

1 **Spatial geochemistry influences the home range of elephants.**

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22 Abstract

23 The unique geochemistry surrounding the Palabora Mining Company (PMC) land may act as a
24 micronutrient hotspot, attracting elephants to the area. The PMC produces refined copper and
25 extracts phosphates and other minerals. Understanding the spatial influence of geochemistry on the
26 home range size of African elephants is important for elephant population management and
27 conservation.

28 The home ranges of collared elephants surrounding the PMC were significantly smaller ($P=0.001$)
29 than conspecifics in surrounding reserves, suggesting that their resource needs were met within
30 these smaller areas. Environmental samples (soil, water and plants) were analysed from the mine
31 area and along six transects radiating from the mine centre. Tail hair and faecal samples from
32 elephants at the PMC, and conspecifics within the surrounding area were analysed. All samples were
33 analysed for minerals essential to health and potentially toxic elements (PTEs; As, Ca, Cd, Cu, Fe, K,
34 Mg, Mn, Na, P, Pb, Se, U, V and Zn). Results show that the geochemistry at the PMC is different
35 compared to surrounding areas, with significant elevations seen in all analysed minerals and PTEs in
36 soil closer to the mine, thereby drawing the elephants to the area. Additionally significant elevations
37 were seen in elements analysed in water and vegetation samples. Elephant tail hair from elephants
38 at the mine was significantly greater in Cd, whilst Mg, P, Cu, As, Cd, Pb and U concentrations were
39 significantly greater in elephant faecal samples at the mine compared.

40 When micronutrient hotspots overlap with human activity (such as mining), this can lead to poor
41 human-elephant coexistence and thus conflict. When managing elephant populations, the influence
42 of mineral provision on elephant movement must be considered. Such detailed resource information
43 can inform conservation efforts for coordinated programmes (UN SDGs 15 and 17) and underpin
44 sustainable economic activity (UN SDG 8, 11 and 12).

45 **Keywords:** *Loxodonta africana*, minerals, mining, potentially toxic elements, elephant movement

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49 1.0 Introduction

50 The increase in human population and global intensification of agriculture have significantly reduced
51 African savanna elephant (*Loxodonta africana*) populations, through habitat reduction and
52 fragmentation, causing the overlap of human and elephant habitation, leading to increased human-
53 elephant conflict (HEC; Blanc, 2008). Elephants are forced into increasingly smaller areas, often
54 restricted by fencing or encroaching anthropogenic activities, resulting in increased pressures on
55 these areas to meet the elephants' resource needs. This can present nutritional challenges, resulting
56 in altered elephant movement patterns and distribution in efforts to seek out required minerals.
57 Elephants move to meet their mineral needs, and use available micronutrient hotspots, causing HEC,
58 when these overlap with human activities (Sach *et al.*, 2019). Minerals are required by elephants for
59 a variety of biological processes including energy metabolism, organ and immune function,
60 reproduction and cellular growth (Ishiguro, Haskey and Campbell, 2018).

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62 Geochemistry influences mineral availability in soils, and thereby in plants and water to elephants
63 (Prins and Langevelde, 2008). Understanding how the geochemistry of an area, and presence of
64 micronutrient hotspots, influences mineral provision to the animal, informs how geochemistry
65 influences home range size, especially when anthropogenic activities constrain long-distance
66 movements. Largely, plants reflect the soil mineral profile, plants growing in deficient areas lack key
67 minerals, which can result in deficiencies in the consumer (elephant). In contrast, plants growing in
68 mineral rich areas pass on the mineral abundance to the consumer (Joy *et al.*, 2015). Geochemical
69 properties (including organic matter and soil pH), and the ability of plants to extract minerals from
70 the soil will influence the availability of these minerals to elephants (Bowell and Ansah, 1994;
71 Maskall and Thornton, 1996).

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73 African elephants move and adapt their food selection, to meet their target levels of (as yet
74 undetermined) minerals (Bax & Sheldrick, 1963). [From here-on reference will be made to mineral in](#)

75 terms of the nutrient requirement for elephants. It is suspected that in volcanic areas such as the
76 Palabora Mining Company (PMC), levels of micronutrients will be elevated, acting as a
77 micronutrient hotspot, with a reduction in elephant home ranges size (Greyling, 2004). This may be
78 beneficial or detrimental to elephants. In areas where the soil is generally deficient in minerals, it
79 may allow elephants to meet their mineral needs within a small area. However, as with other
80 mammals, dietary excess of minerals or potentially toxic elements (PTEs) can occur from
81 overconsumption, causing toxic effects; data is limited as to these threshold levels for elephants
82 (Sach *et al.*, 2019). Elephants are large, slow-growing and can accommodate extended periods of
83 nutrient deficiency due to their nutrient stores (Prins and Langevelde, 2008). Excess consumption of
84 minerals or PTEs to harmful levels is likely to take several years (Ullrey, Crissey and Hintz, 1997).
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86 As well as micronutrients, drivers for elephant movement include availability of food and water,
87 social interaction, human activities, safety and access to shade (Wall, Douglas-Hamilton and Vollrath,
88 2006). The distance travelled by elephants to meet their resource needs, will be reflected in their
89 home range size (de Knegt *et al.*, 2011). Mineral provision influences elephant food selections; for
90 example, the Associated Private Nature Reserves (APNR), South Africa are suspected to have a
91 localised phosphorus (P) deficiency, elephants increased their consumption of leaves from trees that
92 had been fertilised with P (Pretorius *et al.*, 2011, 2012). Secondly, females in family units maximised
93 P intake by ingesting leaves with higher P content, to meet their increased requirements, compared
94 to larger bodied males who consumed other lower P plant parts (Greyling, 2004). Phosphorus plays a
95 role in reproduction and lactation (Groenewald and Boyazoglu, 1980). It is predicted that if an area
96 such as the PMC is a micronutrient hotspot, elephants will remain within the locality, to meet their
97 resource needs for minerals as demonstrated by Tucker *et al.* (2018), especially if the surrounding
98 soils are poor in several essential micronutrients such as P, as suggested by Greyling (2004) and
99 Pretorius (2011, 2012).

100 The aim of this study was to understand the spatial influence of geochemistry on the home range
101 size of elephants, using the Palabora Mining Company (PMC) property and surrounding national park
102 land as a case study of contrasting environments. The following objectives were used to achieve the
103 aim: (1) Determine if mineral levels in soil, forage and water near the mine are greater than the
104 nearby Kruger National Park (KNP)/APNR and hence may influence a reduced elephant home range
105 size; (2) Establish baseline levels for key minerals and PTEs in African elephant tail hair and faeces as
106 potential biomarkers, and (3) Determine if the elephant tissues (tail hair and faecal samples)
107 collected near the mine contain greater concentrations of essential minerals and PTEs, compared to
108 elephants in surrounding reserves, away from the mine.

109 2.0 Materials and methods

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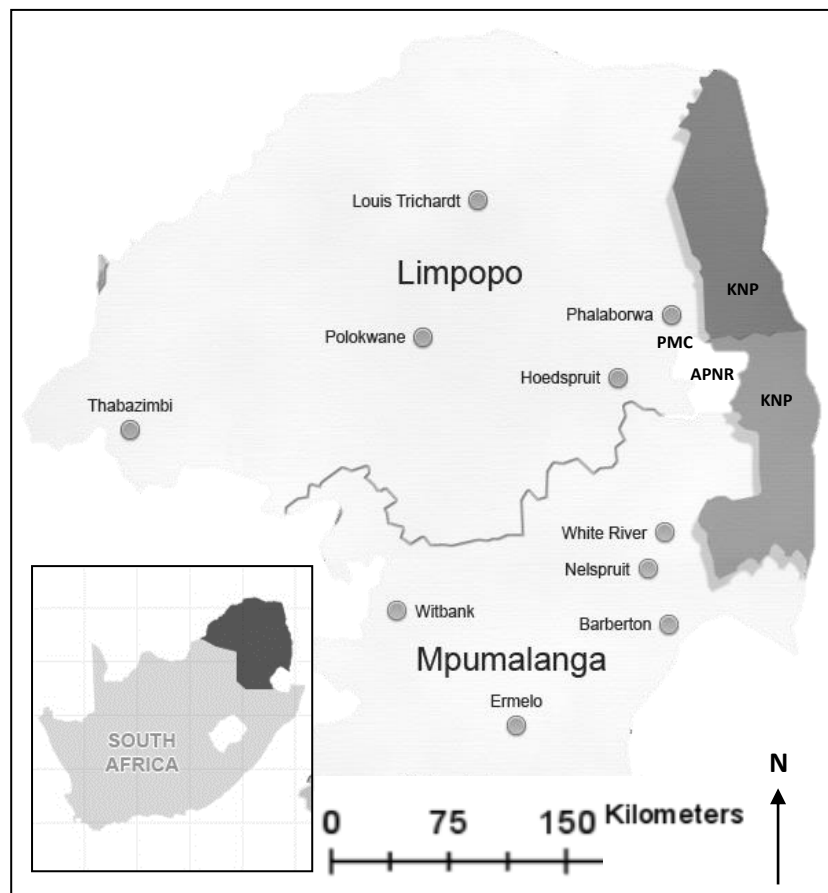
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128 **Figure 1:** Study area showing the Kruger National Park (KNP), Associated Private Nature Reserves
129 (APNR) and Palabora Mining Company (PMC).

130 The study was conducted on the Palabora Mining Company (PMC) land near Phalaborwa town,
131 South Africa and adjacent areas within the KNP and the APNR (Fig. 1). From west to east, the
132 geological succession of the KNP changes from granitic to basaltic. Granites generally form nutrient
133 poor substrates whereas basaltic rocks form nutrient rich substrates (Venter and Gertembach,
134 1986). The APNR is located on the western border of the KNP, and is made up of gneiss, granite or
135 magmatite (Venter and Gertembach, 1986). Elephants can move freely amongst the KNP, APNR and
136 PMC lands. Elephant incursion into the PMC can cause financial losses and risk to elephant and
137 human life. Elephants can damage infrastructure, inhibit mining operations and cause elephant,
138 vehicle and train collisions.

139 In this generally micronutrient poor environment, the Palabora Igneous Complex has a unique
140 mineral rich rock formation. Commercial mining began in 1954, with open-cast mining of foskorite
141 and pyroxenite, thereafter the PMC began mining the same ores for copper and magnetite,
142 developing into the country's main producer of refined copper, operating over 1950 ha (Roux *et al.*,
143 1989). The NGO Elephants Alive (EA) have collared elephants throughout the APNR, and seven
144 elephants utilising the mine area (movements in Fig. 2). The home range of these mine collared
145 elephants was calculated using a-LoCoH 90% (Getz and Wilmers, 2004), and was smaller than that of
146 neighbouring elephants within the APNR (Table 1), animals of the same sex, age category and
147 wearing collars for the same time period were compared. Elephant census data, showed that
148 elephant density within the operational PMC (1.4 per km²) was larger than that within the
149 surrounding KNP (0.8 per km²; Lerm and Swemmer, 2015).

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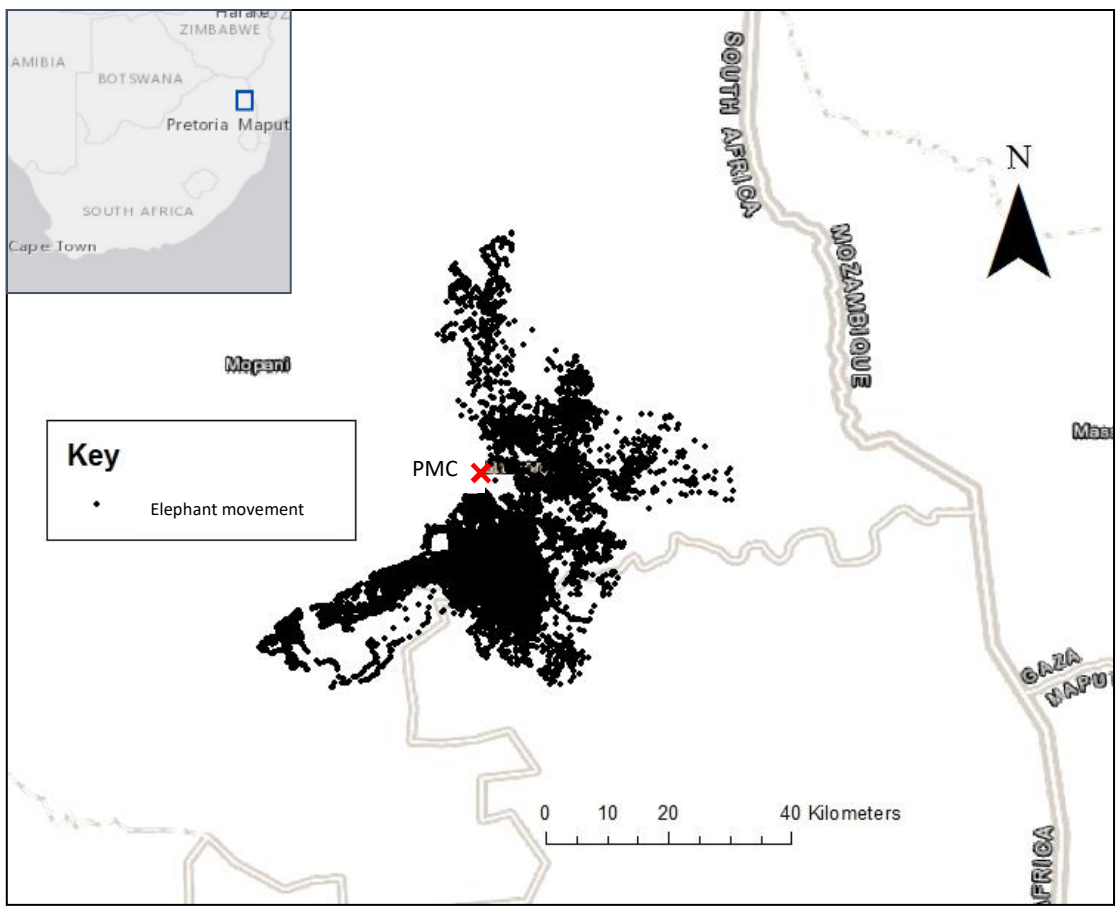


Figure 2: Fixes of collared elephants surrounding the Palabora Mining Company (PMC) site between 15.6.2012 and 23.7.2017

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	Average Home Range calculated using LoCoH 90% (km ²)	Standard error of mean	Min/max (km ²)	Number of elephants
PMC	529	78	200/728	7
Neighbouring reserves	1305	265	498/2244	7

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180 **Table 1:** Home ranges of elephants within the Palabora Mining Company (PMC) land and
181 neighbouring reserves. Full data given in Supplementary Information Table 9.

182 **Sample site selection**

183 Fifty-three sampling sites were selected on six transects radiating out from the PMC, to include
184 points within and outside of the area occupied by the collared elephants at the mine (Fig. 3).
185 Transects were used to observe if an elemental gradient from the PMC was present. Additionally, 43
186 sampling sites were identified within the PMC (Fig. 3). Sample sites were not selected to the north
187 west of the PMC area, this is a fenced urban area with minimal elephant movement.

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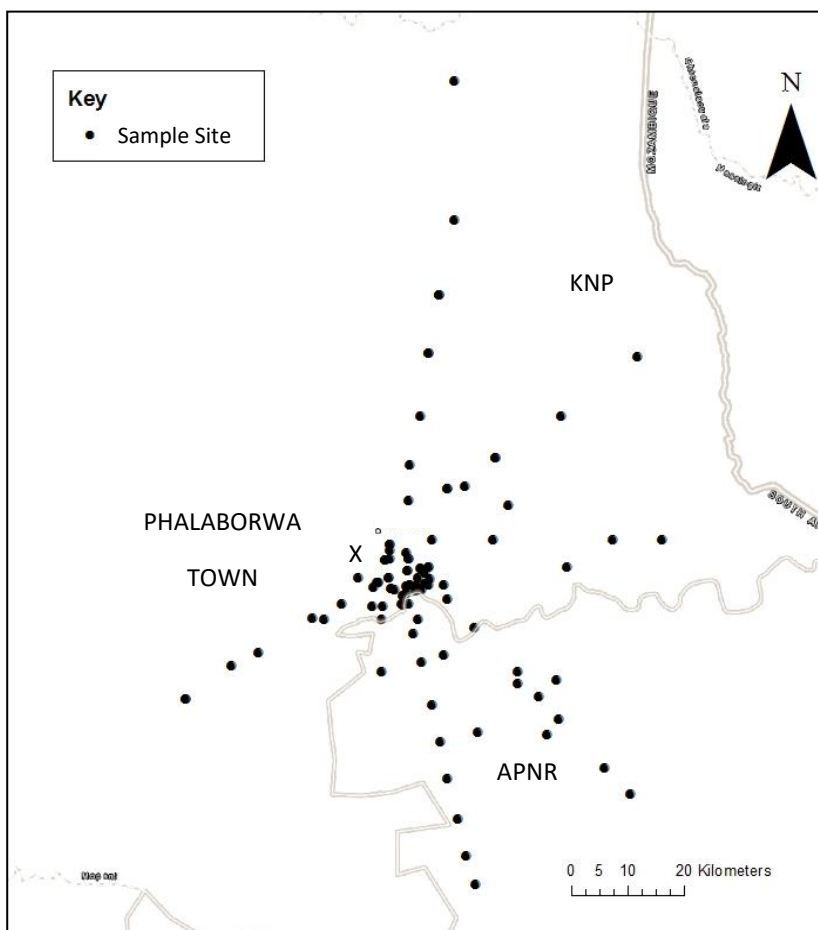
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200 **Figure 3:** Sampling sites for environmental and faecal samples. KNP=Kruger National Park;
201 APNR=Associated Private Nature Reserves. The PMC (Palabora Mining Company) is located where
202 transects cross, south of Phalaborwa town.

203

204 **Sample Collection**

205 Environmental and faecal sampling was conducted during September 2017 and September 2018,
206 within a 50 m radius around each sampling point. Trace element free paper bags were used for
207 plant, soil, faecal and tail hair samples. All samples were transported to the lab within 8 h of
208 collection; plant and water samples in a cooler, tail hair, faecal and soil samples at ambient
209 temperature.

210 Environmental sampling

211 Plant parts (approx. 500g per sample, n=100) were sampled from seven species commonly
212 consumed by elephants (Table 2; Smallei and O’Connor, 2000; Holdø, Dudley and McDowell, 2002;
213 Codron *et al.*, 2006; Pretorius *et al.*, 2011, M Henly pers. comm 2017). Not every species or part was
214 found at the sampling site. Samples were taken randomly from the plant, mixed sized leaves were
215 sampled, branches/ roots of approx. 5cm in length were cut using secateurs and bark was scraped
216 off the trunk using a chisel.

Species	Common name	Part sampled
<i>Colophospermum mopane</i>	Mopane	Leaves
<i>Grewia monticola</i>	Silver Raisin	Bark
		Leaves
<i>Senegalia nigrescens</i>	Knob Thorn	Bark
<i>Combretum apiculatum</i>	Red Bushwillow	Roots
<i>Lannea schweinfurthii</i>	False Marula	Leaves
		Inner bark
<i>Dichrostachys cinerea</i>	Sicklebush	Branches

		Leaves
<i>Maerua parvifolia</i>	Dwarf Bush-cherry	Branches
		Bark
		Leaves

217 **Table 2:** Plant species and plant parts sampled within this study

218

219 Soil samples (n=97, approx. 500g per sample) were collected at each site, from surface soil using a
 220 trowel, to a depth of 15cm, from five separate points within a 1-m² grid. Water was sampled
 221 opportunistically at sample sites, key rivers or identified elephant drinking points (n=36); two 30 ml
 222 samples were collected in Nalgene HDPE bottles, filtered (0.45 µm).

223 Biological Sampling

224 Elephant faecal samples (n=94, approx. 500g per sample) were taken from the centre of fresh, intact
 225 boluses with circumference of >40cm, to indicate adult size (Jachmann and Bell, 1985), as calf
 226 samples on a pre-weaned diet could bias results (Cook *et al.*, 1994). On return to the laboratory,
 227 samples were oven dried at 50 °C for 24 h.

228 Tail hair samples were plucked from the tail (1-3 hairs per animal) between March 2002 and July
 229 2018 during routine collaring operations or management activities throughout the KNP, APNR and
 230 PMC, as part of the South African National Parks Bio-bank (SANParks), or by EA. Tail hair samples
 231 were taken up to 170km from the PMC (n=200 from non-mine collected by SANParks and EA, n=7
 232 from mine area collected by EA). All sedations were carried out using the SANParks SOPs for Capture
 233 Transport (*Standard Operating Procedures for Capture Transport and maintenance in Holding*
 234 *Facilities of Wildlife*, 2017).

235 **Sample Preparation**

236 Soil samples were air-dried, crushed and sieved to ≤2mm particle size and further milled to ≤40µm in
 237 an agate ball mill. Water samples were filtered with a hydrophilic 25mm Minisart filter and acidified
 238 to 1% HNO₃ and 0.5% HCl. Plant and faecal samples were oven dried at 50 °C for 24 h, and passed

239 through a food blender as described by Watts et al. (2019). Elephant tail hair samples were cleaned
240 as described in Middleton et al. (2016) and autoclaved in line with DEFRA requirements.

241 **Sample Digestion for ICP-MS analysis**

242 Soil samples (0.25 g) were digested in a mixed acid solution (HF: 2.5 ml/HNO₃:2 ml/HClO₄:1
243 ml/H₂O₂:2.5 ml) on a programmable hot block; 0.5 g of plant samples or faecal samples were
244 digested in HNO₃:10 ml/H₂O₂:1 ml mixed solution in a closed vessel microwave heating system
245 (MARS Xpress) as described in Watts et al. (2019). Elephant tail hair samples (variable weight) were
246 digested in HNO₃:4 ml/H₂O₂:1 ml mixed solution in a closed vessel microwave heating system (MARS
247 Xpress) as described in Middleton et al. (2016). Tail hairs from the non-mine elephants were
248 digested and analysed whole, and those from the collared elephants at the PMC were cut into 3–5
249 cm sections, down the length of the hair, for future profiling, prior to digestion and subsequent
250 analysis. Soil, plant, faecal material and tail hair data is presented as dry weight.

251 **Elemental Analysis**

252 Elemental analysis was conducted on all prepared samples by inductively coupled plasma mass
253 spectrometry (ICP-QQQ; Agilent 8900x) using collision cell mode (gas modes: H₂ for Se, O₂ for As, He
254 for all remaining elements). Fifteen biologically functional or potentially toxic elements were
255 selected for this study; Ca, copper (Cu), iron (Fe), potassium (K), Mg, manganese (Mn), Na, P,
256 selenium (Se), zinc (Zn), arsenic (As), cadmium (Cd), lead (Pb), uranium (U) and vanadium (V). Sample
257 blanks were run to determine the practical limit of detection (LOD, 3*STDEV).

258 **Analytical Quality Control**

259 The accuracy of the elemental analysis was verified by analysing the following certified reference
260 materials (CRM)s:

- 261 • Human Hair (GBW07601, China)
- 262 • Spinach leaves (SRM1570a, NIST, USA)

- 263 • Tomato leaves (SRM1573a, NIST, USA)
- 264 • Basalt rock (BCR-2 United States Geological Survey, USA)
- 265 • Soil (SRM2711a, NIST, USA)
- 266 • Soil (BGS 102, British Geological Survey, UK)
- 267 • In house human toenail (BAPS 2014) reference material

268 The concentrations of all elements of interest in the reference materials had an acceptable
269 accuracy to the target values, of $97\% \pm 39\%$, data detailed in Supplementary Information Table 3.

270 **Statistical Analysis**

271 The evidence for differences between mine and non-mine elephant home range size was assessed
272 by a Wilcoxon-test of the null hypothesis that the median home range size value was the same for
273 the collared mine and non-mine elephants. Statistical analysis was conducted using 'R' Studio
274 version 3.5.0.

275 The evidence for differences between mine and non-mine elephant tail hair and faecal samples with
276 respect to analytes was assessed by a Student's t-test of the null hypothesis that the mean value was
277 the same for samples from the mine and non-mine. Boundaries to define the mine and non-mine
278 were based on physical land ownership. The t-test was performed assuming that the variances
279 within the two groups were not necessarily the same, and computing effective degrees of freedom
280 for the resulting t-statistic according to the Satterthwaite-Welch equation (Welch, 1947). This is a
281 conservative approach when, as here, the sample sizes are unequal.

282 Each family of tests (t-tests on one matrix for the set of minerals, or tests of trend models for some
283 environmental matrix on the set of minerals) can be regarded as a multiple hypothesis testing
284 exercise, because each mineral was not considered in turn, but rather examined for evidence that
285 specific minerals display behaviour of interest. For that reason we undertook false discovery rate

286 control (FDR) following Benjamini and Hochberg (1995). The FDR is the expected proportion of
287 rejected null hypotheses that should have been accepted. Here we controlled the FDR at 0.05,
288 computing adjusted P-values for each family of tests using the `p.adjust` command in the base
289 statistical library of the R package (R Core team, 2017).

290 The environmental data, on soil, water and plants, were examined for evidence that there is a
291 dependency of the measured concentration on distance from the mine. This was done using a
292 polynomial function of distance. For plants, leaves only were used to demonstrate spatial variation,
293 a full dataset and comparison for the plant data (all plants versus leaves) is in Supplementary
294 Information Table 4. The data on soil, water and plants were collected from transect points radiating
295 from the mine, sampling at more or less regular intervals. Because the samples are not collected
296 from sites selected independently and at random, it is not possible to make sound inferences based
297 on standard ordinary least squares methods (Lark and Cullis, 2004). Rather, it is necessary to fit a
298 linear mixed model (LMM) to the data, with the fixed effects comprising polynomial terms in
299 distance to the mine, and the random effect comprising both an independent and identically
300 distributed error term and a spatially correlated random effect. The models were fitted using the
301 `lme` and `update` functions from the `nlme` library for the R platform (R Core Team, 2017; Pinheiro *et*
302 *al.*, 2018).

303 A quartic polynomial (first, second, third and fourth order terms) in distance was initially fitted to the
304 data by ordinary least squares, and summary statistics and the histogram of the residuals were
305 examined to decide whether to analyse the data on their original units or after transformation to
306 natural logarithms. The full model was then fitted as a LMM using residual maximum likelihood
307 (REML), and models with spherical and exponential correlation functions for the spatially-dependent
308 random effect were compared on their likelihood. The selected spatial correlation function was then
309 retained for all further models for this variable on the matrix being considered. The full quartic
310 model was then re-estimated using ordinary maximum likelihood to allow comparisons with

311 alternative models with different fixed effects. A cubic model was then fitted (i.e., dropping the
312 quartic term), and the quartic and cubic models were compared on the log-likelihood ratio statistic
313 to test the null hypothesis that the coefficient for the quartic term was zero. If this null hypothesis
314 was rejected then the full model was retained and compared with a null model in which the only
315 fixed effect was a constant mean. This latter test was recorded as the strength of evidence for a
316 trend with distance to the mine. If, on the other hand, the null hypothesis was accepted, then the
317 quartic term was dropped and the cubic model compared with a quadratic, and so on.

318 As with the comparisons between the mine and non-mine areas by the t-test, each set of spatial
319 models over all elements on a particular matrix was treated as a family of multiple hypotheses to be
320 tested with FDR control. The same method was used to do this as described above for the t-tests.

321 One data point furthest from the mine was removed, because of the considerable leverage that this
322 could have on a trend model. It was also necessary to “jitter” some of the spatial coordinates,
323 moving them 1 metre in a random direction. This is because, although none of the environmental
324 samples on any matrix were actually from the same location, the GPS coordinates were duplicated
325 as GPS readings are only precise within 6 m. It was one observation out of any such pair that was
326 “jittered” in this way using the jitterDupCoords function from the geoR package in R (Ribeiro and
327 Diggle, 2018).

328 **Statement of Ethical Approval**

329 Required ethical clearance and permits were obtained from relevant authorities

330

331 **3.0 Results**

332 **Home range size**

333 The null hypothesis that the mean home range size was the same for the mine and non-mine areas
334 could be rejected. The Wilcoxon test showed a significant difference between mine and paired
335 conspecifics outside of the mine ($P=0.001$; Table 1; Supplementary Information Table 9).

336 **Environmental samples**

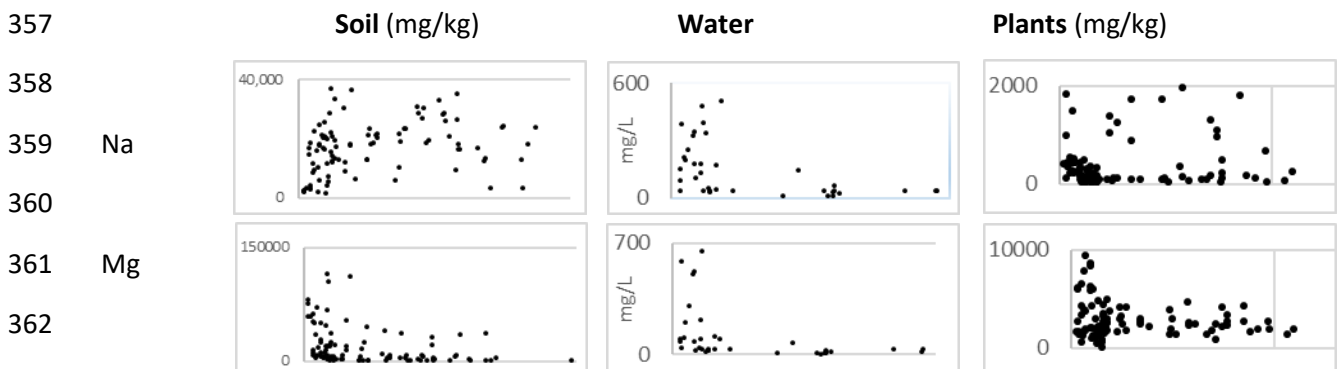
337 With FDR control at 0.05, the null hypothesis of no spatial trend in concentration in the soil with
338 distance from the mine could be rejected for all investigated elements. Inspection of the trend
339 model shows that in all cases concentrations decline with distance (Fig. 4; Table 3; Supplementary
340 Information Table 3 and 8). With FDR control at 0.05, the null hypothesis of no spatial trend in
341 concentration in the water with distance from the mine could be rejected for four investigated
342 elements (Ca, K, Fe and Cu), with concentrations declining with distance (Fig. 4; Table 3;
343 Supplementary Information Table 5 and 8). With FDR control at 0.05, the null hypothesis of no
344 spatial trend in concentration in plants (leaf samples) with distance from the mine could be rejected
345 for nine investigated elements (P, Mg, Mn, Fe, Cu, Zn, Se, Cd, and U), with concentrations declining
346 with distance (Fig. 4; Table 3; Supplementary Information Table 4 and 8).

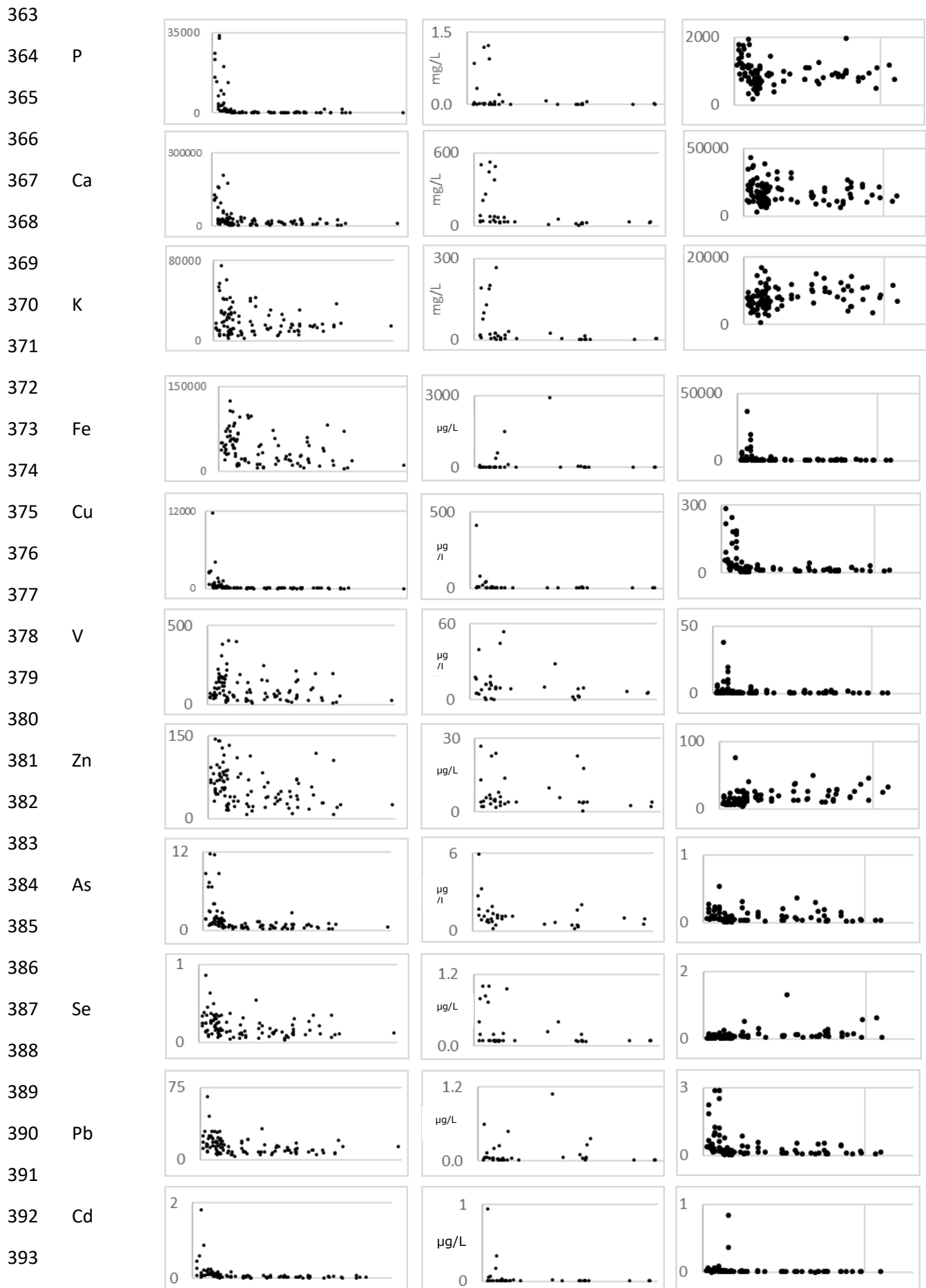
347 **Elephant biomarkers**

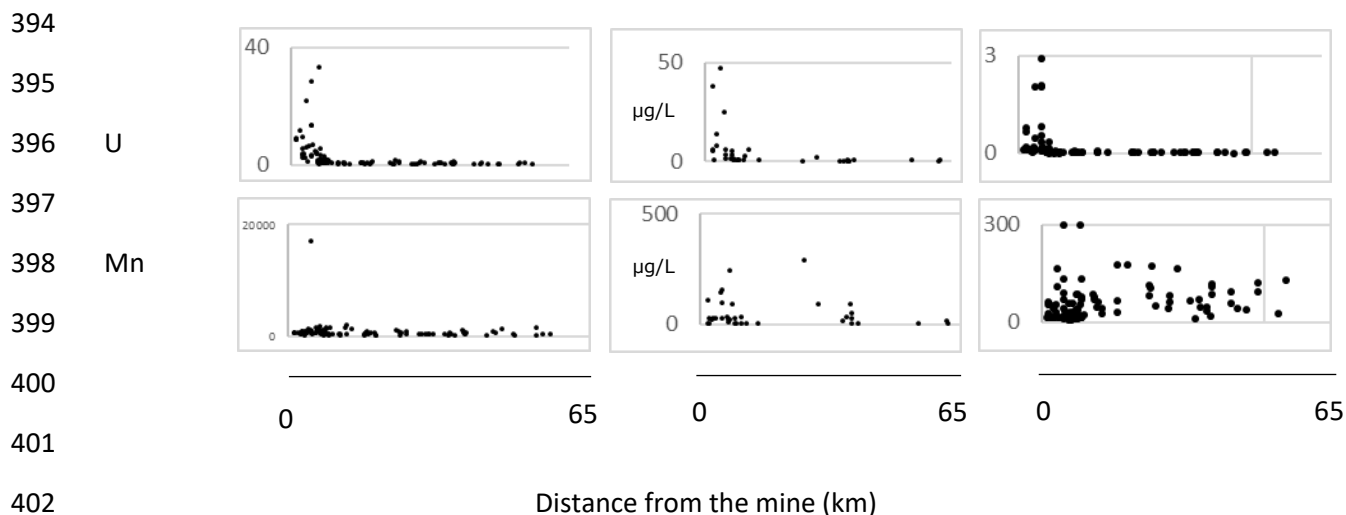
348 With FDR control at 0.05, the null hypothesis of no difference between the mine and non-mine
349 faecal samples could be rejected for Mg, P, Cu, As, Cd, Pb and U (larger concentrations in the
350 elephants near the mine) and Na, Mn, Zn and Se (smaller concentrations in the elephants near the
351 mine; $P < 0.05$; Figure 5; Supplementary Information Table 7; 8).

352 With FDR control at 0.05, the null hypothesis of no difference between the mine and non-mine tail
353 hair samples could be rejected for Cd (larger concentrations in the elephants near the mine) and K
354 and Se (smaller concentrations in the elephants near the mine; $P < 0.05$; Figure 5; Supplementary
355 Information Table 6; 8).

356 **Environmental data**







403 **Figure 4:** Overview of elemental analysis of environmental samples (y-axis), against distance from
 404 the mine (x-axis). Plant data=median of all samples collected (leaves, twigs and branches).

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Element	Soil		Water		Plants/ leaves	
	P-value	Adjusted P-value	P-value	Adjusted P-value	P-value	Adjusted P-value
Ca	0.05	0.043	0.42	0.038	0.336	0.360
I ratio	5.84		0.65		0.926	
number	2		1		1	
P	<.0001	0.000	0.03	0.060	<.0001	0.005
I ratio	40.27		4.82		19.52	
number	4		1		4	
Mg	<.0001	0.000	0.02	0.075	<.0001	0.005
I ratio	31.88		5.42		68.08	
number	4		1		2	
Na	0.04	0.050	0.01	0.525	0.5317	0.532
I ratio	4.44		6.05		1.26	
number	1		1		2	
K	0.04	0.043	0.01	0.038	0.33	0.360
I ratio	4.44		7.88		0.93	
number	1		1		1	
V	0.002	0.003	0.31	0.423	0.10	0.136
I ratio	9.18		1.02		4.60	
number	1		1		2	
Mn	0.001	0.002	0.60	0.692	<.0001	0.020
I ratio	10.47		1.86		6.9662	
number	1		3		1	
Fe	0.0003	0.001	<.0001	0.000	0.03	0.050
I ratio	12.94		42.50		6.77	
number	1		1		2	
Cu	0.009	0.012	0.01	0.038	0.01	0.021
I ratio	9.42		8.78		8.68	
number	2		2		2	
Zn	0.02	0.025	0.96	0.960	0.003	0.009
I ratio	7.96		0.00		8.78	
number	1		2		1	
As	<.0001	0.000	0.16	0.267	0.30	0.360
I ratio	47.96		1.95		3.66	
number	2		1		3	

Se	0.00	0.008	0.11	0.206	0.02	0.038
I ratio	9.60		2.51		5.65	
number	1		1		1	
Cd	<.0001	0.000	0.08	0.171	<0.0001	<0.0001
I ratio	51.20		0.08		25.54455	
number	2		1		1	
Pb	<.0001	0.000	0.77	0.825	0.04	0.060
I ratio	114.46		0.08		6.24	
number	1		1		2	
U	0.002	0.003	0.26	0.390	0.0027	0.009
I ratio	14.44		1.28		11.84	
number	3		1		2	

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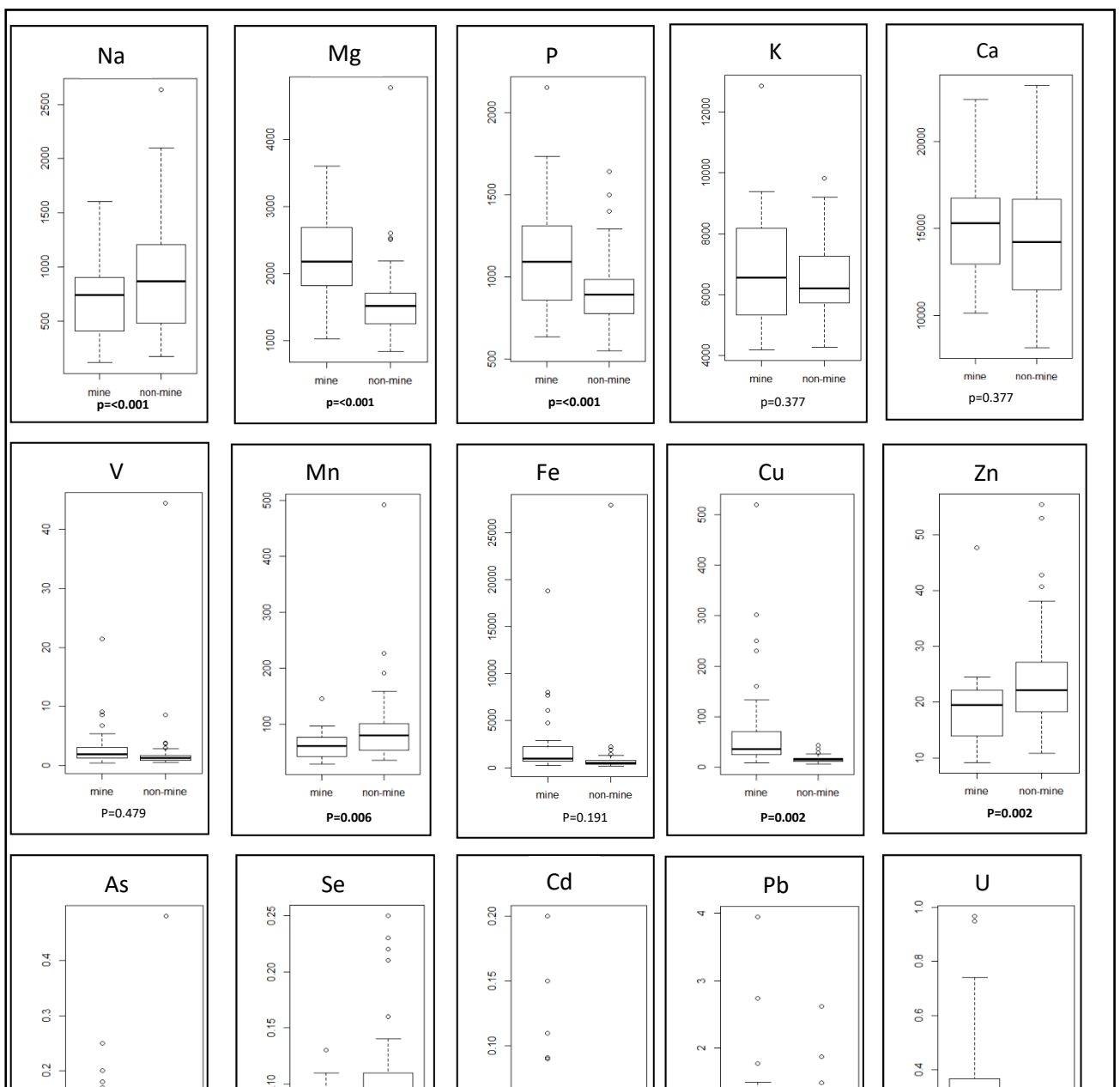
407 **Table 3:** Results of linear mixed model to show significant differences in soil, water and plant (leaf)
 408 concentrations as distance from the mine increased. P-value (<0.05) and adjusted P-values to control
 409 the false discovery rate (FDR) reported.

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412 **Biological data**

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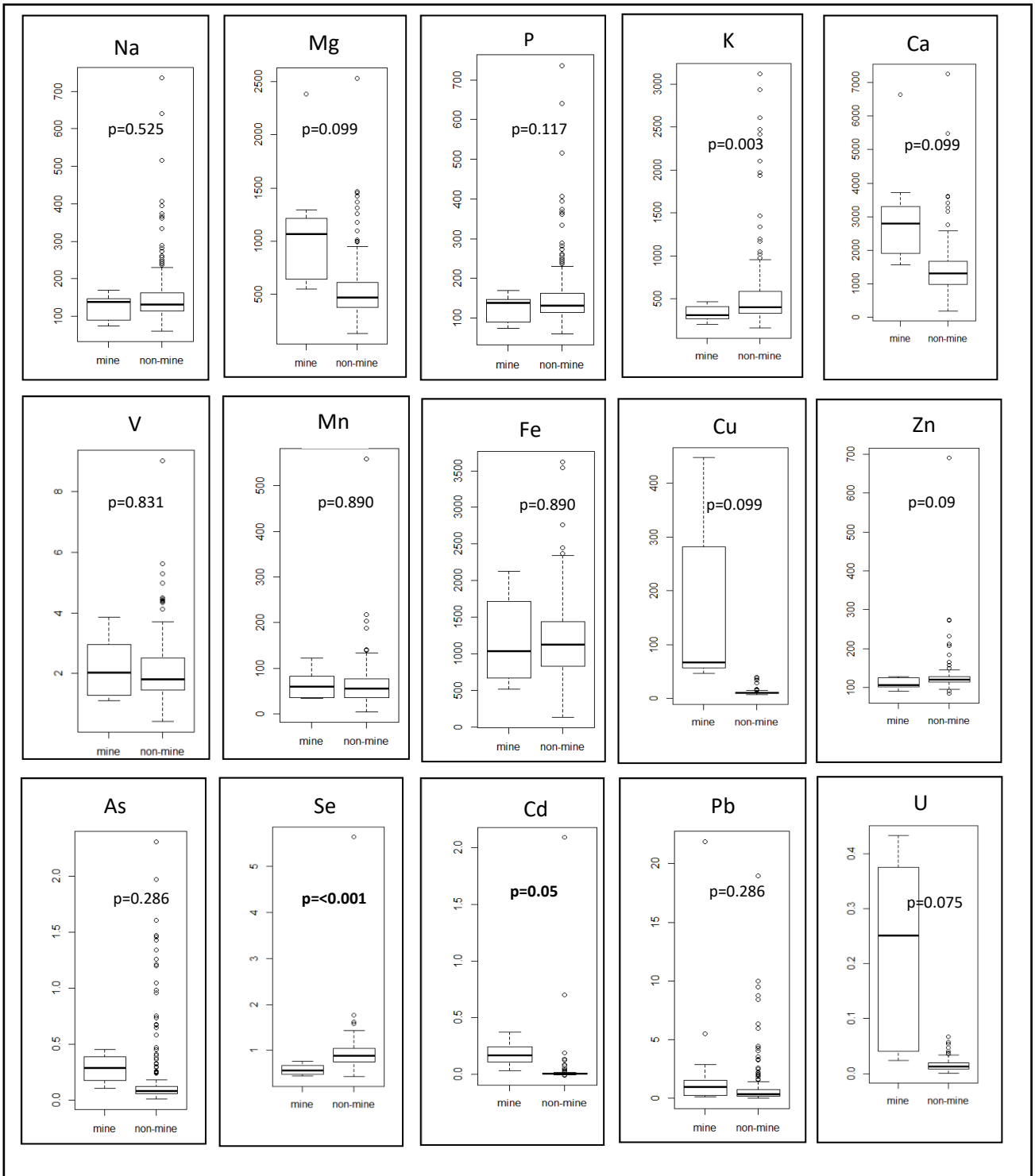
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440 **Figure 5:** Elemental analysis data (y-axis, mg/kg) for faecal samples. Box plots show median, Q2, Q3,
441 max and min. Outliers are defined as $1.5 \times \text{IQR}$. Adjusted P-values are reported to control for false
442 discovery ($p < 0.05$). For mine samples $n = 37$, non-mine $n = 57$.

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469 **Figure 6:** Elemental analysis data (y-axis mg/kg) from tail hair samples from mine and non-mine
 470 elephants, y axis=element concentration (mg/kg). Box plots show median, Q2, Q3, max and min.
 471 Outliers are defined as 1.5*IQR. Adjusted P-values are reported to control for false discovery
 472 ($p < 0.05$). For mine samples $n=7$, for non-mine samples $n=200$.

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475 4.0 Discussion

476 Mineral provision at the PMC was greater than the surrounding areas (Table 3; Fig. 4). Home ranges
477 of the mine elephants were significantly smaller (59% $P=0.001$) than those in the surrounding areas
478 (Fig. 2; Table 1), suggesting that their resource needs, including minerals, were met within this
479 smaller area, close to the PMC (Tucker *et al.*, 2018). A trade-off is likely whereby elephants consume
480 soil and water (or plants) near the PMC to obtain increased levels of Ca, Mg, P, Cu, Zn and Se but
481 also consume PTEs (Pb, U and V). Selenium and Zn are fertility augmenters, benefiting elephants in
482 early life (Hidioglou and Knipfel, 1984; Mistry *et al.*, 2012), whereas the effects on fertility from
483 consuming PTE's to toxic levels may take decades to realise, having a lesser effect on total
484 reproductive output (Kincaid, 1999). An evolutionary advantage may be gained in consuming
485 increased micronutrients at the PMC, at the cost of the increased consumption of PTEs. High
486 consumption of macro-minerals (seen in plants) are under homeostatic control within the elephant,
487 and thus the elephant can buffer increased intake (Kincaid, 1999).

488 Biological samples

489 Tail hair reflects up to 18 months residence, whereas faecal material reflects short-term dietary
490 intake (Bencko, 1995; Wittemyer, Cerling and Douglas-Hamilton, 2009). The differences in tissue
491 biomarkers indicated that short-term environmental differences in availability of minerals consumed
492 by the elephants, appeared to be reflected directly by faecal samples. Whereas, the tail hair data
493 suggested that the elephants moved to obtain required minerals over time, thereby not showing
494 significant differences in as many elements, between mine and non-mine samples (11 of 15

495 elements in faecal material versus 3 of 15 elements in tail hairs). Such temporal variability must be
496 considered in evaluating the use of biomarkers for assessing nutrient status/habitat quality.

497 This study covers the widest range of minerals and PTE analysis in elephant faeces to date (n=97; Fig.
498 5; Supplementary Information Table 7). In Hwange National Park, Zimbabwe, Mg, Na and K data
499 were similar to concentrations found in this study (Holdø, Dudley and McDowell, 2002). However, in
500 this study, faecal Ca concentrations, both from mine and non-mine samples were substantially larger
501 than reported by Holdø et al. (2002) with the minimum and maximum level in this study being 8,100
502 and 23,100 mg/kg DM, respectively, versus 920 and 12,000 mg/kg DM. Additionally, in the APNR,
503 Greyling (2004) reported similar P levels in faecal samples (median 1100 versus 990 mg/kg DM in
504 this study). Faecal samples reflect Ca intake (Sach et al., 2020 unpublished data), therefore increased
505 Ca levels found in in this study could be attributed to increased intake.

506 Faecal samples may not represent a specific location or plant consumed; elephants have a total gut
507 transit time of 11–46 h (Clauss *et al.*, 2003) and walk over 22 km daily (Thomas, Holland and Minot,
508 2012). Faecal samples were a reliable indicator of Ca, P, Se, Cu and As intake (Sach et al., 2020
509 unpublished data) and thus a proxy for elemental status. Significantly greater levels of faecal P, Cu
510 and As were seen in mine samples compared to non-mine samples, indicating that intake of these
511 elements were greater in mine versus non mine. This is also seen in soil, in Cu in water and P and Cu
512 in plants (leaves), supporting this increased intake. Additionally, elephants are frequently
513 documented to participate in geophagy (Holdø, Dudley and McDowell, 2002), and although not

514 specifically reported at PMC, could be in part obtaining these increased elemental levels via
515 geophagy.

516 This study provides the largest multi-element dataset on mineral and PTE analysis data in elephant
517 tail hair (Fig. 6; Supplementary Information Table 6). Hair analysis is routinely used in humans and
518 livestock to assess Se and As levels (Bencko, 1995; Middleton *et al.*, 2016). Duer, Tomasi and
519 Abramson, (2016) analysed an elephant tail hair from a deceased healthy individual from Tsavo
520 National Park, Kenya and reported 11 elements for which concentrations were comparable to the
521 non-mine elephants within this study. However, levels of Mg, Ca, Mn, Cu and Pb in the mine
522 elephant tail hairs were considerably greater than those reported by Duer, Tomasi and Abramson
523 (2016).

524 **Environmental samples**

525 This study agrees with work reported by Ramahlo (2013) within the Phalaborwa region, regarding
526 the impact of mining on soil at surrounding farms, where P, As and Pb levels in soil decreased with
527 increasing distance from the mine. African soils contain high levels of Fe (Siyame *et al.*, 2013), and
528 thus a significant difference between mine/ non-mine faecal or tail hair samples may not be seen
529 (Fig. 5 and 6), as all animals may be consuming to excess. Studies demonstrated elephants
530 selectively drank water with elevated mineral levels; notably Na, iodine (I), sulphur (S), Zn, Ca, Mg,
531 Mn and Fe (Weir, 1972; Sienne, Buchwald and Wittemyer, 2014). Additionally, elephants may spend
532 more time at the PMC site during the dry season, either due to mineral deficiencies in natural forage

533 being heightened in the dry season, or simply for increased water availability within the PMC area
534 (Purdon and van Aarde, 2017).

535 Elemental analysis of plant samples do not always reflect soil due to a variety of factors including soil
536 pH, organic matter and differences in the capacity of individual plant species to accumulate certain
537 elements (Bowell and Ansah, 1994; Maskall and Thornton, 1996). In the Sabi Sands Reserve, South
538 Africa, grasses were analysed from soils of higher mineral levels, yet they accumulated less minerals
539 compared to grasses from soils where the minerals were lower (Ben-Shahar & Coe, 1992), due to
540 differences in soil-to-plant transfer between plant species and the effect of the local micro-climate.
541 Similarly, this variation in soil-to-plant transfer was reflected in this study for Ca, Na, K, V, As and Pb
542 (Fig. 4; Table 3). These elements decreased significantly in soil with distance from the mine, although
543 plants did not follow the same trend. The igneous Phalaborwa apatite would be expected to have
544 low reactivity (i.e. low solubility), hence the elements in the soil may be less available for uptake by
545 plants (Appleton, 2002). Finally high soil Fe, typical of African soils, could also reduce the availability
546 of P to animals via plants, thus the increase in soil P may not be reflected within mine tail hair
547 samples (Fordyce, Masara and Appleton, 1996).

548 5.0 Conclusion

549 The home ranges of the collared PMC elephants are considerably smaller (59% smaller) than
550 elephants in surrounding areas, implying that their resource needs are being met within this
551 relatively compact area. Drivers for elephant movement are multifactorial, yet evidence suggests
552 that these key differences in the geochemistry of the mine compared to the surrounding areas,
553 could act as a driver for elephant movement, resulting in reduced home range size compared to
554 other elephants within this geographical region. Mineral provision to the elephants at the PMC is

555 significantly greater than in surrounding areas, seen most significantly in the soil where all
556 investigated mineral and PTE levels decreased significantly with increasing distance from the mine.
557 These differences suggest that elephants are attracted to this micronutrient hotspot at the PMC, to
558 obtain required minerals.

559 The increased mineral provision and trade off of increased PTE levels were reflected in biological
560 samples of elephant tail hair and faeces. Baseline levels of key minerals and PTEs in African elephant
561 tail hair and faeces were established from this work. The methods described within this natural
562 experiment to investigate how environmental geochemistry influences elephant home range size
563 and potentially movement, facilitates the consideration of intervention to reduce associated HECs at
564 the PMC. This approach could be applied to similar situations, with wider benefits to a variety of
565 stakeholders, informing broader conservation efforts.

566 **6.0 CRediT author statement**

567 *FS, MW, LY, SLE, ED, MH and AS conceptualization and methodology; FS and AB data curation; FS, MH,*
568 *AG, EH and PB investigation; MW, MH, AS and PB resources; FS and RML formal analysis; FS writing*
569 *original draft. All authors contributed critically to drafts and final approval for publication.*

570 **7.0 Declaration of Interest**

571 Ellen Dierenfeld is employed by Ellen Dierenfeld Consulting LLC

572 No other declarations of interest

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583 9.0 References

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