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Supporting Information for
Global diversity and energy of animals shaping the Earth's surface

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Global diversity of animal geomorphic agents and their effects. Mammals (rodents, ungulates, carnivores and marsupials), insects (primarily ants, termites and beetles) and earthworms are the most species-rich classes in terrestrial environments, while small numbers of zoogeomorphic species were identified within bird, reptile and arachnid classes (Fig. 1A and Fig. S1). In freshwaters, fishes, benthic insects and decapod crustaceans account for the majority of reported zoogeomorphic species, with smaller numbers of bivalve, tubificid worm and amphibian species. Notably, research attention is not evenly distributed among reported zoogeomorphic agents. Geomorphic effects of beaver (*Castor canadensis* or *C. fiber*) were reported in 44 papers, and sockeye salmon (*Oncorhynchus nerka*) and Botta's pocket gopher (*Thomomys bottae*) each received attention in >10 publications (Fig. 1A). Other better-known animals such as wild boar, signal crayfish, rabbits and earthworms are also relatively well-studied for geomorphic effects (9-23 publications each) but some globally widespread animals, such as cliff swallows and muskrats, returned only one or two publications in our searches. Most species (90%) were addressed by three publications or fewer, and new zoogeomorphic effects continue to be uncovered: a diverse group of animals first appeared in our dataset post-2019, including multiple dung beetle and ant species, birds (*Leipoa ocellata*), bivalves (*Lampsilis siliquoidea*) and rodents endemic to Chile (*Octodon degus*) and China (*Myospalax cansus, M. fontanierii*). Dam construction or modification of existing dams was reported for four species, including muskrat (*Ondatra zibethicus*) and otter (*Lontra canadensis*) alongside the better-known dam-builders, the Eurasian and North American beavers.

Endangered zoogeomorphic agents include the dung beetle *Typhaeus momus* endemic to Spain and Portugal, the tadpole shrimp *Lepidurus packardi*, endemic to California, Australian marsupials the woylie and numbat (*Bettongia penicillata* and *Myrmecobius fasciatus*), the African giant root rat (*Tachyoryctes macrocephalus*) and the African bush elephant (*Loxodonta africana*). An additional 85 species have population trends that are either in decline (34 species) or unknown (51 species) and hence have the potential to become vulnerable in the future. Further at-risk species include those belonging to globally imperiled taxonomic groups, such as freshwater mussels, mayflies and marsupials, and those considered pests such as the rock-moving Chacma baboon (*Papio ursinus*) and pocket gophers (e.g. *Geomys arenarius* and *Thomomys umbrinus*).

Global abundance and distribution of geomorphic agents. The most globally abundant taxa (exceeding 10^4 records) constitute 37% of zoogeomorphic genera and 8% of genera had records exceeding 10^5, comprising a diverse group of birds, reptiles, mammals, crustaceans, fish, insects, bivalves, amphibians and worms. In contrast 19% of genera are rare and/ or geographically restricted (fewer than 10^2 records) including 10% with 30 or fewer records. Rivers and streams were most heavily studied in the freshwater realm followed by lakes, while similar numbers of studies were uncovered across most terrestrial biomes, except for shrublands, which had fewer (Fig. S4). Freshwater studies were most numerous in North America, the UK, Russia and Brazil, while terrestrial studies were most numerous in Australia, North America and South Africa (see Fig. 5).

Supplementary text for materials and methods

Body size distribution of reported zoogeomorphic agents. For each individual species, we extracted biomass and/or body length data from online species traits databases *(1-9)* for different taxonomic groups (Table S8). Species with missing data following this process were checked against papers in our database, and biomass and/or body length extracted where available. We accepted average, minimum and maximum values reported, which varied among papers. Where a size range was given we took the mid-point of the range. Species data were then averaged at the genus level. Genera with no-species level data were then examined and mostly included termites, ants, caddisflies, mayflies, trueflies and terrestrial worms, introducing bias against smaller species. We therefore manually searched online and extracted body length and/or biomass data for these species from web sources *(6, 10-12)*. In cases where only body length was available, we used existing published regression relationships to convert body length to biomass where possible (Table S9). This resulted in a data set of 302 genera with individual biomass values (Fig. S7).

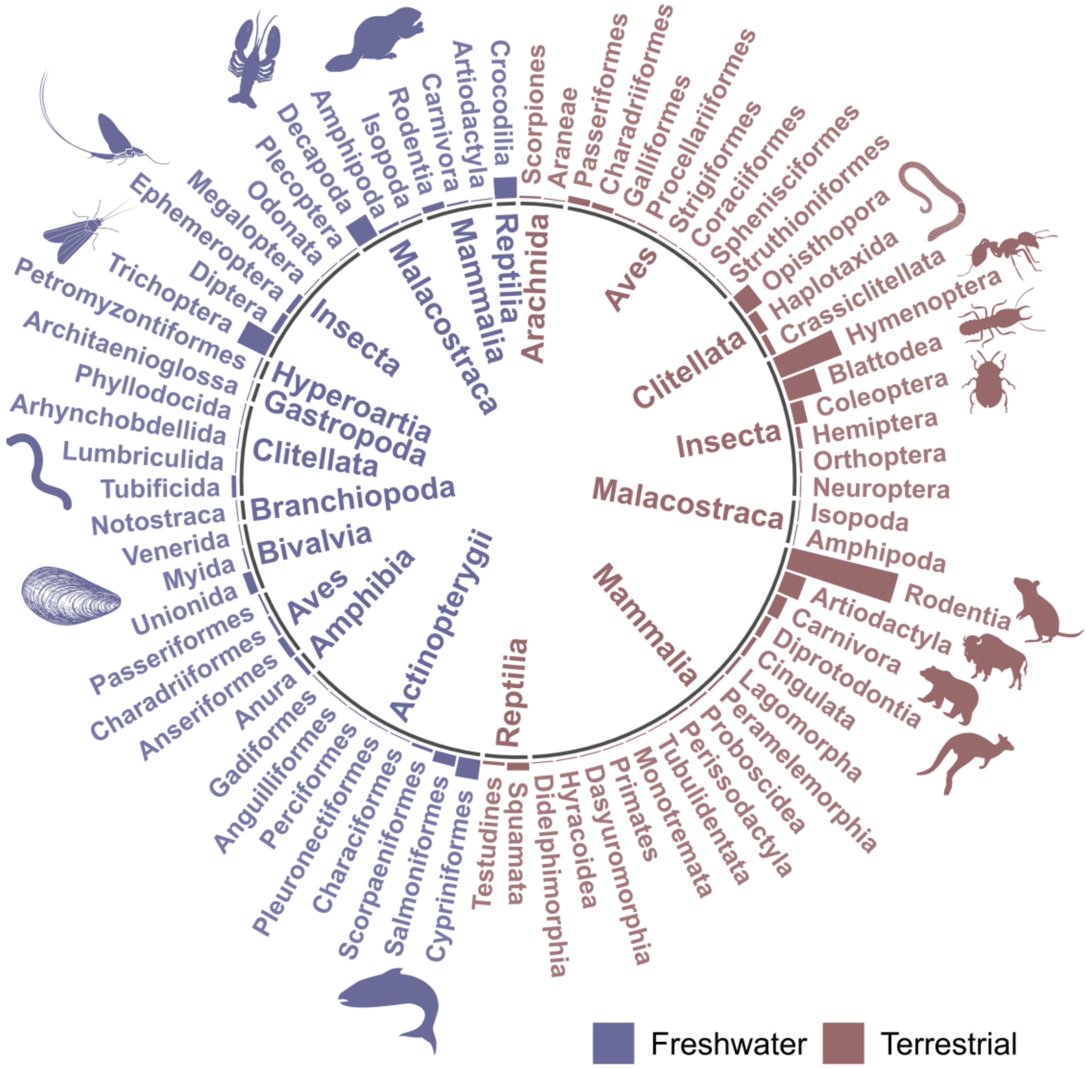

Fig. S1. Radial plot showing number of zoogeomorphic species found within each taxonomic order.

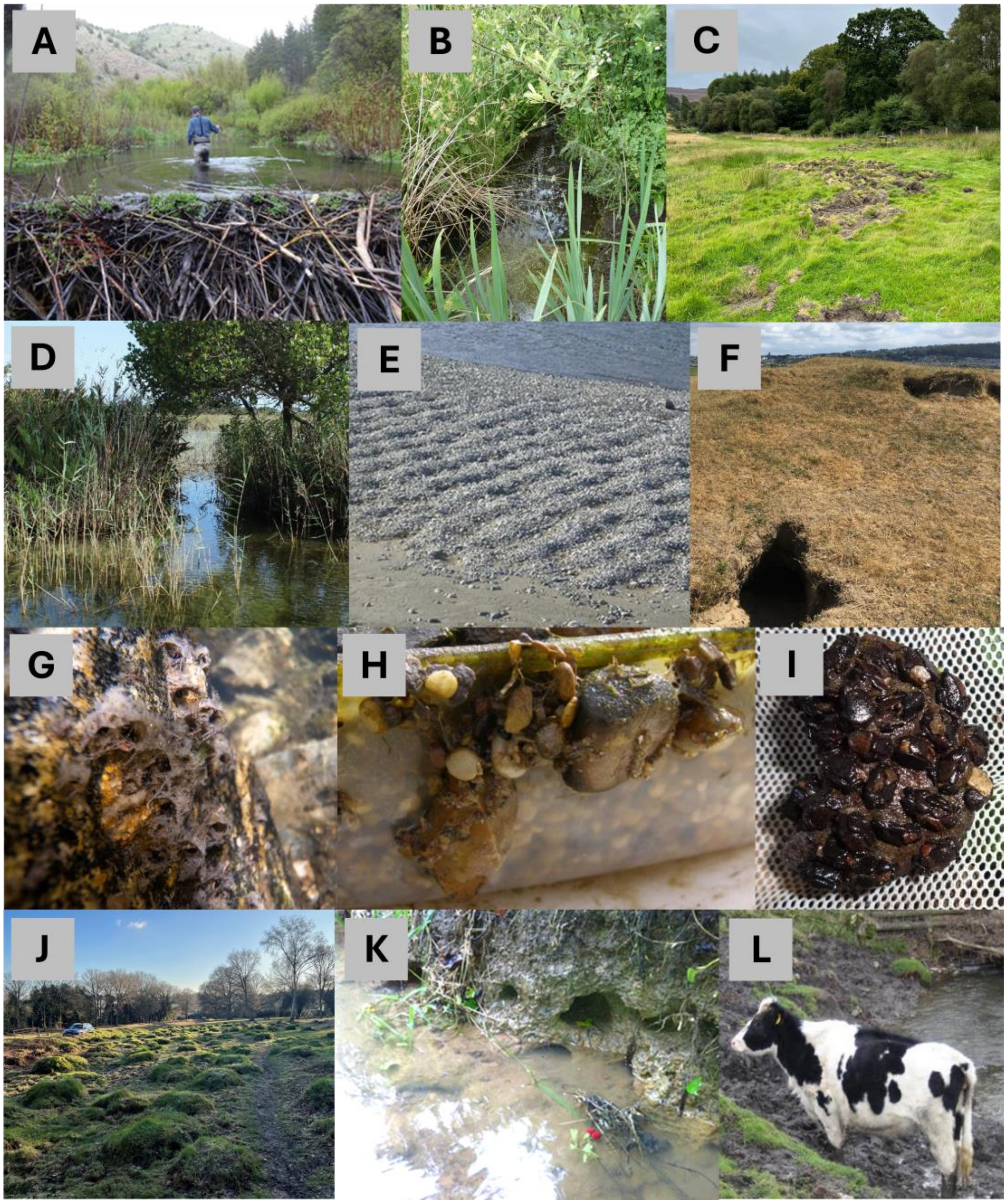

Fig. S2. **Photographs illustrating the diversity of animal geomorphic effects**. (**A**) Dam created by North American beaver (*Castor canadensis*), Idaho, USA (credit Stephen Rice), (**B**) Canal created by Eurasian beaver (*Castor fiber*), Devon, UK (credit Gemma Harvey), (**C**) Rootling of the soil by Mangalica pigs (*Sus scrofa domesticus*), Hepple Wilds, UK (credit Gemma Harvey), (**D**) Drainage channel created by common hippopotamus (*Hippopotamus amphibius*), Tembe Elephant Park, South Africa (credit (*13*) with permission), (**E**) Redds created by Pink salmon (*Oncorhynchus gorbuscha*) on the Fraser River, Canada form gravel bars (credit Mike Church), (**F**) Rabbit burrows (*Oryctolagus cuniculus*), Devon, UK (credit Gemma Harvey), (**G**) Caddisfly (Hydropsychidae) silk, Cherry Creek, USA (credit Greg Cairns), (**H**) Caddisfly (Hydropsychidae) silk binds river gravels (credit Matthew Johnson), (**I**) Caddisfly (*Agapetus*) cases covering a rock (credit Stephen Rice and Matthew Johnson), (**J**) Mounds created by yellow meadow ant (*Lasius flavus*), Hertfordshire, UK (credit Gemma Harvey), (**K**) River bank burrowing by signal crayfish, (*Pacifastacus leniusculus*), UK (credit Stephen Rice and Catherine Sanders), (**L**) Poaching of river bank by cattle (*Bos taurus*), UK (credit Stephen Rice).

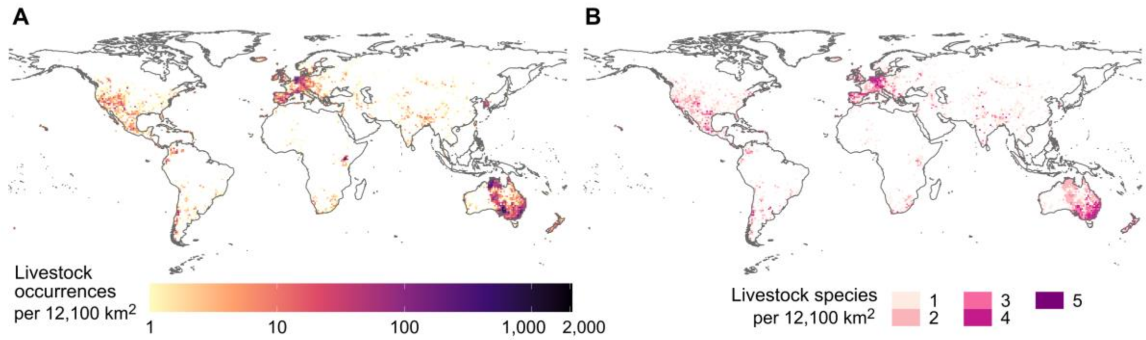

Fig. S3. Global distribution of reported zoogeomorphic livestock species. (A) Global patterns in species abundance (occurrence density) of reported livestock zoogeomorphic agents and (**B**) global patterns in species richness of reported livestock zoogeomorphic agents (maps are based on GBIF occurrence records). The five livestock species represented in these maps are *Bos taurus, Bos grunniens, Capra hircus, Equus caballus* and *Ovis aries*.

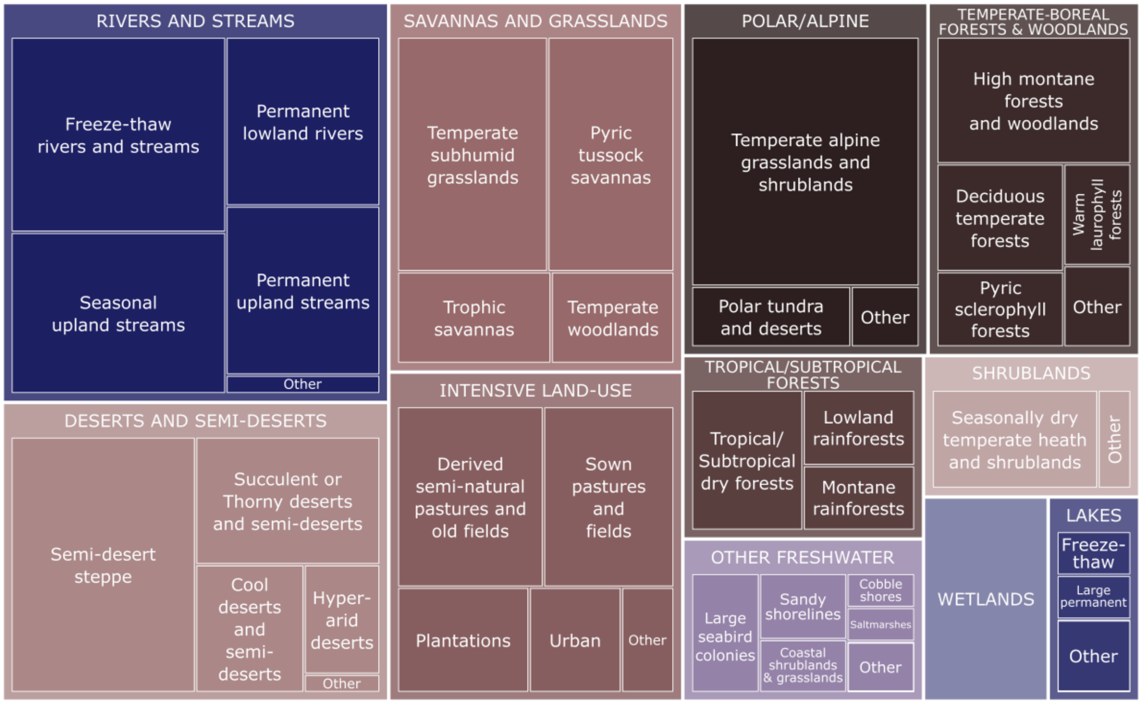

Fig. S4. Frequency of studies reporting zoogeomorphic effects in biomes and ecosystem functional groups across terrestrial and freshwater realms. Categories derived from IUCN (*14*).

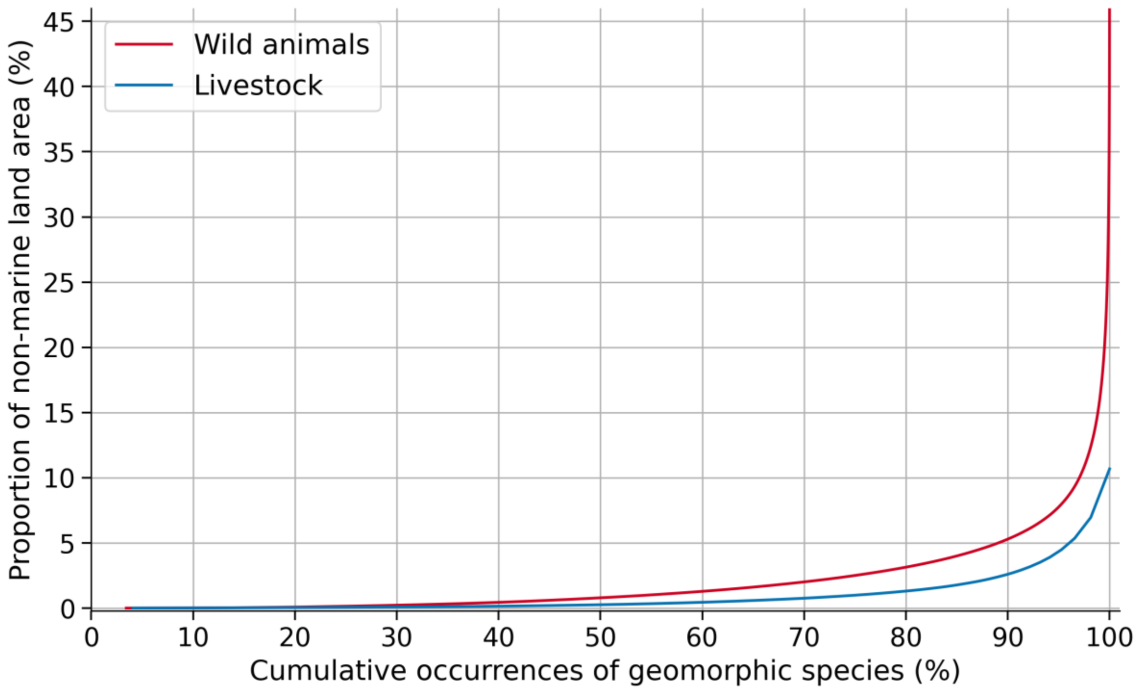

Fig. S5. Spatial distribution of zoogeomorphic species occurrence records derived from GBIF.

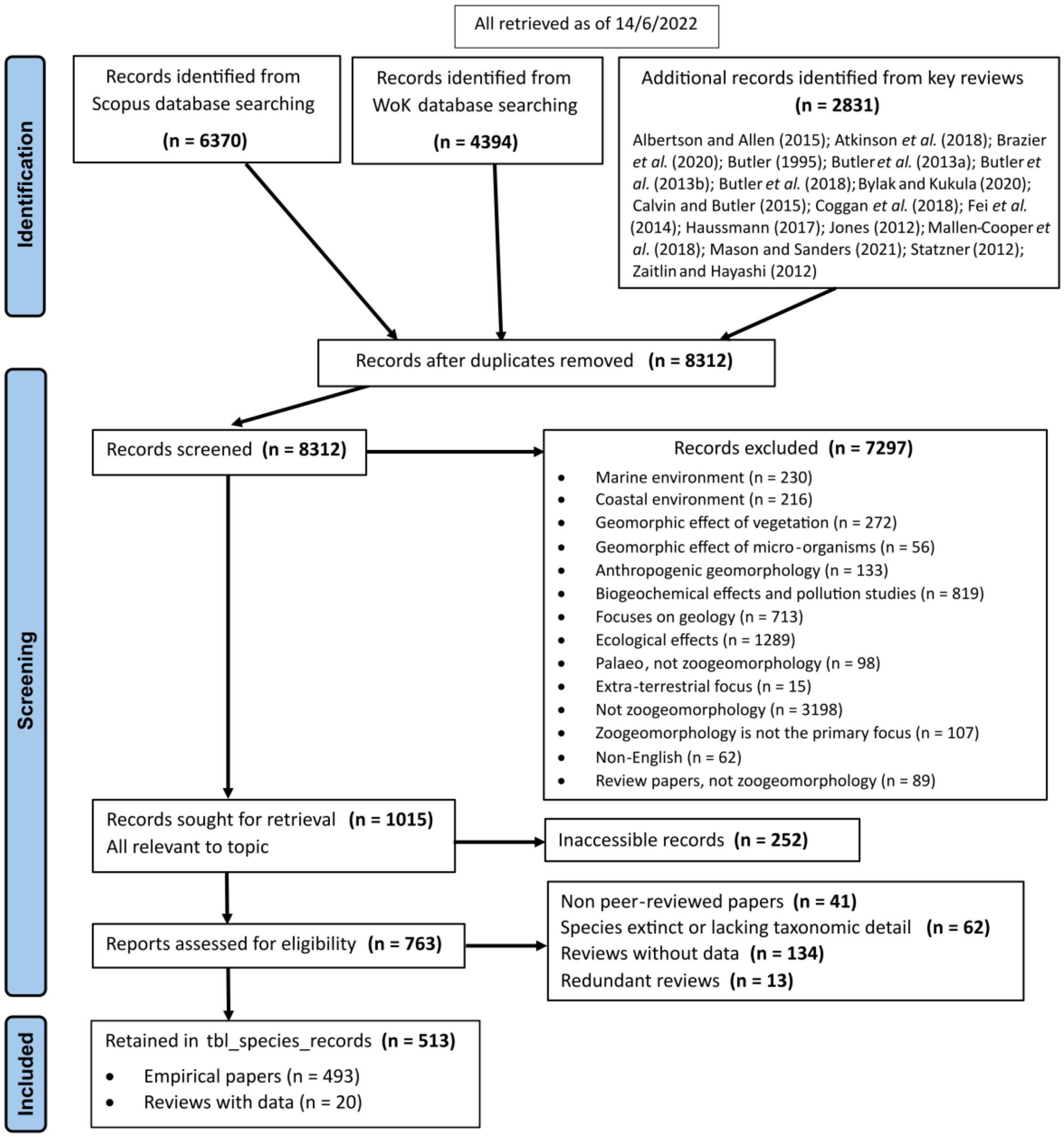

Fig. S6. PRISMA flow diagram illustrating the paper screening and eligibility assessment including reasons for exclusion.

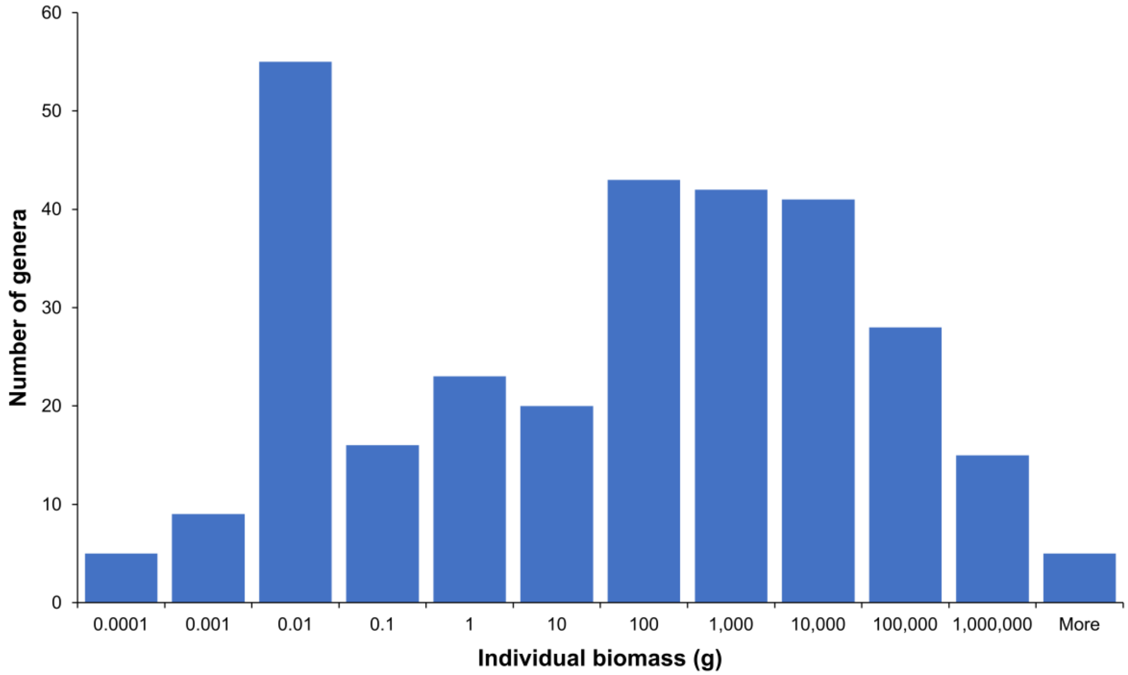

Fig. S7. Frequency distribution of body size (biomass) grouped by genus (n = 302) for all identified zoogeomorphic species with available individual biomass data.

Table S1. Data on genus traits used to identify categories in Fig. 3.

	Genus category			
	Monotypic	**Charismatic**	**Cinderella**	**Latent**
Number of genera in category	41	121	153	47
Total number of records (publications) for animals in this category	71	307	506	125
Number of species in each genus: median (lower quartile, upper quartile)	1 species only	4 (2, 6)	24 (15, 47)	225 (153,392)
% zoogeomorphic species in each genus: median (lower quartile, upper quartile)	100	33 (17, 50)	6 (3, 10)	0.6 (0.3, 1)

Table S2. Estimated global biomass and total energy content of zoogeomorphic species for different taxonomic groups, based on species richness data. Italic numbers show data source references.

		Species richness based estimates				
Taxonomic groups		**Total species**	**Total biomass (Mt Carbon)**	**Zoogeo species %**	**Zoogeo biomass (Mt Carbon)**	**Zoogeo energy (GJ)**
Wild non-marine animals		953,429 (*15*)	360 (*16*)	0.052	0.1869	**7,555,758**
Livestock (5 species)		-	-	-	75 (*15*)	**3,451,800,000**
Wild non-marine mammals		6,258 (*17*)	3 (*18*)	2.557	0.0767	**3,100,733**
Wild land mammals	Rodentia	2,367 (*19*)	0.48 (*18*)	4.478	0.0215	**868,976**
	Proboscidea	3 (*19*)	0.24 (*18*)	66.67	0.1600	**6,468,129**
	Diprodontia	143 (*19*)	0.21 (*18*)	4.196	0.0088	**356,199**
	Lagomorpha	99 (*19*)	0.03 (*18*)	3.030	0.0009	**36,751**
	Carnivora	294 (*19*)	0.09 (*18*)	4.422	0.0040	**160,878**
	Perissodactyla	24 (*19*)	0.03 (*18*)	4.167	0.0013	**50,532**
	Primates	526 (*19*)	0.12 (*18*)	0.190	0.0002	**9,223**
Ants (Formicidae)		15,700 (*20*)	12.3 (*20*)	0.350	0.0431	**1,741,915**

Table S3. Estimated global biomass and total energy content of zoogeomorphic species for different taxonomic groups, based on species occurrence data (*21-25*) and using the total biomass values reported in Table S2.

		Occurrence based estimates			
Taxonomic groups		**Total occurrence**	**Zoogeo occurrence %**	**Zoogeo biomass (Mt Carbon)**	**Zoogeo energy (GJ)**
Wild land mammals	Rodentia	2,043,044	44	0.2127	**8,600,318**
	Proboscidea	4,041	74	0.1788	**7,226,826**
	Diprodontia	618,258	5	0.0112	**453,418**
	Lagomorpha	593,422	44	0.0133	**537,429**
	Carnivora	2,286,074	25	0.0224	**905,175**
	Perissodactyla	25,397	0.4	0.0001	**4,728**
	Primates	83,804	5	0.0061	**246,248**
Ants (Formicidae)		839,780	12	1.4149	**57,196,694**

Table S4. Energy expended by physical geomorphic processes. Italic numbers show data source references.

Disturbance type and source	**Total energy (GJ)**	**Area metric**	**Area (km^2)**	**Energy per unit area ($J\ m^{-2}$)**
150 year storm *(26)*	0.015	Total inundation extent	4.4	3.4
“Large flood” (maximum value) *(27)*	0.15	Total Narmada River catchment area	98,796	0.0015
“Extraordinary flood” 2.5-3 times magnitude of mean annual flood and longer duration (maximum value) (*28)*	0.16	Total Godavari River catchment area	312,812	0.00051
Monsoon season floods (max) (*28)*	0.38	Total Narmada River catchment area	98,796	0.0038
Tropical storm Irene (Saxtons River) (*29*)	0.016	Total Saxtons River catchment area	187	0.086
Tropical storm Irene (Williams River) *(29)*	0.015	Total Williams River catchment area	289	0.052
Annual energy generated by periglacial mountain slope processes, Murtèl cirque, Switzerland *(30)*	118.8	Area of Murtèl cirque	0.48	247,500
Annual energy of rockfalls, Reintal trough valley, Germany *(31)*	67.1	Total catchment area of the Reintal trough valley	17.3	3,880

Table S5. Search strings applied to Scopus and Web of Knowledge (WOK) databases to conduct the systematic review of animal geomorphic agents.

Scopus	Number of results	**WOK**	Number of results
zoogeomorph* AND NOT *marine	76	TS=(zoogeomorph* NOT *marine)	74
(zoogeomorph* OR biogeomorph* OR *geomorph*) AND (agent OR organism OR "ecosystem engineer*" OR fauna* OR animal*) AND NOT *marine	2910	TS=((zoogeomorph* OR biogeomorph* OR *geomorph*) AND (agent OR organism OR "ecosystem engineer*" OR fauna* OR animal*) NOT *marine)	1822
((bioerosion* OR bioprotect* OR bioconstruct*) AND *geomorph*) AND NOT *marine	81	TS=(((bioerosion* OR bioprotect* OR bioconstruct*) AND *geomorph*) NOT *marine)	55
(bio*turbat*) AND NOT (*marine OR sea* OR ocean* OR microb* OR *archaeolog* OR stratigrap*)	2486	TS=((bio*turbat*) NOT (*marine OR sea* OR ocean* OR microb* OR *archaeolog* OR stratigrap*))	1840
((soil OR sediment* OR grain*) AND (animal OR fauna* OR organism OR "ecosystem engineer*") AND *geomorph*) AND NOT (*marine OR pollut* OR microb* OR agri* OR agro*)	817	TS=(((soil OR sediment* OR grain*) AND (animal OR fauna* OR organism OR "ecosystem engineer*") AND *geomorph*) NOT (*marine OR pollut* OR microb* OR agri* OR agro*))	603
Total	**6370**	**Total**	**4394**

Table S6. Review papers relevant to the topic showing the number of references extracted from the reference lists of each paper.

	Review paper	Number of references
1	Albertson, L. K., Allen, D. C. and Trexler, J. C. (2015) 'Meta-analysis: Abundance, behavior, and hydraulic energy shape biotic effects on sediment transport in streams', *Ecology*, 96(5), pp. 1329–1339. https://doi.org/10.1890/13-2138.1 *(32)*	81
2	Atkinson, C. L., Allen, D. C., Davis, L., Nickerson, Z. L. (2018) 'Incorporating ecogeomorphic feedbacks to better understand resiliency in streams: a review and directions forward', *Geomorphology*, 305, pp. 123–140. https://doi.org/10.1016/j.geomorph.2017.07.016 *(33)*	270
3	Brazier, R. E., Puttock, A., Graham, H. A., Auster, R. E., Davies, K. H., Brown, C. M. L. (2021) 'Beaver: Nature's ecosystem engineers', *WIREs Water,* 8(1), p. e1494. https://doi.org/10.1002/wat2.1494 (*34*)	225
4	Butler, D. R. (1995). *Zoogeomorphology: animals as geomorphic agents.* Cambridge: Cambridge University Press. *(35)*	709
5	Butler, D. R., Anzah, F., Goff, P. D. Villa, J. (2018) 'Zoogeomorphology and resilience theory', *Geomorphology*, 305, pp. 154–162. http://dx.doi.org/10.1016/j.geomorph.2017.08.036 *(36)*	49
7	Butler, D. R., Whitesides, C. J., Tsikalas, S. G. (2013) '12.16 The Faunal Influence: Geomorphic Form and Process' in Shroder, J. F. (ed.) *Treatise on Geomorphology*. London: Academic Press. 12, pp. 252–260. https://doi.org/10.1016/B978-0-12-374739-6.00332-8 *(37)*	52
6	Butler, D. R., Whitesides, C. J., Wamsley, J. M., Tsikalas, S. G. (2013) '12.18 The Geomorphic Impacts of Animal Burrowing and Denning' in Shroder, J. F. (ed.) *Treatise on Geomorphology.* London: Academic Press. 12, pp. 271–280. https://doi.org/10.1016/B978-0-12-374739-6.00334-1 *(38)*	112
8	Bylak, A. and Kukula, K. (2020) 'Geomorphological effects of animals in mountain streams: Impact and role', *Science of the Total Environment*, 749, p. 141283. https://doi.org/10.1016/j.scitotenv.2020.141283 *(39)*	145
9	Cavin, R. M. and Butler, D. R. (2015) 'Patterns and trends in the fields of bioturbation, faunalturbation, and zoogeomorphology', *Physical Geography*, 36(3), pp. 178–187. https://doi.org/10.1080/02723646.2015.1026763 *(40)*	27
10	Coggan, N. V., Hayward, M. W., Gibb, H. (2018) 'A global database and "state of the field" review of research into ecosystem engineering by land animals ', *Journal of Animal Ecology,* 87(4), pp. 974–994. https://doi.org/10.1111/1365-2656.12819 *(41)*	249
11	Fei, S., Philips, J., Shouse, M. (2014) 'Biogeomorphic Impacts of Invasive Species', *Annual Review of Ecology, Evolution, and Systematics,* 45, pp. 69–87. https://doi.org/10.1146/annurev-ecolsys-120213-091928 *(42)*	106
12	Haussmann, N. S. (2017) 'Soil movement by burrowing mammals: A review comparing excavation size and rate to body mass of excavators', *Progress in Physical Geography: Earth and Environment*, 41(1), pp. 29–45. https://doi.org/10.1177/0309133316662569 *(43)*	93
13	Jones, C. G. (2012) 'Ecosystem engineers and geomorphological signatures in landscapes', *Geomorphology,* 157-158, pp. 75–87. https://doi.org/10.1016/j.geomorph.2011.04.039 *(44)*	97
14	Mallen-Cooper, M., Nakagawa, S., Eldridge, D. J. (2018) 'Global meta-analysis of soil-disturbing vertebrates reveals strong effects on ecosystem patterns and processes', *Global Ecology and Biogeography*, 28(5), pp. 661–679. https://doi.org/10.1111/geb.12877 *(45)*	85

15	Mason, R. J. and Sanders, H. (2021) 'Invertebrate zoogeomorphology: A review and conceptual framework for rivers', *WIREs Water,* 8(5), p. e1540. https://doi.org/10.1002/wat2.1540 *(46)*	231
16	Statzner, B. (2012) 'Geomorphological implications of engineering bed sediments by lotic animals', *Geomorphology,* 157-158, pp. 49–65. https://doi.org/10.1016/j.geomorph.2011.03.022 *(47)*	149
17	Zaitlin, B. and Hayashi, M. (2012) 'Interactions between soil biota and the effects on geomorphological features', *Geomorphology,* 157-158, pp. 142–152. https://doi.org/10.1016/j.geomorph.2011.07.029 *(48)*	151
Total		**2831**

Table S7. Calorie per gram relationships for different taxonomic groups derived from published literature, together with the average value used in this study to convert biomass (dry weight) to energy. Italic numbers show data source.

Level	Name	Kcal g^{-1}	Notes
Class	Gastropoda (*49*)	4.253	
Class	Amphipoda (*49*)	3.705	
Class	Decapoda (*49*)	4.163	
Order	Ephemeroptera (*50*)	5.596	*Stenonema* genus
Order	Decapoda (*50*)	2.248	*Uca* genus (includes shell)
Order	Orthoptera (*50*)	5.363	*Schistocerca* genus
Order	Opisthopora (*50*)	4.617	Earthworms
Order	Rodentia (*50*)	5.163	Mice
Order	Branchiopoda (*51*)	5.650	Brine shrimp
Order	Actinopterygii (*52*)	4.97	Marine species; used lower of two values
	Average	**4.831**	Excludes *Uca*

Table S8. Traits databases used to extract species body size data to assess body size distribution of animal geomorphic agents. Italic numbers show data source references.

Trait	Unit	Taxa	Source
Biomass	g	Amphibians, birds, fish, mammals, reptiles	O'Gorman and Hone (*1*)
	g	Mammals	COMBINE (*2*)
	kg	Vertebrates, arthropods, worms, molluscs	AnimalTraits (*3*)
	mg (wet weight)	Soil invertebrates	BETSI (*4*)
	g (wet weight)	Crayfish	Anderson and Simon (*5*)
	kg	Mammals	Animal Diversity Web (*6*)
	g	Spiders	World Spider Database (*7*)
Body length	mm	Mammals	COMBINE (*2*)
	mm	Soil invertebrates	BETSI (*4*)
	mm	Spiders	World Spider Database (*7*)
	mm	Ants	GlobalAnts (*8*)
Maximum carapace length	mm	Crayfish	Bland (*9*)

Table S9. References used to derive allometric equations for individual species body size (biomass) estimates where only body length data were available.

Genera	**Reference**
Actionaias, Obliquaria, Ptychobranchus and *Quadrula*	Atkinson *et al. (53)*
Agapetus, Amblema, Asellus, Athripsodes, Borinquena, Cambarus, Campsurus, Chaetopteryx, Coelotanypus, Cricotopus, Ephoron, Eukiefferiella, Gammaridae, Halesus, Hexagenia, Hydropsyche, Lepidostoma, Limnephilus, Macrostemum, Micropterna, Mystatices, Neohagenulus, Polycentropus, Polypedium, Potamophylax, Prodiamesa, Rheotanytarsus, Rhyacophila, Sericostoma and *Stenophylax*	Benke *et al. (54)*
Coptotermes, Cornitermes, Cubitermes, Dicuspiditermes, Heterotermes, Macrotermes, Microtermes, Nasutitermes, Odontotermes, Schedorhinotermes and Tumulitermes	Dahlsjö *(55)*
Allogymnopleurus, Arbanitis, Bubas, Catharsius, Ceratophyus, Copris, Cyclochila, Hemilepistus, Khepher and *Typhaeus*	Ganihar *(56)*
Octolasion	Hale *et al. (57)*

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