Supplementary material

Band phosphorus and sulfur fertilization as drivers of efficient management of nitrogen of maize (*Zea mays* L.)

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Treatments of NP(S) fertilization were as follows: P_0 – control; P_1 – 8.7; P_2 – 17.4 and P_3 – 26.2 kg ha^{-1} of P (17%; 33% and 67% of total P uptake for grain yield = 9.0 t ha^{-1}). The N rates were as follows: N_0 - control; N_1 – 60; N_2 – 120 and N_3 –180 kg ha^{-1} of N. A nitrogen rate 180 kg N ha-1 corresponded to 100% of maize requirement for this nutrient in mineral fertilizers. The effect of mineral fertilization with NPS was compared to the ab-solute control (AC), without fertilization with these components. NPS were applied to the soil using fertilizer NPS(+Zn) in the proportion 20-20-35+0.3 (calculated for N, P_2O_5, SO_3, Zn). The fertilizer is based on two main chemical compounds: di-ammonium phosphate, DAP [$(NH_4)_2HPO_4$] and ammonium sulfate [$(NH_4)_2SO_4$]. Therefore, on plots with localized fertilization P1, P2 and P3, the doses of ammonium nitrogen (NH_4-N) were 20; 40 and 60 kg ha^{-1} of N, and those of sulfur were 14, 28 and 42 kg ha^{-1} of S, respectively. In order to simplify the notation of fertilization treatments, the NPS rates were recorded as P rates. The NPS fertilizer was applied while sowing the seeds. The fertilizer was banded to 5 cm below and away from the seeds. In treatments without NPS fertilization or with low total N rates, maize requirement for N was supplemented with ammonium nitrate (34% N) – broadcast application immediately before sowing. Potassium fertilization was carried out in early spring in the form of potassium salt K(S,Mg) in proportion 41(15,6.5) at the rate of 66.4 kg ha^{-1} of K, regardless of the NPS treatment.

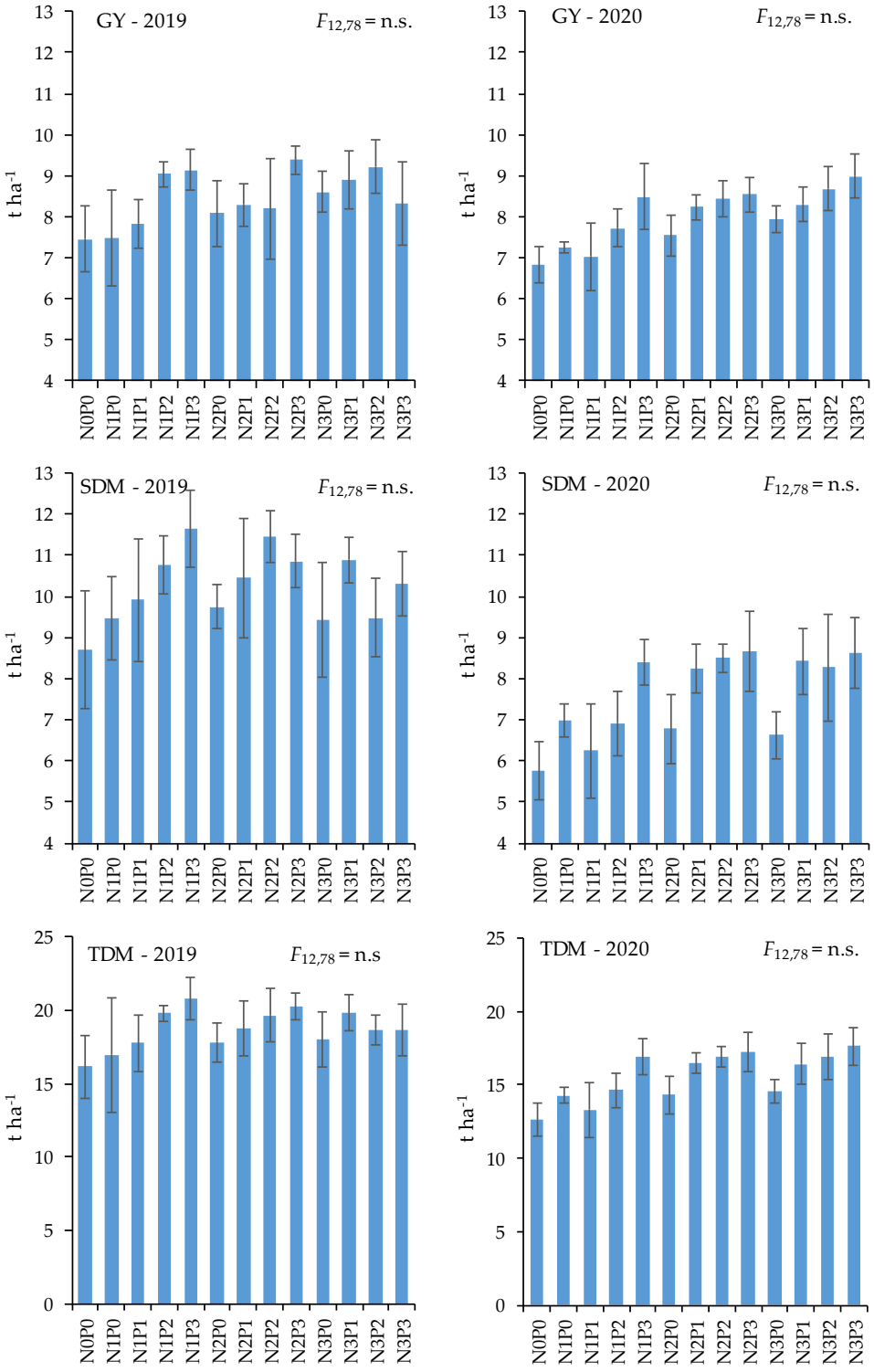

Figure S1. Maize grain yield (GY), crop residues biomass (SDM) and total dry matter (TDM) depending on the year (2019-2020) and fertilization treatments. Means within a column followed by the same letter indicate a lack of significant difference between the fertilized treatments (HSD test). Hatched bars represent 2×SEM ranges.

Table S1. Maize yield components depending on the year and fertilization treatments.

Year Treatment	Plant density No. ha^{-1}	Cob No. plant^{-1}	Thousand grain weight, g	No. of grains cob^{-1}
		Effect of the year (Y)		
2019	74945 ±728	0.99 ±0,01	228.8 ±1,9 [b]	517.6 ±11,8 [a]
2020	75000 ±750	0.99 ±0,01	311.6 ±3,7 [a]	447.8 ±7,8 [b]
		Effect of the treatment (T)		
N0P0	78214 ±1663	0.99 ±0,01	245.9 ±11,1 [b]	459.2 ±33,1
N1P0	74881 ±423	0.99 ±0,02	266.6 ±18,1 [ab]	447.2 ±39,4
N1P1	75357 ±674	0.98 ±0,01	252.0 ±15,6 [ab]	478.9 ±16,9
N1P2	74167 ±650	0.99 ±0,01	273.4 ±14,7 [ab]	508.0 ±17,7
N1P3	74167 ±404	1.00 ±0,01	273.7 ±17,5 [ab]	499.6 ±29,2
N2P0	74167 ±826	0.98 ±0,01	262.7 ±14,3 [ab]	497.1 ±25,5
N2P1	75833 ±892	0.99 ±0,02	279.3 ±18,8 [ab]	473.0 ±22,3
N2P2	76310 ±1034	0.98 ±0,01	280.2 ±20,2 [a]	464.0 ±25,3
N2P3	73214 ±1347	1.01 ±0,01	274.3 ±17,0 [ab]	509.3 ±34,6
N3P0	74881 ±2888	1.00 ±0,01	273.3 ±18,8 [ab]	474.5 ±37,4
N3P1	73929 ±461	1.00 ±0,01	280.6 ±17,3 [a]	479.2 ±30,4
N3P2	74643 ±961	0.99 ±0,005	276.8 ±16,3 [ab]	494.2 ±35,8
N3P3	74881 ±424	0.98 ±0,01	274.0 ±20,6 [ab]	490.9 ±21,7
		ANOVA results (significance level)		
Year	n.s.	n.s.	***	***
Treatment	n.s.	n.s.	*	n.s.
Y × T	n.s.	n.s.	n.s.	n.s.

***, **, * significant at $p < 0.001$; $p < 0.01$; $p < 0.05$, respectively; n.s. – non significant; means within a column followed by the same letter indicate a lack of significant difference between the fertilized treatments (HSD test).

Table S2. Dry matter (DM) at two growth sages (7 leaf and start of lowering), nitrogen concentration in DM; accumulation N in particular plant organs and total N accumulation by maize depending on the year and fertilization treatment

Treatment	Maize DM, g plant^{-1}		Nitrogen concentration g kg^{-1} DM				Nitrogen accumulation g ha^{-1}				
	7 leaf	Flowering	7 leaf	Flowering	Grain	Crop residues	7 leaf	Flowe-ring	Grain	Crop residues	Total
						Year 2019					
N0P0	7.6	81.3	37.8	20.5	14.7	10.0	22.1	125.2	109.9	87.4	197.3
N1P0	8.1	91.3	36.6	26.2	16.4	11.7	22.7	179.5	122.5	110.6	233.0
N1P1	9.5	78.9	40.2	27.7	16.9	12.4	28.6	163.9	132.1	123.4	255.5
N1P2	9.2	93.2	41.2	26.4	17.4	9.7	28.4	184.4	157.0	104.4	261.4
N1P3	9.3	97.3	42.2	25.0	17.8	12.7	29.4	182.2	162.7	147.3	310.0
N2P0	9.8	89.4	37.3	27.6	18.0	12.8	27.8	185.2	145.8	124.6	270.4
N2P1	10.0	89.6	40.9	27.6	17.7	11.0	30.8	185.5	146.5	115.0	261.4
N2P2	8.7	92.1	41.0	26.0	18.4	12.4	27.0	179.6	150.8	142.4	293.1
N2P3	10.2	89.6	40.8	27.1	16.8	12.6	31.3	182.3	157.4	136.8	294.2
N3P0	10.2	93.4	39.8	26.2	18.2	12.8	31.0	183.6	156.9	120.8	277.6
N3P1	11.1	85.5	38.4	24.6	18.7	10.2	32.5	157.8	166.5	111.2	277.6
N3P2	10.5	80.8	42.0	27.3	18.0	13.4	33.1	165.7	165.9	126.6	292.5
N3P3	10.2	95.0	41.9	27.3	18.4	12.8	32.3	194.4	152.7	131.8	284.5
						Year 2020					
N0P0	5.7	83.5	35.0	15.4	13.8	10.5	14.9	96.5	94.3	60.4	154.7
N1P0	6.8	99.6	39.1	15.4	14.7	10.5	19.9	115.0	106.6	73.6	180.3
N1P1	6.2	118.7	43.0	17.3	15.9	10.9	20.0	154.1	112.0	67.7	179.7
N1P2	7.8	102.7	42.1	19.3	16.3	11.0	24.5	148.8	125.7	76.1	201.8
N1P3	8.1	127.3	42.1	17.3	17.0	11.3	25.7	165.2	144.1	95.3	239.4
N2P0	6.4	102.2	44.5	18.0	15.4	12.4	21.5	138.2	116.1	84.0	200.1
N2P1	7.0	121.8	40.3	19.4	16.3	10.1	21.2	177.1	134.1	83.0	217.1
N2P2	9.0	123.6	43.5	19.8	17.0	11.2	29.4	183.3	143.0	95.2	238.2
N2P3	7.7	121.3	41.2	16.5	16.6	11.9	23.9	149.6	142.1	102.9	245.0
N3P0	6.5	113.4	45.6	18.0	17.0	11.0	22.3	153.5	134.9	72.8	207.7
N3P1	6.1	118.3	44.1	18.4	16.5	11.3	20.1	162.8	136.4	95.1	231.5
N3P2	8.6	131.1	42.5	19.8	17.5	12.6	27.5	195.1	152.0	104.2	256.1
N3P3	7.4	125.6	43.9	19.7	18.7	11.5	24.5	186.0	168.3	99.2	267.5

Table S3. Correlation matrix loadings and variance of the significant principal components (PCs) for grain yield of maize and nitrogen use efficiency (NUE) indices (n = 26)

Independent variable	Principal components		
	PC1	**PC2**	**PC3**
GY	0.66	-0.39	0.58
SDM	**0.88**	-0.35	-0.13
TN	**0.84**	-0.54	0.06
NHI	-0.68	0.26	0.62
PFP	0.35	**0.90**	-0.15
AN	0.58	0.48	0.53
PNB	0.46	**0.86**	-0.12
RE	**0.80**	0.50	0.12
IE	**-0.77**	0.54	0.26
PE	0.08	0.10	**0.73**
Ngap	-0.22	-0.92	0.25
Eigenvalue	4.3	3.8	1.7
Variance. %	39.4	34.6	15.9
Cumulative. %	39.4	74.0	89.9

Boldfaced loadings are > 0.70. Key: GY – grain yield; SDM – crop residues (straw) biomass; TN – total N accumulation; NHI – N harvest index; PFP - partial factor productivity of N; AE - agronomic efficiency of N; PNB - partial N balance; RE – apparent N recovery efficiency; IE – internal N utilization efficiency; N_{gap} – N gap.

Table S4. Pearson correlation matrix between maize grain yield (GY), crop residues dry matter (SDM), total nitrogen accumulation (TN) and nitrogen use indices (n = 26)

Traits	GY	SDM	TN	NHI	PFP	AN	PNB	RE	IE	PE
SDM	0.63**									
TN	0.80***	0.90***								
NHI	-0.16	-0.74***	-0.65*							
PFP	-0.22	0.05	-0.19	-0.10						
AN	0.56**	0.24	0.25	0.09	0.51*					
PNB	-0.12	0.15	-0.07	-0.15	0.99***	0.57**				
RE	0.39	0.46*	0.41*	-0.34	0.69***	0.82***	0.76***			
IE	-0.52**	-0.89***	-0.92***	0.81***	0.16	-0.00	0.05	-0.32		
PE	0.30	0.00	0.06	0.31	0.06	0.25	0.09	0.14	0.11	
Ngap	0.35	0.07	0.32	0.09	-0.95***	-0.42*	-0.92***	-0.59**	-0.26	0.04

***, **, * significant at $p < 0.001$; $p < 0.01$; $p < 0.05$, respectively. Key: GY – grain yield; SDM – crop residues (straw) biomass; TN – total N accumulation; NHI – N harvest index; PFP - partial factor productivity of N; AE - agronomic efficiency of N; PNB - partial N balance; RE – apparent N recovery efficiency; IE – internal N utilization efficiency; N_{gap} – N gap.

Table S5. Dry matter and nitrogen management indices depending on fertilization treatment (mean for two years).

Treatment	Dry matter management indices				Nitrogen management indices			
	DMA	DMR	DMRE	CDMR	NA	NR	NRE	CNR
N0P0	102.5 ±15.1	-10.3 ±10.4	-11.9 ±12.4	-8.2 ±10.5	0.78 ±0.14	0.53 ±0.08	36.5 ±5.2	43.3 ±8.6
N1P0	112.2 ±25.0	-14.1 ±18.6	-16.5 ±19.9	-5.7 ±17.9	0.79 ±0.32	0.74 ±0.21	36.8 ±8.1	57.9 ±22,3
N1P1	106.6 ±22.8	-8.1 ±19.2	-24.2 ±25.9	-4.3 ±18.6	0.76 ±0.28	0.86 ±0.22	38.0 ±10.0	57.3 ±14,0
N1P2	134.9 ±18.8	-21.8 ±14.9	-25.9 ±17.0	-16.4 ±12.6	0.91 ±0.18	1.00 ±0.14	44.6 ±4.5	53.7 ±7,6
N1P3	142.1 ±21.2	-23.2 ±16.9	-27.1 ±17.3	-16.6 ±13.3	1.40 ±0.26	0.67 ±0.17	29.0 ±6.9	35.4 ±9,2
N2P0	120.9 ±16.4	-15.8 ±13.1	-21.8 ±15.1	-13.4 ±13.3	1.02 ±0.19	0.75 ±0.15	33.5 ±5.8	44.0 ±9,5
N2P1	127.0 ±18.2	-17.8 ±15.6	-23.3 ±17.7	-14.6 ±12.7	0.74 ±0.22	1.11 ±0.16	45.4 ±5.8	62.6 ±10,0
N2P2	132.4 ±21.4	-23.0 ±15.9	-31.2 ±19.8	-19.0 ±12.7	1.07 ±0.35	0.86 ±0.22	33.2 ±8.5	52.3 ±14,8
N2P3	151.5 ±18.9	-28.5 ±15.2	-36.7 ±18.7	-21.4 ±11.9	1.49 ±0.18	0.57 ±0.16	24.2 ±5.9	27.8 ±7,3
N3P0	119.0 ±22.6	-6.8 ±16.7	-10.2 ±17.9	-1.2 ±13.9	1.06 ±0.28	0.91 ±0.17	41.4 ±7.7	50.6 ±10,6
N3P1	145.2 ±16.9	-28.9 ±16.0	-38.8 ±20.9	-22.7 ±12.5	1.31 ±0.25	0.74 ±0.16	32.8 ±6.6	38.9 ±8,8
N3P2	133.3 ±19.3	-13.5 ±17.2	-22.9 ±17.6	-10.0 ±15.4	1.28 ±0.26	0.85 ±0.21	33.7 ±7.6	41.6 ±11,7
N3P3	131.5 ±15.4	-16.1 ±12.5	-22.4 ±15.8	-13.8 ±10.7	1.15 ±0.25	0.99 ±0.17	37.4 ±6.1	48.3 ±9,8

DMI – dry matter increase ; DMR – dry matter remobilization; NI – nitrogen increase; NR – nitrogen remobilization; DMRE – dry matter remobilization efficiency; CDMR – contribution of DMR assimilates to grain; NRE – N remobilization efficiency; CNR – contribution of remobilized N to grain N content.

Table S6. Correlation matrix loadings and variance of the significant principal components (PCs) for grain yield of maize and dry matter and nitrogen management indices (n = 26)

Independent variable	Principal components		
	PC1	PC2	PC3
GY	0.68	0.57	-0.32
SDM	**0.93**	0.11	0.08
TN	**0.90**	0.37	-0.09
DM2	-0.56	**0.76**	-0.13
N*c*2	**0.91**	-0.02	0.36
N*a*2	0.58	**0.71**	0.34
DMRE	**-0.94**	0.27	-0.10
CDMR	**-0.94**	0.29	-0.07
NRE	**-0.81**	0.38	0.33
CNR	-0.63	0.34	0.69
DM1	**0.92**	0.11	0.10
N*c*1	-0.18	**0.77**	-0.32
N*a*1	**0.88**	0.32	0.01
Eigenvalue	8.1	2.7	1.1
Variance. %	62.3	20.6	8.4
Cumulative. %	62.3	82.9	91.3

Boldfaced loadings are > 0.70. Key: GY – grain yield; SDM – crop residues (straw) biomass; TN – total N accumulation; DM1 – dry matter of plant at 7 leaf growth stage; N*c*1 – N concentration at 7 leaf growth stage; N*a*1 - N accumulation at 7 leaf growth stage; DM2 – dry matter of plant at flowering; N*c*2 – N concentration at flowering; N*a*1 - N accumulation at flowering; DMRE – dry matter remobilization efficiency; CDMR – contribution of DMR assimilates to grain; NRE – N remobilization efficiency; CNR – contribution of remobilized N to grain N content.

Table S7. Pearson correlation matrix between maize grain yield (GY), crop residues dry matter (SDM), total nitrogen accumulation (TN) and nitrogen content at early growth stages and N remobilization and contribution to grain (n = 26)

Traits	**GY**	**SDM**	**TN**	**DM1**	**N*c*1**	**N*a*1**	**DM2**	**N*c*2**	**N*a*2**	**DMRE**	**CDMR**	**NRE**
SDM	0.68***											
TN	0.85***	0.90***										
DM1	0.66***	0.81***	0.83***									
N*c*1	0.32	-0.13	0.12	-0.16								
N*a*1	0.75***	0.78***	0.87***	0.96***	0.11							
DM2	0.10	-0.40*	-0.19	-0.44*	0.61**	-0.29						
N*c*2	0.47*	0.84***	0.78***	0.84***	-0.22	0.79***	-0.62**					
N*a*2	0.68***	0.65***	0.78***	0.61**	0.31	0.69***	0.20	0.64***				
DMRE	-0.45*	-0.88***	-0.73***	-0.82***	0.36	-0.72***	0.76***	-0.90***	-0.38			
CDMR	-0.46*	-0.89***	-0.73***	-0.80***	0.38	-0.70***	0.77***	-0.89***	-0.36	0.99***		
NRE	-0.38	-0.71***	-0.65***	-0.64***	0.32	-0.55**	0.67***	-0.63**	-0.12	0.83***	0.84***	
CNR	-0.46*	-0.47*	-0.51**	-0.49*	0.18	-0.44*	0.51*	-0.33	0.10	0.60**	0.63**	0.85***

***, **, * significant at $p < 0.001$; $p < 0.01$; $p < 0.05$, respectively. Key: GY – grain yield; SDM – crop residues (straw) biomass; TN – total N accumulation; DM1 – dry matter of plant at 7 leaf growth stage; Nc1 – N concentration at 7 leaf growth stage; Na1 - N accumulation at 7 leaf growth stage; DM2 – dry matter of plant at flowering; Nc2 – N concentration at flowering; Na1 - N accumulation at flowering; DMRE – dry matter remobilization efficiency; CDMR – contribution of DMR assimilates to grain; NRE – N remobilization efficiency; CNR – contribution of remobilized N to grain N content.