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Elephant megacarcasses increase local nutrient pools in African savanna soils and plants

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SUPPLEMENTAL MATERIALS

Table S1. Generalized linear mixed model results for soil variables. The same five models were run for each response variable, including a null model, and each included site as a random effect to account for repeat measurements. AICc is Akaike's Information Criterion, and ΔAICc is the difference between a given model and the best fit model for that response variable. Cum.Wt stand for cumulative weight; it gives the sum of Akaike's weights and indicates the likelihood that the models up to that point are the best in the set. Models with a ΔAICc value of 2 are considered roughly equivalent in fit and are italicized. Marginal R^2 is the proportion of variance explained by both fixed and random effects in a model, and conditional R^2 is the proportion of variance explained by fixed effects. Coefficients (± standard error) are shown for each predictor and model and are in log units. Rows are organized in blocks by response variable. Within blocks, models are listed in order of increasing ΔAICc.

Model	**Model Fit**					**Coefficients ± *SE***		
	AICc	**ΔAICc**	**Cum.Wt**	**Mar. R^2**	**Con. R^2**	**Soil**	**Distance**	**Soil × Distance**
Nitrogen (%)								
Soil × Distance	*-227.32*	*0.00*	*0.99*	*0.54*	*0.74*	*-0.26 ± 0.22*	*0.00 ± 0.01*	*-0.03 ± 0.01*
Soil + Distance	-216.13	11.20	1.00	0.46	0.67	-0.48 ± 0.21	-0.01 ± 0.00	
Distance	-214.95	12.37	1.00	0.04	0.52		-0.01 ± 0.00	
Soil	-212.36	14.97	1.00	0.40	0.62	-0.47 ± 0.21		
Null	-211.23	16.09	1.00					
$\delta^{15}N$								
Soil × Distance	*180.87*	*0.00*	*0.77*	*0.55*	*0.70*	*0.39 ± 0.16*	*-0.02 ± 0.01*	*-0.02 ± 0.01*
Soil + Distance	184.66	3.79	0.88	0.50	0.66	0.26 ± 0.15	-0.03 ± 0.00	
Distance	184.67	3.79	1.00	0.34	0.60		-0.03 ± 0.00	
Soil	219.35	38.47	1.00	0.20	0.34	0.28 ± 0.14		
Null	219.96	39.09	1.00					
Nitrate (mg/kg)								
Distance	*624.84*	*0.00*	*0.70*	*0.48*	*0.52*		*-0.14* ± 0.02	

Soil + Distance	627.06	2.23	0.93	0.48	0.52	-0.14 ± 0.27	-0.14 ± 0.02	
Soil × Distance	629.51	4.67	1.00	0.48	0.52	-0.24 ± 0.39	-0.14 ± 0.03	0.02 ± 0.04
Null	649.77	24.93	1.00					
Soil	651.82	26.99	1.00	0.01	0.04	-0.18 ± 0.31		
Ammonium (mg/kg)								
Soil + Distance	*219.52*	*0.00*	*0.65*	*0.58*	*0.77*	*2.49* ± 0.66	*-0.18* ± 0.03	
Soil × Distance	*220.94*	*1.43*	*0.97*	*0.60*	*0.77*	*2.91* ± 0.73	*-0.15* ± 0.04	*-0.07* ± 0.06
Distance	225.87	6.35	1.00	0.21	0.77		-0.18 ± 0.02	
Soil	244.57	25.05	1.00	0.34	0.70	2.51 ± 0.76		
Null	249.38	29.86	1.00					
Phosphate (mg/kg)								
Soil × Distance	*167.99*	*0.00*	*0.98*	*0.52*	*0.79*	*2.20 ± 0.96*	*0.00 ± 0.05*	*-0.46 ± 0.08*
Soil + Distance	178.68	10.69	1.00	0.18	0.18	-0.38 ± 0.70	-0.14 ± 0.06	
Null	180.65	12.66	1.00					
Soil	Model did not converge							
Distance	Model did not converge							
Plant Available Phosphorus (mg/kg)								
Soil × Distance	*447.18*	*0.00*	*0.94*	*0.34*	*0.63*	*0.16 ± 0.62*	*-0.04 ± 0.03*	*-0.13 ± 0.04*
Distance	453.68	6.50	0.98	0.20	0.55		-0.10 ± 0.02	
Soil + Distance	454.80	7.62	1.00	0.26	0.55	-0.66 ± 0.55	-0.11 ± 0.02	
Null	467.35	20.17	1.00					
Soil	469.19	22.01	1.00	0.03	0.30	-0.35 ± 0.47		
Mineral Phosphorus (mg/kg)								
Soil × Distance	*537.77*	*0.00*	*1.00*	*0.86*	*0.95*	*-1.09 ± 0.32*	*0.00 ± 0.00*	*-0.04 ± 0.01*
Soil + Distance	560.48	22.71	1.00	0.82	0.92	-1.35 ± 0.31	-0.02 ± 0.00	
Distance	566.38	28.61	1.00	0.04	0.76		-0.02 ± 0.00	
Soil	573.55	35.78	1.00	0.78	0.89	-1.33 ± 0.31		
Null	579.62	41.85	1.00					
Sodium (mg/kg)								
Soil × Distance	*438.56*	*0.00*	*0.73*	*0.29*	*0.59*	*0.22 ± 0.35*	*-0.03 ± 0.01*	*-0.04 ± 0.02*
Distance	441.09	2.53	0.94	0.22	0.54		-0.05 ± 0.00	
Soil + Distance	443.53	4.97	1.00	0.22	0.54	-0.06 ± 0.35	-0.05 ± 0.01	
Null	464.02	25.45	1.00					

Soil	466.38	27.82	1.00	0.00	0.34	0.00 ± 0.00		
Potassium (mg/kg)								
Soil × Distance	*676.07*	*0.00*	*0.94*	*0.29*	*0.81*	*-0.23 ± 0.42*	*0.01 ± 0.00*	*-0.02 ± 0.01*
Null	682.93	6.86	0.97					
Soil	684.55	8.48	0.99	0.25	0.78	-0.37 ± 0.41		
Distance	685.17	9.10	1.00	0.00	0.72		0.00 ± 0.00	
Soil + Distance	686.89	10.82	1.00	0.26	0.78	-0.37 ± 0.41	0.00 ± 0.00	
Calcium (mg/kg)								
Soil	*749.09*	*0.00*	*0.60*	*0.82*	*0.94*	*-1.45 ± 0.41*		
Soil + Distance	*751.01*	*1.92*	*0.83*	*0.82*	*0.94*	*-1.45 ± 0.01*	*0.00 ± 0.00*	
Soil × Distance	753.00	3.91	0.91	0.82	0.94	-1.42 ± 0.41	0.00 ± 0.01	-0.01 ± 0.01
Null	753.55	4.46	0.97					
Distance	755.37	6.27	1.00	0.00	0.81		0.00 ± 0.00	
Iron (mg/kg)								
Soil	*914.44*	*0.00*	*0.67*	*0.88*	*0.96*	*-1.22 ± 0.28*		
Soil + Distance	916.83	2.39	0.87	0.88	0.96	-1.22 ± 0.28	0.00 ± 0.00	
Soil × Distance	918.54	4.10	0.95	0.88	0.96	-1.19 ± 0.28	0.00 ± 0.00	0.00 ± 0.01
Null	920.27	5.83	0.99					
Distance	922.55	8.11	1.00	0.00	0.82		0.00 ± 0.00	
Magnesium (mg/kg)								
Soil	*700.88*	*0.00*	*0.63*	*0.87*	*0.96*	*-1.53 ± 0.37*		
Soil + Distance	703.33	2.45	0.81	0.87	0.96	-1.53 ± 0.37	0.00 ± 0.00	
Soil × Distance	703.97	3.09	0.95	0.88	0.96	-1.48 ± 0.37	0.00 ± 0.00	-0.01 ± 0.01
Null	706.40	5.52	0.99					
Distance	708.75	7.87	1.00	0.00	0.84		0.00 ± 0.00	
Water (mmol/mol)								
Null	*111.87*	*0.00*	*0.32*					
Distance	*112.09*	*0.22*	*0.61*	*0.03*	*0.38*		*0.02 ± 0.01*	
Soil	*112.92*	*1.05*	*0.80*	*0.12*	*0.40*	*0.45 ± 0.38*		
Soil + Distance	*113.27*	*1.40*	*0.96*	*0.14*	*0.42*	*0.45 ± 0.38*	*0.02 ± 0.01*	
Soil × Distance	115.86	3.99	1.00	0.14	0.42	0.44 ± 0.42	0.02 ± 0.02	0.00 ± 0.03
pH								
Soil × Distance	*55.04*	*0.00*	*0.37*	*0.07*	*0.44*	*0.05 ± 0.07*	*0.00 ± 0.00*	*-0.01 ± 0.00*
Null	*55.26*	*0.22*	*0.71*					

Distance	*56.94*	*1.90*	*0.86*	*0.01*	*0.38*		*0.00 ± 0.00*	
Soil	57.63	2.59	0.96	0.00	0.37	0.00 ± 0.07		
Soil + Distance	59.41	4.37	1.00	0.01	0.38	0.00 ± 0.00	0.00 ± 0.00	

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Table S2. Generalized linear mixed model results for leaf variables. The same five models were run for each response variable, including a null model, and each included site as a random effect to account for repeat measurements. AICc is Akaike's Information Criterion, and ΔAICc is the difference between a given model and the best fit model for that response variable. Cum.Wt stand for cumulative weight; it gives the sum of Akaike's weights and indicates the likelihood that the models up to that point are the best in the set. Models with a ΔAICc value of 2 are considered roughly equivalent in fit and are italicized. Marginal R^2 is the proportion of variance explained by both fixed and random effects in a model, and conditional R^2 is the proportion of variance explained by fixed effects. Coefficients (± standard error) are shown for each predictor and model and are in log units. Rows are organized in blocks by response variable. Within blocks, models are listed in order of increasing ΔAICc.

Model	**Model Fit**					**Coefficients ± *SE***		
	AICc	**ΔAICc**	**Cum.Wt**	**Mar. R^2**	**Con. R^2**	**Soil**	**Distance**	**Soil × Distance**
Nitrogen (%)								
Distance	*56.12*	*0.00*	*0.64*	*0.40*	*0.60*		*-0.03* ± 0.00	
Soil + Distance	*57.79*	*1.67*	*0.92*	*0.43*	*0.61*	*0.13 ± 0.14*	*-0.03 ± 0.00*	
Soil × Distance	60.33	4.20	1.00	0.43	0.61	0.15 ± 0.15	-0.03 ± 0.01	0.00 ± 0.01
Null	89.78	33.66	1.00					
Soil	91.66	35.53	1.00	0.03	0.21	0.10 ± 0.13		
$\delta^{15}N$								
Soil × Distance	*229.95*	*0.00*	*0.95*	*0.51*	*0.77*	*-0.52 ± 0.43*	*-0.11 ± 0.01*	*0.06 ± 0.02*
Distance	236.55	6.60	0.99	0.44	0.70		-0.08 ± 0.01	
Soil + Distance	238.97	9.02	1.00	0.45	0.70	-0.12 ± 0.40	-0.08 ± 0.01	
Null	282.45	52.50	1.00					
Soil	284.30	54.34	1.00	0.04	0.36	-0.30 ± 0.41		
Phosphorus (%)								
Soil × Distance	-87.04	0.00	0.99	0.47	0.75	-0.24 ± 0.31	0.02 ± 0.01	-0.04 ± 0.01
Soil	-76.10	10.94	1.00	0.38	0.68	-0.55 ± 0.31		
Null	-75.98	11.06	1.00					

Soil + Distance	-73.69	13.34	1.00	0.38	0.68	-0.55 ± 0.31	0.00 ± 0.01	
Distance	-73.68	13.36	1.00	0.00	0.56		0.00 ± 0.01	
N:P Ratio								
Soil × Distance	*209.64*	*0.00*	*0.86*	*0.41*	*0.71*	*0.34 ± 0.38*	*-0.05 ± 0.01*	*0.04 ± 0.01*
Distance	214.60	4.96	0.94	0.09	0.59		-0.03 ± 0.01	
Soil + Distance	214.85	5.21	1.00	0.36	0.67	0.62 ± 0.01	-0.03 ± 0.00	
Null	225.74	16.10	1.00					
Soil	226.21	16.57	1.00	0.23	0.57	0.55 ± 0.37		
Sodium (mg/kg)								
Soil + Distance	*839.97*	*0.00*	*0.60*	*0.62*	*0.78*	*-0.99 ± 0.32*	*-0.03 ± 0.01*	
Soil × Distance	*841.56*	*1.59*	*0.88*	*0.62*	*0.79*	*-0.88 ± 0.34*	*-0.03 ± 0.01*	*-0.02 ± 0.01*
Distance	843.18	3.21	1.00	0.09	0.64		-0.03 ± 0.01	
Soil	852.98	13.02	1.00	0.53	0.71	-1.00 ± 0.32		
Null	856.49	16.52	1.00					
Magnesium (mg/kg)								
Soil × Distance	*722.20*	*0.00*	*0.99*	*0.45*	*0.80*	*-0.20 ± 0.28*	*0.00 ± 0.00*	*-0.02 ± 0.01*
Distance	731.74	9.54	0.99	0.07	0.66		-0.01 ± 0.00	
Soil + Distance	732.78	10.58	1.00	0.39	0.76	-0.36 ± 0.28	-0.01 ± 0.00	
Null	743.56	21.36	1.00					
Soil	744.46	22.26	1.00	0.31	0.69	-0.37 ± 0.28		
Potassium (mg/kg)								
Distance	*936.99*	*0.00*	*0.73*	*0.20*	*0.57*		*-0.03 ± 0.00*	
Soil + Distance	939.50	2.51	0.94	0.20	0.57	0.02 ± 0.25	-0.03 ± 0.00	
Soil × Distance	941.96	4.97	1.00	0.20	0.57	0.05 ± 0.26	-0.02 ± 0.01	0.00 ± 0.01
Null	956.55	19.57	1.00					
Soil	958.95	21.96	1.00	0.00	0.38	0.00 ± 0.24		
Calcium (mg/kg)								
Null	*799.64*	*0.00*	*0.42*					
Distance	*800.68*	*1.04*	*0.67*	*0.01*	*0.50*		*0.00 ± 0.00*	
Soil	*801.22*	*1.58*	*0.86*	*0.14*	*0.53*	*-0.20 ± 0.21*		
Soil + Distance	802.36	2.72	0.96	0.14	0.54	-0.20 ± 0.21	0.00 ± 0.00	
Soil × Distance	804.45	4.81	1.00	0.15	0.54	-0.16 ± 0.22	0.01 ± 0.01	-0.01 ± 0.01
Iron (mg/kg)								
Distance	*591.87*	*0.00*	*0.69*	*0.21*	*0.57*		*-0.08 ± 0.01*	

Soil + Distance	594.14	2.27	0.92	0.23	0.58	-0.26 ± 0.50	-0.08 ± 0.01	
Soil × Distance	596.15	4.27	1.00	0.23	0.59	-0.09 ± 0.39	-0.07 ± 0.00	-0.02 ± 0.02
Null	616.95	25.08	1.00					
Soil	619.06	27.19	1.00	0.02	0.48	-0.31 ± 0.00		

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Table S3. Generalized linear mixed model results testing for correlations between leaf and soil micronutrients. The same model was run for each of five micronutrients (Na, K, Ca, Mg, and Fe) with leaf micronutrient concentration as the response variable, soil micronutrient + distance as the main effects, and site as a random effect. Marginal R^2 is the proportion of variance explained by both fixed and random effects in a model, and conditional R^2 is the proportion of variance explained by fixed effects. Coefficients (± standard error) are shown for each predictor and model.

Leaf Micronutrient	**Mar. R^2**	**Con. R^2**	**Soil Micronutrient Coefficient ± *SE***	**Distance Coefficient ± *SE***
Sodium	0.08	0.82	11.56 ± 11.67	-146.47 ± 43.04
Potassium	0.29	0.73	0.00 ± 0.00	-0.06 ± 0.01
Calcium	0.12	0.58	0.00 ± 0.00	0.00 ± 0.00
Magnesium	0.17	0.79	0.00 ± 0.00	0.00 ± 0.00
Iron	0.11	0.32	0.00 ± 0.01	-52.85 ± 20.57

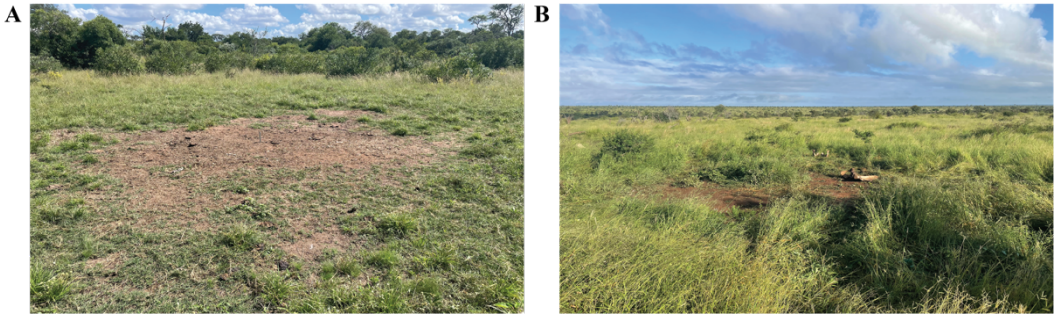

Figure S1. Representative photos of two elephant carcass sites of different ages and soil types. (A) The first site is 67 days postmortem and is on granitic soil. (B) The second site is 811 days postmortem and is on basaltic soil. In both images, there is a visible impact zone with reduced vegetation coverage. At the first site, elephant bones have all been dispersed, though some are still present at the second site. Photos taken by Deron Burkepile at time of sample collection in March 2023.

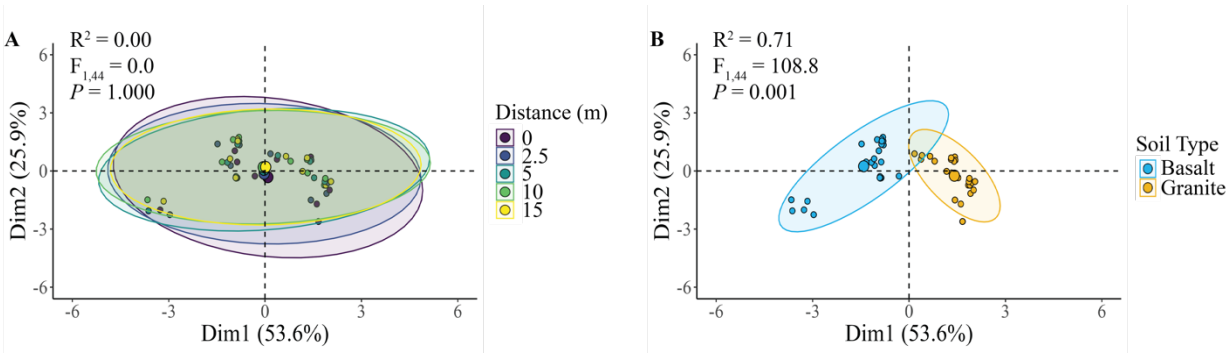

Figure S2. Results from principal component analysis of soil micronutrient composition using Bray-Curtis dissimilarity. Statistical results are from permutational analysis of variance using distance and soil type as covariates. (A) Soil micronutrient composition did not differ significantly with distance from the carcass but (B) was distinct in different soil types.

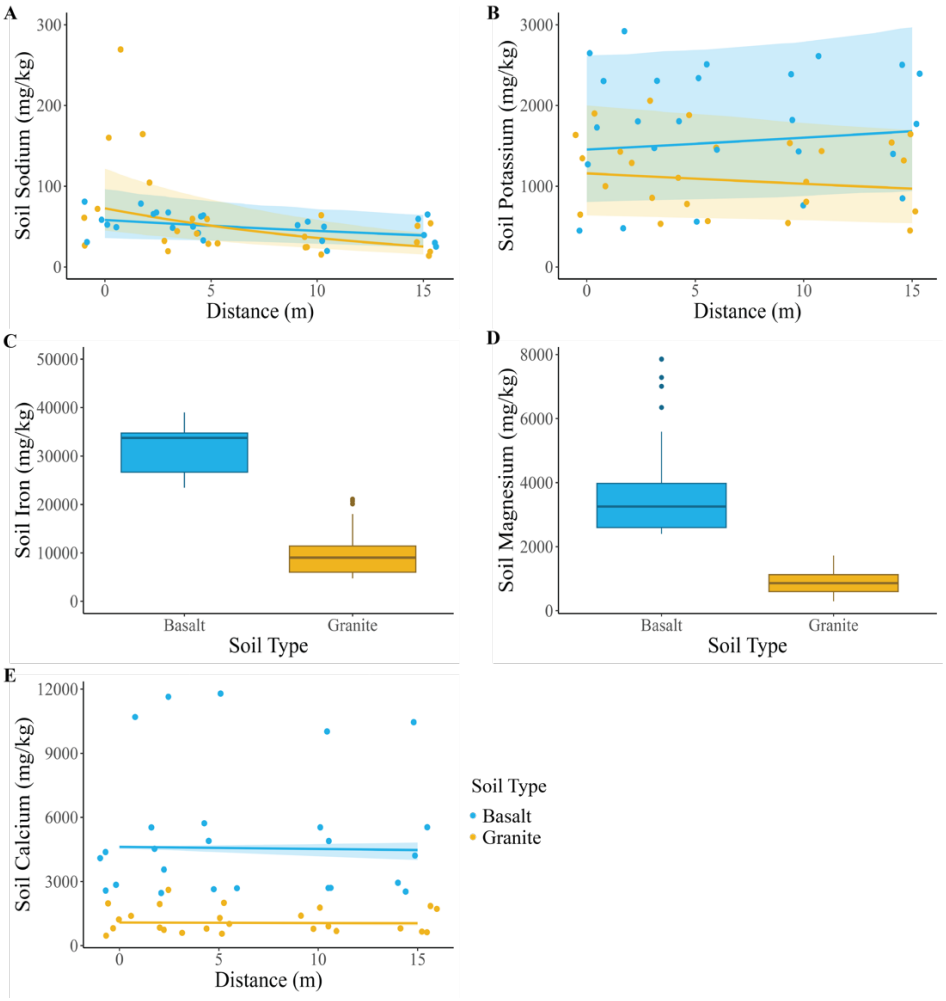

Figure S3. Effects of elephant carcasses on soil micronutrient concentrations in granitic and basaltic soils. (A) Soil sodium and (B) potassium decreased significantly with distance from the carcass, but only in granitic soils. (C) Iron, (D) magnesium, and (E) calcium were greater in basaltic soils. Distance appeared in the top model for calcium, but the effect size was minimal. Points represent individual measurements from soil samples taken at 0, 2.5, 5, 10, and 15m and are offset to be visible when they would otherwise overlap. Lines show predictions calculated from the top generalized linear mixed model, which may include soil type, distance, and soil type by distance interaction as covariates (Table S1). Only significant relationships are shown on plots. Shading indicates the 95% confidence interval.

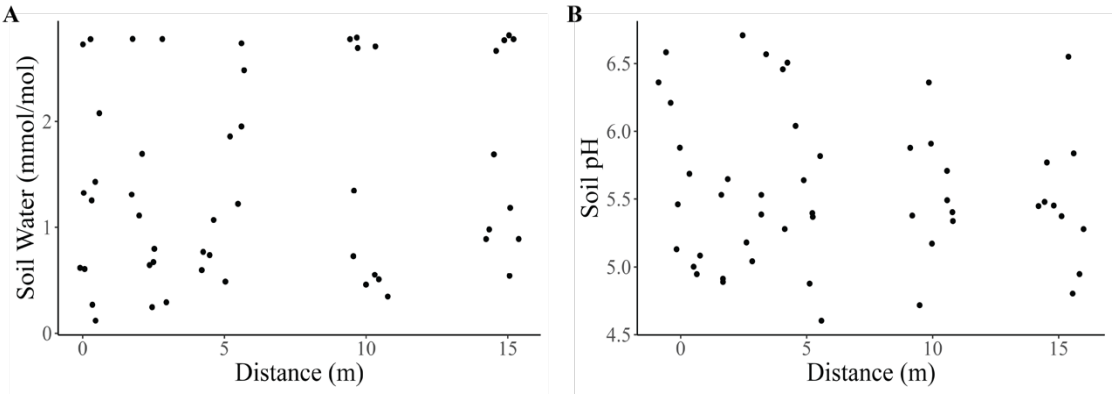

Figure S4. Effects of elephant carcasses on soil water concentration and soil pH. Neither (A) soil water nor (B) soil pH differed with distance or soil type. For both metrics, the set of top models included the null (Table S1). Points represent individual measurements taken at 0, 2.5, 5, 10, and 15m and are offset to be visible when they would otherwise overlap.

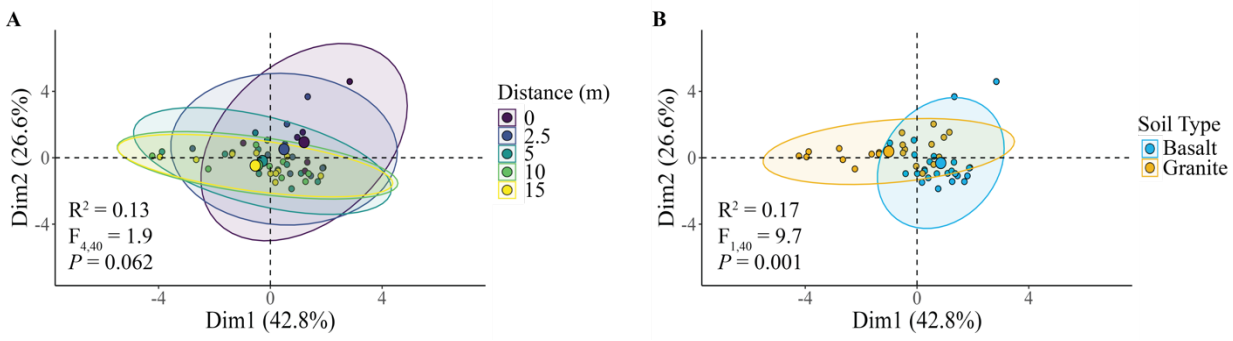

Figure S5. Results from principal component analysis of foliar micronutrient composition using Bray-Curtis dissimilarity. Statistical results are from permutational analysis of variance using distance and soil type as covariates. (A) Foliar micronutrient composition did not differ significantly with distance from the carcass but (B) was distinct in different soil types.

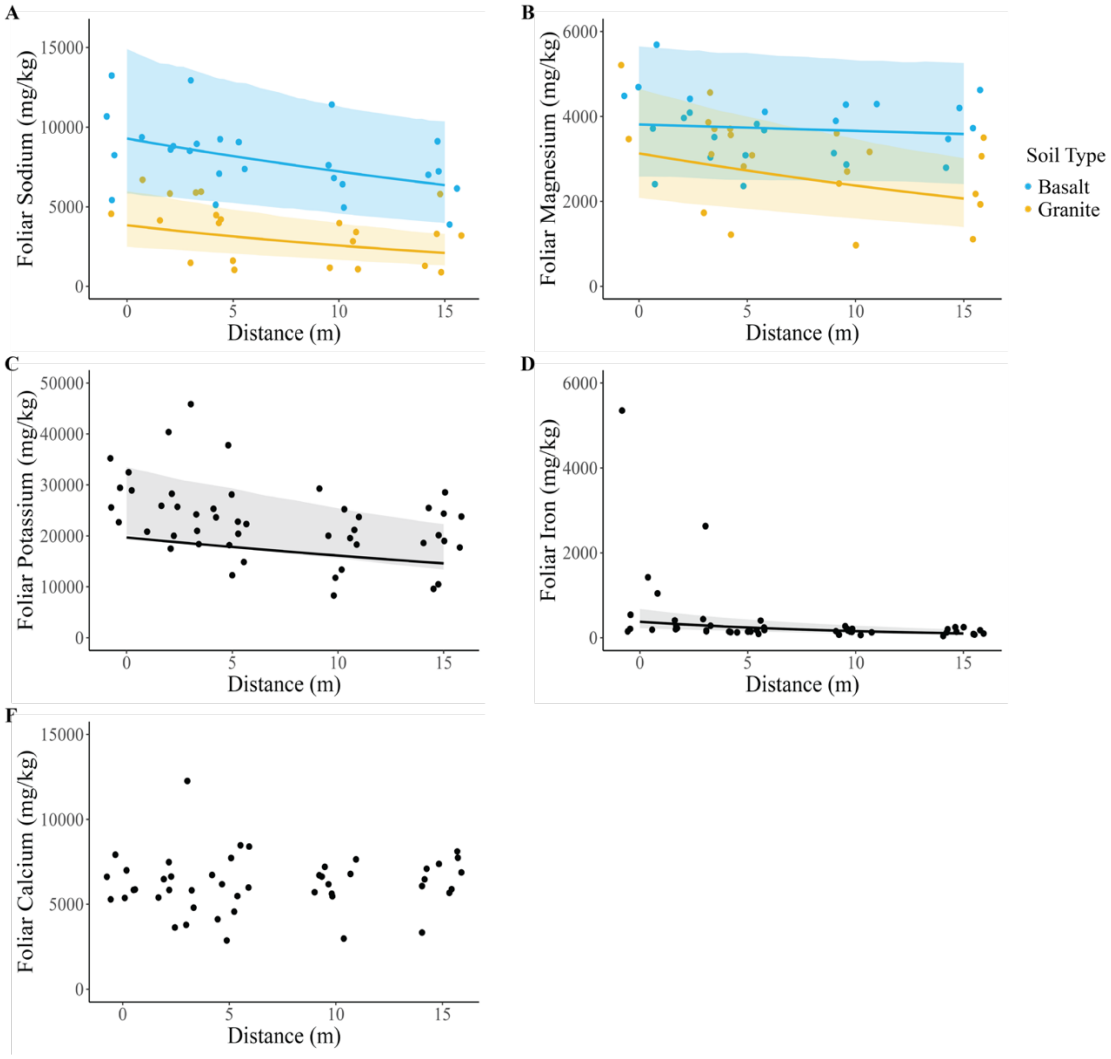

Figure S6. Effects of elephant carcasses on grass foliar micronutrient concentrations in granitic and basaltic soils. (A) Foliar Na and (B) Mg were greatest in basaltic soil and decreased significantly with distance. (C) Foliar K and (D) Fe decreased with distance but did not differ with soil type. (E) Foliar Ca did not differ with distance or soil type. Points represent individual measurements from *U. trichopus* leaf samples taken at 0, 2.5, 5, 10, and 15m and are offset to be visible when they would otherwise overlap. Lines show predictions calculated from the top generalized linear mixed model, which may include soil type, distance, and soil type by distance interaction as covariates (Table S2). Only significant relationships are shown on plots. Shading indicates the 95% confidence interval.