

Table S1 Summary of trial locations, planting dates, sensing dates, and harvest dates used in this study.

Trial	Year	State	Site	Planting date	Sensing date	Harvest date
1	2014	IA	Ames	2014-05-07	2014-06-26	2014-10-17
2	2014	IA	MasonCity	2014-05-09	2014-07-09	2014-10-16
3	2014	IL	Brownstown	2014-04-24	2014-06-13	2014-10-01
4	2014	IL	Urbana	2014-04-25	2014-06-15	2014-09-29
5	2014	IN	Loam	2014-05-19	2014-06-27	2014-10-21
6	2014	IN	Sand	2014-05-19	2014-06-27	2014-10-22
7	2014	MN	NewRichland	2014-05-21	2014-07-07	2014-10-22
8	2014	MN	StCharles	2014-05-16	2014-07-08	2014-10-28
9	2014	MO	Bay	2014-05-02	2014-06-20	2014-09-14
10	2014	MO	Troth	2014-05-02	2014-06-21	2014-09-14
11	2014	ND	Amenia	2014-05-23	2014-07-10	2014-10-01
12	2014	ND	Durbin	2014-05-23	2014-07-10	2014-10-15
13	2014	NE	Brandes	2014-04-19	2014-06-26	2014-10-03
14	2014	NE	SCAL	2014-05-07	2014-06-24	2014-10-22
15	2014	WI	Steuben	2014-05-07	2014-06-25	2014-11-05
16	2014	WI	Wauzeka	2014-05-06	2014-06-25	2014-11-05
17	2015	IA	Boone	2015-05-18	2015-07-07	2015-10-08
18	2015	IA	Lewis	2015-04-29	2015-07-07	2015-10-04
19	2015	IL	Brownstown	2015-04-28	2015-06-16	2015-09-23
20	2015	IL	Urbana	2015-04-23	2015-06-15	2015-09-24
21	2015	IN	Loam	2015-04-29	2015-06-17	2015-10-22
22	2015	IN	Sand	2015-04-29	2015-06-17	2015-10-22
23	2015	MN	NewRichland	2015-04-18	2015-06-26	2015-10-08
24	2015	MN	StCharles	2015-05-01	2015-07-01	2015-10-20
25	2015	MO	LoneTree	2015-04-17	2015-06-19	2015-09-17
26	2015	MO	Troth	2015-04-14	2015-06-10	2015-09-10
27	2015	ND	Amenia	2015-04-24	2015-06-14	2015-09-17
28	2015	ND	Durbin	2015-04-24	2015-06-18	2015-09-16
29	2015	NE	Brandes	2015-04-19	2015-06-29	2015-10-12
30	2015	NE	SCAL	2015-04-24	2015-06-24	2015-10-08
31	2015	WI	Belmont	2015-05-04	2015-07-01	2015-10-21
32	2015	WI	Darlington	2015-05-04	2015-07-01	2015-10-21
33	2016	IA	Crawford	2016-04-26	2016-06-20	2016-10-30
34	2016	IA	Story	2016-05-12	2016-06-28	2016-10-19
35	2016	IL	Shumway	2016-04-25	2016-06-16	2016-09-21
36	2016	IL	Urbana	2016-04-19	2016-06-13	2016-09-27
37	2016	IN	Loam	2016-05-20	2016-06-28	2016-10-12
38	2016	IN	Sand	2016-05-20	2016-06-28	2016-10-16
39	2016	MN	Becker	2016-04-27	2016-06-22	2016-10-14
40	2016	MN	Waseca	2016-05-06	2016-06-27	2016-10-24

41	2016	MO	Bradford	2016-04-16	2016-06-13	2016-10-03
42	2016	MO	Loess	2016-04-06	2016-06-06	2016-09-27
43	2016	MO	Troth	2016-04-13	2016-06-03	2016-09-27
44	2016	ND	Amenia	2016-05-06	2016-06-17	2016-10-07
45	2016	ND	Durbin	2016-05-06	2016-06-21	2016-10-16
46	2016	NE	Kyes	2016-05-05	2016-06-21	2016-09-29
47	2016	NE	SCAL	2016-05-12	2016-06-28	2016-10-18
48	2016	WI	Lorenzo	2016-04-23	2016-06-27	2016-10-24
49	2016	WI	Plano	2016-04-23	2016-06-30	2016-10-24

Table S2 Summary of vegetation index distribution and correlation analysis with corn yield in calibration database from 2014 to 2016 in US Midwest Corn Belt.

Vegetation index	Distribution summary			Correlation (r) with yield
	Mean	Max	Min	
DATT	0.61	0.84	0.43	0.61
MND	0.44	0.72	0.27	0.61
NREI	0.29	0.36	0.25	-0.61
MTCI	1.58	5.17	0.74	0.59
MRESR	2.58	6.17	1.74	0.59
MRETVI	0.10	0.33	-0.08	0.58
MDD	0.08	0.25	-0.04	0.58
MCCCI	0.47	0.78	0.30	0.57
RERVI	2.15	2.66	1.20	0.57
CIRE	1.15	1.66	0.20	0.57
REWDRVI	-0.59	-0.52	-0.75	0.56
MSR_RE	0.64	0.87	0.14	0.55
REVI _{opt}	75.34	97.79	18.58	0.54
MCARI1/OSAVI	0.49	1.07	0.16	0.54
MCARI1	0.33	0.77	0.03	0.54
RETVI	7.66	19.35	0.50	0.54
NDRE	0.36	0.45	0.09	0.53
REOSAVI	0.33	0.42	0.08	0.53
RESAVI	0.30	0.42	0.07	0.51
MRESAVI	0.28	0.42	0.06	0.51
RERDVI	0.28	0.43	0.07	0.50
NNIRI	0.62	0.69	0.41	0.46
REDVI	0.22	0.47	0.05	0.45
SAVI*SR	2.74	5.48	-0.59	0.41
MSAVI	0.57	0.73	0.15	0.40
RVI	8.68	14.31	1.61	0.38
SAVI	0.55	0.72	0.17	0.38
MSR	2.39	3.40	0.38	0.37
WDRVI	-0.01	0.26	-0.68	0.37

RDVI	0.52	0.72	0.16	0.37
VI _{opt}	3.37	4.27	2.51	0.37
MNLI	0.24	0.65	-0.19	0.37
OSAVI	0.66	0.76	0.20	0.36
NLI	0.51	0.73	-0.39	0.36
DVI	0.36	0.71	0.10	0.35
NDVI*RVI	0.27	0.68	-0.31	0.34
NDVI	0.76	0.87	0.23	0.33
MCARI2	0.75	0.96	0.20	0.33
TNDVI	1.12	1.17	0.86	0.33
NRI	0.08	0.25	0.05	-0.32
RENDVI	0.57	0.72	0.14	0.26
RESR	3.94	6.02	1.31	0.24
MTCARI	0.19	0.44	0.06	0.22
MNDRE	0.70	2.40	0.48	-0.18
MCARI2/OSAVI	1.13	1.33	0.85	0.16
MTCARI/OSAVI	0.29	0.73	0.16	-0.14
MERIS	0.23	0.49	0.16	0.09
MEVI	3.33	229.41	-40.37	-0.05
MREDVI	0.14	0.26	0.05	0.02
MCARI1/MRETVI	4.35	1352.48	-437.14	0.01
MTCARI/MRETVI	3.95	2083.12	-390.43	0.00

Note: The formulas and explanations of all vegetation indices were detailed in Lu et al. (2017).

Table S3 Evaluation of IRSCS performance with and without FNR-based threshold anchoring under different environmental and management conditions.

Strategy	Vegetation index	RMSE (kg N ha ⁻¹)	Blocks within ± 45 kg N ha ⁻¹ of EONR (%)	Difference from RSCS (percentage points)
RSCS	NDVI	64	69	-
IRSCS (threshold + bias correction)		62	74	+5
IRSCS (bias correction only)		63	73	+4
RSCS	NDRE	65	65	-
IRSCS (threshold + bias correction)		65	69	+4
IRSCS (bias correction only)		65	68	+3
RSCS	DATT	65	65	-
IRSCS (threshold + bias correction)		66	67	+2
IRSCS (bias correction only)		66	66	+1

Note: RSCS as baseline refers to the original vegetation index–based recommendation.

IRSCS (threshold + bias correction) represents the full IRSCS strategy, in which the recommendation range was constrained by the FNR-based threshold window and further

adjusted using $G \times E \times M$ -based bias correction rules.

IRSCS (bias correction only) represents a sensitivity analysis in which the FNR-based threshold window was removed and only the $G \times E \times M$ -based bias correction rules were retained.

Blocks within $\pm 45 \text{ kg N ha}^{-1}$ of EONR (%) indicates the percentage of blocks for which the absolute difference between the predicted N rate and the economic optimal nitrogen rate (EONR) was within 45 kg N ha^{-1} .

Difference from RSCS (%) represents the change in percentage points relative to the baseline RSCS.

Table S4 Comprehensive decision matrix of threshold refinement and bias-correction rules used in the IRSCS framework.

Water regime	Pre-sidedress weather	CRM (days)	Threshold window (kg N ha^{-1})	Bias correction	Notes
Rainfed	Dry	All	FNR - 135 to FNR + 45	-45 kg N ha^{-1}	Dry conditions tended to overpredict EONR
Rainfed	Wet	≥ 105	FNR - 135 to FNR + 45	+45 kg N ha^{-1}	Wet + long maturity tended to underpredict
Rainfed	Wet	< 105	FNR - 135 to FNR + 45	-45 kg N ha^{-1}	Wet + short maturity tended to overpredict
Rainfed	Normal	All	FNR - 135 to FNR + 45	0	Default scenario
Irrigated	All	All	FNR - 45 to FNR + 45	0	Narrower threshold used to reduce extreme values

Note: Pre-sidedress weather was classified using the precipitation normality index (PNI), defined as the ratio of cumulative precipitation during the pre-sidedress period to the long-term normal for the same period (see Section 2.5). Conditions were categorized as Dry, Normal, or Wet. CRM denotes crop relative maturity, and “All” indicates that the rule applies across all maturity classes. The threshold window defines the allowable range relative to FNR, and the bias correction indicates the fixed adjustment applied under each scenario

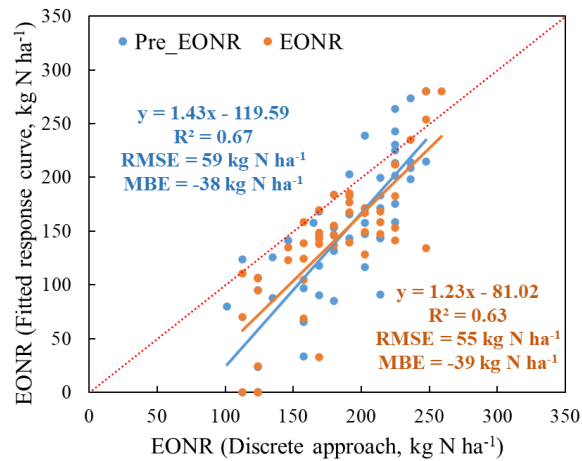


Figure S1 Comparison between discrete and fitted economically optimal nitrogen rates. Pre-EONR represents the economically optimal N rate determined from pre-plant N treatments, while EONR represents the final economically optimal N rate considering total N (pre-plant + sidedress). Discrete Pre-EONR and EONR were derived from the treatment means observed in this study, whereas the fitted economically optimal N rates were obtained from Ransom et al. (2021) based on response curve fitting. The dashed line indicates the 1:1 relationship. Overall, the fitted optima were generally lower than the discrete optima, while the two approaches showed moderate agreement ($R^2 = 0.63$ – 0.67).

Reference

- Lu, J., Miao, Y., Shi, W., Li, J., Yuan, F., 2017. Evaluating different approaches to non-destructive nitrogen status diagnosis of rice using portable RapidSCAN active canopy sensor. *Sci. Rep.* 7, 14073.
- Ransom, C.J., Clark, J., Bean, G.M., Bandura, C., Shafer, M.E., Kitchen, N.R., Camberato, J.J., Carter, P.R., Ferguson, R.B., Fernández, F., 2021. Data from a public–industry partnership for enhancing corn nitrogen research. *Agron. J.* 113, 4429–4436.