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SUPPLEMENTARY INFORMATION

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The legacy of the Pleistocene megafaunal extinctions on nutrient availability in Amazonia

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17

18 Overview

19 In this paper, our goal is to estimate diffusive lateral nutrient fluxes by herbivores. In diffusion,
20 the flux is proportional to the local concentration difference in material, with a constant of proportionality
21 termed the "diffusivity" *D* (length^2/time). The equation that best incorporates the diffusive properties of
22 animals is the following reaction diffusion equation:

23 $$\frac{dP}{dt} = D\frac{\partial^2 P}{\partial x^2} - KP + G \qquad [1]$$

24 where *K* is a first order loss rate and *G* is a gain rate. To calculate a diffusion term we estimate D based
25 on the random walk with the form:

26 $$D = \frac{(\Delta x)^2}{2\Delta t} \qquad [2]$$

27 Where Δx is a change in distance and Δt is a timestep of duration t. In general, a diffusivity can be
28 derived from a random walk [1-3]. The "random walk" has been derived previously [4].

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Justification for the random walk

Individual animals do not move randomly, but the net movement of all animals over long time periods (>1000 years) begins to approximate random motion. There is a large literature describing how different animal species overlap in space by consuming different foods and moving and sleeping in different patterns to avoid a variety of predators[5-7]. Internal demographics of animal groups will also change which will lead to shifting ranges and boundaries of the group over time [8].

Next, large herbivores patterns will change in response to changing climate. For instance, herbivores often track landscape patterns in grass productivity [9] which will change in response to variable rainfall patterns[10], which have experienced large global shifts over the past 15,000 years. Such interannual variation in climate alters the productivity of the landscape, which drives changes in animal foraging intensity [11,12]. These shifting patterns will serve to further move herbivore patterns from their current routes. For instance, in Kenya, during wet years there is a net nutrient input into certain patches because the impala dominate, but in dry years there may be a net loss, because the cattle dominate[13]. Due to these reasons, the net movement of all animals over long periods will approach an approximation of randomness.

As long as there is an underlying substrate concentration gradient, over long periods of time if the net movement is approximately random, animals will move the nutrients across the gradient. This seems to contradict literature showing that megafauna concentrate nutrients in small scale patches [13]. However, there is no contradiction, only a difference in the time, distance, and lack of a substrate concentration gradient. The study on megafaunal nutrient concentration focused on small nutrient patches in central Kenya (~1ha nutrient rich vegetation per 1km^2 nutrient poor vegetation) within homogenous nutrient poor metamorphic soil substrate. To the north of that study sites are rich basaltic soils of N. Kenya and Ethiopia. As these small patches of nutrient concentration shift across the landscape on decadal and larger timescales, nutrients will flow from the nutrient rich basalt to the nutrient poor metamorphic substrate

from patch to patch, through the large herbivores, over hundreds of km's and thousands of years. We have used our model to show a similar process for Kruger Park between nutrient rich basalts and granites in a companion paper[14].

There is evidence that the small scale nutrient hotspots shown in the Augustine et al. 2003 paper will shift with time. That paper depicts the creation of nutrient hotspots by the corralling of cattle where significant quantities of dung accumulate over time[13]. They then measure a significant decline in the nutrients of these areas as they are abandoned over time. It is unlikely that these nutrients are lost but instead redistributed, thus showing how nutrient hotspots can build up but then move over short time periods (~40 years).

This process has also been experimentally demonstrated in a recent study where the authors measured the total seed biomass transported between the white water floodplains and the terra firme forests by a population of wooly monkeys. They show that a single, relatively small species can transport phosphorus in quantities similar to that arriving from atmospheric deposition[15]. There was no net movement of seed biomass between the two regions, but P was transported between the sites only due to the nutrient concentration gradient. There are several other similar studies showing the net movement of nutrients by animals [16,17]. Our mathematical framework enables us to estimate this process over all animals and long periods of time.

Estimate of $D_{excreta}$

Nutrients can be moved by animals through either their dung or flesh. Nutrients moved in dung will have different distance and time scales than those moved in the flesh. We therefore calculate D for each separately. Below we start with D for dung.

Δx is the daily displacement or day range (DD) of a single animal (DD; km), and Δt is a day. The length scale for diffusivity of ingestion and excretion is the day range multiplied by the average gut passage time (PT; fractions of a day). The time scale is again the food passage time (PT). Therefore, putting this in the framework of the random walk, we estimate that the diffusivity for transport of its dung is $D_{exreta} \sim= (DD*PT)^2/(2*PT)$, where the numerator is in km^2 and the denominator is in days.

Estimate of D_{body}

Next, we calculate a D term for nutrients incorporated into the animal's body. The diffusivity for nutrients in an animal's bodymass, D_{bones}, is related to the lifetime of the animal L (days) and the residence time of these nutrients is L. The length scale is the home range (HR; km^2). The mean displacement over the lifetime of an animal is related to the range length (RL) and approximately $HR^{0.5}/2\pi$. Therefore, if HR is the range used throughout an animal's lifetime, then $D_{body} \sim= RL^2/2L$ or $HR/(8\pi^2 L)$, where the numerator is in km^2 and the denominator is in days.

Consumption of nutrients

Next, we need to estimate the amount of food and nutrients consumed by a population of animals per area. P(x,t) is the mass (kg P km^{-2}) of a nutrient. The mass of P at position x at time t+Δt is given by:

$$P(x,t+\Delta t) = P(x,t) - losses + gains \quad [3]$$

The *losses* term is represented in Equation 3 by αp(x,t), the fraction of animals leaving x at time t. The loss of a nutrient in dry matter consumed and transported by a population of animals is

$$\alpha \frac{animals}{km^2} \frac{kgDM/\Delta t}{animal} \frac{kgP}{kgDM}(x,t)\Delta t = \alpha \cdot PD \cdot MR \cdot [P](x,t)\Delta t = \alpha Q[P](x,t)\Delta t \quad [4]$$

The loss rate of P (kg DM km^{-2}) is the population density of animals (PD; #/km^2) consuming dry matter (DM) to fulfil their metabolic requirements (MR; kg DM/animal/day). The product of PD and MR is the population consumption rate of DM (denoted Q here), such that QΔt is the mass of DM consumed in Δt (kg DM km^{-2}). The consumption of the nutrient itself is then determined by Q[P](x,t), which has units kg P km^{-2}, equivalent to P, the numerator on the left. Gains from adjacent regions will be represented as Q[P](x+Δx, t) and Q[P](x-Δx, t). A fraction ε of the consumed nutrient is incorporated into bodymass, while the rest (1-ε) is excreted.

We estimate ε as 22.4% for megafauna based on the gross food assimilation efficiency of elephants [18]. Incorporation of phosphorus into the body is, of course, more complicated with relative P fraction of biomass increasing with size due to the greater investment in bone growth in larger vertebrates [19]. It also changes with animal age as full grown adult vertebrates need less P than immature growing animals. However, since we account for both the fraction in the biomass and the fraction excreted and there are no fates of the nutrient other than bodymass or excrement, we use the simple value of 22.4%.

To account for the large uncertainty in this term, in a sensitivity study we increase and decrease it by 0.1 (12.4% and 32.4%).

Consider the budget of just the fraction (1-ε) of consumed nutrient that will be excreted:

$$P(x,t+\Delta t) = P(x,t) - (1-\varepsilon)\left[\alpha Q[P](x,t) + \frac{\alpha}{2} Q[P](x+\Delta x,t) + \frac{\alpha}{2} Q[P](x-\Delta x,t) \right] \quad [5]$$

By analogy to the derivation the random walk, we arrive at the equation:

$$\frac{\partial P}{\partial t} = (1-\varepsilon) Q D_{excreta} \frac{\partial^2 [P]}{\partial x^2} \quad [6]$$

Adding in the fraction of nutrient incorporated into bodymass we get the complete budget equation:

$$\frac{\partial P}{\partial t} = (1-\varepsilon) Q D_{excreta} \frac{\partial^2 [P]}{\partial x^2} + \varepsilon Q D_{body} \frac{\partial^2 [P]}{\partial x^2} \quad [7]$$

The state variable on the left and the right are not the same; P is per area and [P] is per kg DM. Let B be total plant biomass (kg DM km^{-2}) such that [P]B=P. We note that B has the same units as Q. Dividing both sides by B:

$$\frac{\partial [P]}{\partial t} = (1-\varepsilon) \frac{Q}{B} D_{excreta} \frac{\partial^2 [P]}{\partial x^2} + \varepsilon \frac{Q}{B} D_{body} \frac{\partial^2 [P]}{\partial x^2} \quad [8]$$

B represents total plant biomass but animal consumption is only from edible parts of that biomass. Therefore B' = αB, where α is the edible fraction of total biomass. We assume for simplicity here that all P made available is taken up, on a fast timescale and used in edible parts. We may revisit this assumption in future work. If these fractions can be assumed equal, then:

$$\frac{\partial [P]}{\partial t} = (1-\varepsilon) \frac{Q}{\alpha B} D_{excreta} \frac{\partial^2 [P]}{\partial x^2} + \varepsilon \frac{Q}{\alpha B} D_{body} \frac{\partial^2 [P]}{\partial x^2} \quad [9]$$

If Q/B can be assumed constant, then:

138 $$\frac{\partial P}{\partial t} = \Phi_{excreta} \frac{\partial^2 P}{\partial x^2} + \Phi_{body} \frac{\partial^2 P}{\partial x^2} \quad [10]$$

139 where the [P] terms on both sides have been multiplied by αB, and

140 $$\Phi_{excreta} = (1-\varepsilon)\frac{Q}{\alpha B} D \ = (1-\varepsilon)\frac{PD}{\alpha B} * MR * \frac{(DD * PR)^2}{2 * PR} \quad [11]$$

141 $$\Phi_{body} = \varepsilon \frac{Q}{\alpha B} D = \varepsilon \frac{PD}{\alpha B} * MR * \frac{HR}{8\pi^2 L} \quad [12]$$

142 We solve the equations above using datasets and methods described in the next section.

143

144 *Coefficients for* Φ *from data*

145 We compiled data for as many herbivore species as we could find for weight, day range, home
146 range, lifetime, population density, and metabolic rate. We used a common taxonomic authority [20],
147 available online at http://www.bucknell.edu/msw3/export.asp. We compiled data for terrestrial mammals
148 at the species level (n = 5278 unique taxa) but only used herbivores in our calculations. We collected
149 data for longevity and metabolic rate from the AnAge database [21]; population density [22]; day range [23]; and
150 home range [24], which all include M as a predictor variable, as well as M [25]. We use the equation from [26]
151 for food passage time. Each scaling term is not perfect but will approximate the "average" animal well
152 which is important for our study because we incorporate all animals in the ecosystem. Certain terms,
153 such as that for population density[27], are also more controversial than others, but even population density
154 shows a strong relationship with mass for large animals (although not for smaller animal).

155 We estimated Φ as a function of M in two ways: first, we calculated the allometries for each term
156 as a function of M (using ordinary least squares) and combined the resulting coefficients to yield an
157 allometric equation for Φ that results from scaling arguments (SOM Figure 1 and SOM Table 2). For
158 example, to calculate the grey and black lines for QD_{scaled} in Figure 2a, we calculated the allometries for
159 each attribute and combine them (SOM Figure 1 for herbivores >10kg). Second, we multiplied the terms
160 together to estimate Φ directly, and fit the allometric equation using the data themselves (Figure 2a). In
161 Figure 2, we were able to calculate QD_{fit} for the following fourteen species: *Eulemur fulvus, Propithecus*
162 *verreauxi, Alouatta palliata, Cercopithecus mitis, Colobus guereza, Dipodomys merriami, Perognathus*
163 *longimembris, Apodemus flavicollis, Apodemus sylvaticus, Rattus rattus, Capreolus capreolus,*
164 *Odocoileus virginianus, Cervus elaphus, Kobus ellipsiprymnus*.

165

166

167 *1D solution*

168 Below is the solution for equation 1 in 1 dimension:

169 An ordinary differential equation for a nutrient with exogenous gains G (kg P km^{-2} day^{-1}) and first

170 order losses K (day^{-1}) has the following form:

171 $$\frac{dP}{dt} = -KP + G \qquad [13]$$

172 The steady state P_{ss} of this system is G/K. We then add the diffusion term Φ which adds the potential for

173 lateral fluxes to emerge from horizontal gradients in P:

174 $$\frac{dP}{dt} = \Phi\frac{d^2P}{dx^2} - KP + G \qquad [14]$$

175 We make the following two substitutions, u = KP – G and $v = ue^{kt}$, to get the homogeneous equation

176 $$\frac{dv}{dt} = \Phi\frac{d^2v}{dx^2} \qquad [15]$$

177 We assume a boundary condition with one edge (x=0) with a fixed concentration of a nutrient that is

178 continuously replenished. Crank [28] presented the following solution. Let a line source of material have

179 concentration vo within a domain of width dξ, such that its initial mass is $v_o d\xi$. The general solution for

180 this line source, if diffusion is only in the +x direction, is

181 $$v(\xi,t) = \frac{v_o d\xi}{\sqrt{\pi D t}}\exp\left(\frac{-\xi^2}{4\Phi t}\right) \qquad [16]$$

182 Integrating this expression over dξ yields:

183 $$v(x,t) = \frac{v_o}{\sqrt{\pi\Phi t}}\int_x^\infty \exp\left(\frac{-\xi^2}{4\Phi t}\right)d\xi = v_o\frac{2}{\sqrt{\pi}}\int_{x/\sqrt{4\Phi t}}^\infty \exp(-\eta^2)d\eta \qquad [17]$$

184 where $\eta=\xi/\sqrt{4\Phi t}$. In evaluating the integral, consider the error function

185 $$erf(z) = \frac{2}{\sqrt{\pi}}\int_0^z \exp(-\eta^2)d\eta \qquad [18]$$

where erf(∞) = 1 and erf(0) = 0, and the error function complement erfc(z) = 1-erf(z). The integral then equals

$$\frac{2}{\sqrt{\pi}}\int_{x/\sqrt{4\Phi t}}^{\infty}\exp(-\eta^2)d\eta=\frac{2}{\sqrt{\pi}}\int_{0}^{\infty}\exp(-\eta^2)d\eta-\frac{2}{\sqrt{\pi}}\int_{0}^{x/\sqrt{4\Phi t}}\exp(-\eta^2)d\eta \qquad [19]$$

yielding the solution

$$v(x,t)=v_o erfc(\frac{x}{\sqrt{4\Phi t}}) \qquad [20]$$

By the previous substitutions, $v_o = e^{kt}(KP_o - G)$, where P_o is the nutrient concentration at the x=0 boundary. Backsubstituting $P(x,t) = (v(x,t)e^{-kt}+G)/K$, the solution in conventional units is:

$$P(x,t)=\left(P_o-{}^{G}\!/_{K}\right)erfc\left(\frac{x}{\sqrt{4\Phi t}}\right)+\frac{G}{K} \qquad [21]$$

We use equation 21 to calculate SOM figure 2. We estimate G as 0.48kg P km^{-2} yr^{-1}[29] , and local weathering at 2.5kg P km^{-2} yr^{-1} (see below), for a G of 2.98 kg P km^{-2} yr^{-1} , K as 0.00007 yr^{-1} [30], and P_o as 600 kg km^{-2} (SOM Table 2). These figures show the distribution over time from a starting point for current fauna of $\Phi_{excreta}$ =0.027 km^2 yr^{-1} (SOM figure 2 bottom) and then including the extinct megafauna $\Phi_{excreta}$ = 4.4 km^2 yr^{-1} (SOM figure 2 top).

2D solution

We could not solve equation 1 directly for a 2D scenario and we therefore use the Crank-Nicolson method to numerically solve equation 1 at each pixel at a time step of 10 years [31]. We estimate flooded white water pixels using a map of flooded areas from Hess et al. (2002) calculated using synthetic aperture radar at 30 meter resolution [32]. We then separate nutrient rich white water rivers (including the Ucayali, Maranon, Napo, Caqueta, and Madeira) from nutrient poor black and clear water rivers according to figure 1 in McClain et al. (2008) [33]. We estimate that vegetation growing in the whitewater floodplain have an average leaf P concentration of 1.50 mg g^{-1} which is continuously replenished (600 kg P km^{-2} assuming an average LAI of 4, and a SLA of 100g m^{-2}) (SI Table 1)[34]. We assume an efficient transfer of the phosphorus from the herbivore dung to the edible biota because nutrients, especially P, recycle rapidly and efficiently in tropical forests [35].

We estimate the spatial distribution of dust into the Amazon basin based on figure 8a from Mahowald et al. 2005 [29]. In a sensitivity study we double and halve these numbers due to uncertainty on how these numbers may have varied in the past (i.e. such as due to changes in the jet stream). We estimate soil moisture in the Amazon basin showing a gradual drying from the northwest to the southeast and soil moisture changing from 0.6 to 0.5 m^3 m^{-3} along this gradient. We map higher P concentrations in the more fertile western region following Higgins et al. (2011) figure 3 top [36]. This increased fertility is probably related to the removal of cation-poor surface sediments through river movement which exposes cation-rich sediments from the Pebas formation [36]. We estimate that vegetation in this region has a continually replenished source of 300 kg P km^{-2}. There is very little data on average local weathering rates in the central and eastern Amazon. However, the ratio of P carried by whitewater rivers to the more numerous black and clear water rivers is 806 Mg P versus 43 Mg P. The area of black and clear water rivers are ~3 times greater than white water rivers [33] and the P from black and clear water rivers is from local weathering, dust, and herbivore input. Therefore, we roughly assume the highly weathered Eastern

lowland soils have a local weathering rate of ~2.5 kg P km^{-2}, which we double and halve in a sensitivity study [37]. In addition, if we assume the long term steady state P (G/K) equals the labile P pool, with a median value of ~50Mg km^{-2} in the Eastern Amazon (see below)[38], a loss rate of 0.00007 yr^{-1}(see below) [30], and average dust input of 0.48kg km^{-2} [29], then to achieve steady state, there must be an additional ~2.5 kg P km^{-2} which we attribute to local weathering.

We estimate P losses from the system based on the following equations from Buendia et al. 2010 [30]:

$$LQ(s) = k_l s^c \quad [22]$$

$$L_o = k_r * LQ(s) * P_o \quad [23]$$

$$L_d = LQ(s) * \frac{Pd}{n * Zr * s} \quad [24]$$

Where s is yearly averaged soil moisture (dimensionless), c is 3, k_l is runoff or leakage at saturation which is 0.1 (yr^{-1}), k_r is the losses regulation rate 0.002 (yr^{-1}), P_o is organic P, P_d is the dissolved P, Zr is soil depth (1m), n is soil porosity (0.4), L_o is the loss rate of P_o and L_d is the loss rate of P_d. Equation 9 in Buendia et al.2010 includes a k_f term or a loss rate from ice, wind, humans, or fire which we do not include because we assume these to be minimal in the Amazon forest prior to the widespread arrival of modern humans. We estimate the steady state ratios of P_o to P_d following figure 2 in Buendia et al. 2010. We estimate the average total loss rate for the Amazon Basin is 0.00007 yr^{-1}. Buendia et al. 2010 calculates a steady state L_d for the Amazon basin of ~3.5 kg km^{-2} yr^{-1} and L_o of ~7 kg km^{-2} yr^{-1}. Our loss rates have a similar ratio of ~2 L_o = L_d. This is an important, yet highly uncertain part of our results and therefore as part of a sensitivity study we double and halve the loss rate. Loss rates of P through occlusion of P are an order of magnitude smaller than loss rates of organic and dissolved P (figure 7 in Buendia et al. 2010) and any uncertainty in occlusion rates will be incorporated within the large range of our sensitivity study.

We estimate the mass of both extinct and extant South American fauna from the Pleistocene and the Holocene based on data from Smith et al.2003 (N=904) [25]. At present it is unknown which extinct megafauna would have lived in the Amazon forest. However, based on limited evidence we are able to make two lists, one of those with animals that "probably" would have ranges that would encompass the current Amazon basin, and one "possibly" could have inhabited the Amazon basin. Based on stable isotope evidence of C3 plant consumption and the location of fossil evidence, we assume that the following species inhabited forest areas of the Amazon: *Eremotherium (3500kg) assume 1 of 2 species),Haplomastodon (6000kg), Cuvieronius (5000kg) assume 1 of 2 species, Toxodon (1100) assume 1 of 4 species, Neochoerus (1500kg) assume 1 of 2 species and Tayassuidae (1100kg) assume 1 of 3 species* [39,40]. Based on a more liberal reading of the evidence, we assume the following species could also have dwelled in the Amazon: *Equus santaelenae, Glossotherium, Holmesina (*Personal communication E. Lindsey and A. Barnosky). Based on the QD equation of $0.05*M^{1.17}$, we calculate a QD value for the Amazon basin of 2.4 km^2 $yr^{-1}$for the "probable" group and 6.5 km^2 $yr^{-1}$for the "possible" group including all species from the "probable" group. In our simulations, we use the midrange value of 4.4 km^2 yr^{-1}, and use 2.4 and 6.5 km^2 yr^{-1} in the sensitivity study. We assume that each of these extinct forest megafauna had a distribution of 100% of the basin based on the abundance of megafauna fossil remains throughout South America and widely dispersed large seeded fruits [41,42].

We display our current estimates of vegetation P with total P and labile P from Quesada et al. 2010 fig 2b [38] (SOM Figure 3). We convert this to Mg km^{-2} for each site using soil bulk density and soil depth provided in the supplementary material (S1 C.A. Quesada) of the paper. We also include data from Fyllas et al. 2009 for leaf P concentrations which we show as vegetation P (Mg km^{-2}) with the assumption of a uniform SLA of 100 g m^{-2} and an LAI of 4 [35]. Where the plots overlap (N=49), we calculate the ratio of vegetation P to labile P and use this to estimate % dust P going into vegetation. Parent material and soil evolutionary stage controls long term (geologic) total P concentrations [38]. Our model does not incorporate these properties and will not replicate current total soil P patterns and concentrations. Instead,

276 our simulations more closely replicate vegetation and labile P patterns because the megafauna increase
277 the readily available form of P that is quickly taken up by the vegetation.

278 We assume a steady state in the absence of animal herbivory of G/K (~50Mg km^{-2}), where G is
279 dust plus local weathering (0.48kg P km^{-2} yr^{-1} plus ~2.5 kg P km^{-2} yr^{-1}) and K is 0.00007 yr^{-1}. We
280 estimate a median labile P of 54 Mg km^{-2} P (SOM Figure 3b) in the Eastern Amazon from Quesada et al.
281 2010 and a median vegetation P of 0.4 Mg km^{-2} P (SOM Figure 3c) from Fyllas et al. (2009). We are
282 interested in the dust P that will enter the vegetation pool, which we estimate as ~1% based on the fact
283 that vegetation P is ~1% of labile P (SOM Figure 3a), and therefore, we apply a multiplication of 0.01 to
284 our dust term.

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Continental estimates of D

We used the IUCN spatial database on mammal species and their ranges [43] to develop a gridded, global estimate of QD for modern animals[14]. We used this gridded estimate to calculate QD for modern species for continental estimates of Table 1 and for the Amazon basin for Figure 3. We assigned the mean value for the genera or family to species with no body mass data. Edible biomass at 1° resolution was estimated using foliar NPP from the CASA carbon cycle model [44].

For extinct species, we use the database from Smith et al. 2003 [25]. Since the ranges of individual species are not currently accurately known, we estimate that at a continental scale each species has a range of ~8% of the continent [45]. We estimate the exact range for each species in the same way as Barnosky (2008) with Africa (8.6%), Australia (7.8%), North America (8.2%), South America (7.2%), and Eurasia (8.1%). This is a highly uncertain term, so we add and subtract 30%, which is incorporated into our uncertainty shown in table 1. There was no data for certain extinct species in Smith et al. 2003 for Eurasia and these values were obtained from Barnosky (2008). We assume the percentage of the continent covered in ice during the Pleistocene as: N. America (50%), Eurasia (10%), and S. America (5%) [45].

306

307 *Possibilities to test predictions*

308 We recognise that we do not yet present any direct evidence that nutrient availability across the
309 Amazonia has declined since the megafaunal extinctions. Instead we have put forward a quantified
310 testable model based on available ecological and geophysical evidence. The collection of direct evidence
311 of nutrient decline following megafaunal loss would require a substantial experimental campaign, and
312 here we propose several potential ways to test our predictions from this study. We would predict a
313 greater quantity of phosphorous flowing out the mouth of the Amazon today than during the era when
314 megafauna still were present in the Amazon basin. We can analyse ocean sediment data from the Ocean
315 Drilling Program (ODP) (http://www-odp.tamu.edu/database/) near the Amazon Fan for changing
316 phosphorous and other nutrient concentrations in a manner similar to which has been done for pollen and
317 isotopes[46].

318 We can look for changes in nutrient concentrations across a nutrient concentration gradient in the
319 presence and exclusion of megafauna. Certain parts of Kruger Park have had all animals >5kg excluded
320 from large regions of the park for 37-43 years and the park has a nutrient concentration gradient due to
321 the granite/basalt substrate. We can compare nutrient gradients both where the animals have been
322 excluded and where they still exist. We predict a diffusion of nutrients across the granite/basalt gradient
323 in the regions with the megafauna, but more of a step change nutrient concentrations in the part of the
324 park without megafauna. This can be tested through airborne analysis of exclusion experiments in Kruger
325 National parks [47].

326 For longer time-scale tests we could compare the sharpness of changes in ecosystem P content
327 (plants, litter and labile soil pools) across sharp geomorphological boundaries (e.g. floodplains vs
328 adjoining terraces), in regions with and without megafauna. In the absence of significant lateral diffusion,
329 ecosystem labile P content should show a step-change across the boundary, reflecting the sharp change in

base substrate. With increasing lateral diffusion, this step change in ecosystem P content becomes increasingly blurred, and the degree of blurring is a direct measure of the diffusivity parameter in our equation. We predict that the measured "blurring" will be much greater in megafauna-rich regions of Africa than in the equivalent geomorphological transitions in Amazonia.

Finally, we can directly test our theory by measuring nutrient concentrations near fertilized farms and forests that are regularly raided by megafauna such as elephants (or experimentally fertilize these areas). We can find out when fertilization of the farm began and how often and by which animals it is raided. From this, we would predict a nutrient gradient into the forest from the fertilized farm. We can test the dung piles as well as the vegetation in the area to determine if the rate of nutrient spread matches that of our predictions.

340

341 **SI Table 1 –** Average P concentrations for leaves, wood, bark, and fruits from Terra firme and blackwater
342 forests and whitewater flood plain forests based on data from Furch and Klinge 1989 (leaves, wood and
343 bark) and Stevenson and Guzman-Caro 2010 (fruit) in units of mg g^{-1} [15,34] (N= number of tree species
344 analysed).

	Leaves mg g^{-1}	Wood mg g^{-1}	Bark mg g^{-1}	Fruit mg g^{-1}
Whitewater flood plain	1.50 (N=88)	0.59 (N=60)	0.80 (N=42)	2.2 (N=10)
Terra Firme and blackwater forests	0.55 (N=220)	0.13 (N=246)	0.16 (N=22)	1.6 (N=13)
Difference	0.95	0.46	0.64	0.4

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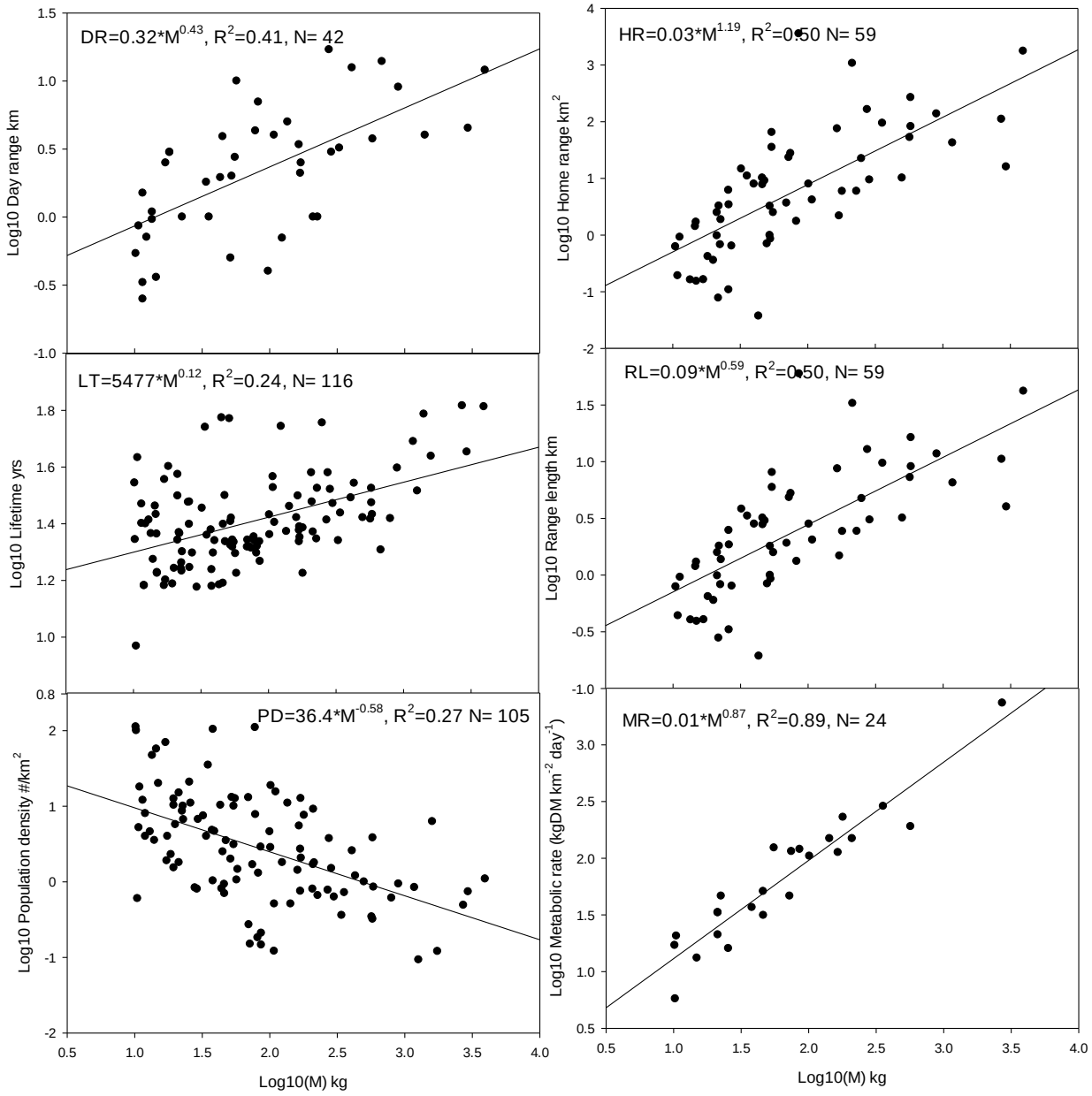
347

348 **SI Table 2 -** Table 1. Allometric fits for herbivores >10kg. For the fecal diffusivity fit equation we use

349 all herbivores to increase the sample size.

Dependent Variable	Units	Equation	N	r^2
Population Density	$\#/km^2$	$36.35*M^{-0.58}$	105	0.27
Metabolic Demand	kgDM/#/day	$0.01*M^{0.87}$	24	0.89
Mature Longevity	Days	$5477*M^{0.12}$	116	0.24
Day Range	Km	$0.32*M^{043}$	42	0.41
Home Range	km^2	$0.03*M^{1.19}$	59	0.50
Range Length (√HR)	Km	$0.09*M^{0.59}$	59	0.50
Passage rate*	Days	$0.29*M^{0.28}$	-	-
Fecal Diffusivity, scaling herbivores >10kg	$(kgDM/km^2)*(km^2/day)$	$0.0065*M^{1.41}$	-	-
Fecal Diffusivity, fit all herbivores	$(kgDM/km^2)*(km^2/day)$	$0.05*M^{1.17}$	14	0.67
Bodymass Diffusivity, scaling herbivores >10kg	$(kgDM/km^2)*(km^2/day)$	$6.5*10^{-7}*M^{1.35}$	-	-

350 *equation from Demment and Van Soest et al. 1985 assuming a digestibility of 0.5 [26]



SOM Figure 1 – Log_{10} mass versus log_{10} transformed values of day range (km) (top left), home range (km^2) (top right), lifetime (yrs) (middle right), range length (the square root of home range) (km) (middle left), population density (number of individuals per km^2) (bottom left), and metabolic rate (kg DM km^{-2} day^{-1}) (bottom right) for herbivores >10kg.

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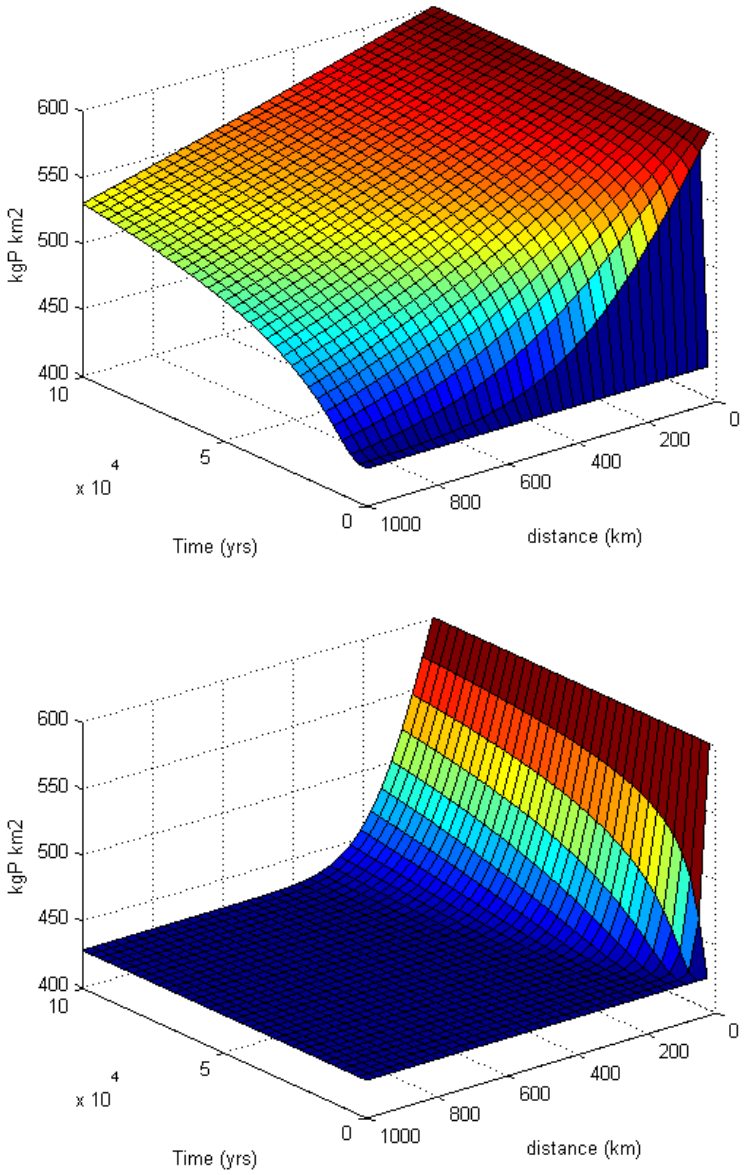

358

359 **SOM Figure 2** – (top) Lateral distribution of nutrients starting from initial conditions over a 1000km

360 distance from a nutrient supply (e.g. the Amazon floodplain) and a 100,000 year period with a $\Phi_{excreta}$

361 value of 4.4 $km^2\ yr^{-1}$(representing lateral diffusion by modern and extinct fauna), (bottom) a $\Phi_{excreta}$ value

362 of 0.027 $km^2\ yr^{-1}$ (representing lateral diffusion by modern fauna only).

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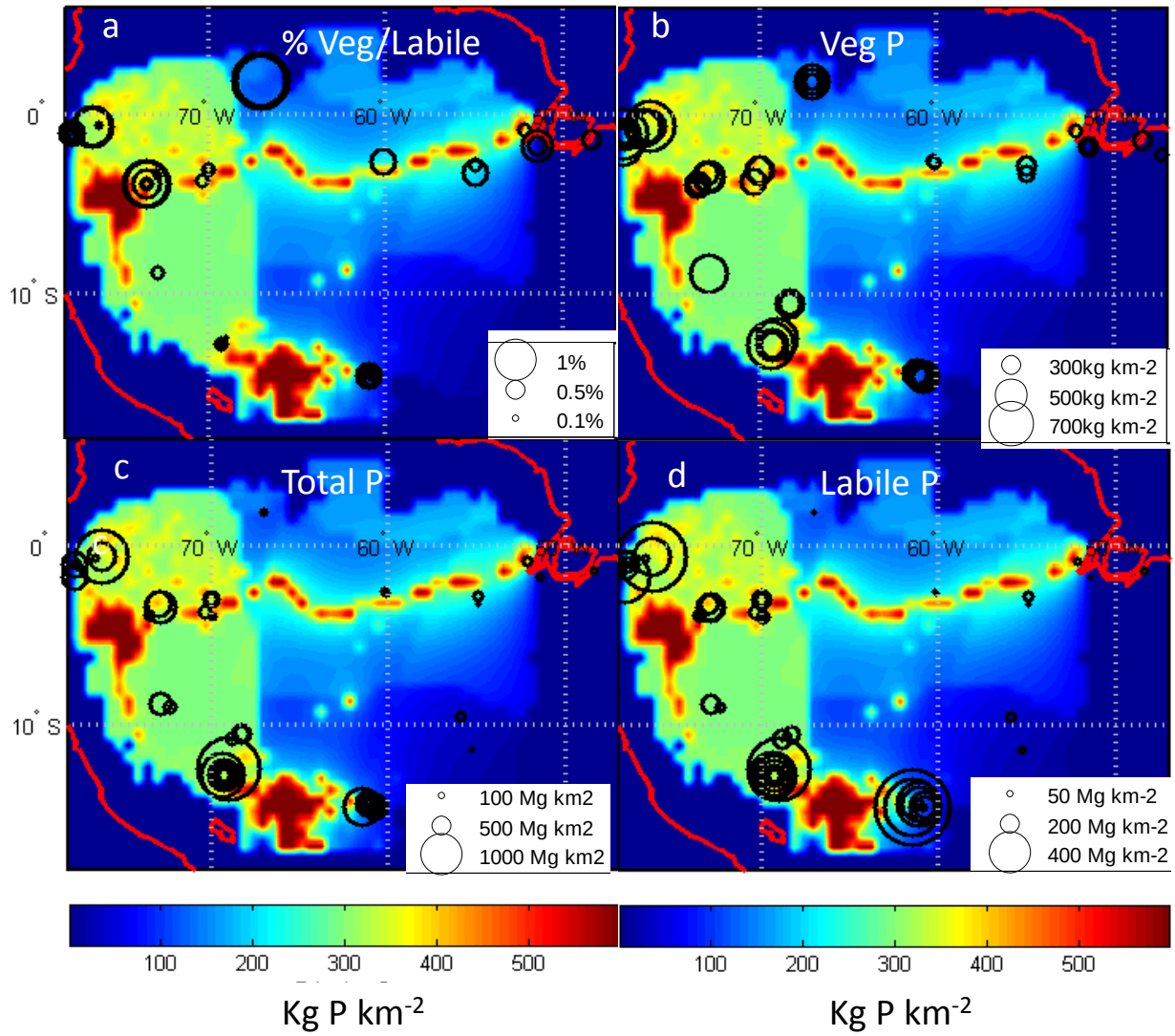

364

365 **SOM Figure 3** – A comparison of our modelled modern-day phosphorus estimates (kg P km^{-2}) (same as

366 Figure 3b) in the background and estimates of (a) percent vegetation/ labile P, (b) vegetation P (kg km^{-2}

367 from Fyllas et al. 2009[35], assuming a SLA of 100g m^{-2} and an LAI of 4), (c) total P (Mg km^{-2}), and (d)

368 labile P (Mg km^{-2}) measured in the Amazon basin from Quesada et al. 2010[38].

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