remote sensing

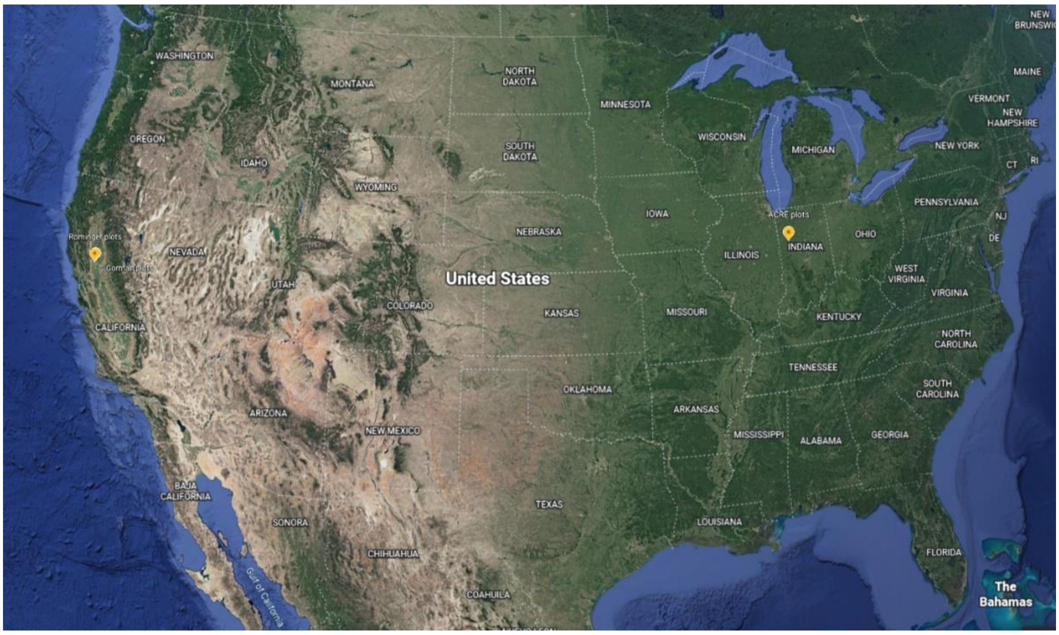

Figure S1. Experiment site locations in Woodland, California (yellow location pin marked as "Rominger plots") and West Lafayette, Indiana (yellow location pin marked as "ACRE plots") [75].

Table S1. Monthly weather averages (precip = precipitation; temp = temperature; deg = degrees).

Year	Location	Month	Mean Monthly Precip (mm)	Mean Air Temp (deg C)	30-Year Mean Monthly Precip (mm)	30-Year Mean Temp (deg C)
2014	Woodland	May	0	21.3	16.8	20.2
		June	0	23.3	5.6	23.5
		July	0	24.9	0	25.4
		August	0.8	23.6	1.3	24.8
		September	10.4	22.8	2.8	23.4
		October	22.6	19.6	21.3	18.8
2017	ACRE	May	156.0	15.8	120.4	16.7
		June	156.5	22.3	125.5	21.8
		July	179.8	23.5	112.8	22.9
		August	123.9	20.7	94.5	21.9
		September	50.5	19.2	78.0	18.4
		October	67.9	14.2	78.5	12.0

Table S2. Soil nutrient characteristics.

Year	Location	Soil Depth (cm)	pH	Organic Matter (%)	K (mg kg^{-1})	P (mg kg^{-1})	Mg (meq L^{-1})	Ca (meq L^{-1})	CEC (meq 100g^{-1})
2014	Gorman	0–15	7.6	1.60	225	43	3.0	2.8	22.5
		15–30	7.8	1.47	237	13	3.9	3.6	23.2
	Rominger	0–15	7.6	2.70	225	7	1.6	1.6	25.8
		15–30	7.6	2.26	169	4	1.7	1.9	26.9
2017	ACRE	0–20	6.4	3.1	151	20	610 ppm	2221 ppm	18.7

Treatment effect on biomass at R6: In the ground reference total dry matter model (stover + grain biomass at R6; TDM), the individual main effects of hybrid, N treatment, and plant density were significant, yet none of the interactions were significant (Table S3). This model accounted for approximately 60% of the variability in the data. Location effects, which included the blocking effects, accounted for the largest portion of explained variability. This was not surprising considering the large difference in environment between our locations in CA and IN. Significant biomass differences between hybrids were found across N rates and densities. Hybrids with the highest biomass were DAS05 and DAS08, significantly greater than DAS09 (Table S4). Increased N levels resulted in significantly greater biomass than those under low N conditions., across all hybrids. Additionally, higher biomass levels were evident at the high planting density.

Treatment effect on total N content: Total N content (TNC) was measured at V12, R1 and R6, and ground reference models were built for each of these measurements. The models for TNC had good fit with residuals less than 30% (Table S3). Location alone accounted for more than 60% of the variability in the data across all three models indicating the substantial effect that environment had on the availability and uptake of N, as anticipated. It is well documented that availability of mineral N (N sourced from organic or non-organic matter) is strongly affected by precipitation, temperature, microbial flora, and soil type [1,76–78]. For TNC at V12, only N and plant density had significant effects on the model (Table S3). By R1, neither hybrid nor N alone were significant main effects for TNC, though plant density continued as a significant fixed effect. Interestingly, there was some hybrid separation at R1 (Table S4). DAS03 had a significantly higher R1 TNC least square mean estimate than DAS07. At R6 all three main fixed effects, hybrid, N, and plant density were significant. However, there was no significant hybrid separation in the conservative Tukey–Kramer analysis, hence TNC was not identified as an N parameter warranting further investigation with HSIs.

Treatment effect on grain yield: The mixed model evaluating the treatment effects on grain yield at all 3 locations explained about 70% of the variability in the data (Table S3). Location effects accounted for more than 70% of the data variability revealing a substantial environmental effect on final grain yields. Hybrid was the only significant main fixed effect for yield.

Table S3. Mixed model analysis of treatment effects and interactions on physiological characteristics across 3 site-years (α = 0.10).

Var	Summary of Fit Model Statistics		Random Effects REML Var Comp Est (% of Total)		Type 3 Tests of Fixed Effects			
					Effect	DF	Den DF	Pr > F
TDM at R6	N Obs	427	Loc	37.4	H	8	12	0.052
					N	2	4	0.068
	AIC	1892.2	N*Loc	10.4	PD	1	363	<0.0001
					H*N	16	363	ns
	Res(%)	43.0	H*Loc	9.2	H*PD	8	363	ns
					N*PD	2	363	ns
TNC V12	N Obs	364	Loc	69.6	H	8	12	ns
					N	2	3	0.013
	AIC	-37.7			PD	1	301	0.002
			N*Loc	2.2	H*N	16	301	ns
	Res(%)	28.2			H*PD	8	301	ns
					N*PD	2	301	ns
TNC R1	N Obs	252	Loc	66.2	H	8	12	ns
					N	2	4	ns
	AIC	2138	N*Loc	10.8	PD	1	190	0.003
					H*N	16	190	0.040
	Res(%)	20.3	H*Loc	2.7	H*PD	8	190	0.007
					N*PD	2	190	ns

TNC R6	N Obs	363	Loc	60.3	H	8	12	0.077
					N	2	4	0.035
	AIC	3132.1	N*Loc	18.3	PD	1	299	0.045
					H*N	16	299	ns
	Res(%)	18.4	H*Loc	3	H*PD	8	299	ns
					N*PD	2	299	ns
GY	N Obs	501	Loc	37.2	H	8	12	0.005
					N	2	4	ns
	AIC	1747.9	N*Loc	25.4	PD	1	436	ns
					H*N	16	436	ns
	Res(%)	27.2	H*Loc	10.3	H*PD	8	436	0.016
					N*PD	2	436	0.001

Notes: TDM = Total Dry Matter (Mg ha^{-1}) (stover + grain); TNC = Total Nitrogen Content (kg N ha^{-1}); GY = Grain Yield at 15.5% moisture content; N Obs = number of observations; AIC = Akaike's Information Criterion; Loc = Location and Blocking effects; N = Nitrogen Treatment; H = Hybrid; PD = Plant Density; DF = Degrees of Freedom for numerator; Den DF = Degrees of Freedom for denominator; ns = Not Significant at $\alpha = 0.10$. For random effects % of total variability reported. For fixed effects, *p*-value reported.

Table S4. Least square mean estimates of plant biomass at R6 (TDM), and N content (TNC) at V12, R1 and R6 for the main fixed effects of hybrid (H), nitrogen (N), and plant density (PD).

Trt Class	**Main Fixed Effects**	**TDM R6 Estimate (Mg ha^{-1})**			**TNC V12 Estimate (kg N ha^{-1})**				**TNC R1 Estimate (kg N ha^{-1})**			**TNC R6 Estimate (kg N ha^{-1})**		
		Means		**SE**	**Means**		**LCL**	**UCL**	**Means**		**SE**	**Means**		**SE**
H	DAS01	22.53	AB	1.53	130	ns	127	133	170	AB	31	212	ns	28
	DAS02	22.71	AB	1.44	138	ns	136	140	173	AB	30	211	ns	27
	DAS03	23.47	AB	1.44	133	ns	131	135	195	A	30	209	ns	27
	DAS04	22.24	AB	1.44	134	ns	132	137	167	AB	30	199	ns	27
	DAS05	24.08	A	1.44	137	ns	135	140	174	AB	30	218	ns	27
	DAS06	22.25	AB	1.53	139	ns	136	142	179	AB	30	214	ns	28
	DAS07	21.37	AB	1.53	118	ns	116	121	148	B	31	185	ns	28
	DAS08	24.54	A	1.53	126	ns	124	129	184	AB	31	223	ns	28
	DAS09	20.68	B	1.44	130	ns	128	132	170	AB	30	194	ns	27
N	High_N	24.25	A	1.41	157	A	155	158	199	ns	31	251	A	29
	Med_N	22.67	AB	1.41	132	A	130	134	166	ns	31	202	AB	29
	Low_N	21.03	B	1.41	110	B	109	112	155	ns	31	169	B	29
PD	High	23.33	A	1.30	136	A	135	137	179	A	29	210	A	27
	Low	21.97	B	1.30	127	B	126	128	168	B	29	205	B	27

Note: Standard errors (SE) reported for all except TNC V12 where 95% upper and lower confidence limits (CL) are shown due to transformation of the response variable. Levels with different letters are significantly different by Tukey–Kramer HSD ($\alpha = 0.10$) within a treatment class (trt class) and physiological variable; ns = not significant.

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