Appendix for *Rewiring food webs via trophic rewilding*

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# Supporting information

## Changes to the PHYLACINE database

We modified the body mass of two extinct species in the PHYLACINE database before modelling and analyses: body mass of the extinct species *Sinomegaceros ordosianus* was set equal to the mass of *Sinomegaceros yabei* and body mass of the extinct *Dusicyon australis* to *Dusicyon avus*.

## Maxent species distribution models

Climatic suitability of terrestrial mammals was modelled using maximum entropy (Maxent) species distribution models (SDMs) using the R package *ma**xnet* based on inhomogeneous Poisson processes (Phillips, Anderson, Dudík, Schapire, & Blair, 2017). Maxent is a presence-background approach, in which environments occupied by a species are contrasted with the available environmental space (Elith et al., 2011; Merow, Smith, & Silander Jr, 2013). To predict distribution of mammals we used four bioclimatic variables from the WorldClim database at 2.5 arc-minute resolution (Fick & Hijmans, 2017): maximum temperature of the warmest month, minimum temperature of the coldest month, precipitation of wettest quarter, and precipitation of driest quarter. We reprojected these bioclimatic variables to a 5 km2 resolution with a Behrmann equal-area projection using bilinear interpolation. To minimize potential issues with multi-collinearity, we ensured that the variance inflation factor among the climatic variables was below 4 (O’Brien 2007).

To overcome biases in the use of SDMs introduced by species’ range contraction due to anthropogenic pressures (Faurby & Aráujo, 2018), we used current and present-natural range maps from the PHYLACINE database (Faurby et al., 2018). Current ranges were generated from the IUCN range polygon maps for current, natural, and reintroduced ranges only (IUCN, 2016). Present-natural ranges are estimates of where species could be today in the complete absence of influence of modern humans (*Homo sapiens*) through time (Faurby & Svenning, 2015). The present-natural ranges combine knowledge of species' current IUCN range with historic distributions, fossil co-occurrence data, and known range modifications caused by humans (Faurby & Svenning, 2015). We generated presence locations within combined current and present-natural range maps with a 20 km separation distance, excluding locations reported above the highest elevation for each species in the IUCN Red List or, if not stated, 4,000 meters, which is roughly the 95 percentile for upper elevations of mammals (IUCN, 2016). Elevation was determined for presence locations using the EarthEnv-DEM90 digital elevation model (Robinson, Regetz, & Guralnick, 2014).

We ran Maxent SDMs with the default settings, besides disabling threshold features to avoid locally overfitted response curves (Merow et al., 2013, 2014). We also increased the number of randomly sampled background records from the default setting of 10,000 to 100,000 to ensure greater representation of environmental variables available within background areas (Guevara, Gerstner, Kass, & Anderson, 2018). For the background area, we calculated species-specific buffers from combined current and present natural ranges to reflect the dispersal abilities of each species. Following previous studies (Hof et al., 2018; Poo-Muñoz et al., 2014), we calculated the buffer size as the maximum distance from the range centroid to the range edge of the largest continuous range; see figure S1 for an example. We only modelled species that had at least 10 presence locations, thus excluding 76 rare species with restricted geographic distribution. In total, we modeled 4,130 of the 4,206 living terrestrial mammals.

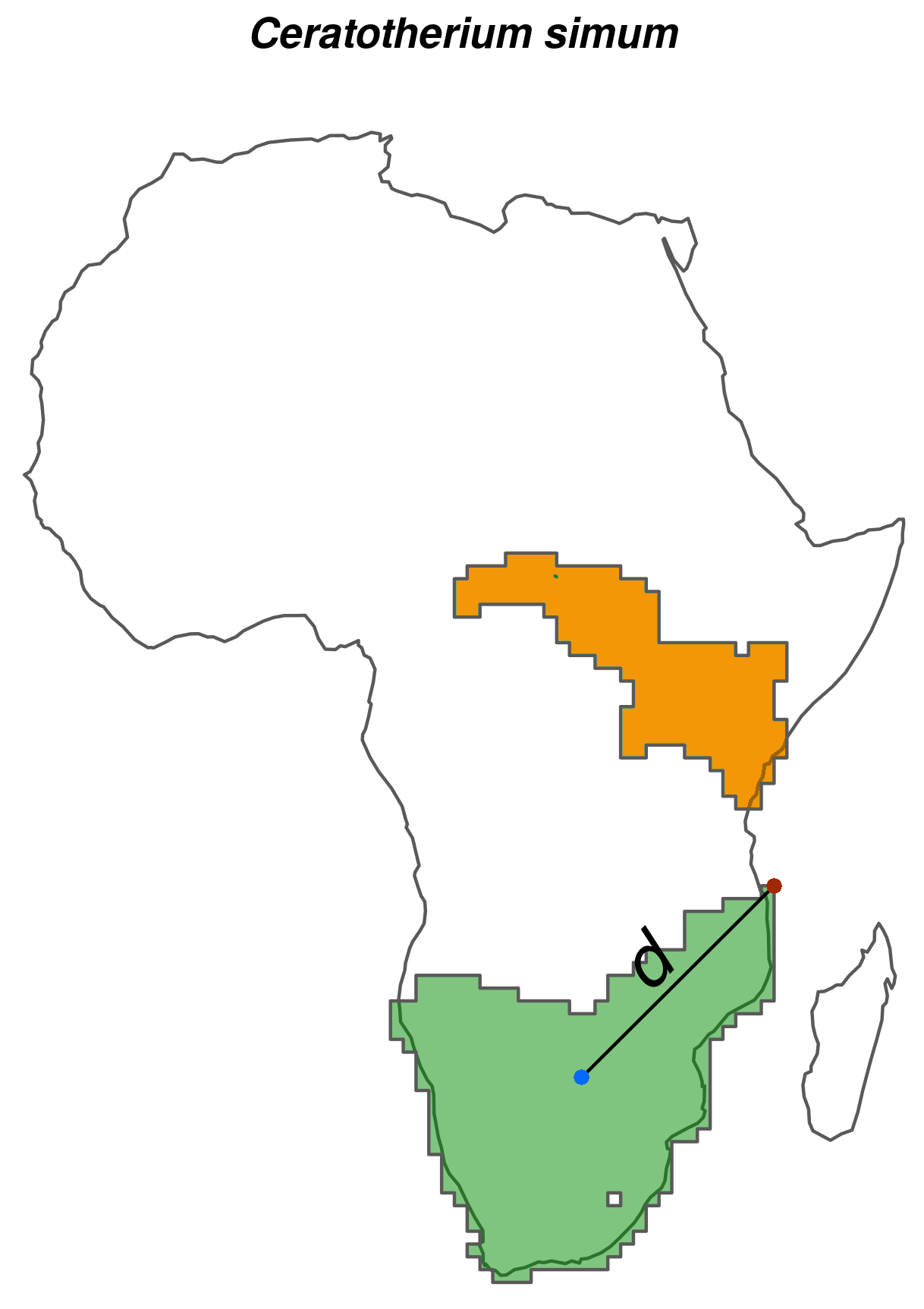


Figure S1: Schematic showing how species-specific background areas were calculated for maximum entropy (Maxent) species distribution models using the white rhinoceros (Ceratotherium simum) as an example. For each species, we calculated background area buffers as the maximum distance (d; black line) between the range centroid (blue point) and edge (red point) of the largest continuous range of the species (green shade). We calculated d for each species to reflect species-specific dispersal capabilities (Hof et al., 2018; Poo-Muñoz et al., 2014).

We assessed the predictive performance of Maxent models through five-fold cross validation using the average continuous Boyce index (CBI; Hirzel, Le Lay, Helfer, Randin, & Guisan (2006)), which indicates how much models discriminate against random expectation, and the average area under the curve (AUC) of the receiver operating plot (AUC; Swets (1988)), which indicates how well models differentiate between presences and pseudo-absences regardless of the degree of difference between them. Values of CBI range between -1 and 1, where values > 0 indicate the model's output is positively correlated with the true probability of presence and values < 0 indicate it is negatively correlated with the true probability of presence. AUC values range from <= 0.5 for models with discrimination no better than random to 1 for models with perfect discrimination between occupied and unoccupied places (Fielding & Bell, 1997). Model fit was inspected by five-fold cross validation of the average omission rate based on the minimum training presence value (ORMTP; Radosavljevic & Anderson, 2014). The values of ORMTP range from 0 for models that are not overfit to 1 for models that are overfit. To convert continuous suitability predictions to binary layers indicating suitable/unsuitable habitat, we used as threshold the suitability value that maximised sensitivity and specificity (MSS), minimizing thus type I and type II errors (Liu, Newell, & White, 2016). We further assessed the performance of Maxent models by comparing projections of climatic suitability with 136 introduction range maps from Lundgren, Ramp, Ripple, & Wallach (2018) (n = 22 species) and the IUCN (IUCN (2016); n = 114 species). Introduced range maps were selected from Lundgren et al. (2018) over the IUCN (IUCN, 2016) for three species found in both datasets (*Cervus elaphus*, *Ovibos moschatus*, and *Rangifer tarandus*).

Evaluation statistics indicated, in general, very high to excellent quality of Maxent models. CBI index and AUC were on average very high (Table S1; figure S2) and ORMTP was in low, indicating that models were in general not overfitted. Also, much of the species' known introduction ranges were captured by Maxent models (figure S2): the median of the predicted introduction range was 0.84, with a median absolute deviation equal to 0.23.

Table S1: Evaluation statistics of the species distribution models (SDMs). CBI indicates how much models discriminate from random expectactions; AUC quantify the performance of models to differentiate between presences and pseudo-absences .

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Evaluation statistic | Median | Median absolute deviation | Mean | Standard deviation |
| Continuous Boyce index (CBI) | 0.93 | 0.08 | 0.87 | 0.15 |
| Area under the curve (AUC) of the receiver operating plot | 0.86 | 0.01 | 0.85 | 0.04 |

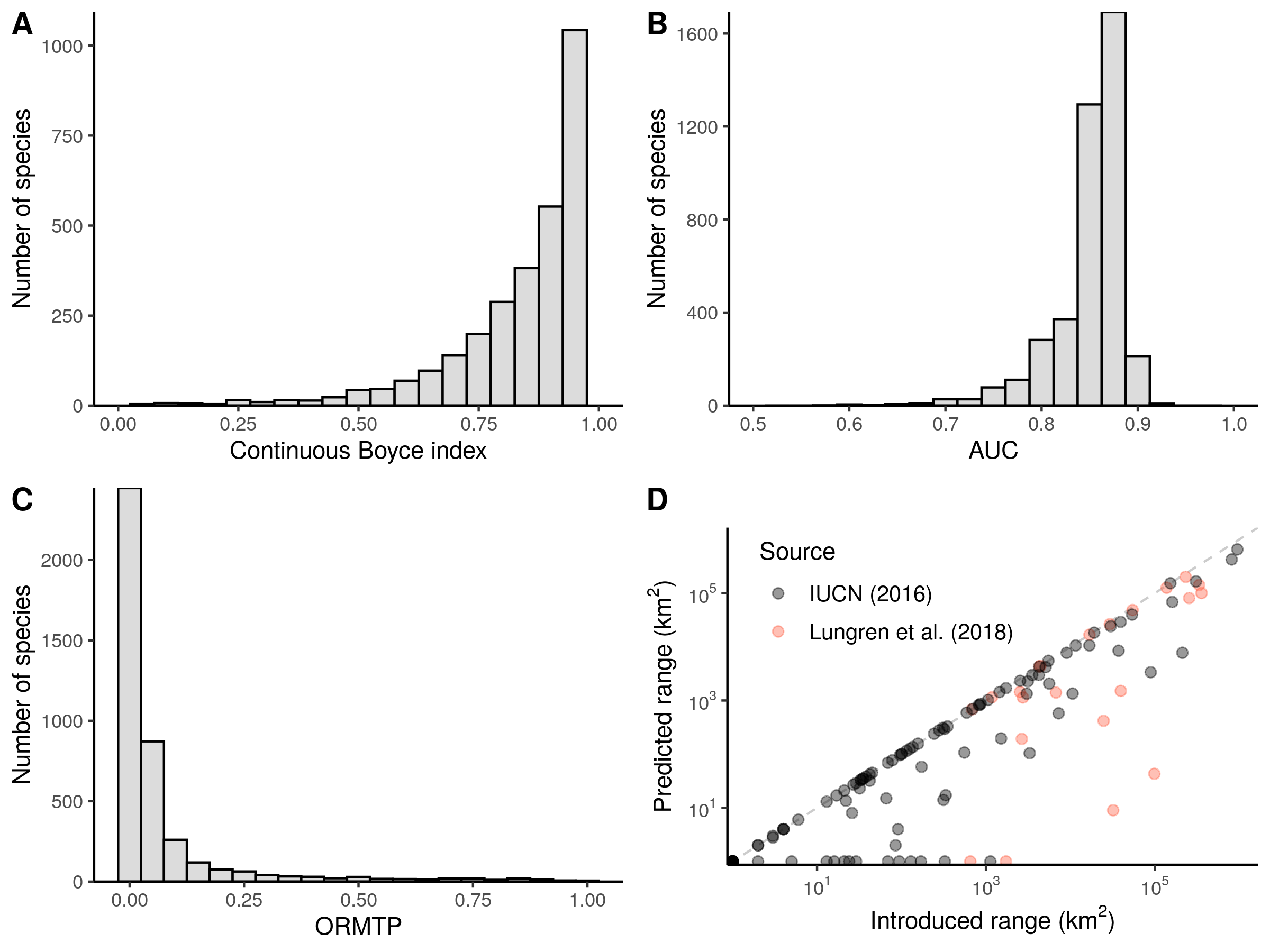


Figure S2: Evaluation statistics of Maxent species distribution models and comparison of predicted ranges to known introduced ranges. Predictive ability of the SDMs are shown by the Continuous Boyce index (A) and the area under the curve (AUC) of the receiver operating plot (B). Model fit is shown by omission rate of minimum training points (ORMTP, C). Most of the range of introduced species was predicted by the Maxent SDMs (D). The introduced ranges were from IUCN introduction ranges (IUCN, 2016) and Lundgren et al. (2018).

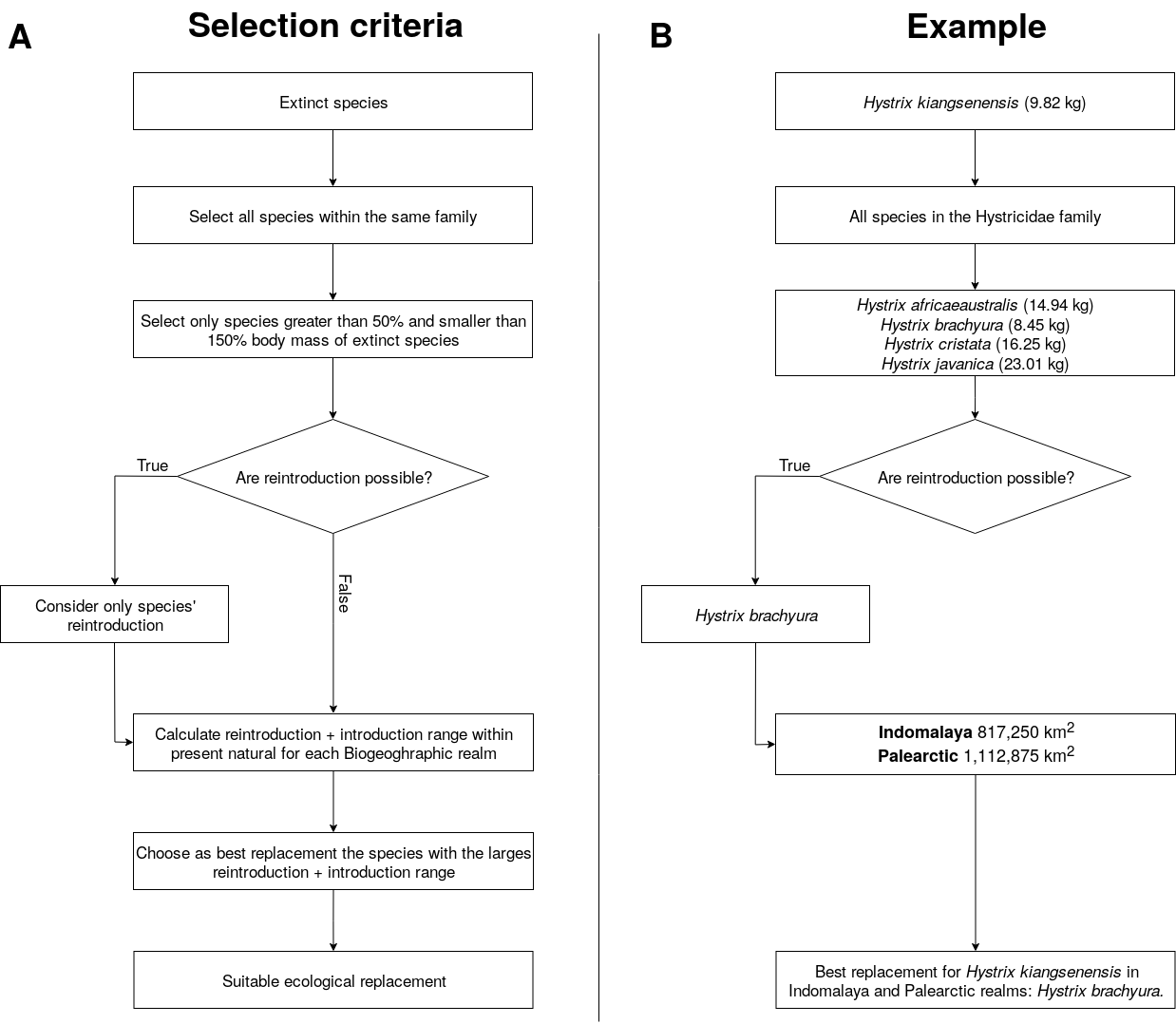


Figure S3: Schematics showing selection of functional analogues to replace extinct species for the trophic rewilding scenario. We show for A) the selection criteria for replacement of extinct species with functional analogues, and B) a worked example of the selection criteria directly alongside for the replacement of the extinct Hystrix kiangsenensis. Note that exceptions to the selection criteria are made for Probescians, Felidae and Ursidae as mentioned in the main text and Supplementary Material.

Table S2: List of extinct terrestrial mammals from the Late Pleistocene and the identified functional analogue to replace them in each biogeographic realm. Only realms with living terrestrial mammals and protected areas >= 5,000 km^2 were considered, excluding thus Antarctica and Oceania realms. We identified functional analogues following the selection criteria written in the main text and shown in Fig. S#. In total, 94 living species were identified that could be used as functional analogues for 127 of the 334 extinct terrestrial mammals.

|  |  |  |
| --- | --- | --- |
| Extinct species | Functional analogues | Biogeographic realm |
| *Vombatus hacketti* | *Lasiorhinus latifrons* | Australasia |
| *Arctodus simus* | *Ursus arctos* | Nearctic |
| *Arctodus simus* | *Ursus arctos* | Neotropic |
| *Arctotherium wingei* | *Ursus americanus* | Neotropic |
| *Tremarctos floridanus* | *Ursus americanus* | Nearctic |
| *Tremarctos floridanus* | *Ursus americanus* | Neotropic |
| *Ursus spelaeus* | *Ursus arctos* | Palearctic |
| *Catagonus stenocephalus* | *Pecari tajacu* | Neotropic |
| *Muknalia minima* | *Pecari tajacu* | Nearctic |
| *Muknalia minima* | *Pecari tajacu* | Neotropic |
| *Tapirus augustus* | *Tapirus indicus* | Indomalaya |
| *Tapirus augustus* | *Tapirus indicus* | Palearctic |
| *Tapirus merriami* | *Tapirus bairdii* | Nearctic |
| *Tapirus rondoniensis* | *Tapirus terrestris* | Neotropic |
| *Tapirus veroensis* | *Tapirus bairdii* | Nearctic |
| *Tapirus veroensis* | *Tapirus bairdii* | Neotropic |
| *Kolpochoerus majus* | *Hylochoerus meinertzhageni* | Afrotropic |
| *Metridiochoerus compactus* | *Phacochoerus africanus* | Afrotropic |
| *Sus bucculentus* | *Sus scrofa* | Indomalaya |
| *Stegodon orientalis* | *Elephas maximus* | Indomalaya |
| *Stegodon orientalis* | *Elephas maximus* | Palearctic |
| *Stegodon trigonocephalus* | *Elephas maximus* | Indomalaya |
| *Elasmotherium sibiricum* | *Ceratotherium simum* | Palearctic |
| *Stephanorhinus kirchbergensis* | *Ceratotherium simum* | Indomalaya |
| *Stephanorhinus kirchbergensis* | *Ceratotherium simum* | Palearctic |
| *Petauroides ayamaruensis* | *Pseudochirulus canescens* | Australasia |
| *Petauroides ayamaruensis* | *Pseudochirulus schlegeli* | Australasia |
| *Bettongia anhydra* | *Bettongia lesueur* | Australasia |
| *Bettongia pusilla* | *Bettongia lesueur* | Australasia |
| *Bettongia pusilla* | *Bettongia penicillata* | Australasia |
| *Potorous platyops* | *Potorous gilbertii* | Australasia |
| *Perameles eremiana* | *Perameles bougainville* | Australasia |
| *Ochotona whartoni* | *Ochotona alpina* | Nearctic |
| *Neovison macrodon* | *Neovison vison* | Nearctic |
| *Conilurus albipes* | *Conilurus penicillatus* | Australasia |
| *Conilurus capricornensis* | *Conilurus penicillatus* | Australasia |
| *Notomys amplus* | *Notomys mitchellii* | Australasia |
| *Notomys longicaudatus* | *Notomys mitchellii* | Australasia |
| *Notomys macrotis* | *Notomys mitchellii* | Australasia |
| *Notomys mordax* | *Notomys alexis* | Australasia |
| *Notomys mordax* | *Notomys aquilo* | Australasia |
| *Notomys mordax* | *Notomys fuscus* | Australasia |
| *Notomys robustus* | *Notomys fuscus* | Australasia |
| *Pseudomys glaucus* | *Pseudomys novaehollandiae* | Australasia |
| *Pseudomys gouldii* | *Pseudomys desertor* | Australasia |
| *Brachyprotoma obtusata* | *Conepatus leuconotus* | Nearctic |
| *Manis paleojavanica* | *Smutsia gigantea* | Indomalaya |
| *Mammut americanum* | *Loxodonta africana* | Nearctic |
| *Mammut americanum* | *Loxodonta africana* | Neotropic |
| *Lagorchestes asomatus* | *Lagorchestes hirsutus* | Australasia |
| *Macropus greyi* | *Thylogale billardierii* | Australasia |
| *Metasthenurus newtonae* | *Macropus rufus* | Australasia |
| *Onychogalea lunata* | *Petrogale lateralis* | Australasia |
| *Procoptodon browneorum* | *Macropus giganteus* | Australasia |
| *Procoptodon gilli* | *Macropus rufus* | Australasia |
| *Protemnodon hopei* | *Macropus antilopinus* | Australasia |
| *Protemnodon hopei* | *Macropus giganteus* | Australasia |
| *Protemnodon hopei* | *Macropus rufus* | Australasia |
| *Protemnodon nombe* | *Macropus giganteus* | Australasia |
| *Protemnodon tumbuna* | *Macropus giganteus* | Australasia |
| *Simosthenurus maddocki* | *Macropus giganteus* | Australasia |
| *Sthenurus andersoni* | *Macropus rufus* | Australasia |
| *Thylogale christenseni* | *Dorcopsulus vanheurni* | Australasia |
| *Troposodon minor* | *Macropus giganteus* | Australasia |
| *Wallabia kitcheneri* | *Macropus fuliginosus* | Australasia |
| *Aztlanolagus agilis* | *Lepus californicus* | Nearctic |
| *Aztlanolagus agilis* | *Lepus californicus* | Neotropic |
| *Aztlanolagus agilis* | *Sylvilagus floridanus* | Neotropic |
| *Hystrix kiangsenensis* | *Hystrix brachyura* | Indomalaya |
| *Hystrix kiangsenensis* | *Hystrix brachyura* | Palearctic |
| *Hystrix refossa* | *Hystrix indica* | Indomalaya |
| *Hystrix refossa* | *Hystrix indica* | Palearctic |
| *Hexaprotodon sivalensis* | *Choeropsis liberiensis* | Indomalaya |
| *Cuvieronius hyodon* | *Elephas maximus* | Nearctic |
| *Cuvieronius hyodon* | *Loxodonta africana* | Neotropic |
| *Notiomastodon platensis* | *Elephas maximus* | Neotropic |
| *Homotherium latidens* | *Panthera tigris* | Palearctic |
| *Homotherium serum* | *Panthera onca* | Nearctic |
| *Homotherium serum* | *Panthera onca* | Neotropic |
| *Leopardus amnicola* | *Catopuma badia* | Nearctic |
| *Leopardus amnicola* | *Leopardus wiedii* | Neotropic |
| *Miracinonyx trumani* | *Puma concolor* | Nearctic |
| *Panthera atrox* | *Panthera tigris* | Nearctic |
| *Panthera atrox* | *Panthera leo* | Neotropic |
| *Panthera spelaea* | *Panthera tigris* | Nearctic |
| *Panthera spelaea* | *Panthera tigris* | Palearctic |
| *Smilodon fatalis* | *Panthera tigris* | Nearctic |
| *Smilodon fatalis* | *Panthera leo* | Neotropic |
| *Smilodon populator* | *Panthera leo* | Nearctic |
| *Smilodon populator* | *Panthera tigris* | Neotropic |
| *Equus francisci* | *Equus ferus* | Nearctic |
| *Equus francisci* | *Equus ferus* | Neotropic |
| *Equus hydruntinus* | *Equus ferus* | Palearctic |
| *Equus ovodovi* | *Equus ferus* | Palearctic |
| *Hippidion devillei* | *Equus ferus* | Neotropic |
| *Hippidion principale* | *Equus quagga* | Neotropic |
| *Elephas iolensis* | *Loxodonta africana* | Afrotropic |
| *Elephas iolensis* | *Loxodonta africana* | Palearctic |
| *Elephas namadicus* | *Elephas maximus* | Indomalaya |
| *Elephas namadicus* | *Elephas maximus* | Palearctic |
| *Elephas naumanii* | *Elephas maximus* | Indomalaya |
| *Elephas naumanii* | *Elephas maximus* | Palearctic |
| *Mammuthus columbi* | *Elephas maximus* | Nearctic |
| *Mammuthus columbi* | *Elephas maximus* | Neotropic |
| *Mammuthus primigenius* | *Elephas maximus* | Indomalaya |
| *Mammuthus primigenius* | *Elephas maximus* | Nearctic |
| *Mammuthus primigenius* | *Elephas maximus* | Palearctic |
| *Cryptonanus ignitus* | *Thylamys venustus* | Neotropic |
| *Dasypus bellus* | *Dasypus kappleri* | Nearctic |
| *Dasypus bellus* | *Dasypus kappleri* | Neotropic |
| *Lagostomus crassus* | *Lagostomus maximus* | Neotropic |
| *Agalmaceros blicki* | *Odocoileus virginianus* | Neotropic |
| *Cervalces scotti* | *Alces alces* | Nearctic |
| *Haploidoceros mediterraneus* | *Cervus elaphus* | Palearctic |
| *Megaloceros giganteus* | *Alces alces* | Palearctic |
| *Morenelaphus brachyceros* | *Ozotoceros bezoarticus* | Neotropic |
| *Navahoceros fricki* | *Odocoileus virginianus* | Nearctic |
| *Navahoceros fricki* | *Odocoileus virginianus* | Neotropic |
| *Paraceros fragilis* | *Ozotoceros bezoarticus* | Neotropic |
| *Rucervus schomburgki* | *Rucervus eldii* | Indomalaya |
| *Sangamona fugitiva* | *Cervus canadensis* | Nearctic |
| *Sinomegaceros ordosianus* | *Alces alces* | Palearctic |
| *Sinomegaceros yabei* | *Alces alces* | Indomalaya |
| *Sinomegaceros yabei* | *Alces alces* | Palearctic |
| *Neochoerus aesopi* | *Hydrochoerus hydrochaeris* | Nearctic |
| *Neochoerus aesopi* | *Hydrochoerus hydrochaeris* | Neotropic |
| *Canis dirus* | *Canis lupus* | Nearctic |
| *Canis dirus* | *Canis lupus* | Neotropic |
| *Dusicyon avus* | *Lycalopex griseus* | Neotropic |
| *Protocyon troglodytes* | *Chrysocyon brachyurus* | Neotropic |
| *Theriodictis tarijensis* | *Chrysocyon brachyurus* | Neotropic |
| *Camelops hesternus* | *Camelus ferus* | Nearctic |
| *Camelops hesternus* | *Camelus dromedarius* | Neotropic |
| *Hemiauchenia macrocephala* | *Lama guanicoe* | Nearctic |
| *Hemiauchenia macrocephala* | *Lama guanicoe* | Neotropic |
| *Hemiauchenia paradoxa* | *Camelus dromedarius* | Neotropic |
| *Palaeolama major* | *Camelus dromedarius* | Neotropic |
| *Palaeolama mirifica* | *Lama guanicoe* | Nearctic |
| *Palaeolama mirifica* | *Lama guanicoe* | Neotropic |
| *Palaeolama mirifica* | *Vicugna vicugna* | Neotropic |
| *Palaeolama weddeli* | *Camelus dromedarius* | Neotropic |
| *Antidorcas australis* | *Pelea capreolus* | Afrotropic |
| *Antidorcas bondi* | *Sylvicapra grimmia* | Afrotropic |
| *Bootherium bombifrons* | *Connochaetes taurinus* | Nearctic |
| *Bubalus palaeokerabau* | *Bos javanicus* | Indomalaya |
| *CapriniGen spA* | *Tragelaphus scriptus* | Afrotropic |
| *Damaliscus hypsodon* | *Tragelaphus scriptus* | Afrotropic |
| *Damaliscus niro* | *Alcelaphus buselaphus* | Afrotropic |
| *Euceratherium collinum* | *Bison bison* | Nearctic |
| *Euceratherium collinum* | *Bison bison* | Neotropic |
| *Gazella atlantica* | *Ammotragus lervia* | Palearctic |
| *Gazella bilkis* | *Capricornis crispus* | Afrotropic |
| *Gazella bilkis* | *Naemorhedus caudatus* | Afrotropic |
| *Gazella bilkis* | *Procapra gutturosa* | Afrotropic |
| *Gazella bilkis* | *Procapra przewalskii* | Afrotropic |
| *Gazella bilkis* | *Eudorcas albonotata* | Palearctic |
| *Gazella saudiya* | *Gazella gazella* | Afrotropic |
| *Gazella saudiya* | *Gazella gazella* | Palearctic |
| *Gazella tingitana* | *Gazella cuvieri* | Palearctic |
| *Hemitragus cedrensis* | *Capra pyrenaica* | Palearctic |
| *Hippotragus leucophaeus* | *Alcelaphus buselaphus* | Afrotropic |
| *Hippotragus leucophaeus* | *Damaliscus pygargus* | Afrotropic |
| *Megalotragus priscus* | *Alcelaphus buselaphus* | Afrotropic |
| *Megalovis guangxiensis* | *Pseudois nayaur* | Indomalaya |
| *Megalovis guangxiensis* | *Pseudois nayaur* | Palearctic |
| *Oreamnos harringtoni* | *Ovis canadensis* | Nearctic |
| *Oreamnos harringtoni* | *Ovis canadensis* | Neotropic |
| *Pelorovis antiquus* | *Bos primigenius* | Palearctic |
| *Rusingoryx atopocranion* | *Kobus ellipsiprymnus* | Afrotropic |
| *Sivacobus sankaliai* | *Capricornis thar* | Indomalaya |
| *Sivacobus sankaliai* | *Capricornis thar* | Palearctic |
| *Soergelia minor* | *Capra sibirica* | Palearctic |
| *Spirocerus kiakhtensis* | *Bos primigenius* | Palearctic |
| *Caipora bambuiorum* | *Brachyteles arachnoides* | Neotropic |
| *Protopithecus brasiliensis* | *Brachyteles arachnoides* | Neotropic |
| *Stockoceros conklingi* | *Antilocapra americana* | Nearctic |
| *Stockoceros conklingi* | *Antilocapra americana* | Neotropic |
| *Tetrameryx shuleri* | *Antilocapra americana* | Nearctic |
| *Tetrameryx shuleri* | *Antilocapra americana* | Neotropic |

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