ADVANCING EARTH AND SPACE SCIENCE

Global Biogeochemical Cycles

RESEARCH ARTICLE
10.1029/2022GB007487

Water Availability and Land Management Control Catchment-Scale Agricultural Nitrogen and Phosphorous Use Efficiencies

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Key Points:

- We explore how climate and agricultural practices affect catchment-scale N and P use efficiencies (nitrogen use efficiency [NUE] and phosphorous use efficiency [PUE]) in the United States
- NUE and PUE increased with evapotranspiration to precipitation ratio and agricultural intensity, but less so in recent time
- Moderate (not damaging) climate drying and water retention in soil increase NUE and PUE and thus lower nutrient losses to water bodies

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Scaini, A., Vico, G., Thorslund, J., Hugelius, G., & Manzoni, S. (2023). Water availability and land management control catchment-scale agricultural nitrogen and phosphorous use efficiencies. *Global Biogeochemical Cycles*, *37*, e2022GB007487. https://doi.org/10.1029/2022GB007487

Received 8 JUN 2022
Accepted 22 DEC 2022

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Abstract In arable systems, large amounts of nutrients, particularly of nitrogen (N) and phosphorus (P), are not efficiently converted into harvestable products and are lost from agricultural systems, with negative consequences for agricultural productivity and the environment. These nutrient losses are mediated by hydroclimatic processes causing nutrient leaching and volatilization. We quantify over the period 1987–2012 how water availability through the evaporative ratio (actual evapotranspiration divided by precipitation) and irrigation, agricultural practices, and edaphic conditions jointly affect nutrient use efficiencies in 110 agricultural catchments in the United States. We consider N and P use efficiencies (nitrogen use efficiency [NUE] and phosphorous use efficiency [PUE]) defined as ratios of catchment-scale N and P in harvested products over their respective inputs, as well as the NUE/PUE ratio, as an indication of catchment-scale N and P imbalance. Both efficiencies increase through time because of changes in climate and agronomic practices. Setting all else at the median value of the data set, NUE and PUE increased with evaporative ratio by 0.5% and 0.2% when increasing the evaporative ratio by 20% and by 4.9% and 18.8% in the presence of irrigation. NUE was also higher in catchments where maize and soybean were dominant (increasing by 2.3% for a 20% increase in maize and soybean fractional area). Soil properties, represented by mineral soil texture and organic matter content, had only small effects on the efficiencies. Our results show that both climatic conditions and crop choice are important drivers of nutrient use efficiencies in agricultural catchments.

1. Introduction

Agricultural production is maintained by large nutrient additions to soils that aim at increasing yields by providing optimal nourishment to crops while minimizing nutrient losses (Fixen et al., 2014). Nevertheless, the efficiency of fertilizer conversion to harvestable products remains generally low (Dhillon et al., 2017; T. Zhang et al., 2015; X. Zhang et al., 2015), and a large fraction of nutrients from fertilizers is lost from the system in gaseous form—contributing to global warming—or transported to water bodies, causing environmental problems such as eutrophication. Decreasing both N and P pollution to soil and water bodies is paramount to reach many agreements targeting sustainability, including the 2030 Sustainable Development Goals (Sutton et al., 2021). However, reducing nutrient loads is costly and requires changes in land use practices and agronomic management (Christianson et al., 2018). To identify management approaches to reduce nutrient load to the environment, we need to quantify how environmental conditions and agricultural management jointly affect the efficiency of nutrient retention in harvested products (i.e., the crop nutrient use efficiency).

An effective indicator of nutrient use efficiency is the ratio of nutrient (e.g., nitrogen, N, or phosphorous, P) removed in harvested products to the total inputs of that nutrient (Lassaletta et al., 2014a; Scaini et al., 2020), hereafter NUE for nitrogen and PUE for phosphorous use efficiencies. These efficiencies can be defined at the field (Weih et al., 2018) or larger scales, such as counties (Swaney & Howarth, 2019b; Swaney et al., 2018b) or—our focus here—catchments. At all scales, NUE and PUE are indirectly affected by climatic conditions via the soil water balance, which mediates plant water use and nutrient uptake, as well as nutrient losses via leaching. Dry conditions reduce not only plant growth and yield but also water percolation below the rooting zone and nutrient leaching and losses by surface runoff, possibly enhancing nutrient use efficiencies (Ullah et al., 2019). In contrast, in wetter conditions, nutrient uptake and yields are higher but so is the potential for nutrient leaching, depressing nutrient use efficiencies (Rupp et al., 2021). Irrigation buffers the variability in precipitation

Writing – review & editing: Giulia Vico, Josefin Thorslund, Gustaf Hugelius, Stefano Manzoni

and warming, promoting yields (Luan et al., 2021; Tack et al., 2017; Troy et al., 2015; T. Zhang et al., 2015; X. Zhang et al., 2015). The effects of irrigation on nutrient use efficiencies depend on the timing and amount of irrigation. By increasing soil water content, irrigation increases crop yields but potentially also nutrient leaching. However, if irrigation is scheduled to meet evaporative demands, such negative effects can be limited, increasing NUE and PUE (Meisinger & Delgado, 2002). In addition to water availability, available energy for crop growth also play a role because conditions promoting nutrient accumulation in biomass could increase the nutrient use efficiencies (dos Santos et al., 2020). However, warm conditions could decrease yields and promote nutrient mineralization at times when plants are not using the released nutrients, thus depressing efficiencies. In the face of these productivity-sustainability trade-offs, there is a need to identify the conditions promoting plant growth and nutrient retention while minimizing nutrient losses.

N and P are key plant nutrients but their dynamics differ in many ways. Plant-available N and P are coupled via crop growth because e the plant tissue N:P ratio is constrained by physiological limits (Güsewell, 2004; Sterner & Elser, 2002). Despite known input and harvested output N:P ratios, the N:P ratio of stored nutrients and of losses at the catchment scale might still vary due to the multiple pathways of N and P internal cycling (Arbuckle & Downing, 2001; Cao et al., 2014; Peñuelas et al., 2012, 2013). The N:P ratios of compounds in solution in surface water bodies and as soil organic matter have been assessed in relation to agricultural practices, but much less so the N:P ratios of harvested products at catchment scale, where hydro-climatic, agricultural, and edaphic controls are combined. Importantly, it remains unclear whether NUE and PUE vary in coordinated or opposite ways at the catchment scale.

There are different pathways of N and P loss from watersheds, thus different agro-pedo-climatic drivers (Alexander et al., 2008), but most studies analyze either N or P cycling, acknowledging that their drivers differ (e.g., Han et al., 2011). Climatic conditions and their effects on the local water dynamics have different impacts on PUE and NUE because N and P have different solubility, as well as contrasting sources and sinks (Malagò & Bouraoui, 2021). The mobile forms of N, particularly nitrate, are quickly lost through leaching, contributing to eutrophication (Diaz & Rosenberg, 2008). Large N losses occur also through volatilization (T. Zhang et al., 2015; X. Zhang et al., 2015). However, N release to streams continues long after inputs are reduced, indicating legacy effects (Basu et al., 2022). As a result of N loss and accumulation in crop biomass (and harvested products), NUE increasing with the ratio of evapotranspiration to precipitation (ET/P), a metric of aridity, because in catchments with high ET/P crops use much of the water from precipitation, thereby reducing soil moisture and N losses (Scaini et al., 2020). Conversely, P is generally less mobile than N and accumulation of anthropogenic P in soil represents a legacy source (A. Sharpley et al., 2013). Even though phosphate in soils is not very soluble (Smil, 2000), over 50% of the total P losses from agricultural lands are due to soil erosion by water, leading to P accumulation in downstream water bodies (Alewell et al., 2020). Despite previous studies on P cycling at the county- to catchment-scale (Han et al., 2011; Swaney & Howarth, 2019b), the relationship between PUE and climatic conditions is not well characterized over large scales and cannot be directly inferred from that of NUE because the loss pathways of these nutrients might differ.

Soil physical and chemical properties influence plant growth and nutrient dynamics and as such also nutrient retention. On the one hand, the capacity of soil to supply N and P depends on the content and composition of the soil organic matter (Matus & Rodríguez, 1994; Reich et al., 2014; Veneklaas et al., 2012) and therefore, nutrient use efficiencies could depend on soil organic carbon (SOC) (which in turn covaries with organic N and P) and clay content (Soinne et al., 2020). On the other hand, soil physical properties such as texture and structure affect soil hydraulic conductivity and water retention capacity and thus nutrient leaching. Moreover, soil texture affects plant response to dry conditions by altering infiltration rates and water holding capacity (Austin et al., 2004), thus mediating not only nutrient losses but also the accumulation of N and P in harvestable products and ultimately NUE and PUE.

Nutrient use efficiencies can be improved via crop breeding and agricultural practices, but there are limitations due to biophysical conditions that control and constrain plant nutrient uptake and losses of nutrients (Berhe et al., 2004). Global NUE and PUE range between ∼20%–50% and ∼10%–20% (up to more than 100%), respectively (A. F. Bouwman et al., 2009; L. Bouwman et al., 2013). Agricultural practices can improve NUE and PUE via changes in both nutrient inputs and outputs. The use of irrigation, inorganic and organic fertilizers, crop rotations involving N fixers, and various tillage methods could promote nutrient use efficiencies (Andresen et al., 2001; Swaney & Howarth, 2019b; Swaney et al., 2018b). However, the contributions of agricultural practices are confounded with those of climatic and edaphic conditions. Teasing apart their contributions requires considering a wide range of conditions in space (different climate, soil, and agronomic conditions) and time (trends in management practices and climate, periods of unusually wet or dry conditions).

These processes driving patterns in NUE and PUE occur at multiple scales but are most studied at the field scale, given its relevance for agricultural management (Weih et al., 2018). However, the catchment scale is more relevant for a holistic assessment of the environmental implications of agricultural systems in terms of nutrient inputs and outputs (Basu et al., 2010; Boyer et al., 2002; Han et al., 2011; Howarth et al., 2012). Still, upscaling from field to catchment is not trivial because of redistribution processes within the catchment that could reduce or amplify the effects of field-scale agricultural management, motivating a top-down approach where catchments are regarded as biogeochemical reactors with emerging nutrient use efficiencies.

To reduce nutrient loads to the environment, we need to explore whether NUE and PUE vary in coordinated or contrasting ways at the catchment scale, in response to combined hydroclimatic, agricultural, and edaphic controls. Scaini et al. (2020) discussed how ET/*P* and time affect NUE across catchments in the United States. Here, we explore how agricultural practices, climate, and edaphic conditions interact to determine catchment-scale agricultural NUE and PUE, as well as their ratio—a measure of contrasting N and P loss pathways. To this aim, we analyzed 110 agricultural catchments in the conterminous United States—where agricultural N surplus needs reduction (Schulte-Uebbing et al., 2022) and climate change effects vary, generally shifting toward drier growing seasons (Basso et al., 2021; McKinnon et al., 2021; Overpeck & Udall, 2020)—and addressed the following questions:

- How are agricultural practices (crop type and irrigation) affecting NUE and PUE (and their ratio) at the catchment scale? We expect that N fixing crops will improve NUE and that both efficiencies will be higher in intensely cultivated and irrigated catchments.
- What is the role of hydroclimatic (water and energy availability) and edaphic (soil texture and organic matter) conditions in driving variations in NUE and PUE (and their ratio)? We expect higher efficiencies with increasing evaporative ratio and in catchments with higher organic matter content.
- How are NUE, PUE, and their ratio changing through time in response to trends in climate and agricultural management? We expect higher efficiencies through time, as nutrient management improves and climate shifts toward drier conditions with higher evaporative ratio.

2. Materials and Methods

2.1. Data

The catchment scale is the most relevant scale to assess the environmental implications of agricultural systems in terms of nutrient export as catchments act as spatial and temporal integrators (Basu et al., 2010). For a view on the integrated effects of agricultural practices and regional conditions, nutrient use efficiency thus needs to be evaluated at the catchment scale. We characterized the catchment water cycle using data on runoff (*R*) from the annual Global Runoff Data Centre database (GRDC, 2011) and temperature (*T*) and precipitation (*P*) from the Climatic Research Unit (CRU) raster database, available at daily and monthly timescales (Harris et al., 2014). Among the catchments from the GRDC database, we selected those that satisfied four criteria: (a) higher than 10% of the area under cultivation of maize, soybean, wheat, alfalfa, other hay, and their combinations on average in the period between 1987 and 2012; (b) catchment area between 1,000 and 9,000 km^2; (c) completeness of data within the 1987–2012 period; and (d) absence of nested catchments within the data set. One hundred and ten catchments satisfied these criteria (Figure 1). In each catchment, we identified the agricultural area for each year as the sum of the area under cultivation of maize, soybean, wheat, alfalfa hay, and other hay. The main results remained unchanged when setting the threshold for minimum agricultural area at 30%. The selected catchments cover a wide range of conditions in the conterminous United States, with largely agricultural catchments in the midwest and lower agricultural areas in the north-west US.

The edaphic properties of soils under agricultural land use in each catchment were characterized by SOC by weight and sand fraction (*Sand*), both obtained from the Soil Property and Class Maps of the Conterminous US data (Ramcharan et al., 2017). Data for a reference depth of 30 cm were used as this intermediate depth reflects parent soil material properties but is also closely connected to plant activity (Soinne et al., 2020).

We considered N and P input via mineral fertilizer, manure, and, for N, biological fixation and atmospheric deposition. County-level crop yield, irrigated, and agricultural areas of maize, soybean, wheat, and hay (as alfalfa hay

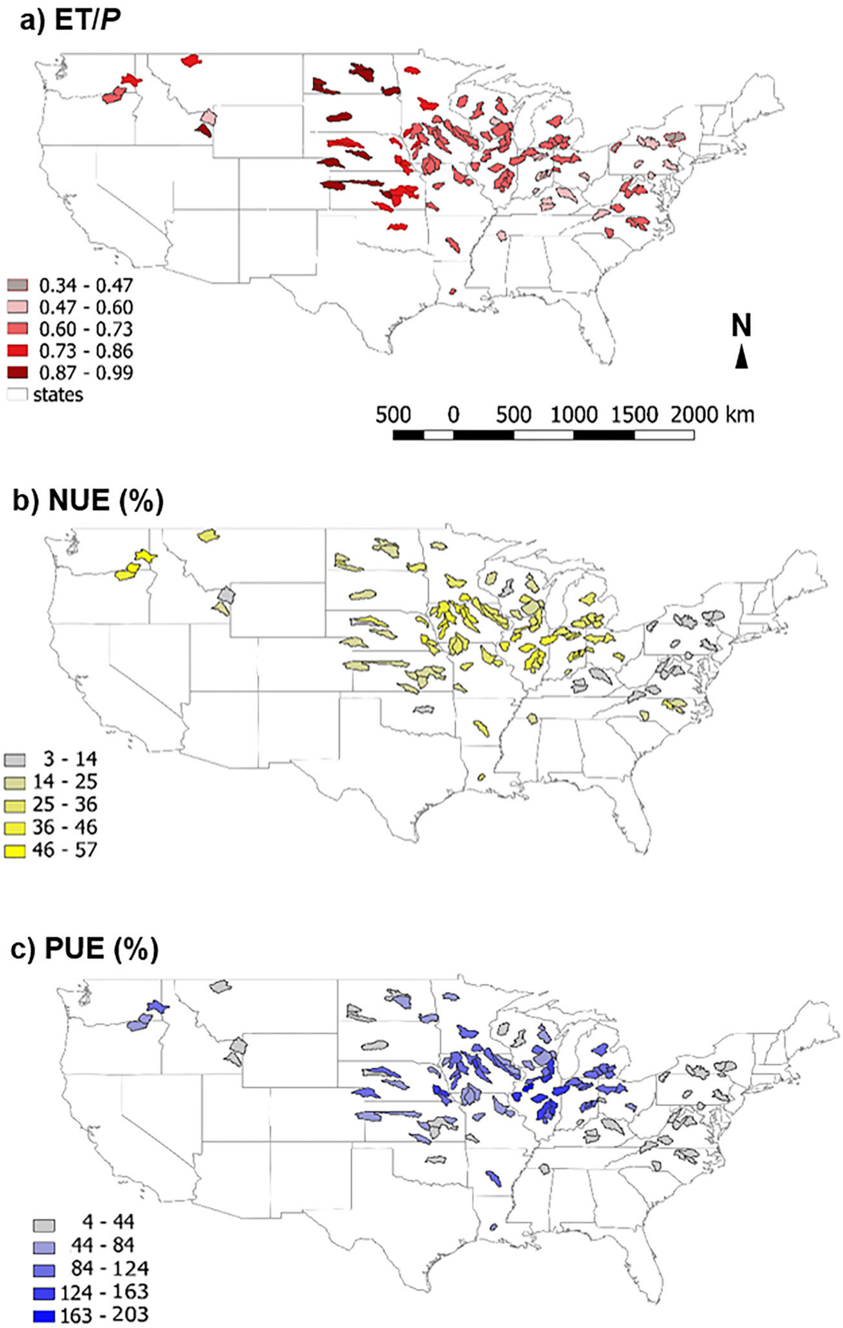

Figure 1. Color-coded catchments illustrating spatial variations in the long-term mean of: (a) evapotranspiration to precipitation ratio, ET/*P*, (b) nitrogen use efficiency (NUE), and (c) phosphorous use efficiency (PUE) (see definitions in Table 1). NUE and PUE are expressed as percentages.

and other hay) were obtained for each year through the survey program of the United States Department of Agriculture's National Agricultural Statistics Services. The annual fertilizer application rates were obtained through the United States Geological Survey county-level estimates of N and P applications from commercial fertilizer for the contiguous United States (Gronberg & Spahr, 2012). N and P inputs to cropland occur mainly in the form of mineral fertilizer (hereafter F_N for N and F_P for P) and manure (M_N and M_P) (Swaney & Howarth, 2019b). Noncropland pasture area was used to infer a conservative estimate of manure N and P applied to cropland (Swaney & Howarth, 2019a, 2019b). The amount of soybean biological N fixation ($F_{N,soybean}$) was estimated as a set proportion of the soybean yield (Lassaletta et al., 2014a, 2014b). In addition, total annual N deposition

Table 1
Table With the Acronyms Mentioned in the Main Text

Symbol	Definition	Explanation	Source	Units
F_P	Phosphorus fertilization rate	Rate of phosphorus fertilizer addition per unit agricultural area of the catchment	Calculated from United States Geological Survey data	kg P ha^{-1} yr^{-1}
F_N	Nitrogen fertilization rate	Rate of nitrogen fertilizer addition per unit agricultural area of the catchment	Calculated from United States Geological Survey data	kg N ha^{-1} yr^{-1}
M_P	Manure phosphorus	Phosphorus excretion from livestock, from Hong et al. (2013)	Calculated from Swaney and Howarth (2019a)—Livestock excretion P (manure) original units: (kg P/km^2 county/yr) available for census years	kg P ha^{-1} yr^{-1}
M_N	Manure nitrogen	Nitrogen excretion from livestock, from Hong et al. (2013)	Calculated from Swaney et al. (2018a)—Livestock excretion N (manure) original units: (kg N/km^2 county/yr) available for census years	kg N ha^{-1} yr^{-1}
I_P	Total phosphorus inputs	$I_P = F_P + M_P$	Calculated from F_P and M_P	kg P ha^{-1} yr^{-1}
Irr	Irrigated catchments	*Irr* = 0 for rainfed, *Irr* = 1 for irrigated (>30% of agricultural area is irrigated)	Calculated from the fraction of agricultural and irrigated area	Nondimensional
$F_{N,soybean}$	Nitrogen fixed by soybean	N fixed by soybean per unit agricultural area of the catchment	Calculated from yield data through the methodology of Lassaletta et al. (2014a) and following Scaini et al. (2020)	kg N ha^{-1} yr^{-1}
DEP_N	Nitrogen deposition	Annual total N deposition per agricultural area of the catchment	Calculated from the North American Climate Integration and Diagnostics (NACID) database Hember (2018)	kg N ha^{-1} yr^{-1}
I_N	Total nitrogen inputs	$I_N = F_N + M_N + F_{N,soybean} + DEP_N$	Calculated from F_N, M_N, $F_{N,soybean}$, and DEP_N	kg N ha^{-1} yr^{-1}
Y_P	Phosphorus in crop yield	Phosphorus in harvested grain per unit agricultural area of the catchment	Calculated from yield data	kg P ha^{-1} yr^{-1}
Y_N	Nitrogen in crop yield	Nitrogen in harvested grain per unit agricultural area of the catchment	Calculated from yield data	kg N ha^{-1} yr^{-1}
PUE	Phosphorus use efficiency	Ratio of phosphorus removed in harvested grain over the sum of all phosphorus inputs (PUE = Y_P/I_P)	Calculated from I_P and Y_P data	Nondimensional (expressed as % in the figures)
NUE	Nitrogen use efficiency	Ratio of nitrogen removed in harvested grain over the sum of all phosphorus inputs (NUE = Y_N/I_N)	Calculated from I_N and Y_N data	Nondimensional (expressed as % in the figures)
P	Precipitation	Annual amount of rainfall per unit area	Calculated from CRU data	mm yr^{-1}
T	Temperature		Calculated from CRU data	°C
ET/*P*	Evaporative ratio	Ratio of actual evapotranspiration to precipitation (*P*)	Calculated	Nondimensional
$A_{T,AG}$	Total agricultural area within a given catchment	Sum of maize, soybean, wheat, and hay (alfalfa and other hay) agricultural area normalized by catchment	Calculated	Nondimensional (expressed as %)
A_{SC}	Fraction of the agricultural area cultivated as soybean and maize	Sum of maize and soybean agricultural area (normalized by catchment) divided by $A_{T,AG}$	Calculated	Nondimensional
Time	5-year intervals	Progressive number indicating the five time periods	Calculated from the annual time series: 1. 1988–1992 2. 1993–1997 3. 1998–2002 4. 2003–2007 5. 2008–2012	Nondimensional

Table 1
Continued

Symbol	Definition	Explanation	Source	Units
Sand	Fraction of sand		Calculated from soil property and class maps of the Conterminous US data (Ramcharan et al., 2017)	g sand (g soil)$^{-1}$ (reported as %)
SOC	Soil organic carbon by weight		Calculated from soil property and class maps of the Conterminous US data (Ramcharan et al., 2017)	g C (g soil)$^{-1}$ (reported as permille)

Note. Acronyms and data sources are available in Tables S1 and S2 in Supporting Information S1.

(N_{DEP}) was obtained from the North American Climate Integration and Diagnostics database (Hember, 2018). Conversely, P atmospheric deposition was neglected on the grounds that is relatively small across the conterminous US (Swaney & Howarth, 2019b). N and P sewage (i.e., biosolids) were also not considered because their input to agricultural lands is negligible (Swaney & Howarth, 2019b).

The analysis was carried out for the 1987–2012 period when all the data were available. Out of the 26 years of data, the analysis was performed using mean values for all variables over 5-year intervals (1988–1992, 1993–1997, 1998–2002, 2003–2007, and 2008–2012). The 5-year averaging limits the uncertainties stemming from changes in catchment water storage, which are neglected in our simplified application of the catchment water balance to estimate long-term ET (Section 2.2). More details are available in Supporting Information S1; the 5-year data are available at Scaini et al. (2022).

2.2. Data Aggregation and Determination of NUE, PUE, and ET/*P*

We considered maize, soybean, wheat, alfalfa hay, and other hay as these crops cover a large share of cropped area in these catchments, with a mean agricultural area of 41% (Figures S1 and S4 in Supporting Information S1). We aggregated all the data to the catchment scale and from annual to 5-year intervals, as detailed in Supporting Information S1. After aggregation at the catchment scale, agricultural yields were transformed into P and N yields, Y_P and Y_N, quantified as the sum of P and N extracted in harvested maize, soybean, wheat, alfalfa hay, and other hay, respectively (Supplementary Methods, Table S3 in Supporting Information S1, Lassaletta et al., 2014a, 2014b). The crop-specific P and N content per unit harvested yield mass was assumed to be independent of growing conditions and time. The total nutrient inputs were estimated as the sum of fertilization rate (F_P) and manure (M_P) for P; for N, as the sum of fertilization rate (F_N), N fixed by soybean ($F_{N,soybean}$), N deposition (N_{DEP}), and manure (M_N).

We calculated PUE as the ratio of P in crop yield (Y_P), per unit of P input (I_P), and NUE as the ratio of N in crop yield (Y_N), per unit of N input (I_N) for each year and then averaged over the 5-year intervals. For each catchment, we also computed the percentage of agricultural area as the sum of maize, soybean, wheat, and hay area normalized by catchment area ($A_{T,AG}$) as well as the fraction of agricultural area cultivated by maize or soybean in each catchment (A_{SC}). The latter is used as an index of agricultural intensity at the catchment scale because catchments with high agricultural area under maize and soybean tend to also have high total agricultural area. Moreover, counties with high areas under maize and under soybean generally overlap in the catchment we considered, and maize and soybean are by far the crops with the highest absolute coverage in most of the selected catchments. The few exceptions are in drier conditions (high ET/*P*, Figure S3 in Supporting Information S1), where wheat covers a higher area. Maize and soybean are often grown in rotation. Thus, combining the fractional areas of these two crops into the fraction A_{SC} allows summarizing agricultural management intensity with a single predictor. The fraction of irrigated area for each catchment was estimated as the fraction of area equipped with irrigation normalized by the total agricultural area (Supplementary Methods). Finally, catchments were classified as irrigated when the fraction of cultivated land that was irrigated was higher than 30%. With this criterion, 26 catchments were classified as irrigated (Figure S1 in Supporting Information S1).

The catchment water use was characterized via the evaporative ratio (i.e., the ratio of ET to P, ET/P). At the catchment scale and over time intervals of one or more years, such as the 5-year period used here, ET can be estimated as $ET = P - R$ (assuming negligible changes in catchment water storage; e.g., Jaramillo & Destouni, 2014). This implies that the evaporative ratio is calculated as $ET/P = 1 - R/P$.

2.3. Linear Mixed Effect Models

We used linear mixed effect (LME) models to disentangle the effects of climate, edaphic conditions, agricultural practices, and land use on NUE, PUE, and their ratios as well as their components (outputs Y_N and Y_P and inputs I_N and I_P).

The initial model, applied separately to each dependent variable, comprised seven fixed factors (Table S4 in Supporting Information S1). Climatic fixed factors were the mean annual temperature (*T*, proxy for energy availability) and the ET/*P* ratio (proxy for water availability). Agricultural management was accounted for by the fraction of the area cultivated with maize and soybean (A_{SC}) and a categorical variable indicating if a catchment was irrigated (*Irr*). *Sand* and SOC were also included as fixed effects capturing edaphic conditions. Finally, we considered *Time* (i.e., the 5-year period, 1–5) among the fixed effects to capture temporal changes in yields that could not be explained by other fixed factors. Two-way interactions were also included because we expected that climatic, edaphic, and land use effects might change through time via interactions with each other. However, we excluded the interactions between *Time* and the edaphic conditions because both *Sand* and SOC are catchment-specific values that do not change over time in our analyses. The catchment identification code was treated as a random effect to consider the variation among catchments (in terms of other soil properties, groundwater, natural vegetation, and urban fraction).

The LME models were fitted with the maximum likelihood (ML) approach using RStudio 1.4 by means of the "lme4" package version 1.1.23 (Bates et al., 2015). The ML was used instead of the Restricted ML as we are using a model simplification procedure based on recommendations from Zuur et al. (2009). Model assumptions were checked using the R package "DHARMa," Residual Diagnostics for Hierarchical (Multi-Level/Mixed) Regression Models (Hartig, 2022). Given that all correlation coefficients among the independent variables are within the −0.48 to +0.35 range, we consider collinearity not being a substantial issue. The LME model was simplified by removing the nonsignificant ($p > 0.05$) fixed factors using "Step," a backward elimination approach (Venables & Ripley, 2002). Model performance was reported using the marginal coefficient of determination R^2 (fraction of variance explained by the fixed effects alone) and the conditional R^2 (total fraction of variance explained) (Nakagawa & Schielzeth, 2013).

3. Results

To provide a general context for the following statistical analysis, we describe qualitative temporal trends in the N and P inputs, outputs, and efficiencies, as well as the edaphic, climatic, and management factors we expect to drive them (Section 3.1). Then, we analyze quantitatively (using LME models) the agricultural, edaphic, and climatic factors driving NUE, PUE, and their ratios (Section 3.2). Finally, we assess the causes of the changes in NUE and PUE by analyzing with LME models how the driving factors affect N and P in harvested products (the numerators of the efficiencies) and in the inputs (the denominators) (Section 3.3).

3.1. General Temporal Trends

The evaporative ratio calculated as a mean over the 26-year period follows an east-west climatic gradient, with high ET/*P* in the west decreasing toward the east (Figure 1). Mean temperature increases with latitude toward the south (Figure S1 in Supporting Information S1). The NUE and PUE vary widely across catchments, with mean values ranging between 8% and 40% (indicating the 10th and 90th percentiles) for NUE (mean value 25%) and between 13% and 130% for PUE (mean value 69%) calculated over the whole period (Figure 1). Both NUE and PUE generally increased through time, on average by 12% and 45%, respectively, although in the last 5 year period analyzed (2008–2012), NUE decreased by 10% and PUE plateaued (0.4% increase) compared with the previous 5 year periods (Figures 2a and 2b). These changes in NUE and PUE can be largely ascribed to changes in the nutrient content in the crop yields. A steady increase occurred for both Y_N (on average 30%) and Y_P (26%) over the first three time intervals, followed by a slight decrease in the last period (5% and 6%, respectively) (Figures 2d and 2e). Nutrient inputs increased less than yields through time for N and even decreased in the case of P: I_N and its components, particularly the rate of soybean N fixation, whose estimate is based on Y_N (Figure S2 in Supporting Information S1), slightly increased through time, with an 8% increase across the whole period. I_P has generally decreased by 20% over the whole period analyzed due to a decrease both in manure and fertilizer applications (Figure S2 in Supporting Information S1). Overall, yields and nutrient inputs tended to be higher in catchments with lower ET/*P*, located in areas with more favorable conditions for agriculture (Figure 1). ET/*P*

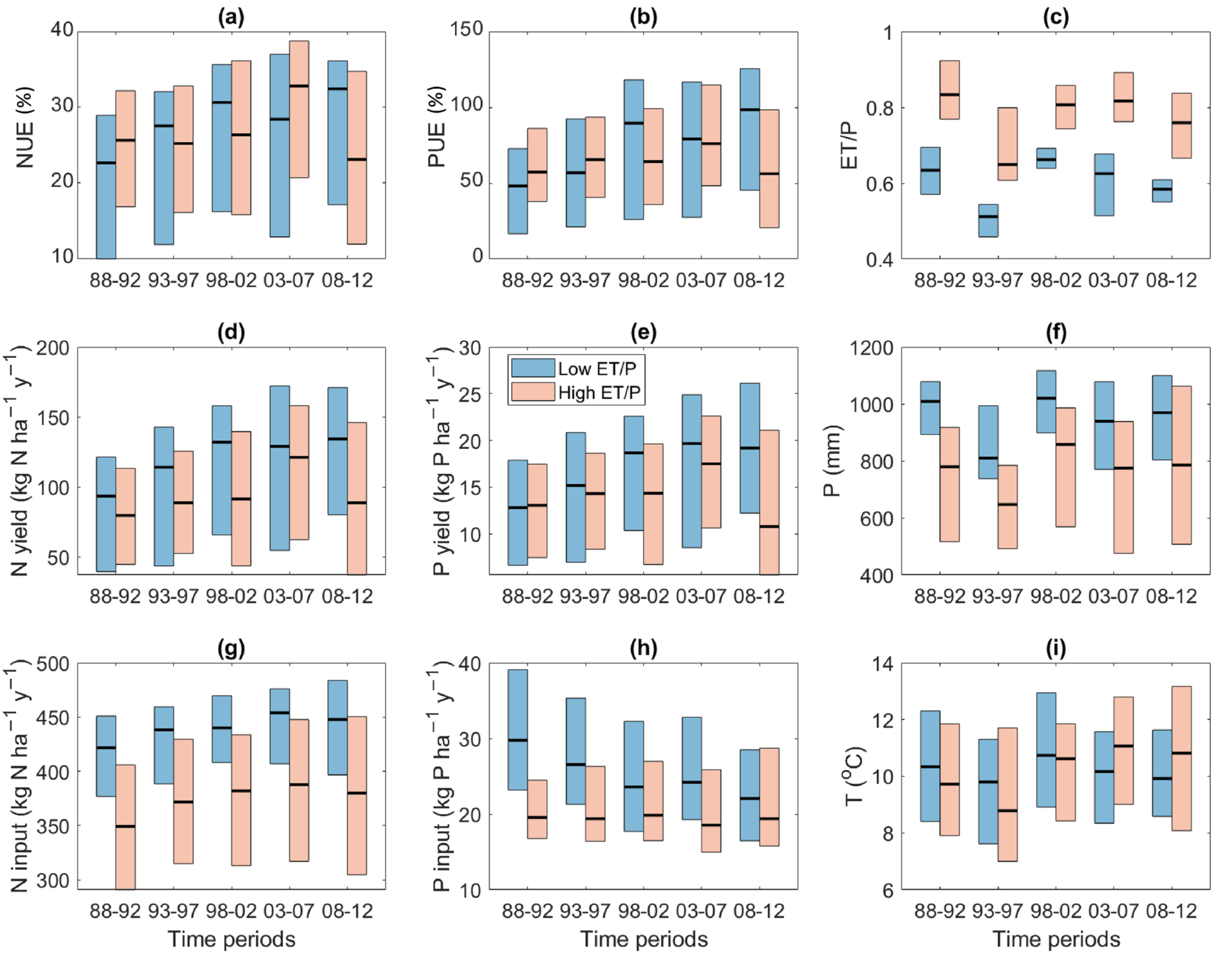

Figure 2. Temporal changes in the following: (a and b) nutrient use efficiencies and their components, (d and e) yields, and (g and h) nutrient inputs; (c) mean annual evapotranspiration to precipitation ratio (ET/*P*); (f) mean annual precipitation; and (i) mean annual temperature. The data are grouped by time period (5 years each) and according to ET/*P* as a proxy of the overall climatic context (relatively wetter conditions with "low" ET/*P* below the median value and drier with "high" ET/*P* above the median value). The thick line indicates the median, and the box extends from the 25th to the 75th percentiles, respectively. Statistical analysis of temporal and climatic effects is presented in Table 2.

effects on NUE and PUE appear limited in Figure 2 but as we will show in the following, they become strong and significant after separating them from other drivers (fixed and random). It is important to emphasize that these trends are due to combined temporal changes in agronomic (crop choice, irrigation, and fertilization) and climatic factors (temperature and water availability). In the next sections, we tease apart the contributions of these factors and that of time per se, the latter representing unspecified sources of temporal variability. In this way, we attribute the variations in the data to specific drivers.

The percentage of agricultural area of the catchments has generally increased (13% increase over the whole period analyzed), suggesting an overall intensification of agricultural land use. Considering individual crops, maize, and soybean areas increased, while wheat and hay decreased in the time period considered (Figure S3 in Supporting Information S1).

3.2. Effects of Agricultural, Edaphic, and Climate Factors on NUE and PUE

The final LME models, after backward elimination, included as predictors: ET/*P*, *Irr*, *Time*, A_{SC}, the interaction between ET/*P* and *Time* and between *Time* and A_{SC} (Table 2). Edaphic factors were not significant in isolation or in interaction with other factors and hence were not retained in the final model. For PUE, also the mean annual temperature, because of its interaction with maize or soybean-cultivated area as well as SOC and the interaction between *Irr* and SOC were significant (at $p < 0.05$). The fixed effects in the final model explained a large fraction of NUE variability (e.g., marginal $R^2 = 0.6$) and most of PUE variability (marginal $R^2 = 0.77$) (Table 2).

Table 2

Linear Mixed Effect Model Results Including Marginal and Conditional Coefficients of Determination (Marginal and Conditional R^2) and Estimates and p-Values of the Fixed Effect Coefficients for Nitrogen Use Efficiency (NUE), Phosphorous Use Efficiency (PUE), and NUE/PUE Ratio

	NUE			PUE			NUE/PUE		
Marginal R^2	0.60			0.77			0.41		
Conditional R^2	0.87			0.92			0.93		
Fixed effects	Estimate	SE	p	Estimate	SE	*p*	Estimate	SE	*p*
Intercept	0.062	0.029	0.035	−0.230	0.138	0.096	0.569	0.079	<0.001
ET/*P* (–)	0.124	0.037	<0.001	0.439	0.116	<0.001	−0.268	0.062	<0.001
Time (–)	0.015	0.007	0.045	0.124	0.023	<0.001	−0.111	0.012	0
A_{SC} (–)	0.263	0.032	<0.001	0.286	0.255	0.264	−0.123	0.161	0.448
Irr (–)	0.050	0.018	0.008	0.601	0.125	<0.001	0.216	0.109	0.049
SOC (permille)				0.008	0.003	0.002			
T (°C)				−0.010	0.009	0.232	0.038	0.007	<0.001
ET/*P*:*Time*	−0.027	0.010	0.007	−0.149	0.031	<0.001	0.098	0.016	<0.001
Time:A_{SC}	0.024	0.005	<0.001	0.073	0.017	<0.001	0.067	0.009	<0.001
A_{SC}:T				0.093	0.026	<0.001	−0.056	0.016	<0.001
Irr:T							−0.037	0.010	<0.001
A_{SC}:*Irr*							0.338	0.119	0.005
Irr:SOC				−0.024	0.008	0.002			

Note. Only terms retained after the backward elimination of nonsignificant effects are reported (those not retained are left blank). The number of observations is 550. SE: standard error; units refer to the independent variables. Model formulations are reported in Table S4 in Supporting Information S1.

ET/*P* and A_{SC} equal to their median values for the whole data set, NUE increases from 24% to 26% while PUE increased from 57% to 78% from the first to the last 5-year period. NUE increased with the fraction of agricultural area cultivated with maize or soybean (A_{SC}), and more so in time. Irrigation increased both NUE and PUE compared with rainfed catchments. Setting all else at the median value of the data set, NUE and PUE increased with evaporative ratio by 0.5% and 0.2% when increasing the evaporative ratio by 20% and by 4.9% and 18.8% in the presence of irrigation; however, the ET/*P* effect decreased through time in both efficiencies (Figure 3). NUE was also higher in catchments where maize and soybean were dominant (increasing by 2.3% for a 20% increase in maize and soybean fractional area).

Different from NUE, PUE was affected by the negative interaction between *Irr* and SOC, which implies that the positive effect of irrigation was lower at higher SOC. A negative interaction was also found between A_{SC} and *Irr*, meaning that the positive effect of the maize-soybean area on PUE was lower in irrigated catchments. Moreover, the positive interaction between A_{SC} and mean temperature on PUE implies that the positive effect of the maize-soybean area was stronger in warmer conditions.

The predictive capacity of the fixed effects for the NUE/PUE ratio was lower than that for NUE or PUE alone, despite the equal or higher number of significant effects than in the models for the other efficiencies (Table 2). ET/*P*, A_{SC}, and time affected NUE/PUE in directions opposite to those for PUE and NUE, indicating that variation in NUE/PUE is mostly governed by variations in PUE (Table 2). In addition, in rainfed catchments, mean annual temperature had a positive direct effect on the NUE/PUE ratio at $A_{SC} < 0.7$ but negative at $A_{SC} > 0.7$ due to the interaction terms between temperature and A_{SC}. The overall effect of ET/*P* on NUE/PUE, at median values of time and A_{SC}, was positive.

The relative changes in NUE and PUE can be explored not only in terms of their ratio (NUE/PUE; Table 2) but also by showing how one efficiency varies against the other (Figure 4). In general, the two efficiencies are well correlated, which is partly expected given their definition (yields appear in the numerators of both). However, the relationship between them breaks down in catchments with high agricultural areas, where NUE stabilizes around 0.4, whereas PUE continues to increase above one. Moreover, the slope of the NUE-PUE relations consistently flattens through time.

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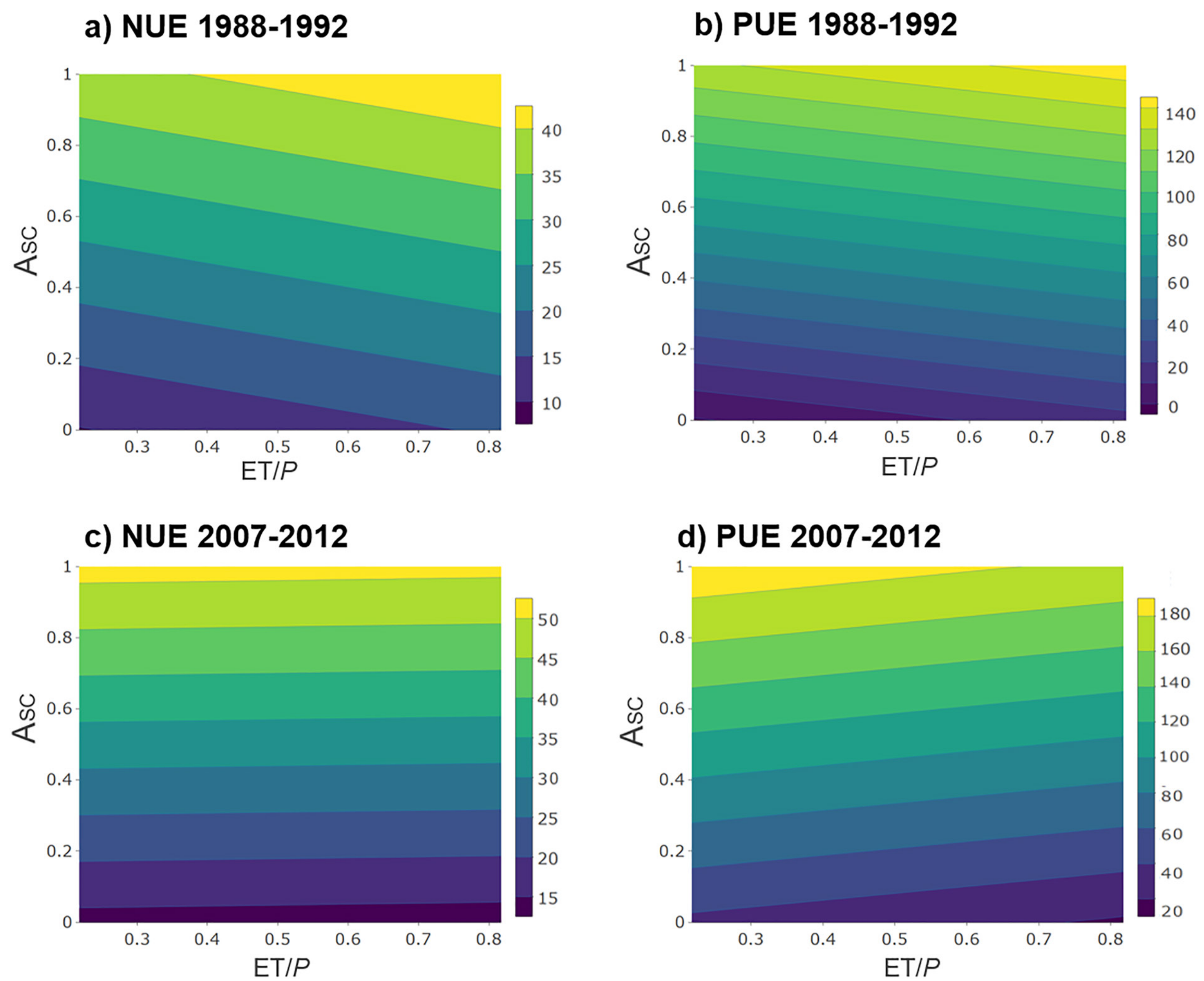

Figure 3. Contour plots showing the dependent variables expressed as percentages, respectively, nitrogen use efficiency (left) and phosphorous use efficiency (PUE) (right), as a function of ET/*P* and A_{SC}. The contour plots are drawn using the fixed effects of the linear mixed effect model, for *Irr* = 0 and for *Time* = 1 (1988–1992; top) and 5 (2008–2012; bottom). In the two PUE graphs (b and d), the contour plots are computed for the median temperature ($T = 10°C$).

3.3. Effects of Agricultural, Edaphic, and Climatic Factors on Nutrient Inputs and Outputs

The role of the predictors of NUE and PUE is mediated by the changes in the N and P inputs and outputs that define the efficiencies. The fixed effects explained most variations of N and P yield (marginal $R^2 = 0.81$ and 0.77, respectively) and of N and P input (marginal $R^2 = 0.53$ and 0.41, respectively) (Table 3). Some effects that were significant both for inputs and outputs (T, A_{SC}:T and *Irr*:T for N, *Irr*:T for P) did not have a significant effect on NUE or PUE, but *Irr*:T had a significant effect on the NUE/PUE ratio (Figure 5). This loss of significance is expected because by calculating ratios, effects with the same sign and importance for the input and output terms can cancel out. In one case, the input (denominator in NUE and PUE) drove the effect on the efficiency (ET/*P* for N), and in three cases the numerator drove the effect (*Irr* for both N and P, *Irr*:SOC for P). In other cases, despite the yields and inputs changing significantly and in the same direction, there was also a significant effect on the efficiencies. In particular, the positive effect of the *Time*:A_{SC} interaction on inputs and outputs of both N and P resulted in a positive effect on NUE.

4. Discussion

Improving NUE and PUE is a critical challenge to meet increasing food demands, not least under increasing hydroclimatic changes. Considering the wide range of nutrient use efficiencies we found, improvements seem possible. In fact, the catchments included in this study exhibit a wide range of NUE and PUE, with values ranging between 8% and 40% (indicating the 10th and 90th percentiles) for NUE and between 13% and 130% for

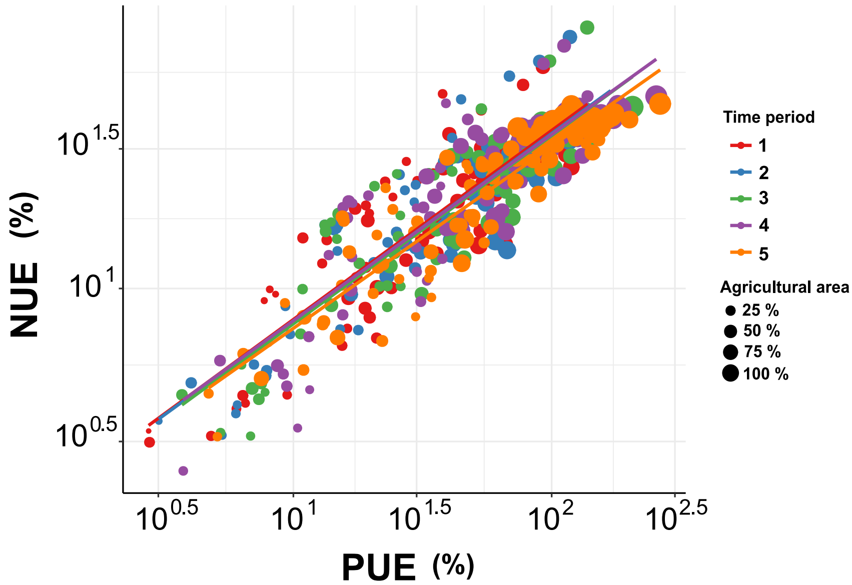

Figure 4. Scatterplot showing the relation between nitrogen use efficiency (NUE) and phosphorous use efficiency (PUE) in time (expressed as 5-year intervals; colors indicate the time interval, while size indicates percentage of agricultural area within the catchment). The decrease through time of the intercepts of the NUE-PUE relations in log-log scale indicates a decrease in NUE versus PUE slopes, whereas the similar slopes indicate consistent downward curvature, causing NUE to stabilize as PUE increases.

PUE (Figure 1). This high variation aligns with regional to global estimates, between 25% and 50% for NUE and between 10% and above 100% for PUE, depending on long-term land use (L. Bouwman et al., 2013; Guo et al., 2020; Lassaletta et al., 2014a; Lun et al., 2018). This variation can be explained by several drivers, including agricultural practices (described in Section 4.1) and climatic conditions (Section 4.2).

4.1. Agricultural Practices Affect NUE and PUE at the Catchment Scale

We show that the fraction of agricultural area under maize or soybean (A_{SC}) has a positive effect on nitrogen and phosphorous use efficiencies (NUE and PUE) with an improvement through time, indicating that nutrient retention by these crops tends to be higher compared to other crops. For PUE, the positive effect of A_{SC} is observed only within the interaction term of A_{SC} with time and temperature, indicating that only recently or in warmer 5-year periods PUE has increased with A_{SC}. The A_{SC} also has a positive effect amplified through time on all outputs and on N inputs as well as the NUE/PUE ratio. The increase in Nitrogen (N) inputs with A_{SC} suggests that soybean N fixation, which has steadily increased in the period considered (Figure S2 in Supporting Information S1), may be driving the effect of A_{SC} on NUE. The positive temperature and negative evaporative ratio (ET/*P*) effects on N inputs could also be caused by N fixation because soybean benefits from warm and humid conditions. However, given the increase in biological N fixation through time, the positive *Time*:A_{SC} interaction indicates that the N fixation affects N inputs more and more positively as maize and soybean area increases. Crop monocultures are common across the conterminous United States (Plourde et al., 2013; Seifert et al., 2017; Wang & Ortiz-Bobea, 2019), and crop diversity has been declining in most regions of the United States over the past decades (Aguilar et al., 2015). Nevertheless, maize and soybean are also grown in rotation. We speculate that part of the positive effect of A_{SC} on the efficiencies could be attributed to the increased capacity to retain nutrients in systems with rotations of soybean (N fixer) and corn (intensive N user) (Pasley et al., 2021). This hypothesis cannot be tested with our data as we do not know the fraction of agricultural areas where rotations are implemented. In general, a more diversified agriculture could have a positive effect on the efficiencies without decreasing yields (Tamburini et al., 2020).

In addition to crop-rotation strategies, adjusting fertilization methods and rates to better suit specific crops as well as using targeted crop species that are more efficient in nutrient use can also increase yields (Ebbisa, 2022; Guo et al., 2020; Pan et al., 2022). Improving such local to regional farmland management strategies could lead to a

Table 3
Linear Mixed Effect Model Results of the 5-Year Means Data Including Marginal and Conditional R^2*, and Estimates and p-Values of Each of the Fixed Effect Coefficients*

	Y_N			Y_P			I_N			I_P		
Marginal R^2	0.81			0.77			0.53			0.41		
Conditional R^2	0.97			0.96			0.92			0.90		
Fixed effects	Estimate	SE	*p*	Estimate	SE	*p*	Estimate	SE	*p*	Estimate	SE	*p*
Intercept	−2.762	10.227	0.787	−0.390	2.083	0.852	232.911	58.992	<0.001	72.514	20.674	<0.001
ET/*P* (–)							−234.831	31.200	0.000	−80.914	26.822	0.003
Time (–)	0.200	0.528	0.705	−0.177	0.084	0.036	6.651	4.141	0.109	−6.468	1.440	<0.001
A_{SC} (–)	196.440	22.934	0.000	23.885	3.488	<0.001	668.469	128.729	0.000	−13.777	14.919	0.356
Irr (–)	34.535	14.634	0.019	12.287	3.812	0.002	95.629	81.133	0.240	7.288	10.001	0.467
SOC (permille)				0.105	0.042	0.013	1.310	1.960	0.505	−1.177	0.492	0.017
Sand (%)										0.580	0.237	0.015
T (°C)	5.033	0.941	0.000	0.615	0.152	<0.001	21.597	4.584	<0.001	0.800	1.398	0.568
ET/*P*:*Time*										7.518	1.512	<0.001
Time:A_{SC}	12.915	1.306	0.000	2.424	0.208	0.000	22.259	4.193	<0.001	5.961	0.812	<0.001
A_{SC}:T	−6.858	2.246	0.002	−0.792	0.345	0.022	−63.745	8.996	<0.001	−3.609	1.480	0.015
Irr:T	−3.299	1.310	0.013	−0.580	0.224	0.010	−16.235	4.478	<0.001	−2.404	0.860	0.006
A_{SC}:*Irr*	−40.449	16.273	0.013	−7.094	2.500	0.005				25.814	10.478	0.014
Irr:SOC				−0.321	0.139	0.023	−6.130	2.847	0.033			
ET/*P*:A_{SC}							408.053	72.342	<0.001			
ET/*P*:*Irr*							115.035	49.261	0.020			
Time:T							−0.761	0.354	0.032	−0.197	0.072	0.007
A_{SC}:SOC							−16.117	3.460	<0.001			
SOC:T							0.461	0.209	0.028			
ET/*P*:SOC										1.482	0.643	0.021
ET/*P*:*Sand*										−0.609	0.299	0.042
ET/*P*:T										3.625	1.778	0.042

Note. The table includes results from the LME model for Y_N, Y_P, I_N, and I_P (expressed in units as in Table 1). Only terms retained after the backward elimination of nonsignificant effects are reported (those not retained are left blank). The number of observations is 550. SE: standard error; units refer to the independent variables. Model formulations are reported in Table S4 in Supporting Information S1.

reduced need for fertilizers and improve both the quality of soil and water resources as well as enhancing future food production at local-global scales (Billen et al., 2021; Chang et al., 2021).

Both NUE and PUE were higher in catchments with substantial irrigation compared with catchments dominated by rainfed agriculture. This effect could be explained by irrigation promoting plant growth and seed yield (Figure 5) but without enhancing nutrient losses as intense precipitation events do (Meisinger & Delgado, 2002). This is confirmed by our data, as the irrigation did not have a direct effect on inputs, while both N and P yields were higher in irrigated catchments compared to mostly rainfed catchments. This is expected because the yields of irrigated crops are partly decoupled from climatic conditions (Luan et al., 2021). Interestingly, and in contrast to results by Luan et al. (2021), in irrigated catchment temperature had a less positive effect on N and P yields.

4.2. Hydroclimatic, But Not Edaphic, Conditions Drive Variations in NUE and PUE and Their Ratio

The main effects and interactions on NUE and PUE are schematically illustrated in Figure 6. First, with regard to climatic conditions, both yields and N inputs—partly due to biological N fixation—are negatively correlated with the evaporative ratio and positively with mean annual temperature, affecting nutrient use efficiencies (Figure 6,

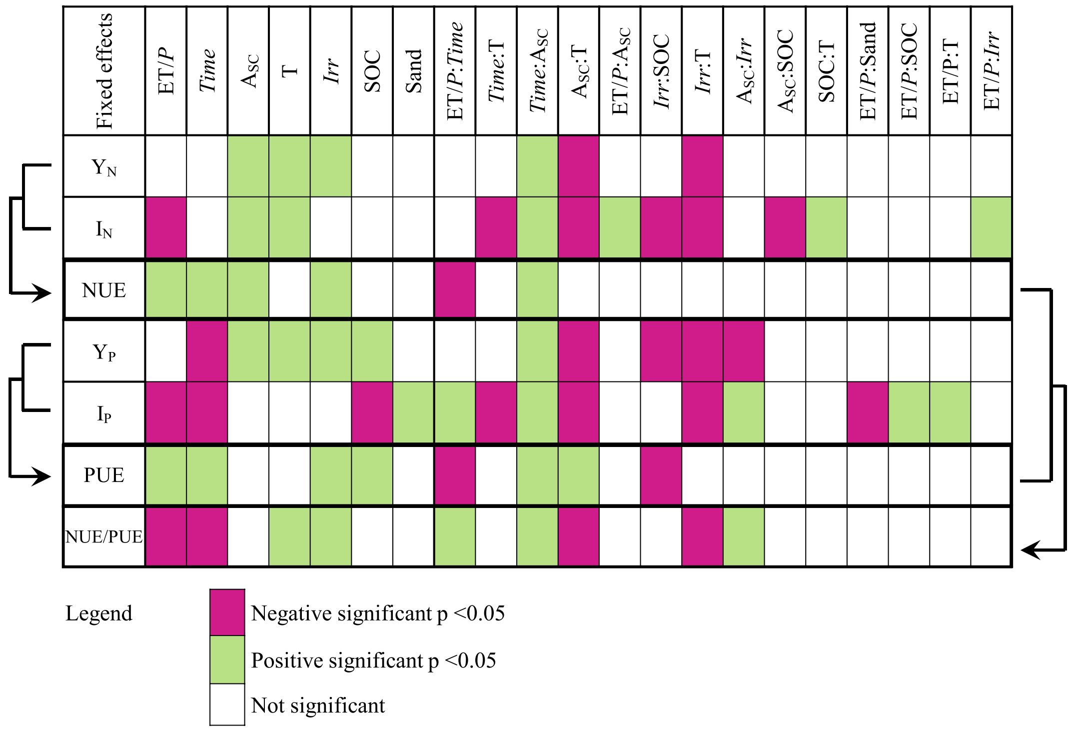

Figure 5. Synthesis of the statistical results, reporting significant ($p < 0.05$) negative (magenta) and positive (green) most relevant fixed effects for nitrogen use efficiency (NUE) and phosphorous use efficiency (PUE), their components (nutrient inputs: I_N and I_P; yields: Y_N and Y_P) as well as the NUE/PUE ratio. Arrows are used to illustrate how the components relate to each of the efficiencies or their ratio.

right). This negative effect of evaporative ratio on N inputs could be explained by soybean fixation being lowered in dry conditions (high evaporative ratio). Surprisingly, the evaporative ratio has no direct or interactive effect on N and P yields, possibly due to a combination of factors. First, different crop types, distributed across drier and wetter climates (Figure S3 in Supporting Information S1), respond differently to climatic conditions so that climatic effects on catchment-scale yields might be masked by a "portfolio effect." This effect emerges

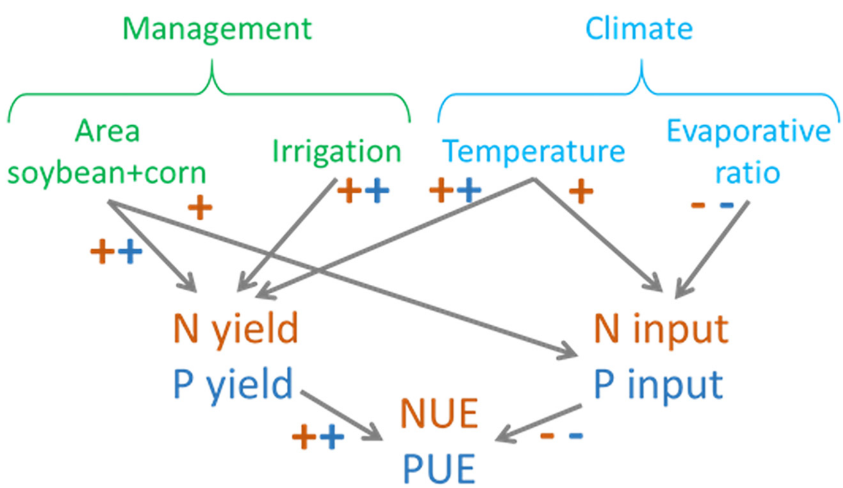

Figure 6. Schematic figure representing the main effects on yields and inputs, which determine nitrogen use efficiency (orange) and phosphorous use efficiency (blue). The signs of the effects also account for interaction effects for a fixed time and soil properties (see Tables 2 and 3, and Figure 5 for a complete presentation of the results), and the arrows represent the direction of the assumed causal relations. By definition yields and inputs have positive and negative effects on the efficiencies, respectively.

when averaging the responses of crops with different thermal optima within the same catchment. Second, yields and climatic conditions are averaged over 5-year periods, reducing their variability but also averaging out any climate-dependent extreme value. Both averaging through time and across crop types can thus decrease climatic signals on yields.

In the conterminous United States, temperature, precipitation, and soil moisture can be limiting factors for maize and soybean growth and yield (Andresen et al., 2001; Joshi et al., 2021; Sacks et al., 2010). Over the past decades and at the regional level, annual precipitation has increased in the Midwest and Northeast and decreased in the West and Southeast (U.S. Global Change Research Program, 2018). Such changes in rainfall affect runoff patterns and the mobilization and transport of N and P. More pronounced yield reductions were observed in the United States under cooccurring warm and dry conditions for soybean (27% decrease) and wet conditions for maize (15% decrease) (Luan et al., 2021). In contrast, we find a positive effect of temperature on both N and P yields and N inputs (Figures 5 and 6) but no effect on the efficiencies (Figure 6). The difference with respect to the results by Luan et al. (2021), which focused on soybean and corn yields at the county level, could again be attributed to a "portfolio effect," as mentioned above.

Both NUE and PUE increased with the evaporative ratio, indicating that higher nutrient use efficiencies occur in catchments where precipitation is mostly converted to evapotranspiration. The effect of the evaporative ratio on NUE (all else being the same) is consistent with results by Scaini et al. (2020) on a smaller data set with lower temporal resolution; notably, the same effect is now found for PUE (which was not considered in that earlier study). The NUE increase with the evaporative ratio supports the expectation that efficient use of rainfall (i.e., high the evaporative ratio) promotes N retention in soils and plants because it implies lower soil moisture, which limits percolation below the root depth and thus nutrient leaching, and also decreases gaseous N losses such as N_2O and N_2 (Butterbach-Bahl et al., 2013). In contrast, catchments with lower evaporative ratios are wetter, which promotes organic N mineralization and ultimately nitrate leaching or gaseous N losses. For example, catchments with higher precipitation and soil moisture are larger sources of nitrous oxide than drier catchments (Hall et al., 2018). These N losses would decrease NUE compared with drier catchments.

As P species are less soluble and prone to leaching, we would expect less strong hydrologic controls on PUE but that is not the case. In fact, the evaporative ratio effect is stronger on PUE than NUE, but accounting for the fact that PUE values are up to four times higher than NUE values, we cannot conclude that the sensitivity of PUE to the evaporative ratio is indeed different from that of NUE.

While we hypothesized that the evaporative ratio increases NUE and PUE based on ecohydrological arguments at the field scale, other hydrological processes are at play at the whole catchment scale. Romero et al. (2016) showed that the presence of reservoirs in a catchment increases the N retention capacity of that catchment by reducing N loads at the catchment outlet. Reservoirs and irrigation systems also recirculate water and increase the catchment-scale evaporative ratio (Gordon et al., 2005). Therefore, the combined increases in water and N retention may explain the positive relationship between nutrient use efficiencies and the evaporative ratio we found.

The edaphic conditions have a limited effect on the nutrient use efficiencies and in particular on PUE. This is against our expectation of an effect of soil texture and organic matter content, possibly in interactions with climatic conditions, motivated by the sensitivity of grassland productivity to changes in precipitation being higher in fine textured soils (Austin et al., 2004). Nevertheless, the sand percentage interacted positively with maize or soybean area when predicting harvested N (Y_N; Table 3), suggesting that sandy soils are particularly productive for maize and soybean. However, we did not detect any interactions of edaphic and climatic conditions. Moreover, soil organic matter often promotes yields, especially under dry conditions (Kane et al., 2021; Oldfield et al., 2019), but has only a positive effect on PUE through Y_P. The effects of soil organic matter on N inputs (presumably through its effect on soybean yield; Table 3) were not sufficient to cause significant variations in NUE. To explain the limited edaphic effects in the LME models, we employed univariate correlations to assess if edaphic conditions were correlated to other predictors of yields and efficiencies that were selected as significant in the LME models (Figure S4 in Supporting Information S1). SOC has no effect on NUE and N yield in the first period of the analysis but has a positive effect in the last one. A positive SOC effect on PUE and P yield in later years is also found in univariate correlations but not when using a LME model. This difference might be related to the major 2012 drought and can be explained by the inverse correlation between SOC and ET/*P* in the later years (from univariate correlations), causing the LME model to attribute variations in yields and efficiencies to the interaction of ET/*P* and *Time* rather than SOC. In fact, the interaction ET/*P*:*Time* is negative for both NUE and PUE, suggesting that the effect of ET/*P* decreases through time, becoming negative in the last periods (as apparent in the univariate correlations). We thus have simultaneously negative ET/*P* effects on the yield and efficiencies and negative correlations between SOC and ET/*P*. Therefore, it is plausible to interpret this chain of correlations as follows: SOC correlates positively with yields and nutrient use efficiencies but in the LME model this effect is masked by the negative ET/*P* effects appearing only in the recent drought years.

Edaphic conditions appeared in some significant interactions with irrigation. Notably, higher SOC decreased the positive effect of irrigation on N inputs, N yield, and PUE. This effect could be explained by the capacity of high SOC soils to buffer variations in soil moisture via increased soil water retention, with the largest increases in sandy and silty soils (Rawls et al., 2003). This effect could reduce the importance of irrigation to sustain crop production and nutrient use efficiencies.

4.3. NUE and PUE Increased Through Time

Both NUE and PUE increased in the study period (Figures 2 and 4), apart from the last 5 years, 2008–2012, when NUE decreased by 10% and PUE plateaued (Section 3.1). The ∼45% increase in PUE through time is consistent with the increase in decadal PUE at the county scale in most US regions, with significant increases in the Basin and Range, Mississippi Portal, and Northern Crescent regions (Swaney & Howarth, 2019b). In contrast, the average ∼12% increase in NUE differs from the previously reported decreases from 49% in 1987–1997 to 45% in 2002–2012, also at the county scale (Swaney et al., 2018b). The increase in nutrient use efficiency has been linked to yield increases associated with stable or decreasing nutrient inputs (Sabo et al., 2021; Swaney & Howarth, 2019b). Our results also highlight a stronger relative increase in PUE as indicated by the NUE/PUE ratios as shown by the progressive change in slope of their relation (Figure 4).

The observed increase in PUE is not necessarily positive for an agricultural system. Soil P mining, defined by P crop production exceeding P inputs and thus leading to PUE > 1, occurs when P is actively mineralized in soils to support plant growth and in excess of P fertilizer inputs. P mining is important especially in the Heartland, Northern Crescent, and Mississippi Portal, whilst the rest of the United States have mostly values below one (Swaney & Howarth, 2019b). In our data set, approximately 30% of the catchments (mostly in the Heartland and Northern Crescent) have a PUE above 1 (and up to 2.3, at annual scale), confirming previous findings (Swaney & Howarth, 2019b). Moreover, the highest PUE values were found in the most recent periods, possibly indicating an intensification of P mining in some areas. Therefore, our results point to a need for a change in the long-term strategy of N and P fertilization to both avoid nutrient pollution and eutrophication and preserve long-term soil fertility.

While PUE > 1 might indicate a loss of soil fertility, it is difficult to determine from the PUE values and trends we have reported how much P immobilized in soils after decades of fertilization is lost to water bodies. In our study, we have not used P loads to quantify PUE, so we could have relatively high PUE values despite significant export of legacy P. In long-term agricultural areas such as most of the catchments within this analysis, the cumulative legacy soil P is often a more important driver of total P loss than the surplus P within a given year (Kusmer et al., 2019; Sabo et al., 2021). To tackle this challenge, strategies to convert legacy P stores into harvested P (e.g., use of bio-fertilizers to mobilize P in the soil) are needed and should be adapted to the characteristics of each catchment (Kusmer et al., 2019; A. N. Sharpley et al., 2015). Combining these strategies would enhance the sustainability of P use in agriculture.

The slopes of the relations between nutrient use efficiencies and evaporative ratio decreased through time because the efficiencies were lower in the last 5 years in catchments with a high evaporative ratio. Therefore, NUE and PUE were less sensitive to the evaporative ratio in the more recent years, as already noted for NUE across two decades by Scaini et al. (2020). Moreover, the increase in NUE and PUE through time is faster in catchments with a higher fraction of area under maize or soybean. Given our results that both the evaporative ratio and agricultural practices affect NUE and PUE, a combined climate and crop-production strategy should be adopted when planning changes in agricultural practices (including landscape diversity and rotations; e.g., Ceglar et al., 2020; Feng et al., 2021). Buffer strips and sedimentation ponds as well as approaches to increase soil infiltration capacity and recycle water—by increasing the evaporative ratio locally—can limit losses of N and P from agricultural land and to protect water quality and soil health in the long-term (Baldwin-Kordick et al., 2022; Roy et al., 2021; A. N. Sharpley et al., 2015). If applied to sufficiently large areas, these methods could improve nutrient use efficiencies also at catchment scale.

4.4. Approach Limitations

By averaging hydrological and agronomic data at 5-year timescale, our approach provides robust estimates of the long-term trends of NUE or PUE and their variations in relation to management and climate. However, this approach does not allow identifying NUE and PUE changes due to extreme climatic conditions at year or seasonal scales, as also discussed in Section 4.2. Moreover, by considering N and P fluxes aggregated at the catchment scale, our approach cannot link nutrient use efficiencies to crop-specific variations in nutrient cycling. In principle, crop-specific short- term variations in nutrient fluxes and efficiencies could be estimated using high resolution remote sensing data (e.g., the cropland data layer from Cropscape over the United States, USDA-NASS, 2017) and modeled crop evapotranspiration but these approaches introduce other uncertainties. Also, these data products would only be available for recent years, thus limiting the duration of the analysis. In addition to the crop-specific estimates, catchment-scale NUE and PUE are influenced by plant breeding and crop varieties that depend on production systems (e.g., Gooding et al., 2012). In our study, N and P contents in harvested products are estimated using constant values after (Lassaletta et al., 2014a), but the intraannual and plant-specific nutrient allocation are actually variable and can only be captured at field-scale (Weih et al., 2018).

Catchment choice can also influence the results (as discussed in Scaini et al. (2020)). Using our inclusion criteria, catchments located in a wide range of climates were considered, which allows identifying climatic effects more easily than with a smaller number of catchments. With a stricter criterion regarding the percentage of agricultural areas, for example, retaining only catchments with at least 30% agricultural area, the analysis would be limited to fewer catchments (only 67) mostly located in the Great Lakes and Mid-West regions. Yet, as shown in Figure S5 in Supporting Information S1, the main results are the same—an indication that the patterns we found are robust to catchment choice and likely not affected by considering catchments with high internal heterogeneity.

5. Conclusion

We quantified how combined water availability, agricultural practices, and edaphic conditions affect N and P use efficiencies (NUE and PUE), as well as their ratio, at the catchment scale. It is at this scale that the impacts of agricultural management and climate on water bodies are most evident. The catchment scale is also suitable for integrating processes occurring in heterogeneous spatial domains (e.g., spatially variable agricultural management) and across a range of timescales (yearly to decadal) as they act as spatial and temporal integrators. Both NUE and PUE increased through time on average by 12% and 45%, respectively, because of simultaneous changes in hydroclimatic conditions and agricultural management. Nutrient use efficiencies increased with high water use efficiency (measured by the evaporative ratio) and irrigation but less so in more recent times. Edaphic conditions did not affect the nutrient use efficiencies directly but the content of organic carbon correlated with yields and efficiencies indirectly through the evaporative ratio. Agricultural intensity had an overall positive effect on the efficiencies (NUE increased with agricultural area under maize or soybean and both efficiencies were higher in irrigated catchments), and this effect increased through time. Given our results that both evaporative ratio and agricultural practices affect NUE and PUE, both climatic conditions and crop choice need to be considered when aiming at more efficient nutrient use in agricultural catchments.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The primary data set including hydro-meteorological, edaphic, and agricultural data as well as nitrogen and phosphorous use efficiency and their ratio is archived with Open Data Commons Attribution License (ODC-By) in the open-access Bolin Centre Database, available at https://bolin.su.se/data/scaini-2023-catchment-1 or through DOI https://doi.org/10.17043/scaini-2023-catchment-1.

Acknowledgments
SM and AS acknowledge support from the Swedish Research Councils (Vetenskapsrådet/Formas/Sida 2016-06313 and Formas 2018-02321) and the Bolin Centre for Climate Research (RA7). GV acknowledges support from the Swedish Research Council for Sustainable Development Formas (Grant 2021-02330). JT was supported by a grant from the Swedish Research Council for Sustainable Development Formas (Grant 2018-00812). The authors would like to thank the reviewers and the editor for their constructive comments.

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