Supplementary Information

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

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Supplementary Tables

Table S1. Linear equations for each optimum nitrogen (N) rate and crop rotation used in Figs. 2 & 3. In each equation the value of x = year, and the p value represents the significance of the slope.

Study	Optimum N rate	Crop rotation	Equation	P value of slope
LTN	Agronomic optimum N rate (AONR)	Continuous Maize	y = 2.382x – 4567	0.0005
	Economic optimum N rate (EONR)	Continuous Maize	y = 2.850x – 5522	<0.0001
	Environmental optimum N rate (EnvONR)	Continuous Maize	y = 1.046x – 1981	0.062
	Agronomic optimum N rate (AONR)	Maize-Soybean	y = 2.80x – 5457	<0.0001
	Economic optimum N rate (EONR)	Maize-Soybean	y = 3.458x – 6782	<0.0001
	Environmental optimum N rate (EnvONR)	Maize-Soybean	y = 2.863x – 5617	<0.0001
Single year (Iowa)	Economic optimum N rate (EONR)	Continuous Maize	y = 0.444x – 709	0.70
	Economic optimum N rate (EONR)	Maize-Soybean	y = 2.215– 4312	0.01
Single year (Illinois)	Economic optimum N rate (EONR)	Maize-Soybean	y = 3.780x – 7448	0.32

LTN = Long-term Nitrogen trials (this study)
Single year (Iowa) = Non-long-term N trials from the Nitrogen Rate Calculator
Single year (Illinois) = Nafziger et al., (2022)

Table S2. Linear equations from Fig. 4, x = year. Statistical significance of the slope is measured using a p value less than 0.05.

Exploratory Variable	Crop rotation	Equation	P value of slope
Yield at Economic Optimum N rate (YEONR)	Continuous Maize	y=121.630x – 233920	<0.0001
Yield at Economic Optimum N rate (YEONR)	Maize-Soybean	y=155.184x – 300075	<0.0001
Yield at Zero N application (Y0)	Continuous Maize	y=-29.594x + 63082	0.13
Yield at Zero N application (Y0)	Maize-Soybean	y=-9.525x + 28554	0.72
Yield Response to N (YEONR-Y0)	Continuous Maize	y=151.224x – 297002	<0.0001
Yield Response to N (YEONR-Y0)	Maize-Soybean	y=164.709x – 325928	<0.0001
N Fertilizer use efficiency (YEONR – Y0)/EONR	Continuous Maize	y=0.442x – 854	0.01
N Fertilizer use efficiency (YEONR – Y0)/EONR	Maize-Soybean	y=0.483x – 939	0.004
N losses (NO_3^- leaching + N_2O)	Continuous Maize	y=0.724x – 1427	0.02
N losses (NO_3^- leaching + N_2O)	Maize-Soybean	y=0.374x – 735	0.03
Net Mineralization (0 N applied)	Continuous Maize	y=-0.288x + 638	0.33
Net Mineralization (0 N applied)	Maize-Soybean	y=0.217x – 343	0.51
$kg_N\ kg_{grain}^{-1}$ (EONR/YEONR)	Continuous Maize	y=0.00004x – 0.04	0.66
$kg_N\ kg_{grain}^{-1}$ (EONR/YEONR)	Maize-Soybean	y=0.00007x – 0.13	0.28
Grain N Export	Continuous Maize	y=0.869x – 1619	0.02
Grain N Export	Maize-Soybean	y=0.996x – 1867	0.01
Grain N Concentration	Continuous Maize	y=-0.006x + 14.1	0.09
Grain N Concentration	Maize-Soybean	y=-0.008x + 16.5	0.005
Precipitation (Growing Season)	----	y=9.630x – 18848	<0.0001

Table S3. Overview of the long-term location characteristics. All locations were comprised of both continuous maize and maize-soybean crop rotation. The years 2017-2019 were removed from the Iowa Locations (see Materials and Methods section Description of the long-term experiments)

Location name	Latitude	Longitude	Study years	N rates
				(kg N ha^{-1})
Ames, IA	42.01	-93.74	1999 - 2021	0, 68, 135, 203, 268
Crawfordsville, IA	41.20	-91.49	1999 - 2021	0, 45, 90, 135, 180, 225, 268
Kanawha, IA	42.91	-93.79	2005 - 2021	0, 45, 90, 135, 180, 225, 268
Lewis, IA	41.33	-95.18	2001 - 2021	0, 45, 90, 135, 180, 225, 268
Chariton, IA	40.97	-93.42	1999 - 2021	0, 45, 90, 135, 180, 225, 268
Nashua, IA	42.94	-92.57	2005 - 2021	0, 45, 90, 135, 180, 225, 268
Sutherland, IA	42.93	-95.54	2000 - 2021	0, 45, 90, 135, 180, 225, 268
Brownstown, IL	38.95	-88.96	1999 - 2008	0, 50, 101, 151, 202, 252
DeKalb, IL	41.84	-88.86	1999 - 2008	0, 50, 101, 151, 202, 252
Dixon Springs Lowland, IL	37.46	-88.72	1999 - 2008	0, 50, 101, 151, 202, 252
Dixon Springs Upland, IL	37.43	-88.66	1999 - 2008	0, 50, 101, 151, 202, 252
Monmouth, IL	40.93	-90.73	1999 - 2008	0, 50, 101, 151, 202, 252
Perry, IL	39.80	-90.82	1999 - 2008	0, 50, 101, 151, 202, 252
Urbana, IL	40.08	-88.23	1999 - 2008	0, 50, 101, 151, 202, 252

Table S4. Equations used to calculate the yield (y) response to N (x) curves, the agronomic optimum N rate (AONR) and Economic optimum N rate (EONR) per site year and rotation combination

Model	Equation	AONR	EONR
Quadratic-plateau	$y = a + bx + cx^2$, $x < x_o$	-b/2c	pr-b/2c
	$y = a + b\,x_o + c\,x_o^2$, $x \geq x_o$		
Quadratic	$y = a + bx + cx^2$	-b/2c	pr-b/2c
Linear-plateau	$y = a + bx$, $x < x_o$	x_o	If $b > pr$, x_o; $b \leq pr$, 0
	$y = a + b\,x_o$, $x \geq x_o$		
Linear	$y = a + bx$	If $b > 0$, mx; $b \leq 0$, 0	If $b > pr$, mx; $b \leq pr$, 0

a = y-intercept
b = linear coefficient
c = quadratic coefficient
x_o = inflection point
mx = maximum applied nitrogen rate per study
pr = price ratio 5.6:1 N fertilizer: maize price (US$ 0.88 kg^{-1}: US$ 0.16 kg^{-1})

Supplementary Figures

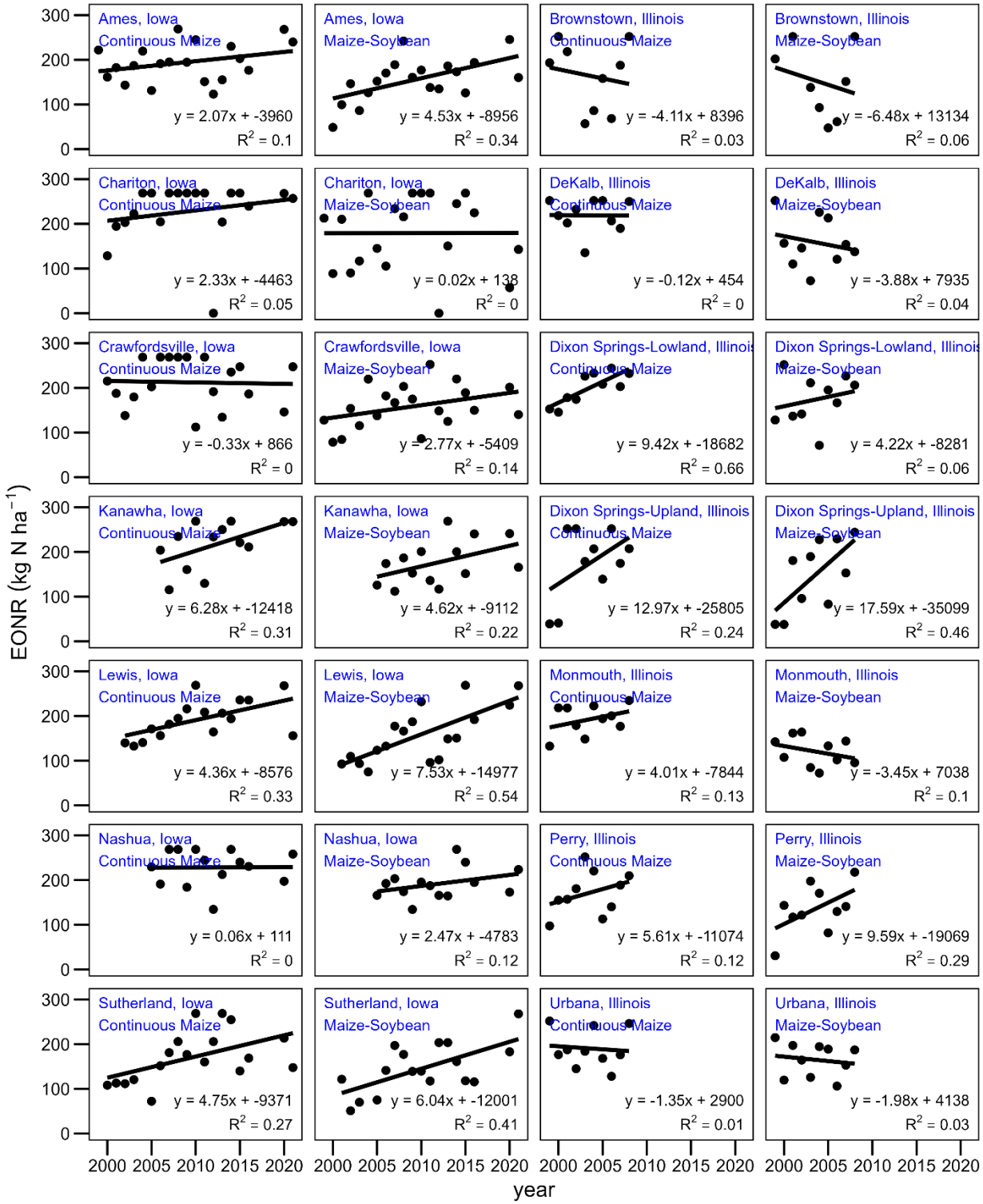

Fig S1. Trends of observed Economic Optimum Nitrogen (N) Rate (EONR) per location per continuous maize and maize-soybean crop rotations. The linear equation plus the R^2 value per panel are shown in the bottom right corner of each panel.

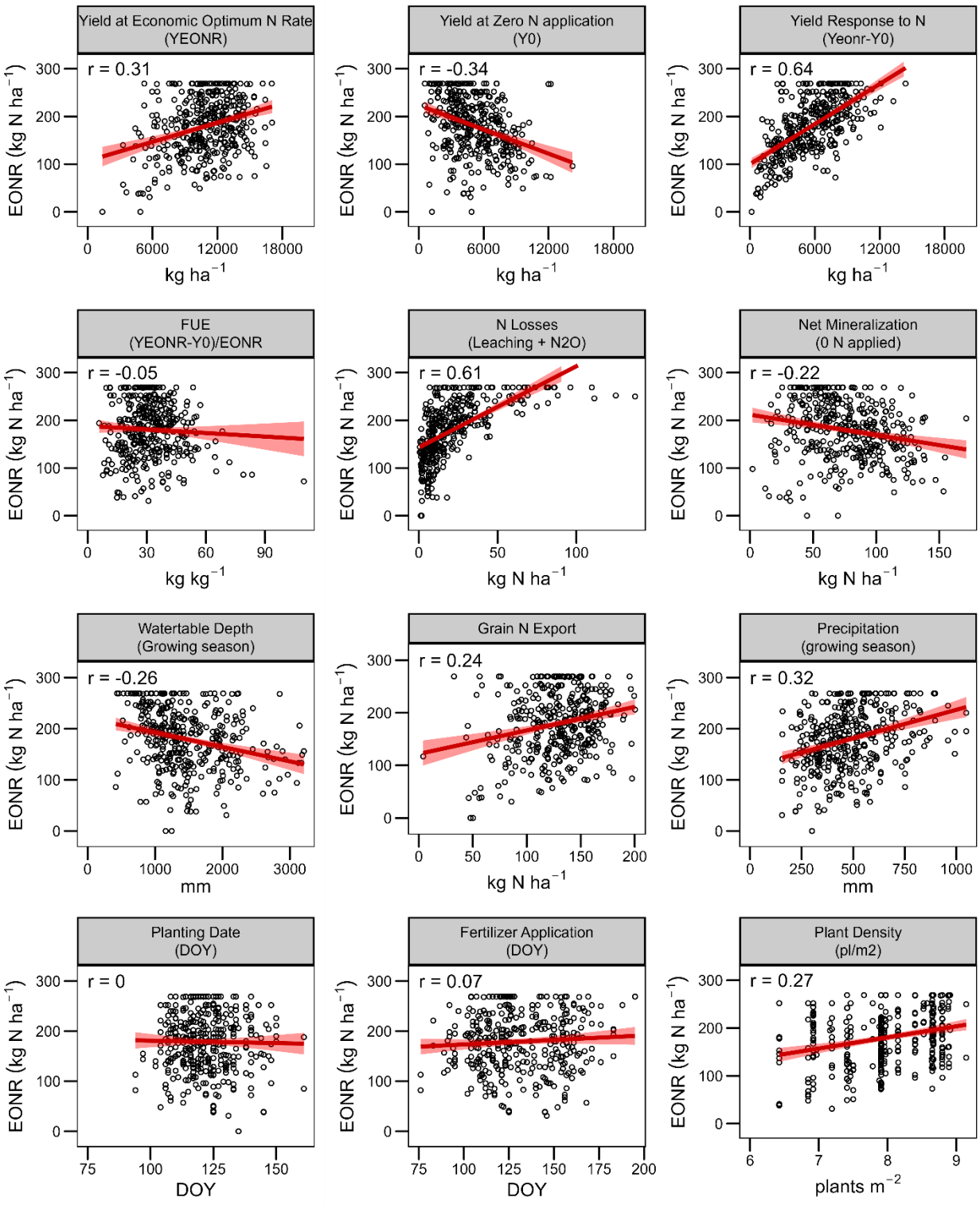

Fig S2. Pearson correlation (r) of the Economic optimum nitrogen (N) rate (EONR) to the explanatory variables. The shaded area represents a 95% confidence interval of the trendline.

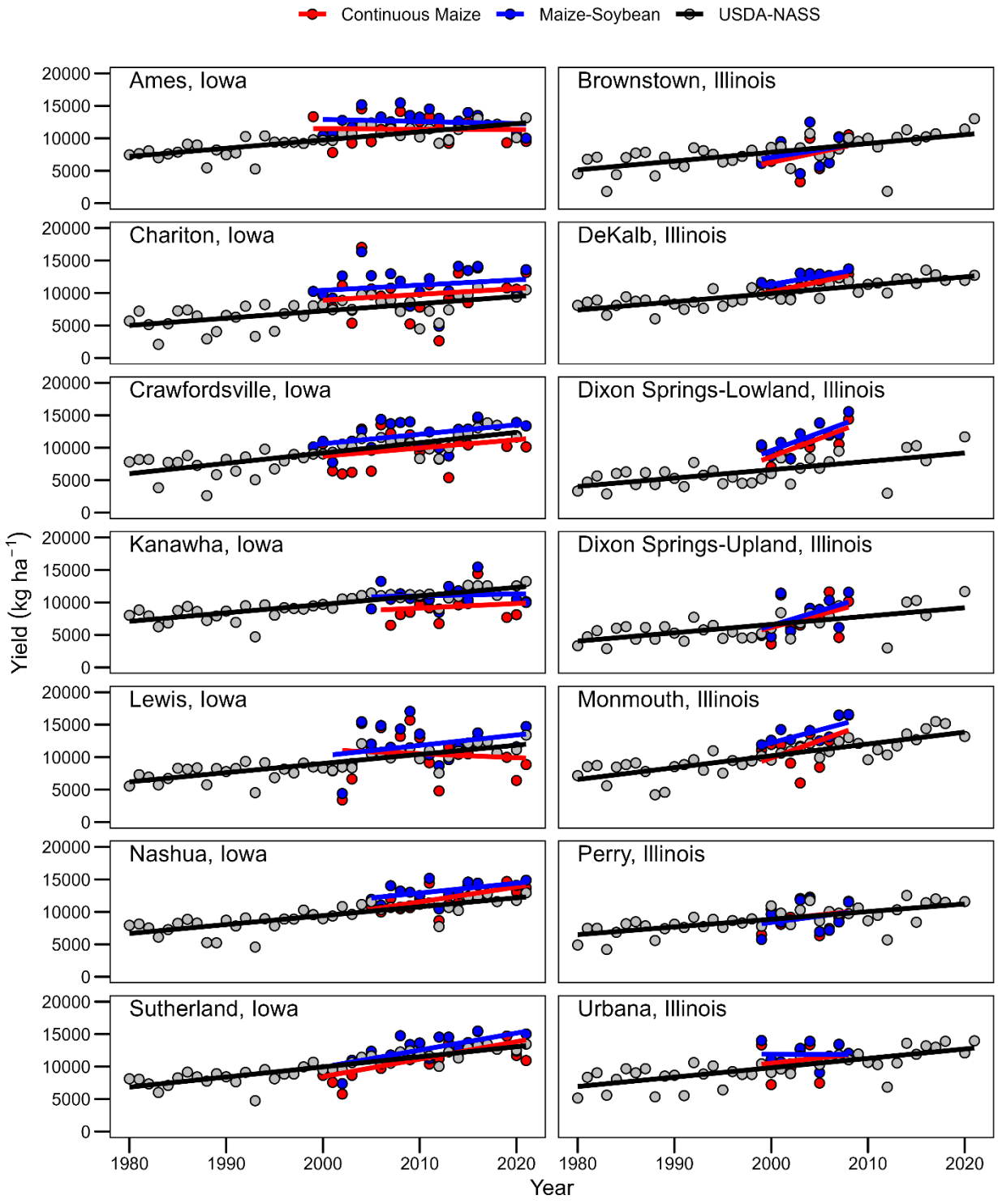

Fig S3. Long-term (1980-2021) county yields in Iowa and Illinois (*gray points*; USDA-NASS) compared to the annual values for the yield at the YAONR per crop rotation (*red* and *blue points* for continuous maize and maize-soybean, respectively).

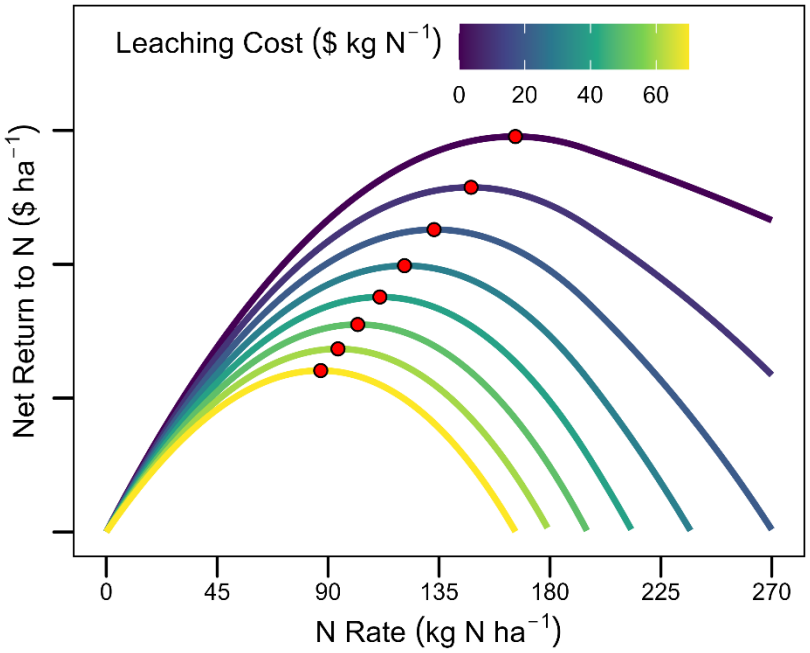

Fig S4. The effect of price associated per kg of nitrate (NO_3^-) leaching on the Environmental optimum Nitrogen (N) rate (EnvONR). The *red* points represent the EnvONR, and the lines are the net return to applied N (the value of grain – the cost of fertilizer and NO_3^- leaching water quality social cost) per associated cost of nitrate leaching.

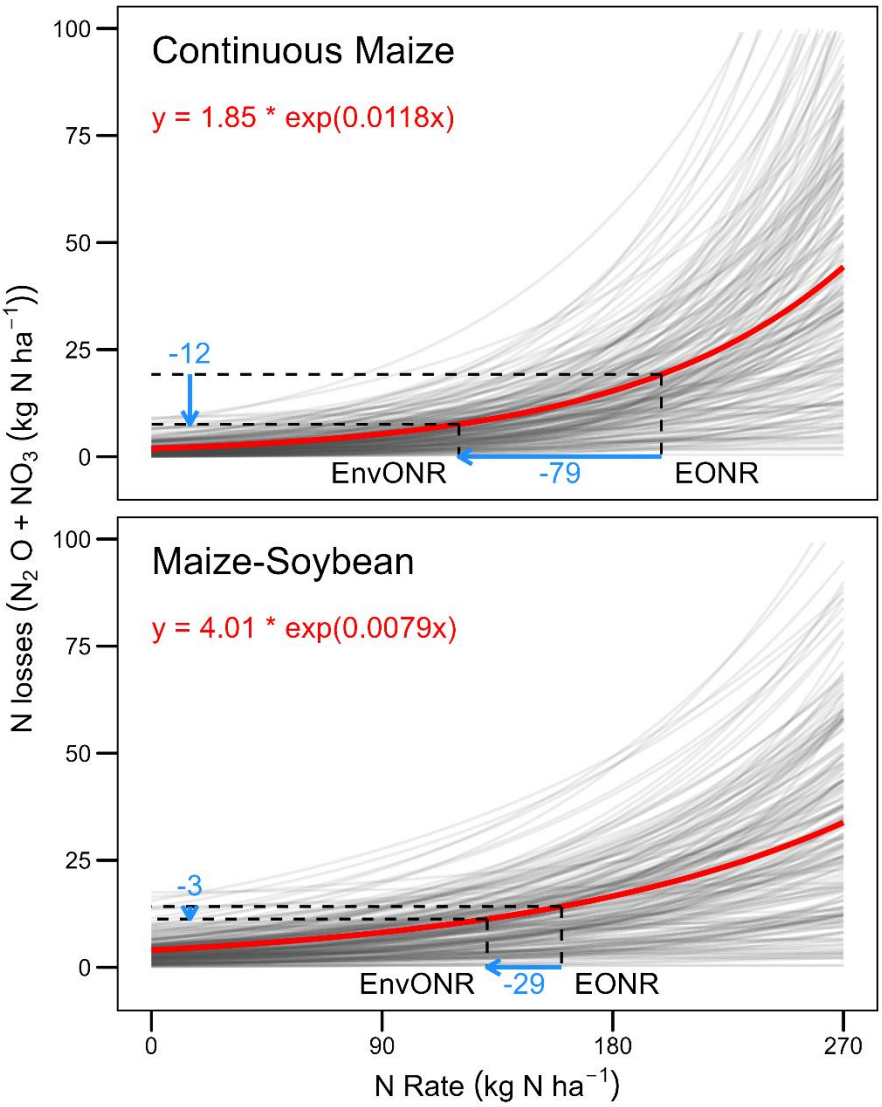

Fig S5. Simulated nitrogen (N) rate vs. total N loss relationship per crop rotation. The *red* and *gray* lines represent the best-fit curve through all the data, individual locations, and years. *Vertical* dashed lines represent the difference in N rates between the Economic Optimum N rate (EONR) and the Environmental Optimum N rate (EnvONR). The *horizontal* dashed lines show the difference in N losses between the EONR and EnvONR.

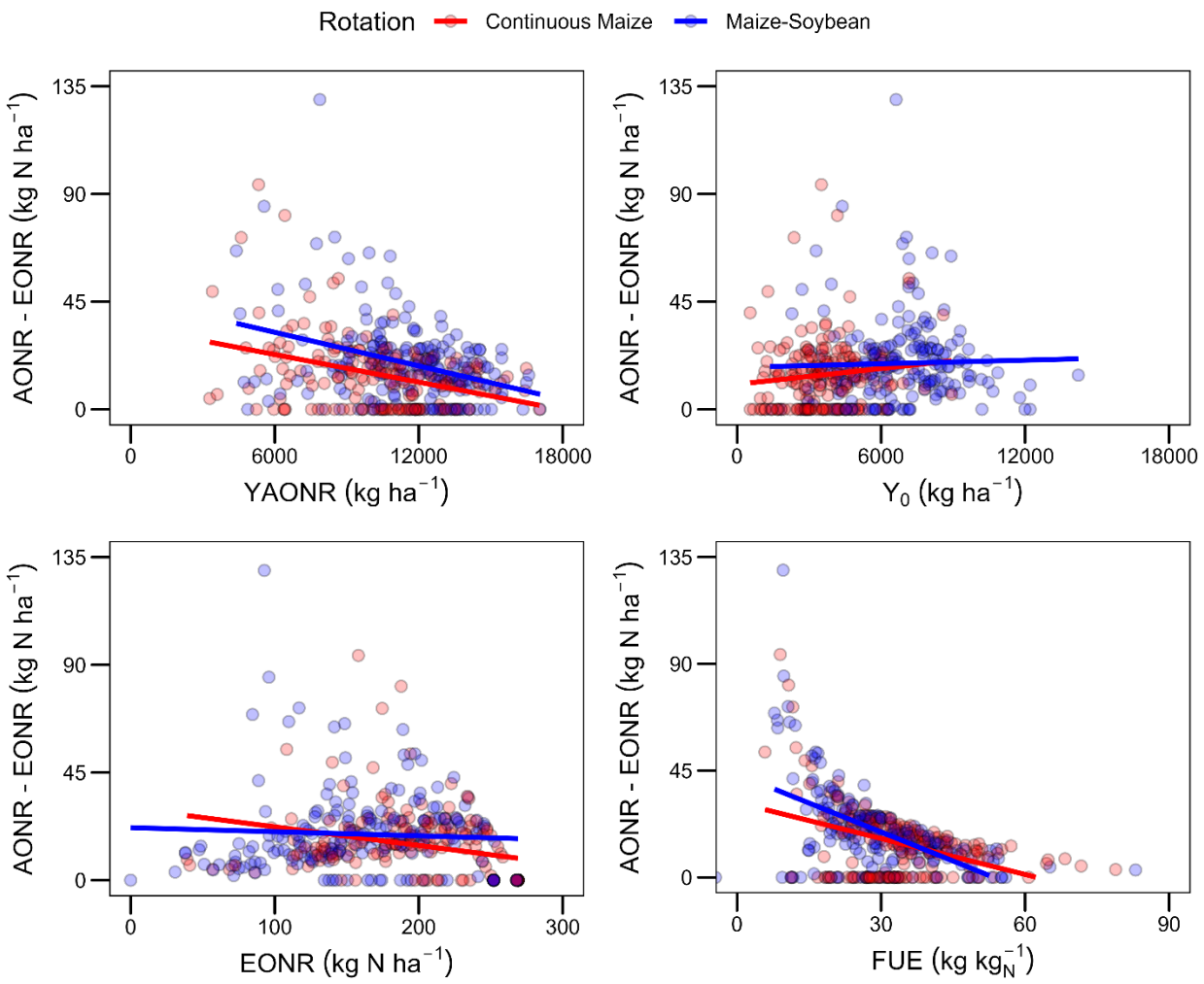

Fig S6. Comparison of factors influencing the difference between the agronomic and economic optimum N rate (AONR and EONR, respectively) per crop rotation. These factors include yield at the AONR (top left panel), yield at zero nitrogen application (top right panel), the EONR (bottom left panel), and the fertilizer use efficiency (bottom right panel).

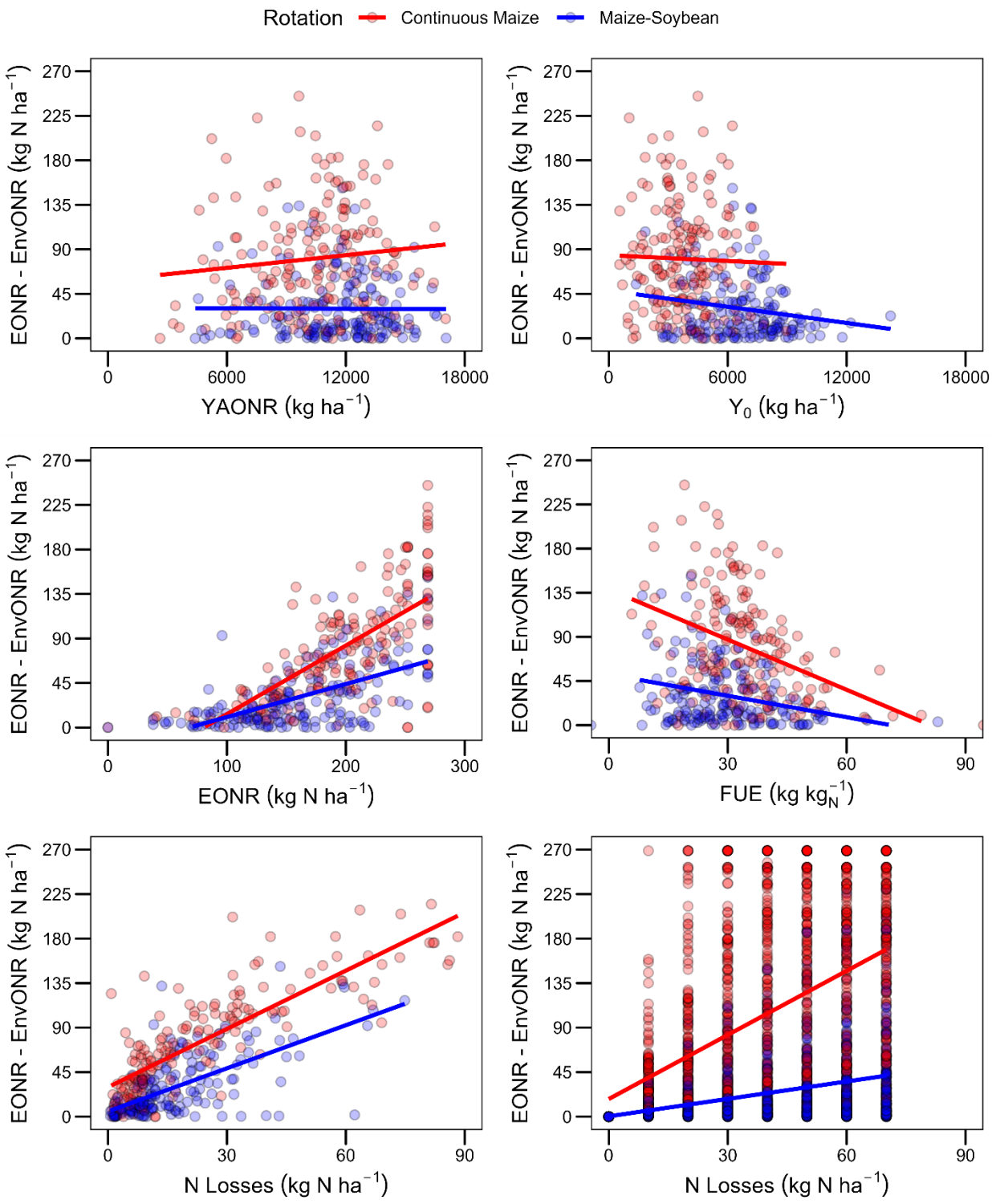

Fig S7. Comparison of factors influencing the difference between the economic and environmental optimum N rate (EONR and EnvONR, respectively) per crop rotation. These factors include the yield at the agronomic optimum N rate (top left panel), yield at zero N application (top right panel), EONR (middle left panel), fertilizer use efficiency (middle right panel), the sum of N losses at the EONR (i.e., nitrate leaching and N_2O emissions) (bottom left panel), and social cost of N losses (bottom right panel).

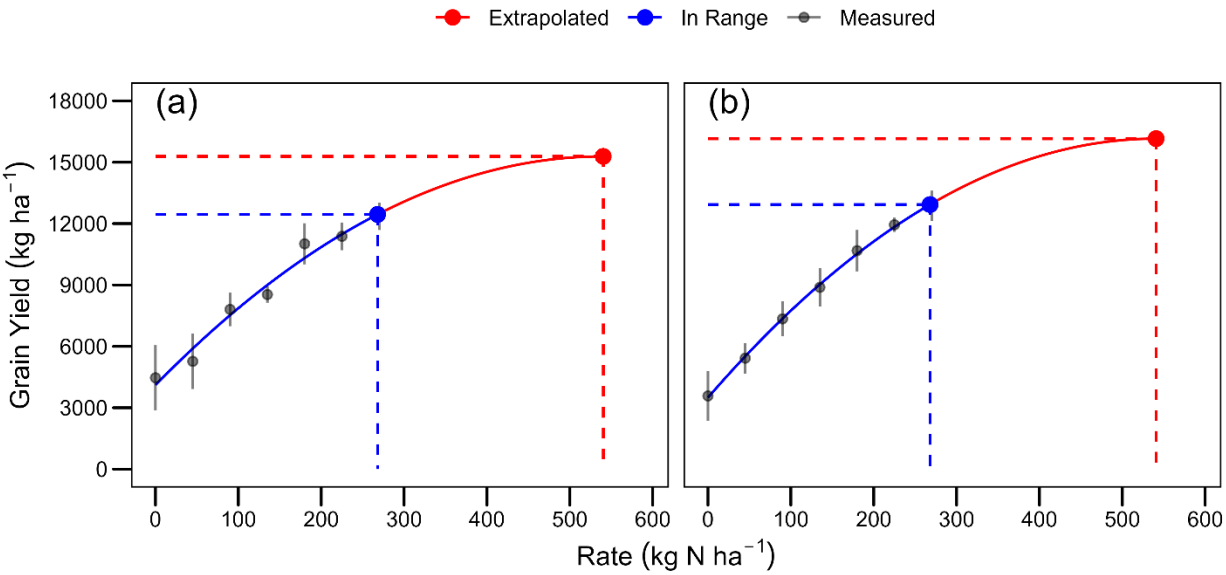

Fig S8. Conceptual figure depicting two examples of the risk in estimating the agronomic optimum N rate when extrapolating yield response functions past the known N rates. Examples are depicted from a continuous maize crop rotation for the site years of Crawfordsville 2004 (panel a) and Lewis 2010 (panel b). The vertical and horizontal dashed lines represent the agronomic optimum N rate and the yield associated with them used in this study (*blue line)* and extrapolated *(red line)*.

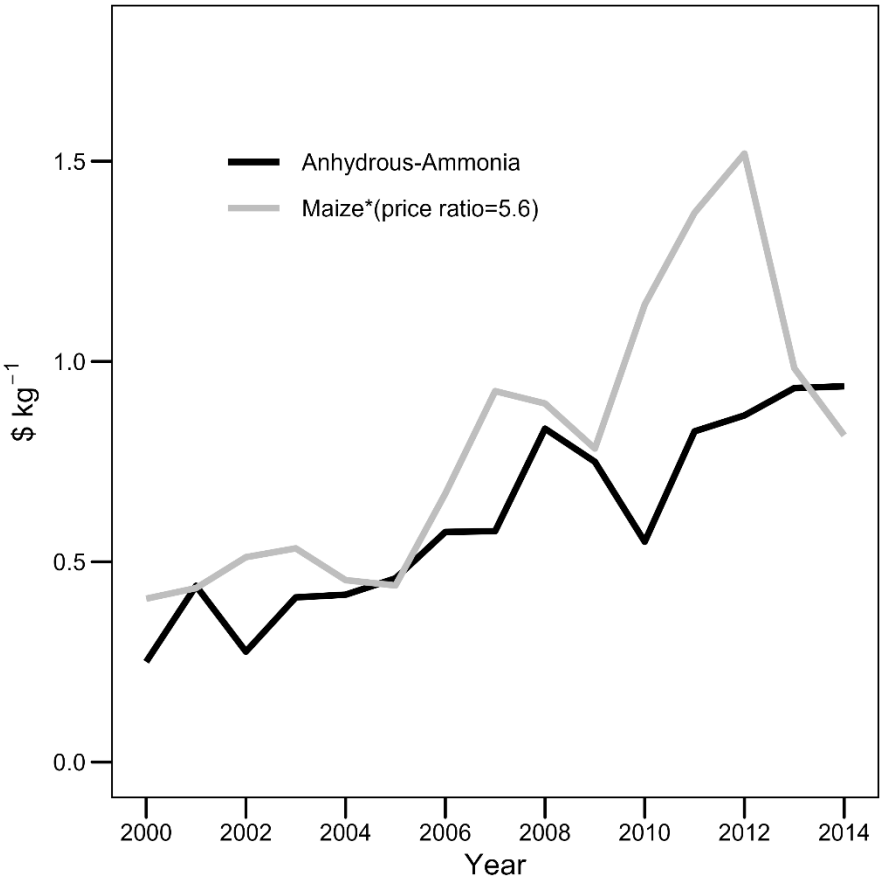

Fig S9. United States Department of Agriculture estimates for annual maize grain and anhydrous ammonia fertilizer prices. Scaled maize grain price and anhydrous ammonia was adjusted by multiplying the maize grain price by the price ratio of 5.6 (price of anhydrous/grain).

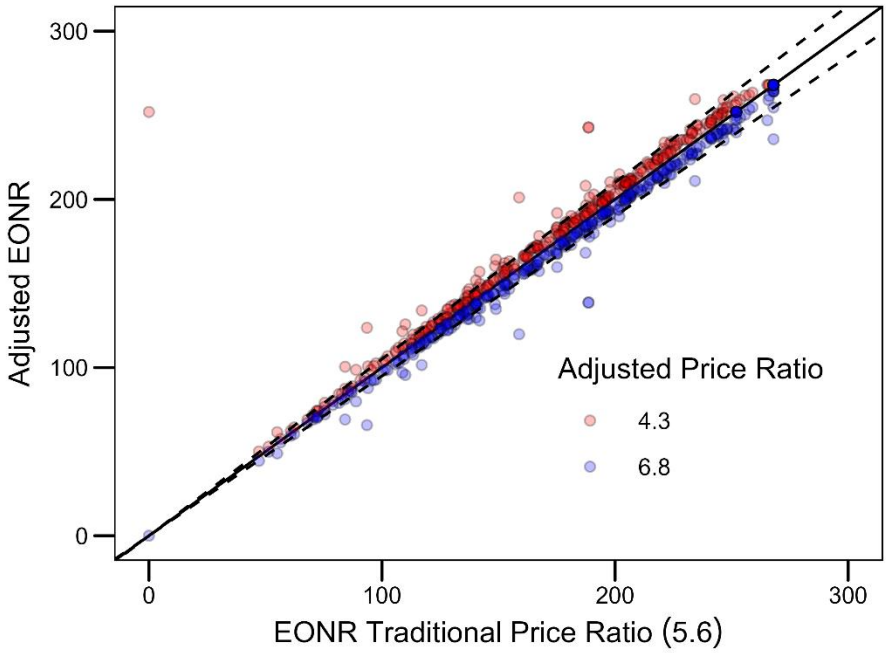

Fig S10. One-to-one comparison of using a traditional fertilizer to grain price ratio (i.e., 5.6) to an adjusted price ratio. The solid *black* line represents the one-to-one line between the EONR given the traditional and the adjusted price ratios, whereas the dashed lines represent a ±5% change from the one-to-one line.

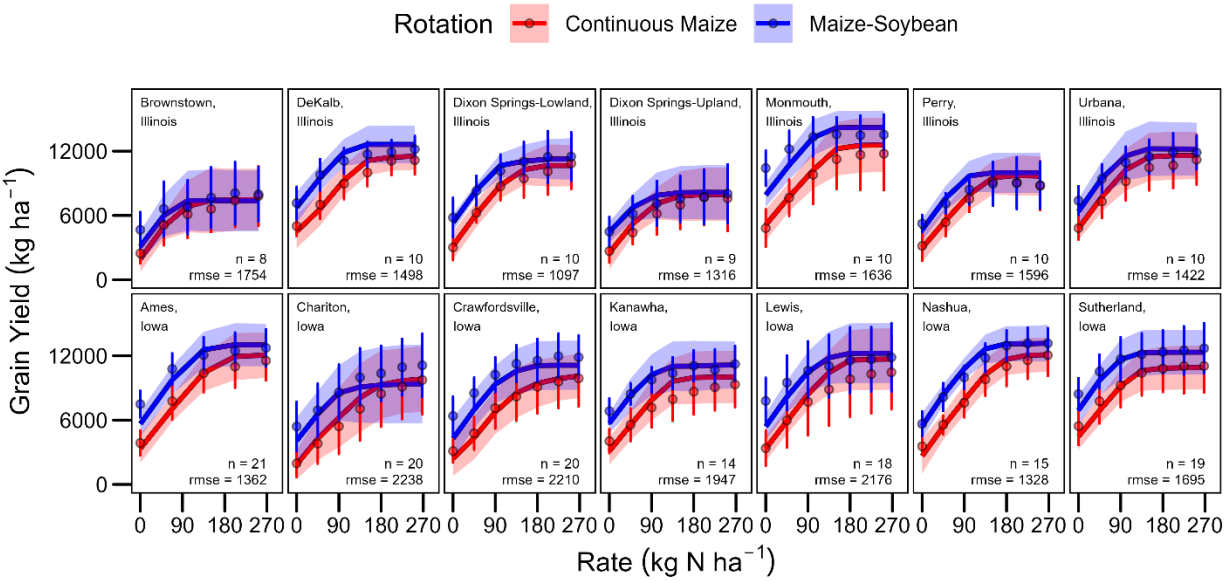

Fig S11. Measured (*points ± standard deviation bars*) and APSIM model simulated (*lines*) yield response to N fertilizer. Data are averaged across all years per location and rotation. The shaded region represents the mean simulated yield ± standard deviation. Source: Baum et al. (2023). The amount of years compared per site and rotation is denoted by n within each panel.