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The optimum nitrogen fertilizer rate for maize in the US Midwest is increasing

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Mitchell E. Baum[1], John E. Sawyer[1], Emerson D. Nafziger[2], Michael J. Castellano[1], Marshall D. McDaniel[1], Mark A. Licht[1], Dermot J. Hayes[3], Matthew J. Helmers[4] & Sotirios V. Archontoulis[1]

Fertilizing maize at an optimum nitrogen rate is imperative to maximize productivity and sustainability. Using a combination of long-term ($n = 379$) and short-term ($n = 176$) experiments, we show that the economic optimum nitrogen rate for US maize production has increased by 2.7 kg N ha^{-1} yr^{-1} from 1991 to 2021 (1.2% per year) simultaneously with grain yields and nitrogen losses. By accounting for societal cost estimates for nitrogen losses, we estimate an environmental optimum rate, which has also increased over time but at a lower rate than the economic optimum nitrogen rate. Furthermore, we provide evidence that reducing rates from the economic to environmental optimum nitrogen rate could reduce US maize productivity by 6% while slightly reducing nitrogen losses. We call for enhanced assessments and predictability of the economic and environmental optimum nitrogen rate to meet rising maize production while avoiding unnecessary nitrogen losses.

Improvements to nitrogen (N) fertilizer management are necessary to address the challenges of food security, environmental degradation, and climate change[1]. These challenges are complicated as sustaining high levels of maize production is dependent on N fertilizer input[2]. Therefore, goals to increase food production and security may come at a potentially greater environmental cost. Globally, the use of N fertilizer has increased 4-fold from 1960 to 2021[3], in large part due to land conversion to cropland[4].

Currently, there are different N management recommendation systems for maize production. Historically, the recommended N fertilizer rate for maize production in the US Midwest was a function of the targeted maize yield using a "kg N per kg grain" ratio[5]. Over the years, other data-driven recommendation systems have emerged, i.e., Maximum Return to Nitrogen[6], while other more technology-driven systems, including remote sensing, novel soil testing, and crop modeling, are currently in research[7–10]. Crop rotation is a common factor considered by many N recommendation systems because rotating maize with soybeans increases maize yield while reducing N rate requirement compared to continuous maize[11,12]. Typically, maize following soybean requires 40 kg N ha^{-1} less N-fertilizer than continuous maize[6,13] because of the increased soil N mineralization caused by the amount and quality of the soybean residue[14,15].

There are different optimal N rates for productivity, profitability, and environmental performance (Fig. 1). The simplest expression is the agronomic optimum N rate (AONR) which maximizes crop productivity; the second and most common is the economic optimum N rate (EONR) which maximizes on-farm partial profit (cost of fertilizer relative to value of grain) and, therefore, is of most interest to farmers. Due to cost associated with purchasing fertilizer, the EONR will never be equal to the AONR and is on average 10% lower than the AONR. Lastly, the environmental optimum N rate (EnvONR), which aims to mitigate the societal cost N losses to the atmosphere and groundwater using a partial profit of grain yield to fertilizer cost plus the cost of N externalities (Fig. 1). The EnvONR has a greater cost associated per unit of applied N and is, therefore, estimated to be 17–41% lower than the AONR[16–18]. While the concept of including a cost to reactive N damaging aquatic ecosystems was promoted years ago[19], adoption has been slow, partly due to ambiguity surrounding the real cost of environmental damage associated with N losses. For that, we used a summary of the potential cost of N loss which attributes cost ranges associated

[1]Department of Agronomy, Iowa State University, Ames, IA, USA. [2]Department of Crop Sciences, College of Agricultural, Consumer, and Environmental Sciences, University of Illinois at Urbana-Champaign, Urbana, IL, USA. [3]Department of Economics, Iowa State University, Ames, IA, USA. [4]Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, IA, USA. e-mail: mebaum@iastate.edu; sarchont@iastate.edu

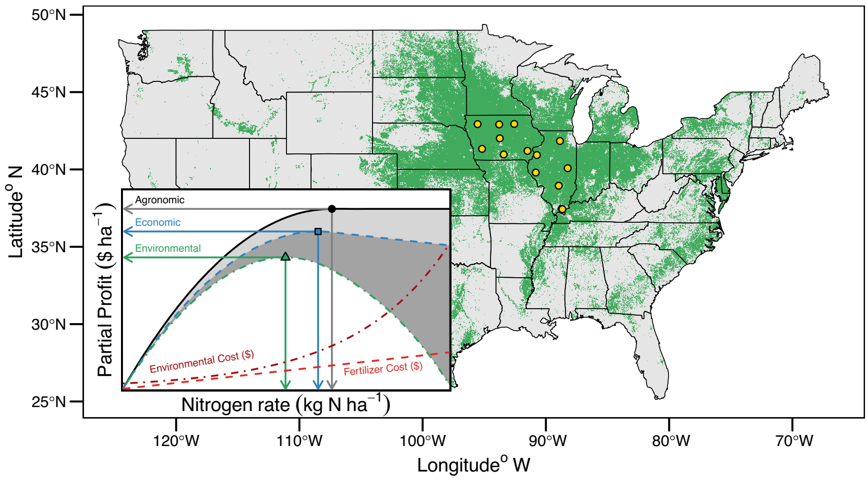

Fig. 1 | USA map illustrating the location of the 14 long-term experiments (*yellow points*) and maize cropland (*green shaded area*) compared to non-maize cultivated area (*gray area*). The insert figure illustrates three derived optimum nitrogen (N) rates: (*black circle*) agronomic optimum N rate (minimum N rate to maximize grain yield); (*blue square)* economic optimum N rate (minimum N rate to maximize net return to N fertilizer cost); and, (*green triangle)* environmental optimum N rate (minimum N rate to maximize return to N fertilizer cost plus societal cost of N losses).

with eutrophication, the increased potential health risk from human consumption, and nitrous oxide and NO_X emissions to the atmosphere[20]. At the field scale, the agronomic efficiency of N fertilizer (kg grain kg^{-1} N) decreases with additional N inputs[2,21], while reactive environmental N losses (denitrification and nitrate leaching) increase with additional N inputs[22–25]. Reducing N rates to mitigate N losses will reduce agronomic output, which is unfavorable as demands for food production and security continue to grow.

Understanding historical temporal patterns in the optimal N rates is imperative to improve existing recommendation tools and inform future decisions. Yet, despite years of research on N fertilizer, no such temporal baseline has been developed. In contrast, we have a good understanding of three key factors influencing these optimal N rates for maize: 1) grain yields have increased by roughly 1.2% per year[26], 2) the concentration of grain N has decreased[27–29], and 3) precipitation is changing towards more spring and less summer precipitation in the US Midwest[30]. These changes are simultaneous and it currently remains unknown how these factors have interacted and affected the optimum N rates for maize over decades of farming. Typically, higher grain yields require more N if other factors are held constant[31], thus increasing the optimum N rates. Lower grain N concentration will reduce grain N demand and optimum N rate due to the plant sequestering more carbon per unit of N uptake[32–34]. Increased spring precipitation will increase N losses to both NO_3^- and N_2O[35] and may increase the amount of fertilizer N necessary to maximize grain yield[36,37]. Yet, the product of these interactive factors remains unknown.

We hypothesize that over the last decades, the optimum N rate for maize production is increasing due to an increase in N outputs to grain and N losses since increased crop yields likely exceed reductions in grain N concentration. To test this hypothesis, we synthesized 14 long-term N experiments ($n = 379$ EONR responses) from major maize-producing states in the US Midwest and quantified temporal patterns on AONR, EONR, and EnvONR (Fig. 1). Long-term experiments offer a viable way to establish trends in agricultural N management[38,39]. While long-term experiments are valuable resources for assessing the performance of alternative N management practices[40], they are also prone to overestimate maize yield response to N because the zero N treatment reaches a different steady state compared to commercial fields without legacy zero N treatments[39]. To enhance our analysis towards creating a robust assessment of the temporal trends in EONR, we sourced additional single-year EONR data from the Corn N Rate Calculator ($n = 176$ EONR values[6,41]). Our experiments account for both continuous maize and maize–soybean, which is important given that crop rotation is a major factor affecting optimal N rates[42,43].

Herein, we demonstrate optimal N rates for US maize production have been increasing simultaneously with grain yields and nitrogen losses over the past few decades. Additionally, our results suggest an expanding gap between the EONR and EnvONR. To explain temporal patterns, we investigated numerous factors related to the optimum N rate, such as grain yield, N fertilizer use efficiency, N losses, and net soil mineralization. For that, we used APSIM, a well-calibrated cropping systems model for the study region[13], to estimate system output such as N losses and soil N mineralization not measured in the experiments. Combining model estimates for the amount of environmental N losses with estimates for the cost of environmental N losses[20,23], we calculated the EnvONR (Fig. 1). This analysis allowed us to explore relationships between optimal N rates and productivity.

Results

Determining temporal patterns in optimum N rates

Results from the 14 long-term experiments showed that all optimal N rates for maize production are increasing (Fig. 2, S1), and the increase was evident in both rotations. Across rotations, the increase in the optimum N-rate was greatest in the EONR (3.16 kg N ha^{-1} yr^{-1}), followed by the AONR (2.6 kg N ha^{-1} yr^{-1}), and then the EnvONR (2.0 kg N ha^{-1} yr^{-1}). The different slopes indicate that the difference between EONR and AONR has decreased over time, while the difference between EONR and EnvONR has increased over time. Across rotations, the difference between AONR and EONR was 3 kg N ha^{-1} in 2020 compared to 14 kg N ha^{-1} in 2000, while the difference between EONR and EnvONR was 70 kg N ha^{-1} in 2020 compared to 46 kg N ha^{-1} in 2000. While the EONR can never equal the AONR due to fertilizer cost, the difference between EONR and EnvONR may shift in magnitude and direction depending on the societal cost of N losses.

The increase in the EONR was 22% greater in the maize-soybean rotation compared to the continuous maize system, indicating that the difference in the EONR between crop rotations is closing, from 44 kg N ha^{-1} in 2000 to 32 kg N ha^{-1} in 2020. This is likely because of the greater increase in grain yield in the maize-soybean system compared to continuous maize (see below). Importantly, the observed within-year variability in optimal N rates was larger than the 20-year temporal increase (Fig. 2).

Single-year on-farm experiments confirmed the increase in the EONR (Table S1; Fig. 3). The combined datasets ($n = 555$ EONR values)

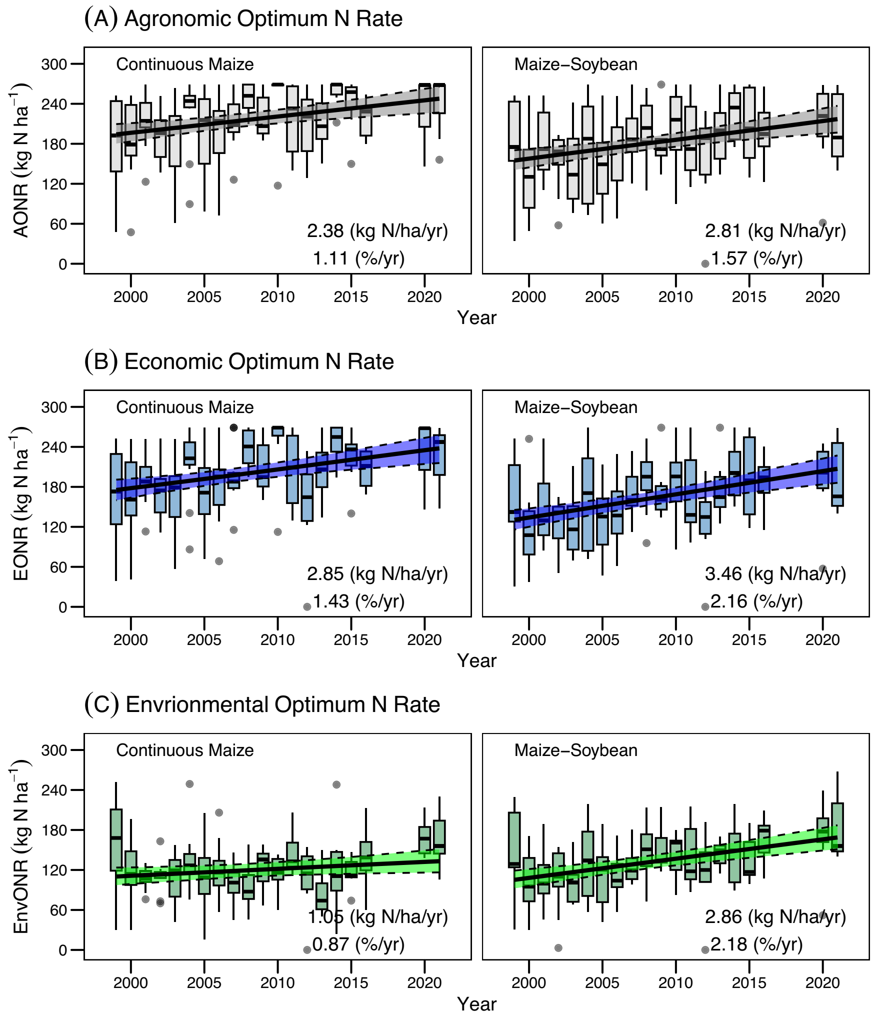

Fig. 2 | Long-term temporal trends of the optimal N rates. Trends illustrate the changes of the agronomic [AONR, (**A**)], economic [EONR, (**B**)], and environmental [EnvONR, (**C**)] optimum N rate per crop rotation across 14 locations. Crop rotation includes continuous maize (*left panels*) and maize-soybean (*right panels*). Lower, mid, and upper hinges of the box correspond to the 25th, 50th, and 75th percentiles, whiskers extend to 1.5 times the interquartile range, and the dots are outliers. The trend lines represent the line that minimizes the sums of squares through the data, surrounded by a 95% confidence interval. The full regression equations are given in Table S1. Within each boxplot there were 8, 11, 11, 12, 13, 14, 14, 14, and 7 observations for the years of 1999, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, and 2009 onward respectively.

were analyzed using a linear mixed effect model showing an average increase in the EONR of 2.8 kg N ha^{-1} (1.7%) per year in maize-soybean rotation and 2.2 kg N ha^{-1} (1.1%) per year in the continuous maize system (Fig. 3; Table S1). Over 29 years, the temporal trends translate to an increase of 81 and 64 kg N ha^{-1} for maize-soybean and continuous maize (Fig. 3). The maize-soybean crop rotation is the dominant cropping system in the US Midwest, comprising nearly 76% of the total maize area[44]. Therefore, a weighted average of the continuous maize and maize soybean slopes was used to estimate the overall relationship between EONR across time, resulting in a change of 2.7 kg N ha^{-1} yr^{-1} or 1.2% per year from 1991 to 2021. Interestingly, the increase in EONR is comparable to the maize yield increase over the same timeframe (1.31% per year, Fig. 4A).

Explaining the temporal patterns in the optimum N rate

To explain the temporal increases of the optimal N rates, we examined nine potentially contributing factors listed in Fig. 4. We found that changes in grain yield and N losses were the main drivers. More specifically, the yield response to N rate, the grain yield difference between optimally fertilized and not fertilized crops, was increased by 3.2% per year and had the highest correlation (r = 0.64, Fig. S2) with the EONR. This increase was a synergy of increasing grain yield at the EONR (1.3% per year) and decreasing grain yield at zero N (−0.3% per year, p > 0.05). It should be noted that the grain yields from our long-term experiments are representative of the region as they agreed well with the corresponding USDA-NASS statistics (r = 0.56, Fig. S3).

Nitrogen losses (NO_3^- leaching, and N_2O) had the second highest correlation with the EONR (r = 0.61, Fig. S2). Nitrogen losses were increasing by 0.37–0.72 kg N ha^{-1} yr^{-1} (Fig. 4E), potentially due to increases in precipitation (9.6 mm yr^{-1}, Fig. 4I), imposing wetter soil conditions. In contrast, the soil N supply, i.e., simulated net N mineralization at zero N fertilizer, had a low correlation with EONR (r = −0.22) and was relatively stable over time compared to other factors (Fig. 4F; Table S2).

The N fertilizer use efficiency, i.e., (yield at EONR − yield at zero N / EONR), increased by 1.5% per year (Fig. 4D) due to greater increases in the yield at EONR compared to yield at zero N (Fig. 4A & B). However, the correlation with EONR was weak (r = −0.05; Fig. S2). The amount of N exported at crop harvest, i.e., grain yield x N concentration, increased by 0.73% per year and had a r = 0.24 correlation with EONR, despite a slight dilution of the grain N concentration over the study period (Table S2). The fact that the change in grain N was lower than

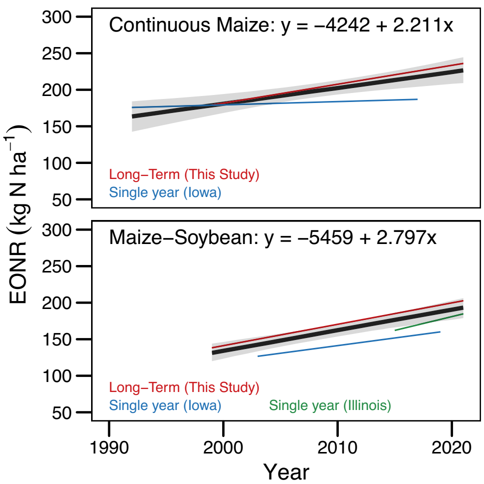

Fig. 3 | Temporal changes in maize's economic optimum nitrogen rate (EONR) over the last 30 years. The solid *black* line (and the corresponding equation) refers to the overall multi-dataset trend per a continuous maize and maize-soybean crop rotation, while the shaded bands around the lines are the 95% confidence interval. Colored lines refer to the overall trend per individual study (see "Methods" section "Enhanced optimum N rate database"). The full regression equations for the single-year lines are given in Table S1.

the change in grain yield at EONR suggests a dilution of N in the grain over time.

Application of nitrogen fertilizer and maize planting dates did not significantly change over the study period and, therefore, did not explain temporal variability in EONR. It should be noted that the time difference between fertilizer and planting date was diminishing at 0.05 days yr^{-1} in our experiments. Lastly, plant density increased, but this increase did not explain well the EONR increase (Fig. S2).

Quantifying the tradeoff between productivity and N fertilizer reductions

Our result indicates that reducing the optimal N rate (from economic to environmental) decreases grain productivity non-linearly because of the nature of maize yield response to N fertilizer (Fig. 1), with the decrease being larger for continuous maize than maize-soybean crop rotation (Fig. 5). The N rate reduction (from economic to environmental optimum N rate) averaged 79 and 29 kg N ha^{-1} for continuous maize, and maize-soybean crop rotation, respectively, resulting in a 14 and 3% reduction in grain yield, assuming \$41 ha^{-1} cost N leaching and a \$30 cost of one-ton carbon equivalent cost of nitrous oxide emissions, which is equivalent to \$14.05 per kg_{N2O_N}[20,23]. Because the cost of leaching estimates has not yet been established in the market, we performed a sensitivity analysis to quantify the impact on the tradeoff relationship (Fig. S4). While using a lower price for the cost of N losses will result in a lower difference between economic and environmental optimum N rates, and hence a lower grain yield reduction, the cost of the N loss did not change the shape of the tradeoff relationship, only the magnitude. Therefore, the developed relationship holds across a range of N loss prices and can be used for decision-making. Furthermore, using APSIM simulated N loss data, we found that reducing the N fertilizer rate from economic to environmental optimum N rate reduced N losses by about 12 and 3 kg N ha^{-1} for continuous maize and maize-soybean (Fig. S5).

Discussion

This study provides actionable data to inform N fertilizer recommendation systems and policy in the US Midwest by establishing and explaining decadal trends in optimum N rates (Figs. 2, 3) and quantitatively linking productivity with environmental sustainability (Fig. 5). We showed that the EONR for maize has increased over the past two decades (Figs. 2, 3) on average within the major maize production region in the US Midwest. The increase in the EONR was previously unknown and has large implications because the EONR is strongly linked to many ecosystem services, including productivity, greenhouse gas emissions, and carbon sequestration[23,45]. The developed decadal trends can inform temporal adjustments in N rate recommendations[46], train models to predict future N rates in the context of climate change[39,47], and improve N and carbon budget estimations for sustainability assessments[48].

The increase in the EONR was greater in the long-term experiments than in single-year experiments (Fig. 3; Table S1), which could be due to the residual carry-over effect of plots consistently being over-under-fertilized, potentially inflating the yield response to N rate, and thus the optimum N rate. However, both long-term and single-year experiments agree on the increasing patterns (Fig. 3; Table S1). Additionally, surveys of on-farm applied N rates (i.e., not optimal) in Iowa, US[49], indicate increasing N fertilizer input trends (3.6 kg N ha^{-1} yr^{-1} from 3.1 to 3.7). In this survey, maize producers in the US Midwest applied a median of 185 to 253 kg N ha^{-1} to continuous maize and 157 to 210 kg N ha^{-1} to maize following soybeans per year. These ranges are comparable with the ranges reported in Fig. 2, but the mean values in the survey appear to be higher than the reported optimum N rates in Fig. 3. From this comparison, we cannot state that farmers overapply N fertilizer because these are two different databases with different fields, weather-years, management practices, and hybrids, but the increasing N rate trend in the survey suggest that maize producers are adapting. Our results provide strong support for this increasing trend. The increase in the EONR was in part explained by increasing grain yields, which in turn is caused by improved genetics, improved agronomic management, and environmental conditions[29,50,51].

Given that maize grain yield and N losses were the two major factors explaining the increase in the optimum N rates (Fig. 4, S2), we believe the trends may continue in the future as long as maize grain yield and spring precipitation continue to increase. In such a case, in the next 20 years, the N fertilizer demand could potentially increase between 44 and 56 kg N ha^{-1} in order to maximize on-farm profits relative to today, translating up to 101 million kg of additional N fertilizer that should be planned for each year assuming planting area remains the same. Given the large within-year variability in EONR (Fig. 2) and the inconsistent EONR trends among individual experimental locations (Fig. S1), there may be opportunities for strategic allocation of N fertilizer across the landscape to maximize productivity and environmental sustainability. Future studies should investigate this further. Moving forward, inexpensive N fertilizer sources may become scarcer as geopolitics accelerate increased fuel prices and destabilize the supply of synthetic N fertilizer[52]. Assuming flat grain prices relative to fertilizer cost suggests that farmers will face reduced partial profits as the cost of N fertilizer increases.

We found the well-known gap in the EONR between crop rotations is closing (Figs. 2, 3; Table S1). Crop rotation is the second most influential factor of EONR after weather variability. We found that a maize-soybean rotation produces, on average, 11% more grain yield with 20% less N fertilizer than continuous maize in line with previous studies[11,12,36,53–55]. The greater increase of EONR in the maize-soybean rotation relative to continuous maize in part is explained by the greater maize yield increase in the maize-soybean rotation (Fig. 4A). We hypothesize this trend will continue in the coming years because commercial maize breeding programs select new cultivars mostly under maize-soybean systems, representing 76% of the rainfed maize production in the US Midwest.

Our results for increased N fertilizer use efficiency (Fig. 4D) are encouraging, considering the urgency to increase environmental sustainability and agree with previous studies[1,33,56]. The increase in N fertilizer use efficiency decelerated the rate of EONR increase. If the N

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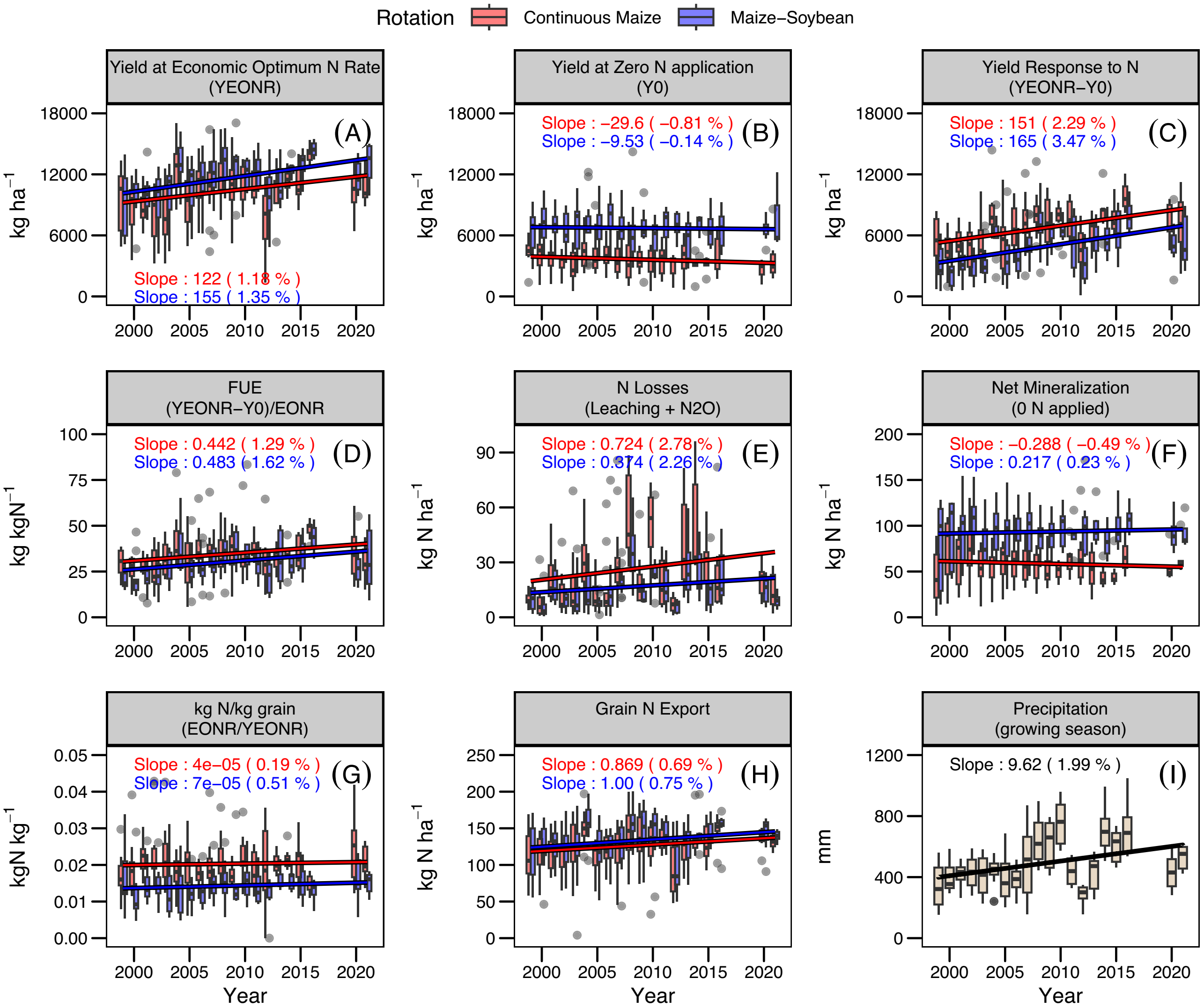

Fig. 4 | Temporal changes in explanatory variables affecting the optimal N rates. Panels represent changes in grain yield (**A**, **B**), yield response to nitrogen (N) (**C**), N fertilizer use efficiency (**D**), N loss (**E**), soil net mineralization (**F**), kg N per kg grain ratio (**G**), grain N (**H**), and precipitation (**I**). The N loss and N mineralization were derived from APSIM simulations (see Methods section). Variables that included crop rotations represent continuous maize with *red* lines and maize-soybean with *blue lines*, while tan boxplots and a black line represent precipitation independent of crop rotation. Slopes refer to the change over time per variable, while values in parentheses represent the slope's relative change. The full regression equations are given in Table S4. Lower, mid, and upper hinges of the box correspond to the 25th, 50th, and 75th percentiles, whiskers extend to 1.5 times the interquartile range, and the dots are outliers. Within each boxplot there were 8, 11, 11, 12, 13, 14, 14, 14, and 7 observations for the years of 1999, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, and 2009 onward respectively.

fertilizer use efficiency were unchanged, the increase in the optimum N rate would have been even greater. Long-standing goals in agriculture to increase efficiencies should be interpreted cautiously regarding actual N rates. The ratio of the EONR to yield at the EONR, which translates to "kg_N per kg_{grain}" was non-changing over the study period. However, our data indicates a mean value of 0.017 (period 2000 to 2020), which is lower than the historically proposed 0.021 kg_N per kg_{grain}[5]. A potential explanation for the reduced kg_N to kg_{grain} could be caused by the reduction in grain protein with breeding over the years[28,29].

The difference between the AONR and EONR decreased over time by 79%, from 14 to 3 kg N ha^{-1} (Fig. 2), primarily due to grain yield increase and nitrogen use efficiency improvement (Fig. S6). While the two optimal N rates will never be equal as long as there is an expense for fertilizer cost, it is encouraging that there is a growing return to N as N rates approach the AONR. Typically, N rates between the AONR and EONR have reduced nitrogen use efficiency and profits[41]. Conversely, we found that the difference between the EONR and EnvONR has increased by 34% (Fig. 2), indicating that EnvONR is increasing at a slower rate than EONR. This is due to the increase in N losses (Fig. 4) at the EONR (Fig. S7) and assuming a fixed cost for N losses. The mean difference between the EnvONR and EONR was 27%, within the range reported in the literature (from 17 to 41%[16–18]). While the differences between the EONR and EnvONR will, in part, be determined by uncertainty in the cost of N losses, our results suggest this difference will continue to grow as N losses continue to increase.

A reduction in N fertilizer rate towards improving sustainability will not have the anticipated reduction in environmental N losses because of the nonlinear relationship between N rate and N loss (Fig. S5). For example, a switch from economic to environmental optimum N rate (29-79 kg N ha^{-1} less fertilizer input) translated to only 3–12 kg N ha^{-1} less N loss as reducing N fertilizer below the optimum N rate, or a weighted average of 5 kg N ha^{-1} between the two crop rotations, and thus, has a minimal impact on N loss according to our simulations (Fig. S5), which are supported by literature[25,57,58]. A reduction in fertilizer N rate should be tailored to areas where farmers apply N rates in excess of the optimum[59]. In these situations, we realize the

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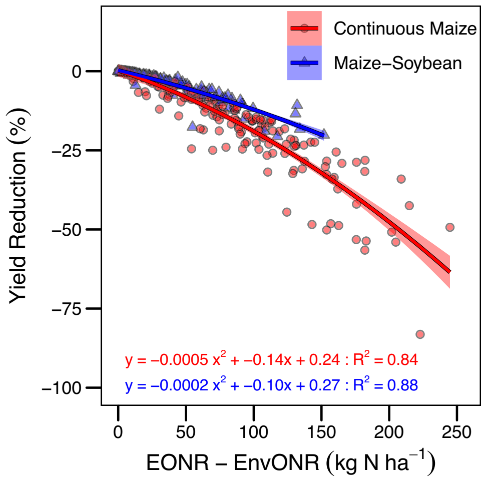

Fig. 5 | The tradeoff between economic and environmental optimum nitrogen (N) rates. Percent grain yield loss per kg N ha^{-1} reduction in optimum N rate (from EONR to the EnvONR). Quadratic regression (lines) best explained the variation in the data, with the shaded area around each line representing a 95% confidence interval.

benefits of N loss savings without sacrificing crop productivity[40]. Additionally, alterations in N management practices may reduce the environmental impact of N application while improving nitrogen use efficiency. Split N application can reduce fertilizer-N losses, especially compared to a single fall application, while increasing fertilizer use efficiency to the environment by better synchronizing fertilizer N with crop demand[60]. However, N losses in some hotspot regions exceed environmental thresholds, beyond which can be mitigated through technological improvements[61]. In such regions, other strategies must be utilized to mitigate environmental damage, such as redistribution of N inputs to more suitable production areas or alleviating crop demand by reducing food waste.

A reduction in N fertilizer input will have a greater impact on grain productivity and profitability than N losses (Fig. 5, S5), which is undesirable given the urgency to increase food production and security[62,63]. We estimated that moving the optimal N rate from economic to environmental optimum would reduce maize yields by 3–14% (Fig. 5), translating to 0.7–3.1 million Mg less maize production in the US Midwest. The reduction in maize yields would be greater on the continuous maize system because this system has a higher EONR and, hence, higher N losses than the maize-soybean system (Fig. 2, S5). Furthermore, planting soybeans prior to maize favors soil N mineralization and higher yields under zero N (Fig. 4B, F), which partially alleviates N fertilizer demand. For these reasons, there is a steeper yield penalty for under-fertilizing a continuous maize system (Fig. 5) combined with a greater proportion of N losses (Fig. S5). Regardless of rotation system, reducing maize production in the US and, therefore, maize exports will create a void in the global market, driving up maize prices, which will incentivize stakeholders to expand land area devoted to maize production by converting new land or existing agricultural lands to maize, with potentially greater adverse environmental impacts[64–66]. A possible solution is to sift the international focus from the demand-side of global markets to the supply-side by setting goals for regional improvement in nitrogen use efficiency, as improved nitrogen use efficiency is the most effective strategy for improving food security, while considering N boundaries[67]. We call for enhanced assessments of the environmental optimal N rate and increasing nitrogen use efficiency strategies considering the need to maintain or even increase the current crop yields.

The science-based tradeoff relationship between productivity loss and reduction in N fertilizer rates (Fig. 5) is a novel tool to guide future policy. Due to non-consensus of the true cost of N_2O emissions and NO_3^- leaching[20,23,40,68], the difference between the environmental and the economic optimum will vary, with lower social cost reducing the difference between the EnvONR and EONR, thus having a lower yield reduction between the two rates and vice versa. However, the quantitative relationship on grain yield between the two rates holds regardless of the cost of the N losses and can be used to develop incentive-based programs.

While our results indicate increases in the optimal N rate over time, not every situation will call for applying more N, especially in fields that currently receive N fertilizer rates in excess of the optimum rate. Year-to-year weather variability is a major factor influencing the EONR[53,69] (Fig. 2), consequently, as climate change is expected to increase weather variability, annual variability of the EONR may also increase. Moving forward, we call for improved and timely predictability of the optimum N rate across space and time under a range of situations (management x genetics) as a solution to maximizing productivity, sustainability, and profitability. To that end, improved prediction of the EONR can further enhance the effectiveness of variable rate applicators, especially in large commercial fields where a uniform EONR may not be sufficient across differing soil types. For that, a coordinated effort at scale is needed following a systems approach to quantify optimal N rates at a spatiotemporal scale coupled with records of crop and soil management. Improved data availability will support recent technological advances in remote sensing, machine learning, and crop modeling, which can assist in the predictability and explanation of factors affecting the EONR[70–72].

Methods

Description of the long-term experiments

We synthesized data from 14 long-term maize yield responses to N rate trials carried out in the two top maize-producing states within the United States of America (i.e., Iowa and Illinois Fig. 1; Table S3). The Illinois experiments started in 1999 and ended in 2008, while data collection in the Iowa experiments started in 2000 and ended in 2021 (Table S3). The Iowa locations received zero N fertilizer in all plots in 2017 and 2018; thus, those years were excluded from the analysis, however, experimentation resumed under the same design resumed in 2019. To avoid the residual effect of zero N fertilizer on the plots during the previous two years, 2019 was also excluded from the analysis. Each studied location contained continuous maize and maize-soybean systems and a minimum of five to seven N rates (Table S3). Each experiment followed a split-plot design with crop rotation as the main plot and N-rate as the sub-plot, containing four replications. Across locations and treatments, grain yield was reported at 15.5% moisture. Nitrogen fertilizer rates ranged from 0 to 268 in Iowa and from 0 to 252 kg N ha^{-1} in Illinois. Experiments followed the predominate farming practices within their surrounding regions, therefore, N fertilizer was applied as a single application roughly ±2 weeks of maize planting[73]. Furthermore, the mean annual precipitation was 922 ± 259 mm per year, and the mean sum of growing degree days (base = 8 °C[74]) between planting and maturity was 1961 ± 173 °C-d. Additional information on the soil water and nutrients of the long-term experiments has previously been reported[13].

Optimum N rate calculations

Using the observed maize yield response to N rate (14 long-term trials) and APSIM model simulated nitrous oxide (N_2O) and nitrate (NO_3^-) leaching data[13], we calculated three optimal N fertilizer rates (Fig. 1):

- AONR: the agronomic optimum (the minimum N rate required to maximize grain yield)
- EONR: the economic optimum (the minimum N rate required to maximize net return to N fertilizer)
- EnvONR: the environmental optimum (the minimum N rate required to maximize environmental performance by considering the cost of N_2O and NO_3^- leaching, added to N fertilizer cost).

For each yield response to N rate within the long-term experiments ($n = 379$ combinations of locations and years and rotations), we fitted four descriptive models: quadratic plateau, quadratic, linear-plateau, and linear. Of the best-fit models, the quadratic plateau was the most common best-fit model, representing 88% of location by year by rotation combinations.

The AONR was calculated from the best-fit model, and it was the inflection point for the quadratic plateau, linear-plateau, and quadratic models while it was the maximum N-rate applied for the linear model. To avoid extremely high values of the convergence point, potentially occurring when the optimal N rate exceeded the maximum N rate (i.e., 252 and 268 kg N ha^{-1} for the Illinois and Iowa locations), it was set to be the maximum N rate to avoid the uncertainty of extrapolating results beyond the tested range of N rates (Fig. S8). The EONR was calculated from the quadratic-type N response models by setting the first derivative of the fitted response curve to a historical price ratio of 5.6:1 N fertilizer: maize price (US$ 0.88 kg^{-1}: US$ 0.16 kg^{-1}). The EONR for linear-plateau and linear models were the joint point and maximum N rate applied. While the N fertilizer price and the corn price have changed over the years, the price ratio has remained fairly constant (Fig. S9) and therefore we used a constant price ratio in our analysis similar to previous studies exploring temporal dynamics in EONR[6,75,76]. Furthermore, we performed a sensitivity analysis in which we changed the price ratio by 22% (from 4.3 to 6.8, Fig. S10) and found that the 1999-2021 median EONR changed only by ±3%, which is well below the variability in the optimum N rate obtained across sites (31%) and years (32%). For these reasons, we did not consider year-specific price values.

The EnvONR was calculated by considering the cost of N loss (N_2O and NO_3^- leaching). The cost associated with the damages of NO_3^- leaching to the environment[20] ($41.15 kg^{-1} N), which includes many categories with the most important to be freshwater eutrophication, groundwater N loading, and the increased risk of colon cancer, nitrate contamination, damages of declining fisheries and degradation of recreational area. Given that this cost is not yet established in the market, we performed a sensitivity analysis ($1 to 70 ha^{-1}) to better understand its impacts (Fig. S4). A higher cost of N losses will favor larger discrepancies between EnvONR and EONR. The N_2O emissions cost[23] was calculated by converting the elemental N within the N_2O compound to the 100-year estimated global warming potential per metric ton of CO_2 with an associated cost of $30 ton^{-1} CO_2. Henceforth, the cost of 1 kg of N_2O was equal to 44/28 (the elemental ratio of N in N_2O) x 0.298 (global warming potential of 1 ton of CO_2) x 30 (the cost associated with 1 ton of CO_2) or 1 kg N_2O emitted to the atmosphere = $14.05. Typically, NO_3^- leaching and N_2O emissions increase exponentially as N rate increases[25,77,78]. Environmental N losses can be estimated using generalized statistical models[16]. However, these models are independent of soil type and weather patterns. We expanded on this approach by simulating the amount of NO_3^- leaching and N_2O emissions using a well-calibrated process-based model capable of simulating spatiotemporal differences to the N loss to fertilizer rate curve[13]. Simulated amounts of N losses per N rate were then used to construct a price ratio between the cost of N losses and fertilizer against the value of grain per N rate. Note we exclude the potential cost of particulate matter PM_{10} and $PM_{2.5}$ from NH_3 volatilization from inorganic fertilizers in this analysis because NH_3 volatilization is marginal within the N management practices used for maize production in the US Midwest[79].

APSIM and environmental loss estimation

The Agricultural Production Systems sIMulator[80] (APSIM) was used to provide insight by estimating N losses, N mineralization, and depth to the watertable. The model has been extensively calibrated and tested in the US Midwest[25,37,72,81–84]. Simulations of the 14 long-term experiments found good performance between measured and simulated yields (Fig. S11), which have also been previously reported[13].

We simulated N loss as the amount of NO_3^- moving below the rooting zone (150 cm depth) and N_2O emitted to the atmosphere per year, location, rotation, and N rate. Previous research in the US Midwest has shown good model agreement with simulated NO_3^- leaching from 56 site-years of data sourced from artificially subsurface-drained field experiments across the US Midwest[25]. Additionally, APSIM has been shown to simulate well N_2O emissions from various N rates in maize-based cropping systems[85]. Furthermore, our N_2O and NO_3^- estimates align with previously established efficiency factors. APSIM simulated N_2O at an average efficiency factor of 2.14% of N_2O per kg N applied, which is within an established 1–3% efficiency factor of observed values[86–88].

Explanatory variables

Using the long-term datasets, we calculated the following explanatory variables: 1) yield response to N rate (yield at optimum N rate minus yield at zero N rate); 2) the N fertilizer use efficiency (yield at optimum N rate−yield at zero N) / EONR); this method was chosen as it isolates the N derived from fertilizer application from mineralized N (C); 3) the kg of applied N per kg maize grain yield ($kg_N\ kg_{grain}^{-1}$ = EONR/yield at EONR) as this ratio is a proxy for the constant-coefficient in the yield goal approach used by farmers[5,89]. Other explanatory factors used to explain variability in EONR are listed in Fig. 4, S2.

Enhanced optimum N rate database

To enhance our understanding of how the EONR has changed over time, we retrieved 155 derived EONR values from response equations in the Corn Nitrogen Rate Calculator for Iowa (http://cnrc.agron.iastate.edu/) that included both maize rotations. These EONR data were selected to reflect single-year N rate responses, and used to compare temporal trends between long-term and single-year datasets (note that the Iowa database is the base for the Corn N Rate Calculator and contains both long-term and single-year trials). We also used the recently reported EONR temporal trend for maize-soybean in Illinois[41] ($n = 21$). The enhanced dataset (Fig. 3) increased the number of EONR observations from 379 to 555.

Statistical analysis

Data analysis was conducted in R version 4.1.2[90]. Optimum N rate trends per crop rotation were determined using a mixed-effect linear model using the *lme* function (version 3.1–164) within the *nlme* package[91], treating location as a random effect. The best-fit model was selected by fitting a simple linear model and increasing model complexity until Akaike's Information Criteria—AIC was no longer decreasing with added factors to the model[92]. The same approach was used when fitting the trends of all experimental data with maximum return to N rate datasets (Fig. 3). Trends of explanatory variables and optimum N rates within a location and rotation were fit using a simple linear model as they lacked factors for added complexity. The significance of an individual slope was tested using a p-value and considered significant at the p-value < 0.05 level. The grain yield-N reduction tradeoff relationship (Fig. 5) was described using a quadratic model. The N loss-N rate relationship (Fig. S5) was described by an exponential model using the *SSasymp* function (version 4.3.2) within the *Stats* package.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The data supporting the findings of this study are available within the Article and Supplementary Data and have become available at Zenodo repository: https://doi.org/10.5281/zenodo.14037090. Any additional information can be provided by request to the corresponding authors.

Code availability

The APSIM crop model can be downloaded from the APSIM webpage (https://www.apsim.info/) and the specific outputs used for this study are described in Baum et al. [13]. The R software can be downloaded from https://www.r-project.org/ and the R scripts used to analyze experimental and simulated data are available at Zenodo repository: https://doi.org/10.5281/zenodo.14037090.

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Author contributions

M.E.B. and S.V.A. performed the data analysis and wrote the original document. J.E.S. and E.D.N. conducted the long-term field studies, compiled the experimental data, and experimental data quality control. M.J.C., M.D.M., M.A.L., D.J.H., and M.J.H. provided disciplinary expertize to expand the scope and interpretation of results. This work was funded by S.V.A. and M.J.C.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Mitchell E. Baum or Sotirios V. Archontoulis.

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