

Supplementary Materials

Soil Fertility Constraints and Exploratory Multivariate Classification of Appalachian Legacy Coal Mine Soils

Debsree Mandal, Jingxin Wang, Jamie Schuler and Shawn Grushecky

Abbreviations: PSR, phosphorus saturation ratio [$\text{molar Mehlich-3 P}/(\text{Al} + \text{Fe}) \times 100$]; LR, lime requirement; OM, organic matter; EC, electrical conductivity. Site names: Marion (sub-locations Rachel and Joanne); Webster (Pardee & Curtin; sub-locations Bolair and Ponds); Glen Rogers Rd and Turkey Creek East (Wyoming County); Monongalia (Reliance Minerals Inc.); Raleigh (WV Land Trust); Fayette, PA.

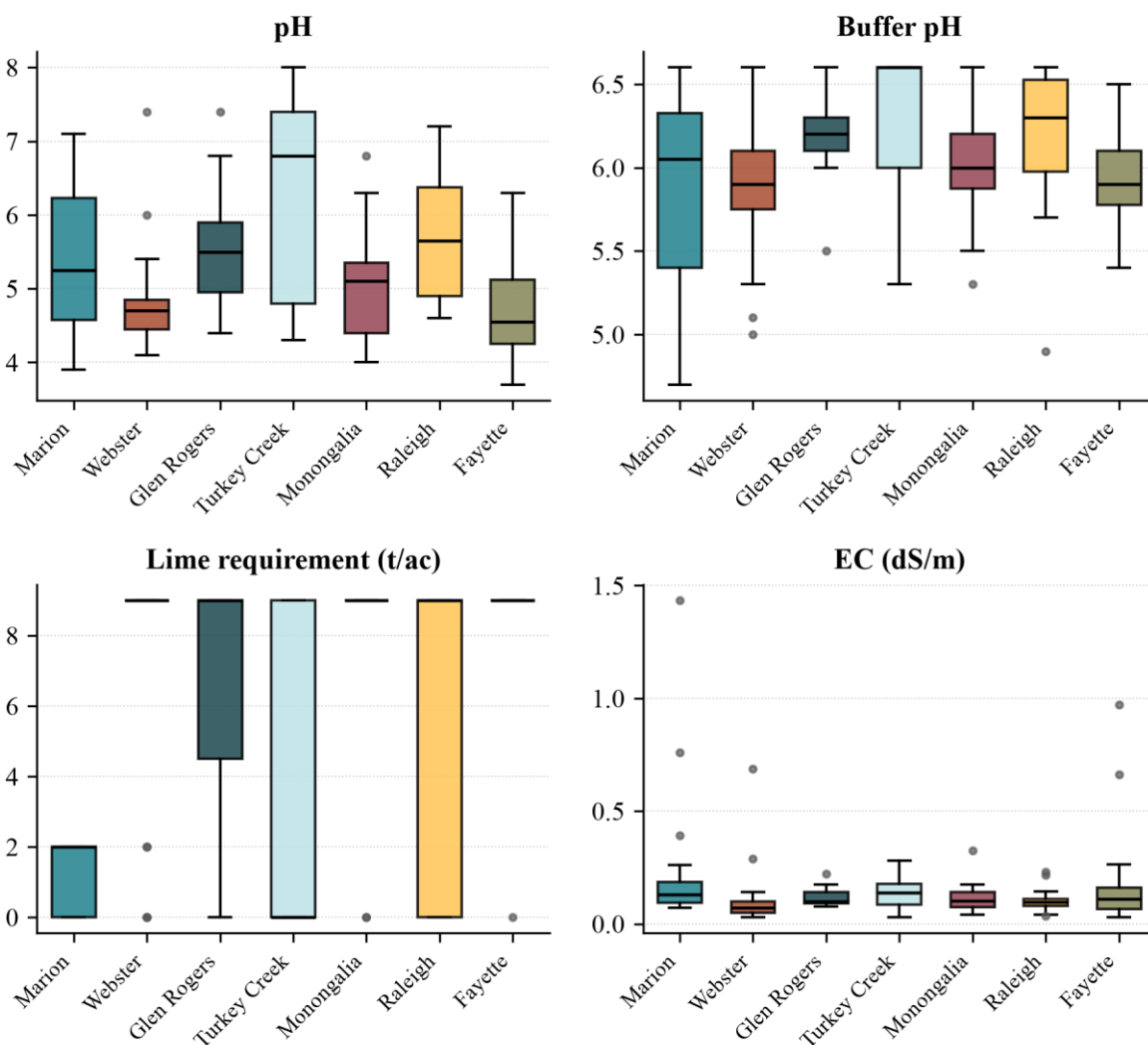


Figure S1. Acidity and buffering indicators (pH, buffer pH, lime requirement, and EC) by site. Boxes show the median and interquartile range; whiskers extend to $1.5 \times \text{IQR}$.

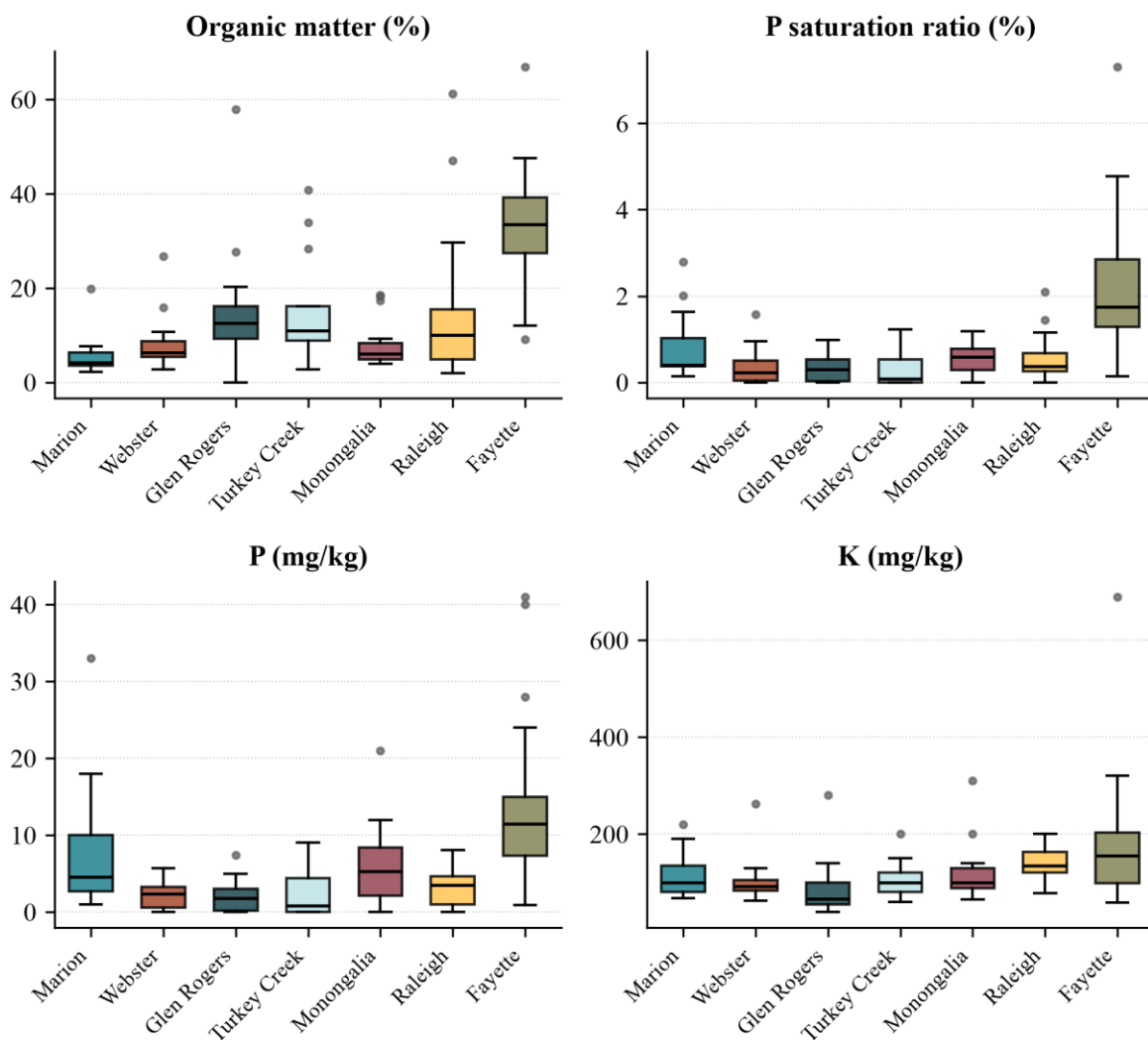


Figure S2. Organic matter and nutrient indicators (OM, PSR, P, and K) by site. Boxes show the median and interquartile range; whiskers extend to $1.5 \times \text{IQR}$.

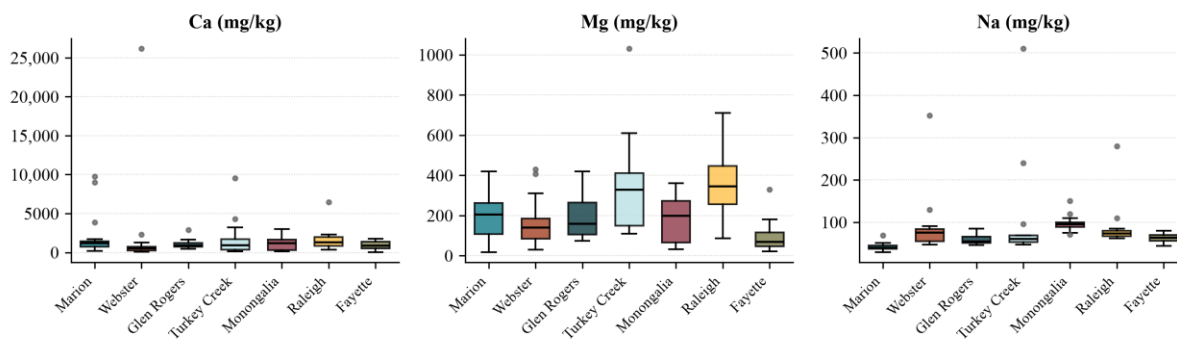


Figure S3. Exchangeable macro-cations (Ca, Mg, and Na) by site. Boxes show the median and interquartile range; whiskers extend to $1.5 \times \text{IQR}$.

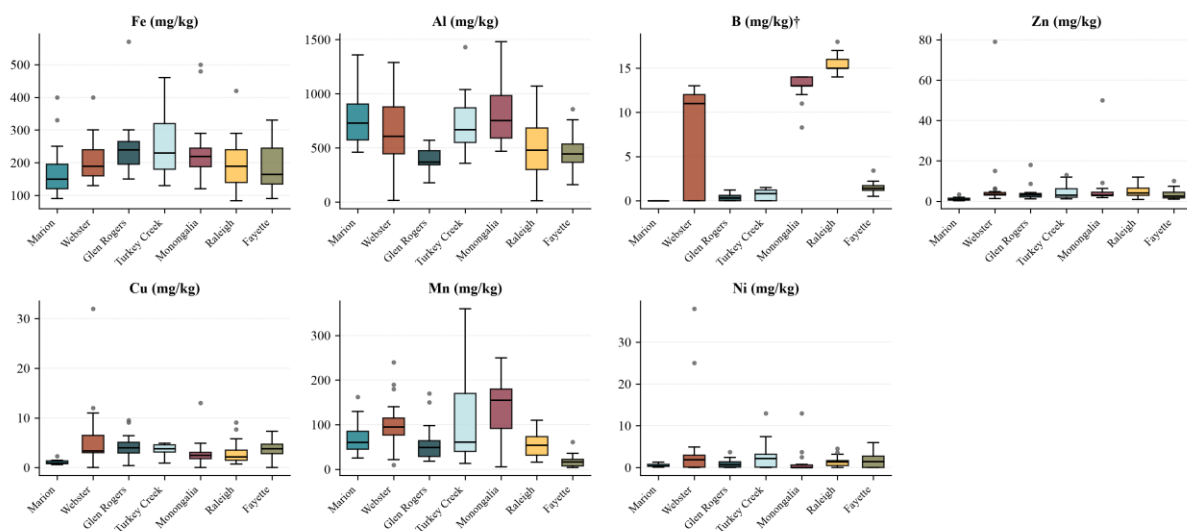


Figure S4. Micronutrients and trace elements (Fe, Al, B, Zn, Cu, Mn, and Ni) by site. Boron values coincided with laboratory batch (Table S7). Boxes show the median and interquartile range; whiskers extend to $1.5 \times \text{IQR}$.

Table S1. By-site descriptive statistics for 18 soil properties (mean, median, SD, minimum, maximum).

Property	Site	n	Mean	Median	SD	Min	Max
pH	Marion	20	5.33	5.25	0.99	3.90	7.10
	Webster	23	4.83	4.70	0.70	4.10	7.40
	Glen Rogers Rd	19	5.56	5.50	0.78	4.40	7.40
	Turkey Creek East	13	6.29	6.80	1.46	4.30	8.00
	Monongalia	20	5.06	5.10	0.72	4.00	6.80
	Raleigh	20	5.72	5.65	0.89	4.60	7.20
	Fayette, PA	20	4.75	4.55	0.69	3.70	6.30
Buffer pH	Marion	20	5.88	6.05	0.57	4.70	6.60
	Webster	23	5.87	5.90	0.39	5.00	6.60
	Glen Rogers Rd	19	6.23	6.20	0.25	5.50	6.60
	Turkey Creek East	13	6.32	6.60	0.41	5.30	6.60
	Monongalia	20	6.00	6.00	0.31	5.30	6.60
	Raleigh	20	6.19	6.30	0.43	4.90	6.60
	Fayette, PA	20	5.92	5.90	0.28	5.40	6.50
Lime requirement	Marion	20	1.40	2.00	0.94	0.00	2.00
	Webster	23	7.22	9.00	3.49	0.00	9.00
	Glen Rogers Rd	19	6.63	9.00	4.07	0.00	9.00
	Turkey Creek East	13	3.46	0.00	4.56	0.00	9.00
	Monongalia	20	8.10	9.00	2.77	0.00	9.00
	Raleigh	20	5.40	9.00	4.52	0.00	9.00
	Fayette, PA	20	8.55	9.00	2.01	0.00	9.00
Organic matter	Marion	20	5.43	4.25	3.73	2.20	19.80
	Webster	23	7.89	6.30	4.96	2.70	26.80
	Glen Rogers Rd	19	14.81	12.60	12.01	0.00	57.90
	Turkey Creek East	13	15.61	11.00	11.53	2.70	40.80
	Monongalia	20	7.72	6.10	4.64	4.00	18.50
	Raleigh	20	14.43	10.05	15.30	1.90	61.20
	Fayette, PA	20	32.73	33.50	12.66	9.10	66.90
EC	Marion	20	0.238	0.129	0.323	0.072	1.435
	Webster	23	0.108	0.072	0.137	0.029	0.686
	Glen Rogers Rd	19	0.119	0.100	0.039	0.078	0.223
	Turkey Creek East	13	0.138	0.138	0.077	0.029	0.281
	Monongalia	20	0.114	0.103	0.064	0.042	0.324

PSR	Raleigh	20	0.103	0.096	0.050	0.035	0.229
	Fayette, PA	20	0.183	0.110	0.230	0.029	0.972
	Marion	20	0.79	0.41	0.72	0.13	2.79
	Webster	23	0.36	0.23	0.39	0.00	1.58
	Glen Rogers Rd	19	0.32	0.29	0.31	0.00	0.98
	Turkey Creek East	13	0.27	0.08	0.39	0.00	1.22
	Monongalia	20	0.55	0.59	0.37	0.00	1.19
	Raleigh	20	0.54	0.37	0.52	0.00	2.09
	Fayette, PA	20	2.23	1.75	1.65	0.14	7.30
	Marion	20	7.74	4.55	7.66	1.00	33.00
P	Webster	23	2.23	2.40	1.75	0.00	5.70
	Glen Rogers Rd	19	1.96	1.80	2.05	0.00	7.40
	Turkey Creek East	13	2.43	0.80	3.01	0.00	9.00
	Monongalia	20	5.88	5.30	5.14	0.00	21.00
	Raleigh	20	3.34	3.50	2.39	0.00	8.10
	Fayette, PA	20	14.12	11.50	11.12	0.90	41.00
	Marion	20	115.25	99.50	42.11	68.00	220.00
	Webster	23	101.43	92.00	39.78	62.00	263.00
	Glen Rogers Rd	19	84.53	66.00	54.95	39.00	280.00
	Turkey Creek East	13	107.38	100.00	38.29	60.00	200.00
K	Monongalia	20	115.95	100.00	55.71	65.00	310.00
	Raleigh	20	138.45	135.00	31.95	78.00	200.00
	Fayette, PA	20	179.55	155.00	136.61	58.00	690.00
	Marion	20	2,008.50	1,210.00	2,631.56	190.00	9,760.00
	Webster	23	1,710.61	570.00	5,352.36	63.00	26,160.00
	Glen Rogers Rd	19	1,064.21	920.00	527.37	450.00	2,870.00
	Turkey Creek East	13	1,906.15	960.00	2,606.38	160.00	9,550.00
	Monongalia	20	1,170.00	1,240.00	856.17	150.00	3,020.00
	Raleigh	20	1,549.00	1,325.00	1,308.26	380.00	6,440.00
	Fayette, PA	20	894.60	910.00	530.49	22.00	1,780.00
Ca	Marion	20	182.80	205.00	113.22	17.00	420.00
	Webster	23	159.30	140.00	107.00	31.00	430.00
	Glen Rogers Rd	19	187.89	160.00	95.01	74.00	420.00
	Turkey Creek East	13	346.92	330.00	253.78	110.00	1,030.00
	Monongalia	20	180.00	200.00	106.73	32.00	360.00
Mg							

Fe	Raleigh	20	365.05	345.00	170.94	87.00	710.00
	Fayette, PA	20	91.45	70.00	72.23	22.00	330.00
	Marion	20	172.90	150.00	79.11	90.00	400.00
	Webster	23	205.17	190.00	67.29	130.00	400.00
	Glen Rogers Rd	19	243.16	240.00	92.20	150.00	570.00
	Turkey Creek East	13	258.46	230.00	101.89	130.00	460.00
	Monongalia	20	236.00	220.00	96.76	120.00	500.00
Al	Raleigh	20	194.70	190.00	76.43	84.00	420.00
	Fayette, PA	20	186.00	165.00	73.15	90.00	330.00
	Marion	20	767.00	730.00	235.08	460.00	1,360.00
	Webster	23	644.30	610.00	334.08	16.00	1,290.00
	Glen Rogers Rd	19	400.53	370.00	101.41	180.00	570.00
	Turkey Creek East	13	721.54	670.00	285.30	360.00	1,430.00
	Monongalia	20	799.00	755.00	263.66	470.00	1,480.00
Na	Raleigh	20	496.70	480.00	277.32	14.00	1,070.00
	Fayette, PA	20	469.50	445.00	172.21	160.00	860.00
	Marion	20	41.40	40.00	8.90	29.00	69.00
	Webster	23	84.22	76.00	61.37	47.00	352.00
	Glen Rogers Rd	19	57.68	55.00	10.05	46.00	85.00
	Turkey Creek East	13	109.69	61.00	130.57	47.00	510.00
	Monongalia	20	97.35	96.00	16.92	71.00	150.00
B	Raleigh	20	85.05	73.50	47.12	62.00	280.00
	Fayette, PA	20	63.00	63.50	9.35	44.00	80.00
	Marion	20	0.00	0.00	0.00	0.00	0.00
	Webster	23	6.73	11.00	6.00	0.00	13.00
	Glen Rogers Rd	19	0.32	0.30	0.35	0.00	1.20
	Turkey Creek East	13	0.75	0.80	0.60	0.00	1.50
	Monongalia	20	12.96	13.00	1.38	8.30	14.00
Zn	Raleigh	20	15.40	15.00	1.05	14.00	18.00
	Fayette, PA	20	1.49	1.40	0.61	0.50	3.40
	Marion	20	1.15	0.85	0.71	0.30	3.30
	Webster	23	7.34	3.40	15.85	1.40	79.00
	Glen Rogers Rd	19	3.94	3.20	3.76	1.20	18.00
	Turkey Creek East	13	4.92	3.10	3.88	1.20	13.00
	Monongalia	20	5.94	3.10	10.52	1.80	50.00

Cu	Raleigh	20	4.88	4.15	2.84	0.90	12.00
	Fayette, PA	20	3.40	2.55	2.42	1.00	10.00
	Marion	20	1.07	0.95	0.41	0.60	2.30
	Webster	23	5.98	3.40	6.43	0.00	32.00
	Glen Rogers Rd	19	4.16	4.00	2.33	0.40	9.50
	Turkey Creek East	13	3.65	3.80	1.18	0.90	4.90
Mn	Monongalia	20	2.85	2.50	2.71	0.00	13.00
	Raleigh	20	3.00	2.15	2.22	0.70	9.10
	Fayette, PA	20	3.87	3.80	1.74	0.00	7.30
	Marion	20	69.55	60.50	36.07	25.00	162.00
	Webster	23	100.51	95.00	52.36	9.70	240.00
	Glen Rogers Rd	19	58.68	49.00	41.01	18.00	170.00
Ni	Turkey Creek East	13	119.38	61.00	120.62	13.00	360.00
	Monongalia	20	135.82	155.00	65.30	5.50	250.00
	Raleigh	20	55.50	54.00	28.41	16.00	110.00
	Fayette, PA	20	17.22	17.00	13.72	3.90	61.00
	Marion	20	0.57	0.40	0.33	0.10	1.30
	Webster	23	4.24	1.90	8.93	0.00	38.00
	Glen Rogers Rd	19	0.93	0.70	0.97	0.00	3.70
	Turkey Creek East	13	3.02	2.20	3.87	0.00	13.00
	Monongalia	20	1.10	0.00	2.96	0.00	13.00
	Raleigh	20	1.45	1.35	1.26	0.00	4.50
	Fayette, PA	20	1.80	1.45	1.92	0.00	6.00

Units as in Table 2 of the main text.

Table S2. Significant pairwise site comparisons (Dunn's test; Bonferroni-adjusted $p < 0.05$) for properties with a significant Holm-adjusted Kruskal-Wallis test.

Property	Site 1	Site 2	z	p (Bonferroni)
pH	Webster	Turkey Creek East	-3.28	0.022
pH	Webster	Raleigh	-3.26	0.023
pH	Glen Rogers Rd	Fayette, PA	3.13	0.037
pH	Turkey Creek East	Fayette, PA	3.44	0.012
pH	Raleigh	Fayette, PA	3.42	0.013
Buffer pH	Webster	Glen Rogers Rd	-3.09	0.042
Buffer pH	Webster	Turkey Creek East	-3.45	0.012
Buffer pH	Turkey Creek East	Fayette, PA	3.29	0.021

Lime requirement	Marion	Webster	-4.33	<0.001
Lime requirement	Marion	Glen Rogers Rd	-3.61	0.007
Lime requirement	Marion	Monongalia	-4.82	<0.001
Lime requirement	Marion	Fayette, PA	-5.18	<0.001
Lime requirement	Turkey Creek East	Monongalia	-3.28	0.022
Lime requirement	Turkey Creek East	Fayette, PA	-3.60	0.007
Organic matter	Marion	Glen Rogers Rd	-4.16	<0.001
Organic matter	Marion	Turkey Creek East	-3.71	0.004
Organic matter	Marion	Fayette, PA	-6.99	<0.001
Organic matter	Webster	Fayette, PA	-5.32	<0.001
Organic matter	Monongalia	Fayette, PA	-5.33	<0.001
Organic matter	Raleigh	Fayette, PA	-4.02	0.001
EC	Marion	Webster	3.52	0.009
PSR	Marion	Fayette, PA	-3.06	0.046
PSR	Webster	Fayette, PA	-5.32	<0.001
PSR	Glen Rogers Rd	Fayette, PA	-5.39	<0.001
PSR	Turkey Creek East	Fayette, PA	-5.34	<0.001
PSR	Monongalia	Fayette, PA	-3.71	0.004
PSR	Raleigh	Fayette, PA	-4.16	<0.001
P	Marion	Webster	3.15	0.034
P	Marion	Glen Rogers Rd	3.47	0.011
P	Webster	Fayette, PA	-5.28	<0.001
P	Glen Rogers Rd	Fayette, PA	-5.50	<0.001
P	Turkey Creek East	Fayette, PA	-4.64	<0.001
P	Raleigh	Fayette, PA	-3.97	0.002
K	Webster	Raleigh	-3.26	0.024
K	Webster	Fayette, PA	-3.16	0.033
K	Glen Rogers Rd	Raleigh	-4.72	<0.001
K	Glen Rogers Rd	Fayette, PA	-4.63	<0.001
Ca	Marion	Webster	3.16	0.033
Ca	Webster	Raleigh	-3.51	0.010
Mg	Marion	Raleigh	-3.28	0.022
Mg	Webster	Raleigh	-4.01	0.001
Mg	Turkey Creek East	Fayette, PA	4.46	<0.001
Mg	Monongalia	Raleigh	-3.28	0.022
Mg	Raleigh	Fayette, PA	5.82	<0.001
Fe	Marion	Glen Rogers Rd	-3.25	0.024
Al	Marion	Glen Rogers Rd	4.63	<0.001
Al	Marion	Raleigh	3.25	0.024
Al	Marion	Fayette, PA	3.64	0.006
Al	Webster	Glen Rogers Rd	3.16	0.033
Al	Glen Rogers Rd	Turkey Creek East	-3.55	0.008
Al	Glen Rogers Rd	Monongalia	-4.92	<0.001
Al	Monongalia	Raleigh	3.54	0.009
Al	Monongalia	Fayette, PA	3.93	0.002
Na	Marion	Webster	-5.38	<0.001
Na	Marion	Turkey Creek East	-3.78	0.003

Na	Marion	Monongalia	-8.22	<0.001
Na	Marion	Raleigh	-5.94	<0.001
Na	Marion	Fayette, PA	-3.73	0.004
Na	Webster	Monongalia	-3.12	0.038
Na	Glen Rogers Rd	Monongalia	-5.44	<0.001
Na	Glen Rogers Rd	Raleigh	-3.19	0.030
Na	Turkey Creek East	Monongalia	-3.51	0.009
Na	Monongalia	Fayette, PA	4.49	<0.001
B	Marion	Webster	-3.71	0.004
B	Marion	Monongalia	-6.83	<0.001
B	Marion	Raleigh	-8.59	<0.001
B	Marion	Fayette, PA	-4.04	0.001
B	Webster	Monongalia	-3.36	0.017
B	Webster	Raleigh	-5.18	<0.001
B	Glen Rogers Rd	Monongalia	-5.29	<0.001
B	Glen Rogers Rd	Raleigh	-7.03	<0.001
B	Turkey Creek East	Monongalia	-3.94	0.002
B	Turkey Creek East	Raleigh	-5.50	<0.001
B	Raleigh	Fayette, PA	4.55	<0.001
Zn	Marion	Webster	-5.46	<0.001
Zn	Marion	Glen Rogers Rd	-4.26	<0.001
Zn	Marion	Turkey Creek East	-4.25	<0.001
Zn	Marion	Monongalia	-4.76	<0.001
Zn	Marion	Raleigh	-5.68	<0.001
Zn	Marion	Fayette, PA	-3.74	0.004
Cu	Marion	Webster	-5.76	<0.001
Cu	Marion	Glen Rogers Rd	-5.05	<0.001
Cu	Marion	Turkey Creek East	-4.44	<0.001
Cu	Marion	Raleigh	-3.21	0.028
Cu	Marion	Fayette, PA	-5.06	<0.001
Mn	Marion	Fayette, PA	4.31	<0.001
Mn	Webster	Fayette, PA	6.06	<0.001
Mn	Glen Rogers Rd	Monongalia	-3.43	0.013
Mn	Glen Rogers Rd	Fayette, PA	3.32	0.019
Mn	Turkey Creek East	Fayette, PA	4.24	<0.001
Mn	Monongalia	Raleigh	3.45	0.012
Mn	Monongalia	Fayette, PA	6.84	<0.001
Mn	Raleigh	Fayette, PA	3.39	0.015
Ni	Webster	Monongalia	3.15	0.035

94 significant pairs in total; 83 excluding boron. Positive z indicates higher mean rank for Site 1.

Table S3. Spearman rank correlation matrix for 18 soil properties (n = 135).

	pH	BpH	LR	OM	EC	PSR	P	K	Ca	Mg	Fe	Al	Na	B	Zn	Cu	Mn	Ni
pH	1.00																	

BpH	0.92	1.00																
LR	-0.58	-0.55	1.00															
OM	-0.16	-0.12	0.23	1.00														
EC	0.41	0.36	-0.36	0.15	1.00													
PSR	-0.16	-0.16	0.18	0.07	0.02	1.00												
P	-0.25	-0.29	0.21	0.06	0.03	0.92	1.00											
K	0.17	0.09	-0.08	0.17	0.30	0.29	0.30	1.00										
Ca	0.79	0.68	-0.47	0.03	0.63	-0.01	-0.06	0.26	1.00									
Mg	0.73	0.63	-0.38	-0.11	0.36	-0.27	-0.32	0.26	0.68	1.00								
Fe	-0.26	-0.24	0.21	0.17	0.13	-0.19	-0.10	-0.12	-0.16	0.01	1.00							
Al	-0.31	-0.44	0.06	-0.24	-0.07	-0.11	0.19	-0.00	-0.23	-0.17	0.23	1.00						
Na	0.13	0.10	0.11	0.04	0.02	-0.09	-0.06	0.22	0.15	0.22	0.15	0.22	1.00					
B	-0.01	-0.01	0.32	0.07	-0.21	0.10	0.11	0.19	0.05	0.16	0.02	0.01	0.67	1.00				
Zn	0.21	0.15	0.03	0.33	0.18	-0.09	-0.10	0.21	0.18	0.35	0.20	-0.10	0.54	0.33	1.00			
Cu	0.03	0.07	0.04	0.41	0.08	-0.22	-0.25	0.08	-0.04	0.04	0.15	-0.13	0.30	0.09	0.53	1.00		
Mn	0.24	0.17	-0.21	-0.46	0.09	-0.24	-0.22	-0.08	0.15	0.36	0.13	0.20	0.28	-0.00	0.32	-0.09	1.00	
Ni	0.08	0.03	-0.07	0.12	0.23	-0.18	-0.18	0.18	0.11	0.28	0.17	0.02	0.08	-0.06	0.36	0.26	0.26	1.00

BpH, buffer pH; LR, lime requirement. With $n = 135$, $|\rho| \geq 0.17$ corresponds to unadjusted $p < 0.05$; pairs with $|\rho| \geq 0.5$ are listed with Holm-adjusted p-values in Table 4 of the main text.

Table S4. Within-site Shapiro–Wilk p-values and Brown–Forsythe tests of homogeneity of variance among sites.

Property	Marion	Webster	Glen Rogers Rd	Turkey Creek East	Monongalia	Raleigh	Fayette, PA	BF W	BF p	Sites non-normal
pH	0.173	<0.001	0.279	0.040	0.215	0.075	0.145	3.62	0.002	2
Buffer pH	0.120	0.417	0.019	<0.001	0.882	0.006	0.975	2.25	0.042	3
Lime requirement	const.	<0.001	const.	const.	const.	const.	const.	2.78	0.014	7
Organic matter	<0.001	<0.001	<0.001	0.023	<0.001	<0.001	0.279	3.09	0.007	6
EC	<0.001	<0.001	0.009	0.744	0.003	0.010	<0.001	1.61	0.151	6
PSR	<0.001	0.002	0.026	0.002	0.418	0.003	0.007	4.82	<0.001	6
P	<0.001	0.096	0.015	0.009	0.038	0.399	0.003	4.88	<0.001	5
K	0.040	<0.001	<0.001	0.194	<0.001	0.892	<0.001	2.61	0.020	5
Ca	<0.001	<0.001	<0.001	<0.001	0.101	<0.001	0.436	0.64	0.699	5
Mg	0.381	0.007	0.084	0.014	0.083	0.692	<0.001	3.53	0.003	3
Fe	0.003	0.024	<0.001	0.350	<0.001	0.067	0.098	0.28	0.945	4
Al	0.261	0.671	0.096	0.163	0.078	0.773	0.808	3.20	0.006	0
Na	0.022	<0.001	0.017	<0.001	0.017	<0.001	0.882	1.95	0.078	6
B	const.	<0.001	0.005	0.048	<0.001	0.009	0.023	16.20	<0.001	7
Zn	0.007	<0.001	<0.001	0.017	<0.001	0.177	0.005	0.59	0.736	6
Cu	0.012	<0.001	0.155	0.134	<0.001	0.001	0.815	2.64	0.019	4

Mn	0.060	0.076	<0.001	0.007	0.606	0.336	0.002	5.64	<0.001	3
Ni	0.029	<0.001	0.010	0.005	<0.001	0.052	0.007	2.03	0.066	6

Values are Shapiro–Wilk p-values; const., two or fewer distinct values (test not computable, treated as non-normal). BF, Brown–Forsythe (median-centred Levene) statistic and p-value. Under the pre-specified rule, ANOVA would have required normality at all seven sites and BF $p \geq 0.05$; no property met both conditions.

Table S5. Pooled-sample distributional statistics (all sites combined; reported for completeness only).

Property	n	Skewness	Excess kurtosis	Shapiro–Wilk W	p
pH	135	0.87	−0.02	0.922	<0.001
Buffer pH	135	−0.72	0.37	0.942	<0.001
Lime requirement	135	−0.63	−1.55	0.644	<0.001
Organic matter	135	1.82	3.17	0.774	<0.001
EC	135	4.93	29.48	0.480	<0.001
PSR	135	3.34	15.96	0.674	<0.001
P	135	2.85	10.14	0.695	<0.001
K	135	4.28	29.68	0.676	<0.001
Ca	135	7.02	60.56	0.373	<0.001
Mg	135	1.73	5.10	0.869	<0.001
Fe	135	1.45	2.97	0.895	<0.001
Al	135	0.67	0.43	0.966	0.002
Na	135	5.36	35.37	0.488	<0.001
B	135	0.52	−1.60	0.744	<0.001
Zn	135	7.23	59.98	0.341	<0.001
Cu	135	4.62	33.95	0.654	<0.001
Mn	135	1.60	3.20	0.858	<0.001
Ni	135	6.11	44.80	0.402	<0.001

Pooled statistics combine samples from sites with different distributions and were not used to select site-comparison tests (main text, Section 2.4).

Table S6. Per-variable measures of sampling adequacy (MSA) for the primary PCA (17 properties, n = 135).

Property	MSA
pH	0.651
Buffer pH	0.659
Lime requirement	0.657
Organic matter	0.608
EC	0.577
PSR	0.520
P	0.515
K	0.701
Ca	0.716
Mg	0.759
Fe	0.703
Al	0.353
Na	0.733
Zn	0.771
Cu	0.716
Mn	0.656
Ni	0.758
Overall KMO	0.645

MSA < 0.5 is conventionally considered unacceptable; Al was retained a priori and its exclusion was evaluated in the sensitivity analyses (main text, Tables 6 and 7).

Table S7. Extractable boron and sodium by site and laboratory receipt date.

Site	Received	n	B median	B range	Na median	Na range
Marion	2024-02-23	20	0.00	0.0–0.0	40	29–69
Webster	2024-08-06	13	12.00	9.8–13.0	82	65–130
Webster	2025-07-22	10	0.00	0.0–0.7	55	47–352
Glen Rogers Rd	2025-07-22	19	0.30	0.0–1.2	55	46–85
Turkey Creek East	2025-07-22	13	0.80	0.0–1.5	61	47–510
Monongalia	2025-06-11	2	13.00	12.0–14.0	83	71–95
Monongalia	2025-06-13	18	13.00	8.3–14.0	96	75–150
Raleigh	2025-06-11	20	15.00	14.0–18.0	74	62–280

Fayette, PA	2025-07-22	20	1.40	0.5–3.4	64	44–80
-------------	------------	----	------	---------	----	-------

Values in mg kg⁻¹ (Mehlich-3). Within Webster, which was analyzed in two batches, B differed by about an order of magnitude between batches, and the entire Marion batch reported B = 0. B was therefore excluded from the primary multivariate analyses. Na at Webster also differed between batches (Mann–Whitney p = 0.003), so a batch contribution to Na cannot be excluded.

Table S8. Dataset reconciliation from the laboratory export to the analysis dataset.

Step	Records	Note
Records in laboratory export	156	
Exact duplicate records removed (same laboratory ID and site)	–20	136 records; matches the number of analyses invoiced by the laboratory
Cross-site duplicate (laboratory ID 25-3255 listed under Webster and Glen Rogers Rd)	–1	Retained under Webster, the site indicated by the field identifier
Site assignment corrected (laboratory ID 25-3296)	0	Listed under Turkey Creek East in the submitted dataset; assigned to Fayette (received with, and numbered in sequence with, the Fayette submission; same sampling date)
Site assignment corrected to the field log (laboratory IDs 24-4813 to 24-4815)	0	Listed under Glen Rogers Rd in the submitted dataset (laboratory label SITE 3, PLOT 1–3); assigned to Webster (Ponds sub-location, field samples 1–3) following the field sampling log: sampled 9 July 2024 and received by the laboratory on 6 August 2024, before the only Glen Rogers Rd visit (7 August 2024)
EC values completed from the WVU laboratory reports (25-3260, 25-3267, 25-2769)	0	Missing from the dataset analyzed in the original submission; one each from Webster, Glen Rogers Rd, and Raleigh
Unique field samples used in all analyses	135	Marion 20; Webster 23 (Bolair 20, Ponds 3); Glen Rogers Rd 19; Turkey Creek East 13; Monongalia 20; Raleigh 20; Fayette 20; complete data for all 18 properties
Samples with a recorded sampling position (spatial analyses)	132	132 distinct positions (field log and placemarks); positions not recorded for 2 Marion samples and 1 Glen Rogers Rd sample; the spatial analyses used 129 positions, excluding the 3 Webster Ponds positions, which lie about 15 km from Bolair
Records in the originally submitted analysis that were not field samples	7	Bootstrap-generated records included in the original submission (n = 143); excluded from all primary analyses and used only in a sensitivity analysis (n = 142; main text Tables 6 and 7)

No values were imputed. Each sample was a single core. The sampling target was 20 samples per site; it was met or exceeded at five sites (20–23 samples); at Glen Rogers Rd, 20 samples were collected but one was not analyzed (n = 19), and only 13 samples could be collected at Turkey Creek East, where much of the surface is bare coal refuse and spoil with limited safe access to the site interior (main text, Section 2.2).

Table S9. Laboratory methods used by the WVU Davis College Soil Testing Laboratory for the 18 soil properties.

Property	Procedure	Instrument	Unit	Reference
pH	Glass electrode, 1:1 soil:water (5 cm ³ soil + 5 mL water, 15 min); two-point calibration (pH 4.0, 7.0)	pH meter	–	WVU SOP; [Sikora & Moore 2014]
Buffer pH	Mehlich buffer (initial pH 6.6) added to the pH suspension; buffer acidity = (6.6 – BpH) × 4 meq (100 cm ³) ⁻¹	pH meter	–	Mehlich 1976
Lime requirement (LR)	Laboratory recommendation derived from buffer pH and crop code, for limestone of ≥ 90% CCE; reported as 0 or a single batch-specific rate in this dataset	Calculated	t ac ⁻¹	WVU SOP

Organic matter (OM)	Loss on ignition: mass loss between 105 °C (2 h) and 400 °C	Muffle furnace, balance	%	Nelson & Sommers 1996
Electrical conductivity (EC)	1:1 soil:water extract (20 g + 20 mL, shaken 30 min); cell calibrated with 0.01 M KCl (1.412 dS m ⁻¹)	Conductivity meter	dS m ⁻¹	Rhoades 1996
P, K, Ca, Mg, Na, Fe, Al, Mn, Zn, Cu, B, Ni	Mehlich-3 extraction, 2.5 cm ³ soil + 25 mL (1:10), 5 min at 200 oscillations min ⁻¹ , immediate filtration; mg kg ⁻¹ = (extract mg L ⁻¹ – blank) × 10	ICP-OES (PerkinElmer 2100)	mg kg ⁻¹	Mehlich 1984; WVU SOP
Phosphorus saturation ratio (PSR)	Molar Mehlich-3 P/(Al + Fe) × 100, reported by the laboratory as P saturation; verified by recalculation	Calculated	%	Sims et al. 2002

Sample preparation: air-dried below 30 °C, crushed, and sieved to < 2 mm. Reporting resolution: 0.1 mg kg⁻¹ for macronutrients (P, K, Ca, Mg, Na) and 0.01 mg kg⁻¹ for micronutrients; the ICP-OES detects macronutrients to 0.1 mg L⁻¹ and micronutrients to 0.01 mg L⁻¹. Values reported by the laboratory as zero were analyzed as zero. Quality control: method blank and check samples in each extraction run; internal loam reference soil after every 60 samples; calibration verified every 30 samples, with reanalysis of all samples since the last acceptable check if a check failed; participation in the North American Proficiency Testing program since 2014. Ni is reported on the laboratory reports, although it is not listed among the calibration standards in the published SOP. Source: Pena-Yewtukhiw, E.M., Operational Procedures WVU Davis College Soil Testing Lab (2021), https://researchrepository.wvu.edu/cgi/viewcontent.cgi?article=4220&context=faculty_publications.

Table S10. Sampled extent, spacing of sampling positions, and Mantel tests of geographic versus soil-chemical distance by site.

Site	n	n located	Positions	Hull area (ha)	Max. distance (m)	Median NN (m)	NN range (m)	Mantel r	p
Marion	20	18	18	4.9	505	35	24–66	0.34	0.002
Webster	23	20	20	7.7	412	41	15–92	–0.05	0.646
Glen Rogers Rd	19	18	18	3.8	548	26	6–58	0.17	0.042
Turkey Creek East	13	13	13	2.1	285	35	9–105	0.13	0.210
Monongalia	20	20	20	2.9	307	27	19–58	0.14	0.076
Raleigh	20	20	20	1.8	437	18	2–37	–0.06	0.696
Fayette, PA	20	20	20	2.6	220	22	8–76	–0.07	0.719

Coordinates in UTM zone 17N. NN, nearest-neighbour distance. Mantel r, Spearman correlation between geographic distance and Euclidean distance on the 17 winsorized, standardized properties used in the PCA; one-sided p from 999 permutations. Marion comprises two sub-locations (Rachel and Joanne) about 0.3 km apart, which inflates its maximum distance. At Webster, only the 20 Bolair positions were used; the three Ponds positions, about 15 km away, are too few for a separate within-sub-location analysis and were excluded (n located refers to the positions used).

Table S11. Within-site global Moran's I for each soil property (inverse-distance weights).

Property	Marion	Webster	Glen Rogers Rd	Turkey Creek East	Monongalia	Raleigh	Fayette, PA
pH	0.38**	–0.01	0.17*	0.07	0.17**	0.12	–0.05
Buffer pH	0.35**	0.07*	0.14*	0.02	0.21**	0.11	–0.06
Lime requirement	0.24*	–0.02	–0.02	0.03	–0.04	0.15	–0.00
Organic matter	0.04*	–0.06	–0.04	0.12*	–0.08	–0.10	0.04*
EC	0.01	–0.06	–0.05	0.16*	0.02*	–0.07	–0.07
PSR	0.10*	0.13*	–0.02	–0.07	–0.05	0.51*	–0.02
P	0.06*	0.11*	–0.09	–0.05	–0.00	0.21	0.01
K	–0.00	–0.05	–0.00	–0.04	–0.14	0.16	–0.11
Ca	0.12*	–0.06	0.03	0.19*	0.21**	–0.10	–0.02
Mg	0.41**	–0.01	0.00	–0.05	0.21**	0.07	–0.14
Fe	–0.07	–0.13	–0.09	0.01	–0.11	–0.11	–0.02
Al	–0.10	0.11*	–0.02	0.14*	0.20**	0.03	0.01
Na	–0.08	–0.06	–0.00	–0.09	–0.02	0.00	–0.06

B	const.	-0.09	0.05	0.23**	-0.06	-0.21	-0.00
Zn	0.10*	-0.06	-0.02	-0.03	-0.05	-0.15	0.01
Cu	-0.11	-0.00	0.00	-0.12	-0.06	-0.04	0.20**
Mn	-0.05	-0.14	-0.11	0.03	0.14**	-0.03	-0.14
Ni	-0.08	-0.04	-0.34	-0.02	-0.06	0.01	-0.11

Values are Moran's I; the expectation under no autocorrelation is $-1/(n-1)$ (-0.05 to -0.08). * one-sided permutation $p < 0.05$ (999 permutations); ** also significant after Benjamini–Hochberg FDR control across the 125 tests. const., constant values (B at Marion). Only samples with a recorded position were used (at Webster, Bolair positions only) (Table S10).

Table S12. Public mine-land records at the sampling positions of each site.

Site	Record	Located positions	Status	Nearby inventoried problems
Marion	WVDEP permits R000282 and O002183 (American Bituminous Power Partners; issued 26 Mar 1982 and 2 Feb 1983); refuse fills: Joanne refuse area, Joanne slurry impoundment	18/18 within permits	Permit active; inspection status RC (reclaimed, chemical treatment of water)	Nearest e-AMLIS problem 0.6 km (Rachel portals)
Webster	Bolair: WVDEP permit U013883 (Spring Ridge Coal Co.; issued 20 Jul 1983; revoked 12 Sep 1997); refuse fill (18.5 ac); special-reclamation areas U-138-83 and R-722. Ponds: no permit, refuse fill, or special-reclamation area	Bolair: 20/20 within refuse fill; 11/20 within permit; 15/20 within special-reclamation areas. Ponds: 0/3	Bolair: revoked; bond forfeited (Office of Special Reclamation). Ponds: –	Bolair: Bolair (Mace) and Bolair (Gilkerson) burning refuse, 0.43 and 0.48 km, reclamation completed (state emergency program). Ponds: Upper Gauley River Refuse (WV004416; surface burning, hazardous equipment and facilities, dangerous piles), 22–39 m from the problem-area polygon, reclamation completed
Glen Rogers Rd	None at the sampled positions	0/18	–	Glen Rogers Waterline Extension (WV005701; drinking-water supply), about 7 m, completed; Glen Rogers mine shafts (WV006584), 0.2 km, completed; Glen Rogers Complex (WV000182), 1.6 km, pending None within 2.5 km
Turkey Creek East	WVDEP permit O004782 (Road Fork Development Co.; issued 24 Aug 1982); refuse fill: Refuse Area No. 2	13/13 within permit; 11 within refuse fill	Permit renewed; inspection status A2 (active, reclamation only)	–
Monongalia	WVDEP AML problem area WV000488, Goshen Road Refuse Pile; permit U100693 (Mays Run Mine; issued 16 Feb 1994)	19/20 within problem area; 6/20 within permit	Problem area: reclamation completed (surface burning, dangerous pile, clogged stream); permit completely released	–
Raleigh	WVDEP AML problem area WV005637, Little Whitestick Ck. Refuse Pile	20/20 within problem area	Reclamation pending (dangerous piles, portals, impoundment, clogged stream); listed for Infrastructure Investment and Jobs Act funding	Cranberry Creek Refuse (spoil area), pending, adjacent
Fayette, PA	e-AMLIS problem area PA002751, Rowes Run (WVDEP layers not applicable)	Nearest problem location about 60 m	Vertical openings completed; dangerous pile pending; reclamation of the ~900,000 yd ³ refuse pile funded in March 2026	Grindstone (PA004883), 1.4 km, pending

Located positions were overlaid on the WVDEP AML problem-area polygons (data update 7 July 2026), WVDEP permit-boundary, refuse-fill, and special-reclamation layers, and OSMRE e-AMLIS problem locations (accessed 8 October 2026).

Distances are from the nearest located sampling position to the e-AMLIS problem point. Inspection-status and permit-status

codes are as defined in the WVDEP layers. These records document regulatory status and problem types but do not give the dates, methods, or materials of reclamation work.

Detailed site-level distribution of mapped points

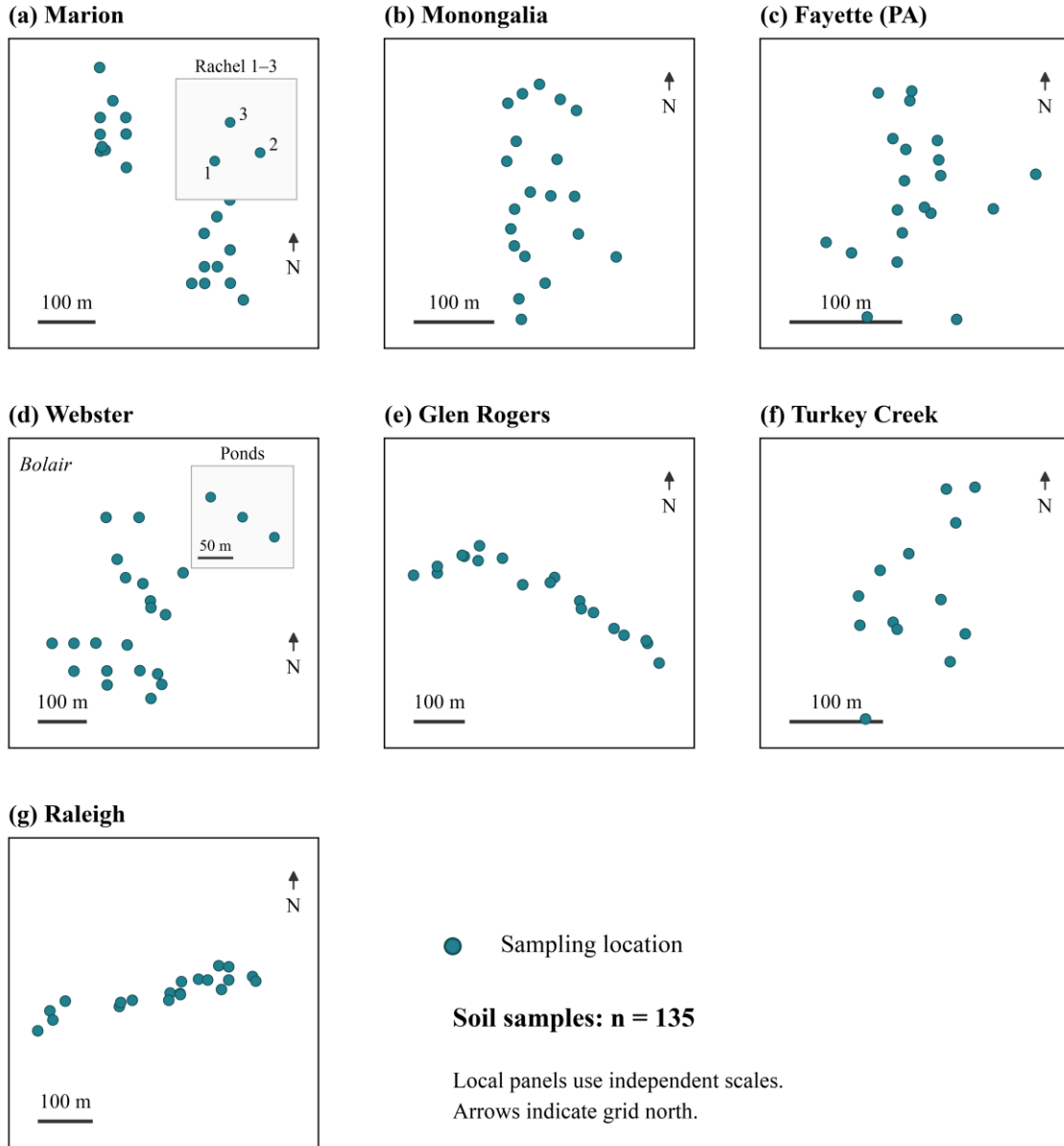


Figure S5. Sampling positions within each of the seven sites (local panels use independent scales; arrows indicate grid north). Positions are from placemarks recorded during fieldwork and the field sampling log; positions were not recorded for three samples (two at Marion and one at Glen Rogers Rd), and the approximate positions drawn for them (e.g., Rachel positions 2 and 3 in panel a) are for orientation only and were not used in the spatial analyses (main text, Section 2.2). In panel a, the northwestern cluster is the Rachel sub-location and the southeastern cluster is the Joanne sub-location. In panel d, the Bolair sub-location is shown; the three Ponds positions lie about 15 km to the east and are shown in the inset.



Figure S6. Site photographs taken at the time of sampling: (a) Marion, coal-refuse pile and benches with sparse dry grasses; (b) Marion, excavated pit holding orange, iron-stained water; (c) Marion, reclaimed grassland; (d) Marion, reclaimed area with shrubs, young trees, and a pond (a–d, December 2023, winter); (e) Webster (Bolair), mixed conifer–hardwood forest with fern and herbaceous understory; (f) Webster (Bolair), open herbaceous–shrub clearing; (g) Glen Rogers Rd, dense herbaceous and shrub cover with a wet opening; (h) Glen Rogers Rd, shrub thicket; (i) Turkey Creek East, bare coal-refuse/spoil surface with rock fragments; (j) Turkey Creek East, grass and herbaceous cover at the site margin; (k, l) Monongalia, old-field grassland with scattered shrubs and young trees (autumn); (m) Raleigh, shaley spoil slope with young pines and sparse grasses; (n) Raleigh, orange iron-oxide-stained seep, consistent with mine drainage; (o) Fayette, PA, coal-refuse pile under young deciduous forest (winter); (p) Fayette, PA, reddish oxidized or burnt refuse mound with leaf litter.

Data S1. Sample-level soil-test dataset (135 samples): laboratory ID, site, county and state, sub-location, field-log sample number, sampling and laboratory receipt dates, position status, 18 soil properties, and sampling coordinates rounded to 0.001° (provided as a separate Excel file, Data_S1_sample_level_dataset.xlsx, with a variable dictionary, and as a CSV copy, Data_S1_sample_level_dataset.csv).