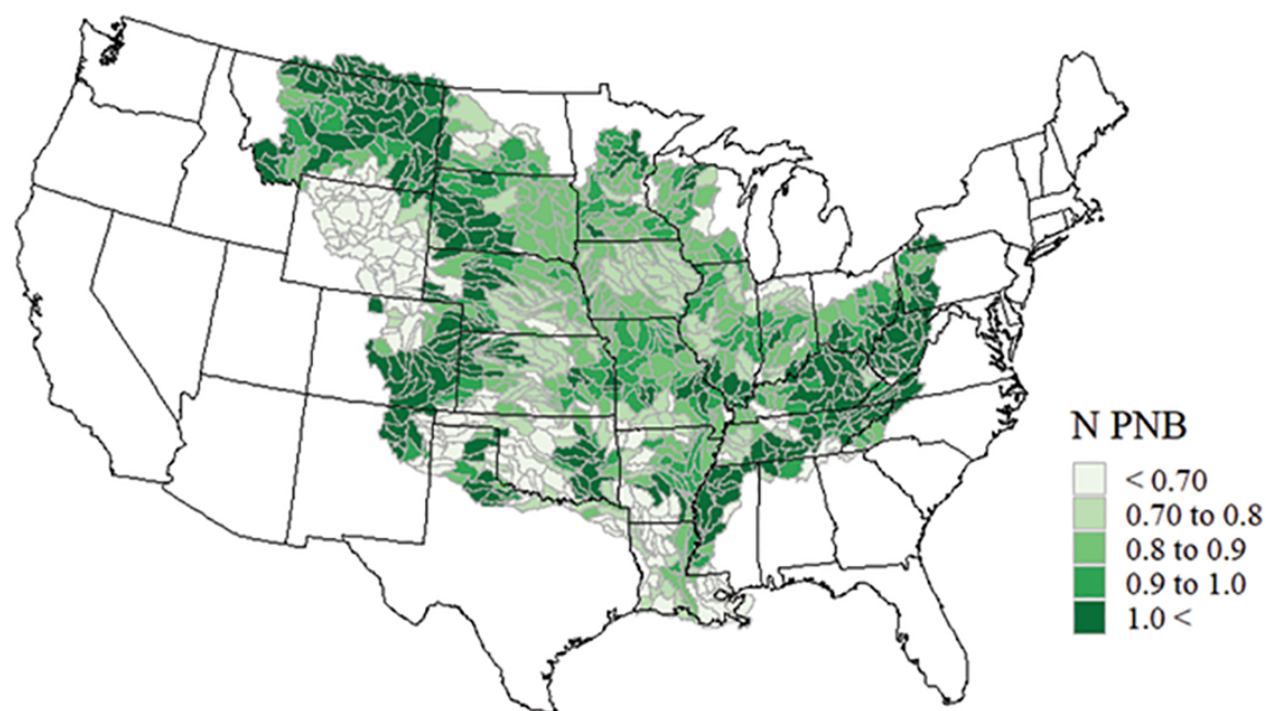


Potassium (2013-2016)

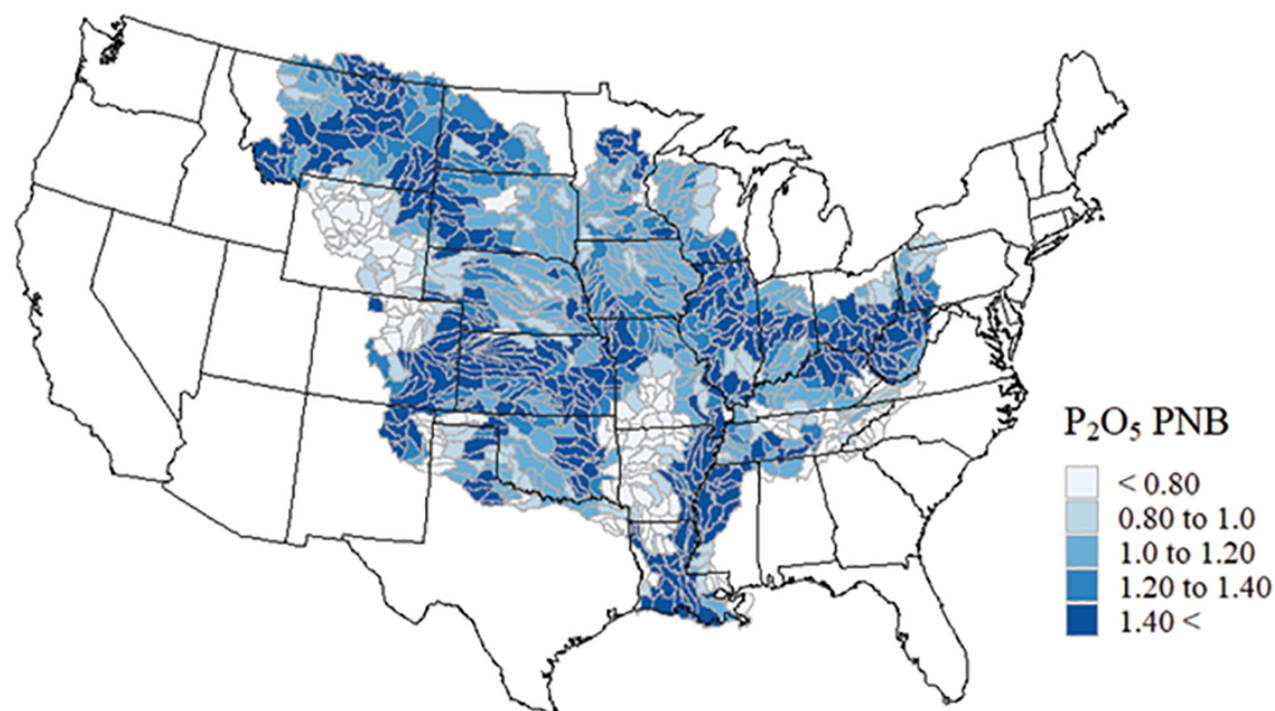


Figure 4, Nitrogen, phosphorus, and potassium mean partial nutrient balance (PNB) from 2013 to 2016 for each U.S. HUC2 (two-digit) watershed (NuGIS, [2021](#)). Partial nutrient balance is calculated by dividing the amount of nutrients removed with harvest by those applied to cropland. Source of nutrients considered were fertilizer, manure, and biological N fixation of legumes.

Nitrogen (2013-2016)



Phosphorus (2013-2016)



Potassium (2013-2016)

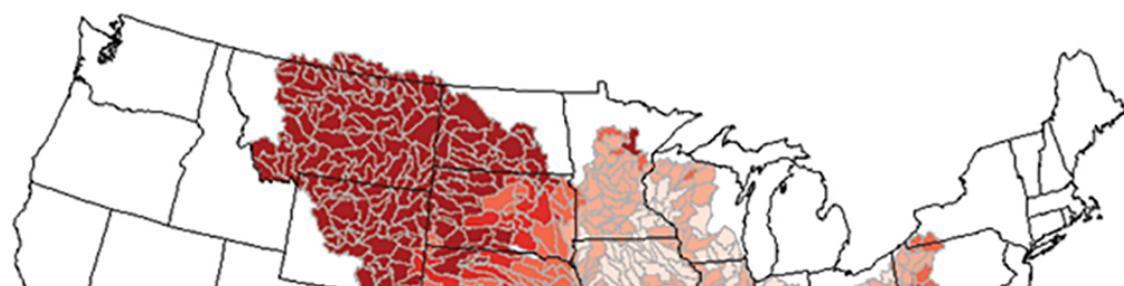


Figure 5, Nitrogen, phosphorus, and potassium mean partial nutrient balance (PNB) from 2013 to 2016 for each U.S. HUC 8 (eight-digit) watersheds within the Mississippi River Basin (NuGIS, 2021). Partial nutrient balance is calculated by dividing the amount of nutrients removed with harvest by those applied to cropland. Source of nutrients considered were fertilizer, manure, and biological N fixation of legumes.

Cropping system performance metrics like NUE have implications for both agronomic production and environmental quality. Excess nutrients are certainly susceptible to losses to air and water, but also might be applied (in regard to P and K) to increase soil test levels to an optimum category. Integrating NUE assessments within the framework of hydrologic regions can then inform on production and environmental performance within the scope of the data used for the assessment. Figure 4 shows the same U.S. NUE data for N, P, and K (2013–2016) but appropriated to each two-digit (HUC2) watershed region. Nitrogen, P, and K PNB values are in the range of 0.66 to 1.01, 0.55 to 1.76, and 0.71 to 6.70, respectively. Again, it is important to interpret these values in reference to the regional growing conditions, cropping systems, and management systems used. For these reasons, it is difficult to compare the Southeast U.S. (South Atlantic–Gulf watershed) to the Northeast (New England watershed) directly. Instead, these values should act as indices to inform performance improvement within the scope of region-specific potential conditions.

The scale of watershed-level assessments can be further reduced to eight-digit (HUC8) watersheds within larger hydrologic regions (Figure 5). Figure 5 shows the PNB of N, P, and K for each HUC8 watershed within the Mississippi River Basin (MRB) from 2013–2016. It then becomes very apparent that variability within larger hydrologic regions and states exists and can change drastically across the landscape. For example, PNB values for all nutrients vary from less than 0.1 to greater than 25 for HUC8 watersheds within the MRB for the years presented.

On-Farm NUE and Implications for 4R Nutrient Stewardship

While national, regional, or watershed NUE trends can inform large-scale assessments of nutrient use for crop production, on-farm NUE measurements vary considerably. Methods of NUE using PFP and PNB can be calculated with only nutrient application and yield data required; thus, both represent an easy means of tracking NUE. An example of comparing on-farm NUE values with regional or national scales is shown in Table 2. Economic case studies conducted by The Fertilizer Institute with participating farmers across the country analyzed their nutrient use and yield data to calculate NUE for N using the PNB method. Participating farmers utilized concepts of 4R nutrient stewardship that were appropriate for their respective regions and crops (e.g., all N application schemes included split applications or the use of an enhanced-efficiency N source). More details on the specific nutrient management systems can be found at <https://www.4rfarming.org/>. A brief comparison of NUE values in Table 2 indicates considerable difference between each scale. While the reasoning is specific to each farm that the numbers represent, assuming all of the NUE values represent similar N management techniques would not make sense either. At best, these data indicate that adoption of the specific practices that these on-farm case studies represent improves NUE compared with the mean values for their respective counties, states, and national values. The simplest conclusion can indicate that regardless of N management techniques, these specific farms are using applied N as good or better than mean values representing their geographies, which would allow less N to be lost to the environment. Certainly a comparison among fields or on a sub-field scale could answer more specific questions about how efficiently the N is being used by the crops.

Table 2. Comparison of on-farm, county, state, and national nitrogen use efficiency (NUE) using partial nutrient balance

Note: Comparisons of on-farm, county, state, and national NUE by each respective year the crops were grown. Partial nutrient balance calculated for nitrogen by dividing pounds of removed nutrients with harvest by pounds of nutrients applied for each respective year of the data collection.

Crop	Crop specific	Across all crops			
	Crop yield	On-farm	County	State	National
	bu ac ⁻¹	lb N removed	lb N applied ⁻¹		
Corn (grain)	202	1.02	0.85	0.86	0.74
Cotton	840	1.13	1.19	0.74	0.74
Winter wheat	93.0	1.25	1.27	1.00	0.74

Nutrient use efficiency is an extremely informative metric for agronomic and environmental performance of cropping systems. Measuring and assessing NUE on your farm or customers' farms allows for a more detailed look into how nutrient use can improve resource use efficiency for growing crops and reduce potential losses to the environment.

Helpful Considerations When Using NUE as a Metric

If you are using NUE as a metric for your farm or that of your growers, some helpful considerations are as follows:

- Interpretation of mobile and immobile nutrient NUE values may be influenced by differences in uptake, utilization, partitioning, and removal with harvest.
- Select the NUE term to address your question (e.g., grain harvest per unit of nutrient or nutrient balance after inputs and removal is considered).

- General trends of mean PFP in the U.S. indicate increasing N, P, and K NUE in corn grain production; increasing P and neutral K NUE in soybean production; and increasing P and K and neutral to decreasing N NUE in wheat production from 1694 to 2018.
- National, state, or even watershed baselines are good benchmarks to start with, but values representing your local conditions may prove better for comparisons.
- Nutrient use efficiency can be improved or affected by management decisions and can be considered when identifying ways of improving the agronomic, economic, or environmental components of your nutrient management system.

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