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Hydro-climatic controls explain variations in catchment-scale nitrogen use efficiency

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Keywords: nitrogen use efficiency, evaporative ratio, agriculture, evapotranspiration, precipitation, fertilization, catchment scale

Supplementary material for this article is available online

Abstract

The efficiency of fertilizer conversion to harvestable products is often low in annual crops such that large amounts of nutrients are lost from fields with negative consequences for the environment. Focusing on nitrogen (N) use efficiency (NUE: the ratio of N in harvested products over the sum of all N inputs), we propose that hydrological controls can explain variations in NUE, because water mediates both the uptake of N by plants and N leaching. We assess these controls at the catchment scale, at which the water balance can be constrained by precipitation and runoff data and NUE can be quantified with census data. With this approach we test the hypotheses that a higher evaporative ratio (ET/P: the ratio of evapotranspiration over precipitation) increases N retention, thereby increasing NUE both across catchments at a given time and through time. With data from 73 catchments in the United States, encompassing a wide range of pedoclimatic conditions for the period 1988–2007, we apply a linear mixed effect model to test the effect of ET/P on NUE. Supporting our hypotheses, ET/P was positively related to NUE, and NUE increased through time. Moreover, we found an interaction between ET/P and time, such that the ET/P effect on NUE decreased in the period 1998–2007. We conclude that climatic changes that increase ET/P without negatively affecting yields, will increase N retention in the examined catchments.

1. Introduction

Adequate nutrient supply is required to achieve high crop yields. Among the macronutrients, nitrogen (N) is typically provided as chemical fertilizer or fixed by legume crops frequently grown in rotation with other annual crops. However, especially in annual crops, most of the N supplied is not recovered in biomass or harvested products, but rather lost to volatilization, denitrification, and leaching. These N losses have negative consequences both to the environment and human health as they pollute water, land, and the atmosphere (Park *et al* 2012, Sabo *et al* 2019). For these reasons, balancing N supply and crop demand is key to minimizing tradeoffs among yield, profit, and environmental protection (Cassman *et al* 2002, Bowles *et al* 2018).

In agricultural and plant ecology research, nitrogen-use efficiency (NUE) is commonly used to assess the balance between N supply and crop demand. NUE at the field or stand scale considers the mass balance between either the plant-internal or soil available N amount and the biomass output (net accumulation or harvested yield) (Reich *et al* 2014, Weih *et al* 2018). These field-scale NUE concepts adequately capture the plant internal processes of N uptake, re-allocation and conversion to biomass, but they do not consider N flows in larger

Table 1. Acronyms and symbols employed in the manuscript.

Symbol	Definition	Explanation	Source	Units
ET/P	Evaporative ratio	Ratio of actual evapotranspiration (ET) to precipitation (P), estimated as ET/P = 1-R/P	Calculated from P and R	-
F_N	Nitrogen fertilization rate	Rate of N fertilizer addition per unit agricultural area of the catchment	Calculated from United States Geological Survey data	kg N ha^{-1} y^{-1}
$F_{N,soy}$	Nitrogen fixed by soybean	N fixed by soybean per unit agricultural area of the catchment	(Lassaletta *et al* 2014a)	kg N ha^{-1} y^{-1}
I	Total Nitrogen inputs	$I = F_N + N_{DEP} + F_{N,soy}$	Calculated from F_N, N_{DEP}, and $F_{N,soy}$	kg N ha^{-1} y^{-1}
N_{DEP}	Nitrogen deposition	Annual total N deposition per agricultural area of the catchment	(Hember 2018)	kg N ha^{-1} y^{-1}
NUE	Nitrogen use efficiency	Ratio of N removed in harvested grain over the sum of all N inputs (NUE = Y_N/I)	(Lassaletta *et al* 2014a)	-
P	Precipitation	Annual volume of rainfall per unit catchment area	(Harris *et al* 2014)	mm y^{-1}
R	Runoff	Annual river discharge volume per unit catchment area	Global Runoff Data Centre	mm y^{-1}
T	Temperature	Mean annual temperature	(Harris *et al* 2014)	°C
Y	Crop yield	Harvested grain per unit agricultural area of the catchment	Calculated from United States Department of Agriculture data	kg ha^{-1} y^{-1}
Y_N	Nitrogen in crop yield	N in harvested grain per unit agricultural area of the catchment	Calculated from yield data	kg N ha^{-1} y^{-1}

geographic areas such as catchments. To identify strategies to increase large-scale crop productivity while decreasing N losses, a large-scale NUE definition was proposed as the ratio of N removed in harvested products (Y_N) to the total N inputs (I; all symbols are defined in table 1) (Gao *et al*, Lassaletta *et al* 2014a, Davidson *et al* 2015, Swaney *et al* 2018,). This definition is insensitive to aspects of nutrient use efficiency that are associated with yield quality or plant internal resource (re-)allocation, which are important, for example, in many perennial crops (Weih *et al* 2018). However, we adopt it here given its applicability to catchment-scale N budgets. Crop breeding and improved agricultural practices can increase NUE, but there are intrinsic limits to such improvements set by the biophysical conditions that control plant uptake and losses of N. In fact, despite improvements since the 1980s (Cassman *et al* 2002), the conversion of fertilizer N to harvested N yield is still low and variable (Weih *et al* 2018). These low conversion rates are partly a result of low fertilizer prices that promote over-fertilization (Zhang *et al* 2015), but within a given socio-political context, they are due to combined biological and hydrological causes.

High yields achieved thanks to fertilizers (Sadras and Angus 2006, Cabrera-Bosquet *et al* 2007) and a large water supply (Blum 2009, Vico and Porporato 2015), would increase NUE = Y_N/I by increasing Y_N. However, added inorganic N and moist soils promote N losses and decrease NUE (Cassman *et al* 2003). Hence, there is a trade-off between achieving high yields and high NUE that is mediated by soil moisture. All else being equal, a crop that uses more water from rainfall or irrigation leaves the soil relatively drier and thus less prone to leaching compared with a crop with lower transpiration. Moreover, crops with larger biomass draw more inorganic N from the soil than slow-growing crops thereby reducing N losses. Therefore, both plant water use and N uptake (and thus N losses) are constrained by water availability, which sets limits to the achievable NUE. In addition to these biophysical controls, climatic factors constrain the water balance, and in turn NUE. In more arid conditions, the evaporative ratio (i.e. the ratio of evapotranspiration (ET) to precipitation (P), ET/P) increases, and less water percolates below the rooting depth (causing N leaching) or is lost through surface runoff (R). Therefore, along a climatic gradient of increasing P, we expect increasing yield due to higher ET (Blum 2009, Vico and Porporato 2015), but decreasing ET/P, which implies a lower NUE.

However, estimating ET—especially over large areas—can be challenging due to the numerous factors affecting water transport from the soil to the atmosphere. As an alternative to process-based methods, we employ here a data-driven approach based on the water balance at the catchment scale. At this scale and in the long-term (when water storage changes can be neglected), ET can be approximated as the difference between incoming precipitation

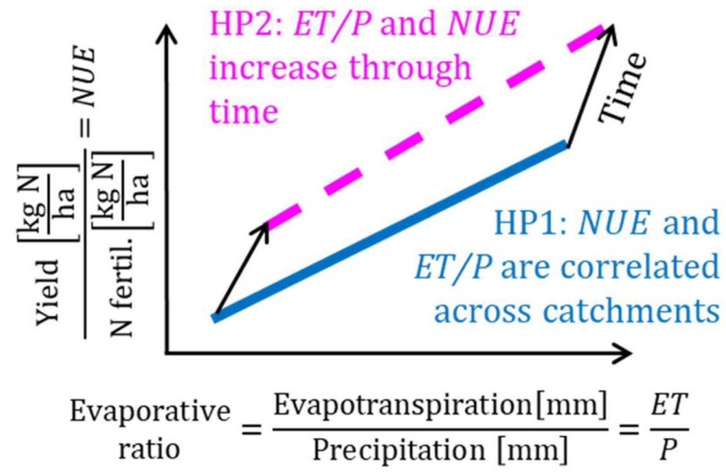

Figure 1. Conceptual figure showing the tested hypotheses on the relation of NUE and evaporative ratio (ET/P).

and runoff, which are both measured across much of the globe (e.g. Jaramillo and Destouni 2014). Thus, at the catchment scale, the evaporative ratio can be estimated as ET/P = 1-R/P and this estimate can be used as an explanatory variable for NUE also calculated at the catchment scale as NUE = Y_N/I. Previous studies used catchments as a unit to calculate N budgets and related N export to anthropogenic N inputs and climatic conditions (e.g. Boyer *et al* 2002, Howarth *et al* 2012, Sabo *et al* 2019, Chukalla *et al* 2020). However, these studies did not link NUE to ET/P at this scale as we propose here.

To summarize biophysical and hydrological factors affecting NUE, we can use a simple process-based model that partitions soil solutes between plants (via uptake) and groundwater (via leaching) (Manzoni *et al* 2011) (supplementary information section 2.4.1 avaliable online at stacks.iop.org/ERL/15/094006/mmedia). This model predicts that, in the long term, the fraction of a solute (here N) retained in vegetation is proportional to ET/P. Because N in the harvestable yield is proportional to the whole plant N, we expect NUE to be proportional to ET/P. This relation implies that crops using water efficiently also use N efficiently, reducing both water losses as runoff, and N leaching losses. It also implies that for any given crop, relatively drier conditions characterized by higher ET/P increase both the crop water use efficiency and NUE. Following from this logic, we hypothesize that NUE is, in general, positively correlated to ET/P at the catchment scale (figure 1).

In addition to variations in NUE across catchments, we can consider how the NUE-evaporative ratio relationship varies through time. Specifically, higher temperature can increase potential evapotranspiration, and thus ET/P, unless precipitation increases faster than ET (Van der Velde *et al* 2014, Jaramillo and Destouni 2014). Also increasing atmospheric carbon dioxide concentration can affect ET, but the direction of this effect is debated (Hasper *et al* 2016, Jaramillo *et al* 2018). It is also challenging to isolate the impacts of climate change on yields and hence on the NUE (Kukal and Irmak 2018), in part because climate change occurs slowly over time and agronomic practices change faster. To match the temporal scale of these slow changes, it is relevant to interpret the relationship between NUE and ET/P across longer time periods. This brings about our second hypothesis that both NUE and ET/P increase through time at decadal time scale (figure 1). The hypothesized temporal trends of NUE and ET/P are expected to be similar unless more efforts are put into increasing initially low NUE. If that is the case, the NUE-ET/P relations will flatten through time.

With the general aim of quantifying changes and drivers of NUE at the catchment scale, we test our hypotheses, that NUE is correlated to ET/P across catchments and both increase through time, using data from 73 catchments in the contiguous United States that represent a broad range of climatic and agronomic conditions. Temporal changes in NUE and ET/P are evaluated across two decades (1988–1997 vs. 1998–2007) in the selected catchments. The choice of this region is motivated by its intensively-managed agricultural landscape that is vulnerable to climate-driven shifts in water availability (Müller *et al* 2018) and high nitrogen losses (low NUE) due to high fertilization rates and a short period of vegetation cover (Bowles *et al* 2018).

2. Methods

All symbols are defined in table 1 and detailed information on the data analysis is provided in the supplementary information. Catchments from the World Meteorological Organization's Global Runoff Data Centre (GRDC) database were selected following these criteria: (i) mean agricultural area, considered as sum of wheat, soy and corn area across

Table 2. LME model formulation and results including Akaike's Information Criterion (AIC), adjusted R^2, estimates and p-values of each of the fixed effect coefficients (see Table SI6 for results from the LME model including agricultural area as fixed effect).

Model: 'NUE ~ ET/P + Time + ET/P*time + (1|catchment ID)'						
Model fit statistics		Fixed effects coefficients				
AIC	R^2 adjusted		Intercept	ET/P	Time	ET/P*time
−122	0.93	estimate	0.389	0.402	0.243	−0.269
		p-value	0.004	0.029	0.006	0.022

the period between 1987 and 2007, higher than 10%; (ii) catchment area comprised between 1000 and 9000 km^2; (iii) completeness of runoff (R), precipitation (P), yield (Y) and fertilizer input (F_N) data, (iv) no nested catchments. In the 73 selected catchments, R was retrieved from the GRDC database. The temperature (T) and P data were extracted from the Climatic Research Unit (CRU) raster database (Harris *et al* 2014).

The fertilizer application rate was obtained through the United State Geological Survey (USGS) county-level estimates of nitrogen and phosphorus applications from commercial fertilizer for the contiguous United States (Gronberg and Spahr 2012). The nitrogen deposition (N_{DEP}) was obtained from the North American Climate Integration and Diagnostics (NACID) database of estimates of annual total nitrogen deposition (Hember 2018). County-level corn, wheat, and soy production, yield, agricultural areas and irrigated areas were obtained through the survey program of the United States Department of Agriculture's National Agricultural Statistics Services (NASS).

The analysis was carried out for the 1987–2007 time period, when all the data were available. The procedure used to aggregate all data to the catchment scale and annual scales is provided in Supplemental Information. The annual catchment-scale aggregate Y_N, expressed as the sum of the nitrogen extracted in harvested corn, soybean and wheat, was computed after Lassaletta *et al.* (2014a). The amount of soybean biological N fixation ($F_{N,soy}$) was estimated as a fixed proportion of the soybean yield (Lassaletta *et al* 2014a). For each year, NUE was calculated as the ratio of total crop yield per unit of N input, estimated as the sum of F_N, $F_{N,soy}$ and N_{DEP}.

To compare NUE and ET/P, their mean values in each catchment were calculated for period 1: 1988–1997 and period 2: 1998–2007. Using a shorter averaging window would not alter the results, but short-term climatic fluctuations tend to increase the variability in the NUE and ET/P trends (not shown). Moreover, the two decadal mean values of temperature, agricultural areas, and irrigated areas were computed for each catchment.

To test our two hypotheses—that NUE is positively related to ET/P, and more so through time—we considered ET/P and time as our main fixed effects, including also the interaction ET/P*time in a linear mixed-effect (LME) model. Time is considered as a categorical variable (i.e. period 1 or 2). Acknowledging the potentially large intrinsic variation among catchments (soil, groundwater, natural vegetation, urban fraction), catchment identification code (GRDC) was treated as a random effect. In addition, since land management could be confounded with changes in climatic conditions, we also included cultivated and irrigated areas as fixed effects in a second LME model (including two- and three-way interactions). Data were checked for normality using the Anderson-Darling test. Effects with $p < 0.05$ are reported as significant.

3. Results

3.1. Hydrological and land use controls on NUE

The long term mean NUE and ET/P in the selected catchments are shown in figures 2(a)–(b), respectively. In general, ET/P increases spatially from East to West following the natural gradient of decreasing precipitation. NUE tends to be higher in the latitudinal band between 40° and 45° North, and lowest in the southern- and northernmost catchments. Catchments with low agricultural coverage and in dry climates tend to have relatively high evaporative ratios, typically 0.7 and above, as well as NUE values covering most of the range observed, from 0.4 to 1.3.

The simplest LME model with only ET/P and time as fixed effects showed a significant and positive effect of ET/P on NUE, thus supporting our first hypothesis (table 2). Also, time had a significant positive relationship with NUE in a given catchment; i.e. for most catchments NUE was higher in the second period than in the first, confirming our second hypothesis (table 2). There was also an interaction between ET/P and time, indicating that the slopes of the NUE-ET/P relations differed between the two periods (figure 2(c)). Specifically, the relation was less steep in the second period. In addition to the expected effects of ET/P and time on NUE, there was pronounced variation among catchments.

A more complex LME model including agricultural area and irrigated area in each catchment as fixed effects showed that only the former had a positive effect on NUE (table SI6; figure 2(c)). Adding agricultural area as explanatory variable and its interactions improved the LME model as indicated by a lower AIC

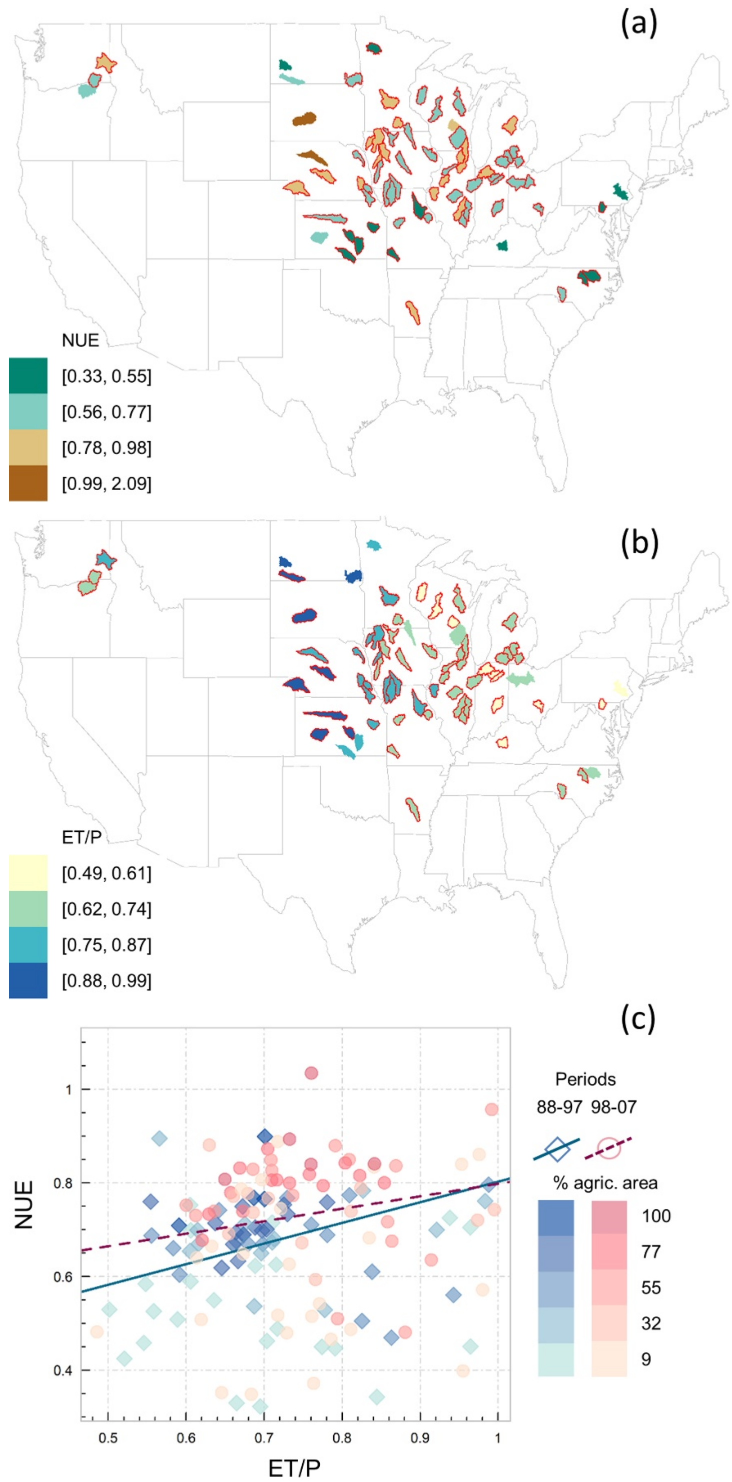

Figure 2. (a) Mean evaporative ratio (ET/P) and (b) mean N-use efficiency (NUE) over the 20-year period across the catchments used in the analysis. Catchments highlighted in red exhibit increased NUE or ET/P from period 1 to period 2. (c) Relationship between NUE and ET/P color-coded according to period 1 (1988–1997, blue line and symbols) and period 2 (1998–2007, magenta line and symbols); the symbol size represents the percentage of agricultural area. In all legends, the values in square brackets are the ranges of each category.

(−122 for the simpler LME model, −145 for the more complex one).

3.2. Contributions to changes in NUE and evaporative ratio

The components of the NUE and evaporative ratio changed between the two time periods (figure 3). To allow a visual comparison, all changes are reported as ratios of values in the second period over those in the first one. The Y_N (numerator in the NUE) increased in the second period with a mean relative change ± standard deviation of 1.21 ± 0.11. The total N input (denominator in the NUE) showed a relative change of 1.12 ± 0.17, due to an overall increase

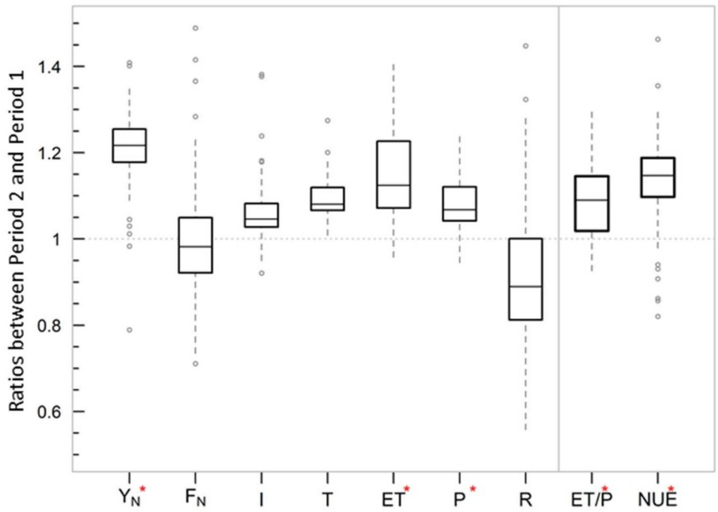

Figure 3. Box plots of the ratios between periods 2 and 1 of the components of nitrogen use efficiency (NUE) and evaporative ratio (ET/P): N in crop yield (Y_N), N fertilization rate (F_N), N input (calculated as the sum of applied F_N, N fixed by soybean and N deposition), evapotranspiration (ET), precipitation (P), runoff (R) and temperature (T). The ratios between periods 2 and 1 of ET/P and NUE are shown on the right of the figure. The asterisks indicate statistical significance (Wilcoxon test, $p < 0.05$).

of both $F_{N,soy}$ and N_{DEP} (not shown) that was partly compensated by a non-significant decrease of fertilizer application. Because yield increased more than N inputs, NUE increased through time (figure 3). The components of the water balance changed in different directions, with an overall mean increase in P (relative change of 1.08 ± 0.06) and an overall mean decrease in R (relative change of 0.90 ± 0.21), resulting in higher ET in the second period. Since ET increased more than P, overall the evaporative ratio ET/P increased (figure 3). All the catchments became warmer (relative T change of 1.09 ± 0.05), with an increase up to 0.3 °C, possibly driving the increase in ET and ET/P.

4. Discussion

N-use efficiency is a useful performance metric for agricultural systems. The agronomic and climatic drivers of NUE have been studied at different scales—from field-scale (e.g. Weih *et al* 2018), to catchments (Sabo *et al* 2019), regions (Swaney *et al* 2018), and national or global scales (Lassaletta *et al* 2014a, 2014b). However, in most previous studies, NUE had not been linked to evapotranspiration or the evaporative ratio—a key factor summarizing how crops use water and how much water remains available to transport nutrients out of the fields. This link can be established at the catchment scale, where evapotranspiration can be constrained by precipitation and runoff via the catchment water balance (Jaramillo and Destouni 2014). Therefore, calculating NUE at the catchment scale is advantageous with respect to other approaches as it allows exploring hydrological controls on N cycling at spatial and temporal scales relevant for testing the consequences of land management policies.

4.1. Hydro-climatic and land use controls on NUE

Both our hypotheses were supported. First, NUE increased with the ET/P ratio, supporting the idea that efficient use of rainfall promotes N retention in soils and plants. Second, NUE increased through time due to either increasing ET/P, which is mostly caused by changed climate, or improved agronomic practices. Moreover, there was an interaction between NUE and ET/P indicating that NUE was less sensitive to ET/P in the more recent study period.

These patterns can have been caused by several mechanisms. NUE increased by approximately 10% between the two periods because the harvested N in yield increased, despite increased N inputs (figure 3). While there was a slight decrease in fertilizer application (figure 3), the total N input had actually increased due to an overall increase of both N fixation by soybean and N deposition (see also Du *et al* 2014, Collett *et al* 2016). Had we extended the study period, results would probably have been different, as a marked decline in yields and NUE occurred in 2012 due to drought (Swaney *et al* 2018). However, this decrease is regarded as an anomaly in a context of increasing efficiency in the United States (Sabo *et al* 2019).

The increase in NUE could also be explained by lower N losses both along the climatic gradient (i.e. moving westward towards drier catchments) and between time periods (i.e. with increasing mean temperatures). Previous studies across catchments showed that riverine N exports are related to N inputs, and the fraction of N inputs exported increases with runoff (Howarth *et al* 2012). This suggests that catchments with higher water availability (lower ET/P) retain N less efficiently, similar to our conclusion.

Regarding temporal trends, historical data indicate a positive association between N loads in rivers, annual precipitation, and extreme springtime precipitation (Ballard *et al* 2019, Howarth *et al* 2012). These trends are consistent with our findings that wetter conditions (i.e. lower ET/P) decrease NUE by promoting N losses. In all the catchments, temperature increased up to 0.3 °C between the two periods (figure 3), likely increasing ET/P and decreasing runoff, despite higher precipitation. Indeed, runoff coefficients (discharge divided by rainfall, which is inversely related to ET/P) have decreased in the south-central region of the United States, partly due to groundwater withdrawals to support irrigated agriculture, while they have increased in the north-central United States, due to wetter conditions (Mccabe and Wolock 2016). Similar to the trend we found, climatic changes are expected to reduce N leaching to streams because of higher temperatures and evaporative demand in the majority of the contiguous United States, with the exception of the Pacific Northwest and Northern California, where leaching might increase due to projected increases in P associated to more moderate warming (Alam *et al* 2017).

Here we focused on large-scale hydrological controls on NUE, though both land use and agricultural management at field to farm scale affect NUE locally. The agricultural coverage can affect NUE because fields where annual crops are grown are typically bare for part of the year, potentially causing N losses that would not occur had a continuous vegetation cover been in place. However, the fraction of agricultural area had a positive effect on NUE (Table SI6), probably because catchments with high proportion of agricultural area were also characterized by intensive and relatively efficient maize-soybean rotations. In addition to agricultural coverage, management practices can also increase NUE. These increases are especially expected where NUE was initially low (Bowles *et al* 2018), resulting in a flattening of the NUE-ET/P relation in the second period and causing the negative interaction between NUE and ET/P that we found. Improved management can also raise the yield ceiling, which provides an incentive for farmers to apply more N to achieve higher yield at the cost of lower NUE (Davidson *et al* 2015, Zhang *et al* 2015, Chukalla *et al* 2020). To avoid excessive leaching of N, precision agriculture techniques tuned to meet the plant needs, or use of cover crops, should be implemented (Hedley 2015). Moreover, crop choice correlates with climatic conditions, and N inputs from N fixers in crop rotations depend on water availability, creating indirect climatic effects on NUE that would not be captured by our simple model based solely on ET/P. Therefore, shifting management strategies could concurrently increase ET/P and NUE, but our approach cannot disentangle direct climatic and indirect agronomic drivers of NUE.

Future climatic conditions will require adaptation of current agricultural practices, including improved rates and timing of fertilization to synchronize nutrient amendments with crop phenology (Howden *et al* 2007, Bowles *et al* 2018). Higher evaporative demand will require switching to irrigated farming where the increase in ET cannot be met by natural rainfall or increasing irrigation amounts (Schlenker *et al* 2003, Schlenker and Roberts 2009). Indeed, across our dataset, the small number of catchments that were irrigated exhibited a decrease in P over the second period. The few catchments where NUE decreased in the second period are also primarily located in the dry climate zone, suggesting that drying *per se* does not improve NUE because it can lower yields despite increasing ET/P, such as during the 2012 drought (Swaney *et al* 2018, Sabo *et al* 2019). Therefore, based on our results, only climatic changes causing higher ET/P without negatively impacting yields are expected to improve NUE.

4.2. Approach benefits and limitations

Our approach has the advantage of leveraging data that are readily available and assessing interactions between the water and N cycles at the catchment scale, which are relevant for large-scale nutrient management. This approach shares the advantages of earlier N budget calculations at the catchment scale (Boyer *et al* 2002, Howarth *et al* 2012), where N fluxes rather than NUE were evaluated. However, the NUE approach used here does not accommodate all dimensions of nutrient use efficiency that are important in a local perspective. For example, yield quality aspects and plant internal nutrient (re-)allocation are better addressed by using field-scale approaches (Weih *et al* 2018), and the simple definition of NUE we used does not include N release from organic matter mineralization (for a discussion on this point, see supplementary information section 2.4.2). Furthermore, our approach has some methodological limitations that need to be considered. We estimated NUE based on yields of three major crops, but fertilizer data are aggregated at the county level, potentially causing an underestimation of NUE in catchments where a large fraction of fertilizer is used for other crops. However, catchments with lower coverage by the three major crops have large areas dedicated to pastures, which rely less on fertilizers than the major crops and do not count towards yield calculations. Therefore, we do not expect a strong bias in our NUE estimates in those catchments.

Moreover, only 73 catchments with complete datasets were selected. These cover largely the Great Lakes and Mid-West regions, but not the Southern and Western regions (figure 2(a)), where only a few catchments are present. This could bias our results spatially. Even where there is good spatial coverage, there are catchments with clear differences. For example, two catchments, Bad River (South Dakota) and North Loup River (Nebraska), are characterized by low fertilizer application (<25 kg ha^{-1} y^{-1}), located in dry climate, and characterized by decadal mean of NUE higher than 1. Removing these two catchments from the LME analysis, time remained a highly significant driver of NUE, but with no significant effect of ET/P. Therefore, catchment choice—which in our case was limited by data availability—might affect some results. Having a more complete and denser coverage would strengthen our conclusions, and would allow for inclusion of additional explanatory variables for NUE.

The theoretical correlation between NUE and ET/P rests on the assumption that N in the marketable yield is proportional to the whole plant N (Reich *et al* 2014). This proportionality is not fixed, because more fertilization results in greater allocation of N into harvested products and different types of crops exhibit different allocation strategies. Despite this variability, the theoretical prediction of a correlation between NUE and ET/P still holds. The fertilizer data are aggregated at the county level, so they do not allow assessing NUE of specific crops (Gronberg and Spahr 2012). Moreover, catchment-scale NUE is influenced by developments at field scale affecting individual plant performance (i.e. plant breeding) and the properties of the production system that affect NUE. For example, the introduction of short-grown wheat varieties has influenced within-plant N allocation and weed abundance (Gooding *et al* 2012). Combining crop-specific fertilization data and these local-scale improvements in NUE could result in catchment-scale NUE changes, but our approach cannot attribute the observed catchment-scale NUE to specific local-scale variations.

By focusing at the decadal time scale, our approach is not able to track temporal redistributions of water and nutrients in the catchment, which occurs at the seasonal or even precipitation event scale. On the one hand, more frequent high intensity rainfall events (Cao *et al* 2018), are expected to increase leaching without much impact on the long-term mean ET; i.e. expected warming might increase ET/P on average, but that does not mean that nutrients will be efficiently retained due to higher rainfall intensity. On the other hand, lengthening of the growing season (Mccabe *et al* 2015) is shifting the timing of N applications. Our approach cannot link observed NUE to these short-term variations in N cycling; however, by averaging hydrological and agronomic data at the decadal time scale, it provides robust estimates of the directions of NUE and ET/P changes.

5. Conclusions

The frequently used field-scale NUE concepts hold for plant stands and pot-grown plants, but they miss interactions between nutrient and hydrological cycles that emerge at catchment scale because of spatial heterogeneities and nutrient recirculation in the landscape. Catchments offer opportunities to characterize the coupled nutrient flows and hydrological processes—specifically evapotranspiration. We used this approach to characterize long-term ET fluxes in relation to NUE across 73 catchments in the United States and test two hypotheses: 1) NUE is positively correlated to ET/P across catchments, and 2) NUE and ET/P increase through time at decadal time scale. The results supported both hypotheses, indicating that climatic changes or land use management that promote evapotranspiration over runoff and deep percolation without lowering yields, also promote nutrient retention in and extraction from agroecosystems.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request

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