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Mitigating GHG emissions: A global ecosystem service provided by obligate scavenging birds

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A B S T R A C T

Dead animals release greenhouse gases to the atmosphere through natural decomposition or because they have to be processed by disposal methods such as composting or rendering. Obligate scavenging birds (vultures) consume dead animals and are among the most efficient terrestrial scavengers. They may therefore contribute to a considerable reduction in sources of greenhouse gases. Here, we quantify the global contribution of vultures in reducing greenhouse gas emissions by consuming organic material. First, we evaluated a scenario where all the dead animals that can be consumed by vultures every year have to be disposed of by composting, anaerobic decomposition (e.g., burial), anaerobic digestion or rendering. Second, we assessed a scenario in which dead animals are left to decompose in the environment. Current vulture populations (~134–140 million individuals) may reduce emissions of 3.03–60.70 Tg CO_2 eq. per year, depending on the disposal method implemented, without considering carcass transport to disposal plants. Alternatively, they may reduce emissions of 13.02 Tg CO_2 per year if dead animals remain in the environment. Over recent years a decline in vulture populations worldwide has led to a decrease of a 30 % in their capacity to mitigate greenhouse gases emissions. A few abundant vulture species reduce almost 98 % of the maximum emissions potentially removed worldwide by all extant vulture species over one year. This ecosystem service contributed by vultures to humans and nature cannot easily be replaced by other species, including humans. Moreover, supplanting this contribution with alternative carcass disposal methods is expensive and harmful to the environment due to emissions generated in the process. Our results highlight an important service that vultures provide worldwide, which is relevant in the current context of global warming.

1. Introduction

The climate change associated with greenhouse gases (GHG) constitutes a severe environmental problem worldwide and has a negative impact on human wellbeing, natural resources and biodiversity. Human activities such as fossil fuel burning, changes in land use, livestock production, agriculture, industry, and air and maritime transport are major sources of greenhouse gases globally (Caro et al., 2014; Cowart et al., 2003; Raupach et al., 2007). Worryingly, greenhouse emissions caused by human activities have accelerated over recent decades (Gills and Morgan, 2020; Raupach et al., 2007). These emissions retain heat in the atmosphere, increasing global mean temperatures, which in turn produces changes in precipitation patterns and in the frequency and severity of extreme climatic events (Hughes, 2000). These changes have several consequences for the ecosystem, biodiversity, and human lives (Hughes, 2000; Vitousek, 1994); for instance, global warming is already affecting the physiology, phenology, and distribution of many taxa (e.g., plants, insects, mammals and birds), which could produce alterations in their interactions and even lead to extinctions (Hughes, 2000). Under this complex scenario, it is essential to reduce the current level of greenhouse gas emissions produced by human activities and prevent the generation of new ones.

Decomposing organic material produces gases (Carter et al., 2006; Coe, 1978; Sakata et al., 1980; Zeng, 2015). Animal mortalities, both wild and domestic, are thus potential sources of greenhouse gases that are emitted into the environment (Gwyther et al., 2011; Yuan et al., 2012; Zeng, 2015). While dead animals can be disposed of using methods such as burning, burial, incineration, rendering, composting and anaerobic digestion, these methods produce varying quantities of emissions, and most are expensive (Gooding and Meeker, 2016; Gwyther

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et al., 2011; Xu et al., 2007; Yuan et al., 2012). In addition, dead animals rotting in the environment also emit greenhouse gases such as Nitrous oxide (N_2O), Carbon dioxide (CO_2) or Methane (CH_4) into the atmosphere (Dalva et al., 2015; Sakata et al., 1980; Zeng, 2015). Worryingly, some of the gases emitted by animal mortalities such as methane are currently rising at alarming rates in the atmosphere (Tollefson, 2022). Therefore, animal mortalities per se are a source of greenhouse gases due to their subsequent decomposition process or treatment by disposal methods (Xu et al., 2007; Yuan et al., 2012; Zeng, 2015).

Obligate scavenging birds (hereafter, vultures) consume a diet based on dead animals, currently mainly livestock but also several wildlife species (Arrondo et al., 2019; Ferguson-Lees and Christie, 2001; Lambertucci et al., 2009). In fact, they are considered one of the most efficient terrestrial scavenger species (Ruxton and Houston, 2004), performing an important ecosystem service by efficiently removing decomposing organic material from the environment (Houston, 1986; Lambertucci et al., 2021; Sebastián-González et al., 2019). This reduces not only sources of dangerous pathogens, which could be of importance for disease regulation (Plaza et al., 2020), but also gases produced by rotting organic material. Moreover, this ecosystem service has the financial benefit of reducing the cost of using alternative disposal methods to remove carcasses (Grilli et al., 2019; Morales-Reyes et al., 2015). Vultures arrive and feed quickly on animals that have recently died, the consumption of a medium-sized carcass possibly taking only few minutes when many birds are present (Arrondo et al., 2019; Carrete et al., 2010; Houston, 1986; Ogada et al., 2012b). If vultures are not present, carcasses tend to remain longer in the environment, decomposing and producing greenhouse gases (Coe, 1978; Dalva et al., 2015; Markandya et al., 2008; Sakata et al., 1980; Zeng, 2015). Moreover, if carcasses remain in the environment in populated areas, especially in sites where there are strict regulations regarding dead animal disposal (see Morales-Reyes et al., 2015), they have to be removed and disposed of by methods such as composting or rendering that produce varying levels of emissions (Gooding and Meeker, 2016; Gwyther et al., 2011). However, information is still lacking on the potential role of vultures as reducers of greenhouse gas emissions from dead animals at a global scale.

Here, we evaluate the ecosystem service vultures provide by removing potential sources of greenhouse gases at a global scale, in this case dead animals. To this end, we calculated the quantities of dead animals that vultures could consume each year on a global level, which in turn would reduce this source of emissions (rotting organic material) or the need to use artificial methods of carcass disposal. We then analyzed the quantity of greenhouse gas emissions that carcasses consumed by vultures could produce globally if they had to be disposed of by one of four disposal methods (composting, anaerobic decomposition, anaerobic digestion, and rendering), or if they remained in the environment without being consumed. Finally, we addressed scenarios of vulture population abundances and trends in diverse geographical areas in order to evaluate the consequences of the decrease or increase in vulture populations in terms of their role as reducers of sources of greenhouse gas emissions.

2. Methods

2.1. Quantification of the reduction in greenhouse gas emissions by vultures

To estimate the mitigation of greenhouse emissions by vultures, we calculated the organic material that these birds consume per year, on a global level. Then, we considered different decomposition scenarios where vultures are absent. First we evaluated a scenario where carcasses consumed by vultures have to be disposed of by alternative methods (composting, anaerobic decomposition, anaerobic digestion, rendering), and then we considered a scenario where carcasses consumed by vultures remain in the environment without disposal treatment and not consumed by other scavengers. We only focused on the carcass handling process, not evaluating the emissions associated with the transport of dead animals to disposal plants (Table 1). Including those emissions would increase the GHG emissions of disposal methods, therefore, our results are conservative in this sense.

Table 1
Methodology implemented to compute emissions removed by vultures.

	Basis*	Equations for calculation of emissions (E)	Reference
Composting	A carcass weighing 1000 kg produces 4000 kg CO_2 eq.	E (kg CO_2 eq./year) = OMC (kg/year)/1000 kg × 4000 kg CO_2 eq.	Gooding and Meeker (2016)
Anaerobic decomposition	A carcass weighing 500 kg produces 720 kg CO_2 eq.	E (kg CO_2 eq./year) = OMC (kg/year)/500 kg × 720 kg CO_2 eq.	Yuan et al. (2012)
Anaerobic digestion	A carcass weighing 1000 kg produces 500 kg CO_2 eq.	E (kg CO_2 eq./year) = OMC (kg/year)/1000 kg × 500 kg CO_2 eq.	Gooding and Meeker (2016)
Rendering	A. carcass weighing 1000 kg produces 200 kg CO_2 eq.	E (kg CO_2 eq./year) = OMC (kg/year)/1000 kg × 200 kg CO_2 eq.	Gooding and Meeker (2016)
Natural decomposition	A carcass weighing 1000 kg produces 858 kg CO_2	E(kg CO_2/year) = OMC (kg/year)/1000 kg × 858 kg CO_2	Zeng (2015)

* These values do not consider emissions generated by the transport of carcasses to disposal facilities.

2.1.1. Organic material consumed by vultures per year

To obtain a global estimate of the organic material consumed by vultures per year, we computed the daily food intake for a typical individual of each of the 22 vulture species present in the world that consume mainly animal tissues. We excluded the palm-nut vulture (*Gypohierax angolensis*) because its diet is based mainly on palm fruits (Ferguson-Lees and Christie, 2001). For this, we considered that vultures feed as much as they can to cover their daily caloric requirements. We computed the daily food intake (FI) of each vulture species following the methodology of Grilli et al. (2019). Briefly, we estimated daily food intake as:

$$FI\,(g/day) = FMR\,(kJ/day)/(6.65\,kJ/g \times 0.769)$$

where 6.65 kJ is the caloric content per gram of a small mammal (Hamilton, 1985), 0.769 (76.9%) is the assumed mean assimilation efficiency and FMR is the field metabolic rate, calculated as 10.9 $M^{0.64}$, where M is the body mass (Bozinovic and Medel, 1988). We divided the result obtained by 1000 in order to obtain FI (kg/day). We reported a range of FI (kg/day) according to the known range of body mass of individuals (i.e., using the minimum and maximum values of body mass reported to calculate the FI, Table 2). We then multiplied FI (kg/day) (kilograms of daily food intake per day) by the global population estimate for each species of vulture (Nv) and by 365 to obtain kilograms of organic material consumed (OMC) per year by each vulture species population.

$$OMC\ (kg/year) = FI\ (kg/day) \times Nv \times 365(days)$$

We determined the ranges (minimum and maximum) of OMC by each species population according to: 1) the range of FI (min–max) of individuals, and 2) the range of estimates of numbers of individuals composing each vulture population (i.e., we multiplied the minimum and maximum value of FI by the minimum and maximum numbers of individuals respectively for each vulture species to obtain a range of OMC; see Table 2). The body mass range of each species was obtained

Table 2
Vulture species, conservation status, body mass, estimated global populations, daily food intake and maximum emissions potentially removed per year, for each vulture species.

Species	Conservation Status*	Body mass (kg)	Global populations	Food intake (kg/day)	Comp Tg CO_2 eq./year	A. Dec Tg CO_2 eq./year	A. Dig Tg CO_2 eq./year	Rend Tg CO_2 eq./year	Nat Tg CO_2/year
Gyps bengalensis	CR	3.5–6.0**	3500–15,000**	0.395–0.558	0.00201845–0.0122202	0.000726642–0.004399272	0.000252306–0.001527525	0.000100923–0.00061101	0.000432958 –0.002621233
Gyps africanus	CR	4.15–7.2	270,000	0.44–0.627	0.173448–0.2471634	0.06244128–0.088978824	0.021681–0.030895425	0.0086724–0.01235817	0.037204596 –0.053016549
Gyps tenuirostris	CR	5.5–6.3	1500–3750**	0.527–0.575	0.00115413–0.003148125	0.000415487–0.001133325	0.000144266–0.000393516	5.77065E-05–0.000157406	0.000247561 –0.000675273
Gyps indicus	CR	5.5–6.3	45,000**	0.527–0.575	0.0346239–0.0377775	0.012464604–0.0135999	0.004327988–0.004722188	0.001731195–0.001888875	0.007426827 –0.008103274
Gyps rueppelli	CR	6.8–9.0	30,000	0.604–0.723	0.0264552–0.0316674	0.009523872–0.011400264	0.0033069–0.003958425	0.00132276–0.00158337	0.00567464 –0.006792657
Gyps coprotheres	VU	7.1–10.9	8000–10,000**	0.621–0.817	0.00725328–0.0119282	0.002611181 0.004294152	0.00090666–0.001491025	0.000362664–0.00059641	0.001555829 –0.002558599
Gyps fulvus	LC	6.2–11.3	80,000–900,000	0.569–0.836	0.0664592–1.098504	0.023925312–0.39546144	0.0083074–0.137313	0.00332296–0.0549252	0.014255498 –0.235629108
Gyps himalayensis	NT	8.0–12.0	100,000–499,999	0.67–0.869	0.09782–0.634368731	0.0352152–0.228372743	0.0122275–0.079296091	0.004891–0.031718437	0.02098239 –0.136072093
Neophron percnopterus	EN	1.6–2.4	18,600–54,000	0.239–0.31	0.006490284–0.0244404	0.002336502–0.008798544	0.000811286–0.00305505	0.000324514–0.00122202	0.001392166 –0.005242466
Necrosyrtes monachus	CR	1.5–2.6	197,000	0.229–0.326	0.06586498–0.09376412	0.023711393–0.033755083	0.008233123–0.011720515	0.003293249–0.004688206	0.014128038 –0.020112404
Trigonoceps occipitalis	CR	3.3–5.3	5500	0.38–0.515	0.0030514–0.00413545	0.001098504–0.001488762	0.000381425–0.000516931	0.00015257–0.000206773	0.000654525 –0.000887054
Sarcogyps calvus	CR	3.7–5.4	3500–15,000	0.40–0.521	0.002044–0.0114099	0.00073584–0.004107564	0.0002555–0.001426238	0.0001022–0.000570495	0.000438438 –0.002447424
Torgos tracheliotos	EN	5.4–9.4	8500**	0.521–0.743	0.00646561–0.00922063	0.00232762–0.003319427	0.000808201–0.001152579	0.000323281–0.000461032	0.001386873 –0.001977825
Gypaetus barbatus	NT	4.5–7.2	2000–10,000**	0.464–0.627	0.00135488–0.0091542	0.000487757–0.003295512	0.00016936–0.001144275	0.000067744–0.00045771	0.000290622 –0.001963576
Aegypius monachus	NT	7.0–12.5	25,200–34,200	0.615–0.892	0.02262708–0.044539344	0.008145749–0.016034164	0.002828385–0.005567418	0.001131354–0.002226967	0.004853509 –0.009553689
Coragyps atratus	LC	1.6–2.2**	120,000,000**	0.239–0.293	41.8728–51.3336	15.074208–18.480096	5.2341-6.4167	2.09364–2.56668	8.9817156 –11.0110572
Cathartes aura	LC	0.9–2.0	13,154,065	0.165–0.276	3.168814259–5.304403019	1.140773133–1.909585087	0.396101782–0.663050377	0.158440713–0.265220151	0.679710658 –1.137794448
Cathartes melambrotus	LC	1.17–1.65	100,000	0.196–0.244	0.028616–0.035624	0.01030176–0.01282464	0.003577–0.004453	0.0014308–0.0017812	0.006138132 –0.007641348
Gymnogyps californianus	CR	8.2–14.1	201	0.681–0.964	0.000199846–0.000282895	7.19447E-05 0.000101842	2.49808E-05–3.53619E-05	9.99231E-06–1.41448E-05	4.2867E-05 –6.06811E-05
Vultur gryphus	VU	7.5–15	10,000	0.643–1.003	0.0093878–0.0146438	0.003379608–0.005271768	0.001173475–0.001830475	0.00046939–0.00073219	0.002013683 –0.003141095
Cathartes burrovianus	LC	0.95–1.55	500,000–4,999,999	0.171–0.234	0.12483–1.708199658	0.0449388–0.614951877	0.01560375–0.213524957	0.0062415–0.085409983	0.026776035 –0.366408827
Sarcoramphus papa	LC	3.0–3.75	1000–50,000	0.358–0.413	0.00052268–0.030149	0.000188165–0.01085364	0.000065335–0.003768625	0.000026134–0.00150745	0.000112115 –0.006466961
Total	—	—	**134,563,566–140,412,214**	—	**45.72230098–60.70034397**	**16.46002835–21.85212383**	**5.715287622–7.587542997**	**2.286115049–3.035017199**	**9.80743356 –13.02022378**

Comp: Composting, A. Dec: Anaerobic decomposition (e.g., burial), A. Dig: Anaerobic digestion, Rend: Rendering, Nat: Natural decomposition.
* CR: Critically Endangered, E: Endangered, VU: Vulnerable, NT: Near Threatened, LC: Least Concern.
** These population estimates and body mass ranges were obtained from Birds of the World Database. The rest of the population estimates were obtained from IUCN Red List, and Grilli et al. (2019) in the case of *Cathartes aura*. The rest of the body mass ranges were obtained from Ferguson-Lees and Christie (2001). For complete details, see methods section.

Table 3
Greenhouse gases potentially reduced by vultures, based on four disposal methods and natural decomposition before and after their population changes (decreasing-increasing) in three geographical areas (India, Africa, and Europe).

Geographical area	Species	Past populations*	Current populations**	Composting Tg CO_2 eq./year		Anaerobic decomposition Tg CO_2 eq./year		Anaerobic digestion Tg CO_2 eq./year		Rendering Tg CO_2 eq./year		Natural decomposition Tg CO_2/year	
				Before	After	Before	After	Before	After	Before	After	Before	After
India	*Gyps bengalensis*	3,500,000–15,000,000	3500–15,000	2.0184–12.2202	0.0020–0.0122	0.7266–4.3992	0.0007–0.0043	0.2523–1.5275	0.0002–0.0015	0.1009–0.6110	0.0001–0.0006	0.4329–2.6212	0.0004–0.0026
	Gyps tenuirostris-Gyps indicus	1,453,125–1,523,437	46,500–48,750	1.1180–1.2789	0.0357–0.0409	0.4025–0.4604	0.0128–0.0147	0.1397–0.1598	0.0044–0.0051	0.0559–0.0639	0.0017–0.0020	0.2398–0.2743	0.0076–0.0087
Africa	*Gyps africanus*	2,700,000	270,000	1.7344–2.4716	0.1734–0.2471	0.6244–0.8897	0.0624–0.0889	0.2168–0.3080	0.0216–0.0308	0.0867–0.1235	0.0086–0.0123	0.3720–0.5301	0.0372–0.0530
	Gyps rueppelli	1,000,000	30,000	0.8818–1.0555	0.0264–0.0316	0.3174–0.3800	0.0095–0.0114	0.1102–0.1319	0.0033–0.0039	0.0440–0.0527	0.0013–0.0015	0.1891–0.2264	0.0056–0.0067
	Gyps coprotheres	100,000–125,000	8000–10,000	0.0906–0.1491	0.0072–0.0119	0.0326–0.0536	0.0026–0.0042	0.0113–0.0186	0.0009–0.0014	0.0045–0.0074	0.0003–0.0005	0.0194–0.0319	0.0015–0.0025
	Neophron percnopterus	250,000	20,000	0.0872–0.1131	0.0069–0.0090	0.0314–0.0407	0.0025–0.0032	0.0109–0.0141	0.0008–0.0011	0.0043–0.0056	0.0003–0.0004	0.0187–0.0242	0.0014–0.0019
	Necrosyrtes monachus	1,158,823	197,000	0.3874–0.5551	0.0658–0.0937	0.1394–0.1985	0.0237–0.0337	0.0484–0.0689	0.0082–0.0117	0.0193–0.0275	0.0032–0.0046	0.0831–0.1183	0.0141–0.0201
	Trigonoceps occipitalis	137,500	5500	0.0762–0.1033	0.0030–0.0041	0.0274–0.0372	0.0010–0.0014	0.0095–0.0129	0.0003–0.0005	0.0038–0.0051	0.0001–0.0002	0.0163–0.0221	0.0006–0.0008
	Torgos tracheliotos	40,000	8000	0.0304–0.0433	0.0060–0.0086	0.0109–0.0156	0.0021–0.0031	0.0038–0.0054	0.0007–0.0010	0.0015–0.0021	0.0003–0.0004	0.0065–0.0093	0.0013–0.0018
Europe	*Gyps fulvus*	5000–8000	95,930–122,452	0.0041–0.0097	0.0796–0.1494	0.0014–0.0035	0.0286–0.0538	0.0005–0.0012	0.0099–0.0186	0.0002–0.0004	0.0039–0.0074	0.0008–0.0020	0.0170–0.0320
	Neophron percnopterus	6777–10,000	6100–9000	0.0023–0.0045	0.0021–0.0040	0.0008–0.0016	0.0007–0.0014	0.0003–0.0005	0.0002–0.0005	0.0001–0.0002	0.0001–0.0002	0.0005–0.0009	0.0004–0.0008

* The references to obtain this data are presented in the section 3.3 "vulture population trends and greenhouse gas emissions". For India Prakash et al. (2007). For Africa Ogada et al. (2016b) and IUCN red list. For Europe IUCN red list and Del Moral and Molina (2018).
** The current populations were obtained from IUCN red list and Bird of the word database (see Table 2 and methods section).

from Ferguson-Lees and Christie (2001) and Birds of the World Database (https://birdsoftheworld.org/bow/home). Ranges of population estimates for each vulture species were obtained from Birds of the World Database and from IUCN Red List (IUCN, 2021; Table 2). In the case of the turkey vulture (*Cathartes aura*) we used the global population estimates from Grilli et al. (2019). The population abundances used should be taken with caution since several are rough estimates, and populations may have changed. However, for the purpose of this article they give an approximate value for potential scenarios of carcass removal.

2.1.2. GHG emissions reduced by vultures

We first considered the emissions that would be generated if all carcasses currently consumed by vultures were disposed of using four different artificial disposal methods: composting, anaerobic decomposition (e.g. burial), anaerobic digestion, and rendering (for more details of these disposal methods, see Gwyther et al., 2011 and supplementary material, Table S1). We selected these disposal methods because they are commonly used worldwide, and at the same time they generate reliable scientific information regarding GHG emissions (Gwyther et al., 2011). For composting, anaerobic digestion, and rendering we used the approach proposed in Gooding and Meeker (2016). For anaerobic decomposition (e.g., burial) we used the approach proposed in Yuan et al. (2012). Second, we considered the emissions that would be generated if all carcasses currently consumed by these birds were to decompose in the open environment, based on the approach proposed in Zeng (2015). These different approaches enabled us to compute the emissions generated by dead animals.

The equations used to estimate the emissions that would be produced by carcasses that vultures consume per year, if they were to be disposed of with alternative disposal methods, are reported in Table 1. For instance, the anaerobic decomposition (e.g., burial) of a carcass weighing 500 kg produces 720 kg CO_2 eq. based on Yuan et al. (2012). Therefore, to compute the emissions that would be generated by all the carcasses consumed by vultures worldwide, if these carcasses were disposed of by anaerobic decomposition, we divided the estimated OMC (kg/year) (food intake per year) of each vulture population (by species) by 500 to obtain an approximate number of carcasses weighing 500 kg that these populations can consume per year (Table 1). We then multiplied by 720 the number of carcasses each vulture species consumed per year to obtain the kilograms of CO_2 eq. that it could prevent annually (Table 1). Finally, we summed up the values of kg CO_2 eq. obtained for each vulture species to obtain a value for the emissions that the global vulture population (all the species) could reduce per year. The same methodology (with the corresponding equations) was used to compute emissions if all carcasses consumed by vultures per year were disposed of by anaerobic digestion, composting or rendering (Table 1). The greenhouse emissions produced by these alternative disposal methods were expressed in Tg CO_2 eq., since disposal procedures (composting, anaerobic decomposition, anaerobic digestion and rendering) release a mix of gases such as CH_4 or N_2O. The CO_2 eq. is a unit that describes, for a certain mixture and quantity of greenhouse gases, the amount of CO_2 that would have the same global warming potential (IPCC, 2006).

To estimate the emissions generated by dead animals if all carcasses consumed by vultures worldwide were to remain in the environment, we followed the methodology implemented by Zeng (2015) (Table 1). We considered a cow carcass to contain 23.4% of Carbon (C); thus a carcass weighing 1000 kg contains 234 kg of Carbon (Zeng, 2015). Multiplying this value by the molecular weight ratio of CO_2 (44) to Carbon (12), i.e., 44/12) gives the number of kilograms of CO_2 emitted by a cow carcass of 1000 kg (EPA, 2008), in this case 858 kg of CO_2. We followed the same methodology implemented for each of the alternative disposal methods but with the appropriate equation (see Table 1). Units of greenhouse gas emission produced by natural decomposition (emissions generated by dead animals if all carcasses consumed by vultures were to remain in the environment) were expressed in Tg CO_2, since the methodology proposed by Zeng (2015) computes the values based only on CO_2 and not on mixed gases.

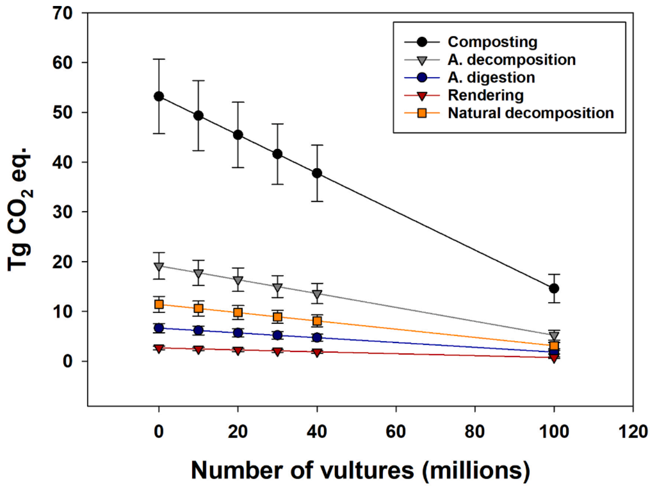

Fig. 1. Reduction of greenhouse gas emissions generated by dead animals, according to the abundance of vultures (in millions) and methods implemented to dispose of carcasses (composting, anaerobic decomposition, anaerobic digestion, rendering) or natural decomposition in the environment (see details in Methods). Emissions generated by disposal methods are expressed in Tg CO_2 eq. Emissions generated by natural decomposition are expressed in Tg CO_2 (see, material and methods). The points represent mean values and the bars the maximum and minimum emissions vultures could reduce (see Methods section for more detail). Note that we only focused on the carcass handling process, not evaluating the emissions associated with the transport of dead animals to disposal plants; including those emissions would increase the GHG emissions of disposal methods above the natural decomposition.

For GHG emitted by disposal methods (composting, anaerobic decomposition, anaerobic digestion and rendering) and environmental decomposition, we reported a range of emissions removed according to minimum and maximum values OMC (Table 2).

2.2. Vulture population trends and greenhouse gas emissions calculation

To evaluate how population trends of vultures may influence the potential mitigation of GHG emissions produced by dead animals, we evaluated the consequences of the decrease or increase of vulture populations in different regions of the world (India, Africa, Europe and America). For this, we computed vulture population changes, based on the available bibliography (see section 3.3 Vulture population trends and greenhouse gas emissions, and Table 3), and calculated the GHG emissions potentially removed using the general methodology presented above.

3. Results and discussion

3.1. Greenhouse emissions reduced by vultures globally

When obligate scavenging birds are present in the environment, they consume the available carcasses in a few hours or days (Arrondo et al., 2019; Carrete et al., 2010). However, when these birds are absent or present in low abundance, carcasses remain in the environment for a longer period of time (Markandya et al., 2008) and may have to be removed by other disposal methods (Gwyther et al., 2011). Indeed, this happens in geographical areas with strict regulations concerning dead animal disposal as Spain (Morales-Reyes et al., 2015). The remaining option is for the animals to decompose naturally in the environment. Both disposal and natural decomposition of these carcasses release greenhouse gases into the environment (Gooding and Meeker, 2016; Morales-Reyes et al., 2015; Zeng, 2015). By efficiently removing the carcass, vultures reduce the potential emissions produced by animal

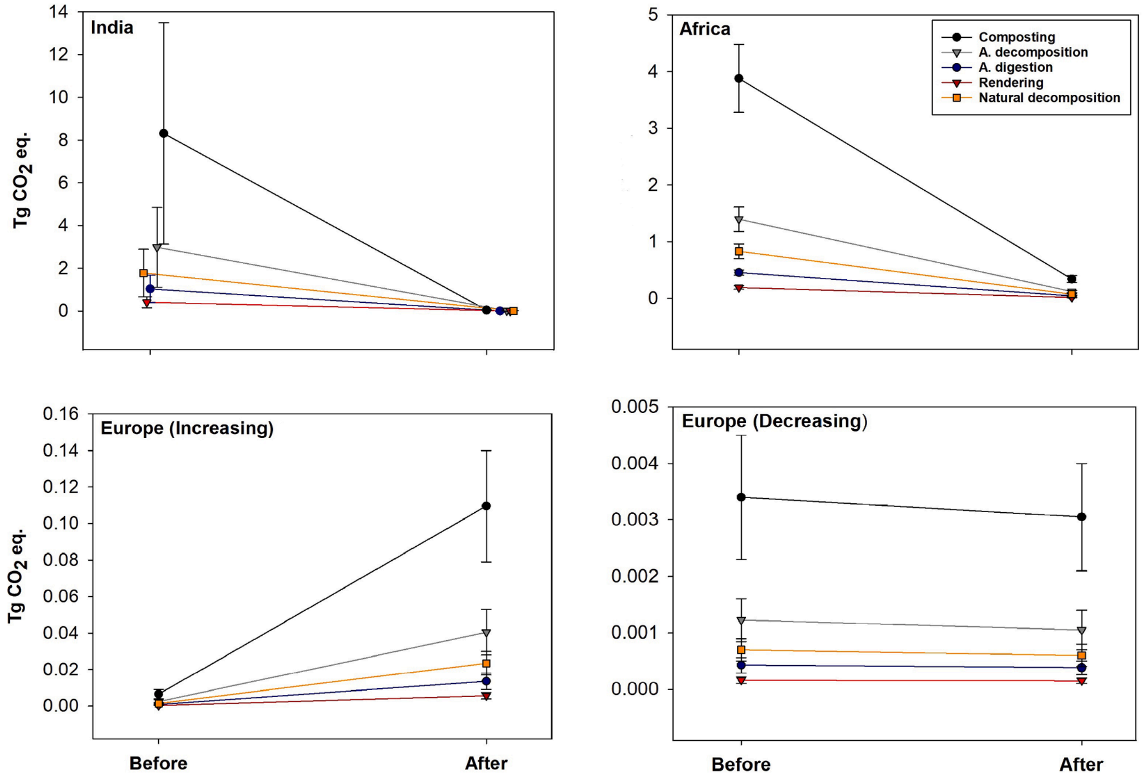

Fig. 2. Greenhouse gas emissions potentially reduced by vultures' consumption of carcasses per year (before and after decreases in populations) in three regions of the world (India, Africa, Europa). Scenarios consider that all carcasses they consume are disposed of by composting, anaerobic decomposition, aerobic digestion, rendering, or carcasses remain in the environment without being consumed. In the case of Europe, there are two opposite scenarios: increasing populations (considering the increase in griffon vulture abundance in recent years in Spain) and decreasing populations (considering the population decrease of Egyptian vultures). Emissions generated by disposal methods are expressed in Tg CO_2 eq. Emissions generated by natural decomposition are expressed in Tg CO_2 (see material and methods). The points represent mean values and the bars the maximum and minimum emissions vultures could reduce (see methods section for more detail).

disposal methods (e.g., burial, composting, rendering) or natural decomposition, thus preventing emissions generated by these options.

Our estimates showed that vultures may prevent the generation of between 3.03 and 60.70 Tg CO_2 eq. per year globally, depending on the artificial method implemented for carcass disposal (Table 2, Fig. 1). This reduction reaches 13.02 Tg CO_2 per year globally in the case of carcasses decomposing naturally in the environment (Table 2, Fig. 1). To put these values into context, 60.70 Tg CO_2 eq. is equivalent to the total US emissions produced by boats and ships in the year 2001, and 46% of the US emissions produced by commercial aircraft for the same year (Cowart et al., 2003). Also, it represents 12.61% of US emissions produced in 2005 by the livestock, poultry and crop sectors (Del Grosso et al., 2008), 9.63% of the emissions produced in 2007 by the livestock production sector (meat, milk and eggs) in Europe (Bellarby et al., 2013) and the 15% of emissions generated by the livestock sector in 2014 in Pakistan (Habib and Khan, 2018). Moreover, it represents the 7.5% of the emissions generated by fires from March 2019 to February 2020 in Australia (Shiraishi and Hirata, 2021). Therefore, only one threatened group – vultures – whose populations have already been decimated, can remove a significant amount of organic material from the environment, thus providing the service of preventing emission of these greenhouse gases to the atmosphere.

This contribution from vultures to humans and the ecosystem is important not only when considering livestock, but also rotting dead wildlife in general. Vultures are suffering a marked decline in their populations on all the continents where they occur (Buechley and Şekercioğlu, 2016; Ogada et al., 2012a; Santangeli et al., 2022), so under the current scenario of global warming it is essential to preserve them and their contributions. The efficient ecosystem service of greenhouse gas reduction provided by these birds cannot be easily replaced by other scavenging animals in the same geographical areas (Hill et al., 2018). Using alternative disposal methods to replace the carcass elimination service that vultures provide will lead to an increase in both greenhouse gas emissions and financial costs (Gwyther et al., 2011; Morales-Reyes et al., 2015).

3.2. *The least concern vultures are the most important contributors*

As expected, our estimates show that the most abundant vulture species are the most relevant at disposing of sources of greenhouse gases. For instance, the American black (*Coragyps atratus*), turkey, lesser yellow-headed (*Cathartes burrovianus*) and griffon (*Gyps fulvus*) vultures together may reduce between 2.97 and 59.44 Tg CO_2 eq. per year (depending on the artificial method that might be implemented) and 12.75 Tg CO_2 per year if the carcasses were to remain in the environment (Table 2). These values represent almost 98% of the maximum emissions potentially removed worldwide by all vulture species per year. These results highlight the importance of monitoring and considering conservation action not only for threatened vultures, but also for the most abundant species, which contribute most in terms of reducing potential sources of greenhouse emissions. However, the less abundant vulture species may cover other areas where the most abundant species are not present, so this should also be considered.

The high abundance of some vulture species often exacerbates conflicts with humans, who may resort to lethal strategies to remove them (Ballejo et al., 2020; Lambertucci et al., 2021). For instance, American black vultures are blamed for livestock predation, property damage and putting human health at risk (Kluever et al., 2020; Lowney, 1999). This negatively affects people's perception of the species, resulting in lethal elimination strategies, e.g., poisoning (Ballejo et al., 2020; Kluever et al.,

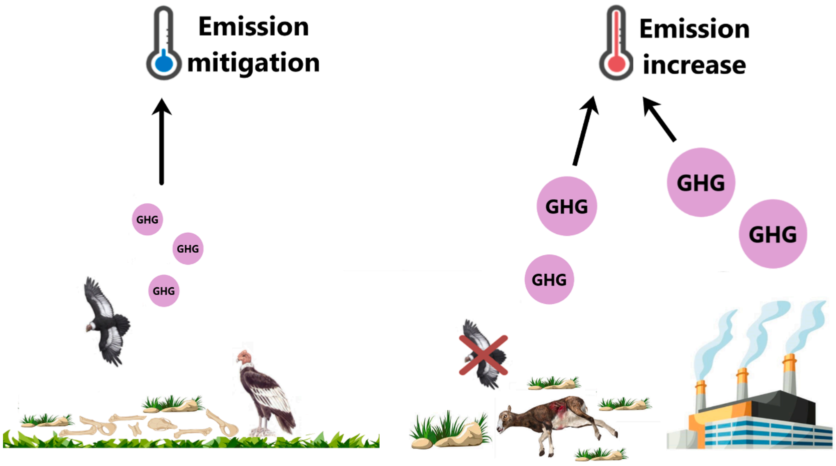

Fig. 3. Scheme of the emissions generated by dead animals and the contributions of vultures in reducing sources of GHG emissions when removing the carcasses. When vultures are present (left panel) they consume carcasses, reducing emissions associated with decomposition of the dead animal or alternative disposal methods (transport and disposal of carcasses). When vultures are not present (right panel) carcasses remain for more time in the environment, generating greenhouse gases and spreading pathogens. This could be associated with the need to implement alternative disposal methods, which also generate greenhouse gases. GHG = greenhouse gases emissions including N_2O, CO_2 or CH_4.

2020). Similarly, griffon vultures are blamed for livestock predation, with similar results (Margalida et al., 2014). The importance of these species for the ecosystem and even human well-being must be emphasized, to mitigate the negative attitudes of humans toward them (Lambertucci et al., 2021). In this sense, our results are important in terms of improving tolerance toward these birds, promoting the role of vultures not only because they reduce the presence of dead animals, which are sources of pathogens and food sources that might attract conflictive species (e.g., feral dogs and rats) (Plaza et al. 2020), but also because they reduce greenhouse gas emissions.

3.3. *Vulture population trends and greenhouse gas emissions*

3.3.1. *India*

Indian (*Gyps indicus*), slender-billed (*Gyps tenuirostris*) and white-rumped (*Gyps bengalensis*) vultures were among the most abundant large birds in the world until recent decades (Ferguson-Lees and Christie, 2001; Pain et al., 2008). However, their populations declined abruptly at the end of the 20th century due to exposure to diclofenac residues in carcasses they consumed (Pain et al., 2008: Prakash et al., 2007). In India, the population of white-rumped vultures in 2007 was reduced to 0.1% of the 1992 population; the Indian and the slender-billed vulture populations combined in 2007 represented just 3.2% of their 1992 abundance (Prakash et al., 2007). Based on these figures (a reduction of 97–99%), our estimate of populations of these species before the diclofenac crisis was approximately 3,500,000–15,000,000 for white-rumped vultures and 1,453,125–1,523,437 for Indian and slender-billed vultures combined (Table 3).

This catastrophic depletion of vulture populations in India has substantially reduced their contribution to humans and nature (Markandya et al., 2008; Ogada et al., 2012a). In the case of mitigating greenhouse gas emission, the decrease in vulture populations represented an almost complete loss (~99%) of their capacity to prevent the emissions produced by dead animals (Table 3, Fig. 2). For instance, before the diclofenac crisis vultures from India may have reduced greenhouse gas production by 0.67–13.5 Tg CO_2 eq. per year, depending on the method used for carcass disposal (Table 3, Fig. 2), and 2.89 Tg CO_2 per year if carcasses decompose naturally in the environment (Table 3, Fig. 2). Currently, they may prevent 0.002–0.05 Tg CO_2 eq. per year, depending on the disposal method implemented, and 0.01 Tg CO_2 per year in the natural decomposition scenario (Table 3, Fig. 2). These values highlight the magnitude of the cost of the catastrophic decrease in vulture populations in this geographical area in terms of their contribution to humans and the ecosystem.

The Indian scenario is a good example of how catastrophic decreases in populations of obligate scavenging birds could have diverse impacts on the ecosystem and human well-being. Some of these impacts are very evident and tangible; e.g., more carcasses remaining in the environment that potentially favors outbreaks of infectious disease, an increase in feral dogs and rats, and an increase in the cost of carcass removal using alternative methods (Markandya et al., 2008; O'Bryan et al., 2018). Other consequences are less obvious. The cost in terms of removal of sources of GHG emissions by vultures remains hidden, less tangible and difficult to evaluate. However, as we show here, the loss of this contribution could be noticeable in relation to declining vulture populations in India.

3.3.2. *Africa*

Like India, Africa was one of the most important areas for several vulture species. However, this continent has suffered a marked decline in vulture populations over the last 50 years due to threats associated with human activities, especially poisoning and the trading of parts, which together accounted for 90% of the reported deaths of these birds in the last decades (Ogada et al., 2016b). Populations of bearded (*Gypaetus barbatus*), Egyptian (*Neophron percnopterus*), white-backed (*Gyps africanus*), Rüppell's (*Gyps rueppellii*), cape (*Gyps coprotheres*), hooded (*Necrosyrtes monachus*), lappet-faced (*Torgos tracheliotos*), and white-headed (*Trigonoceps occipitalis*) vultures have on average decreased 62 %, with some species decreasing more than 80% (Ogada et al., 2016b) (Table 3). Worryingly, vulture populations continue to decline, especially due to intentional poisoning (Ogada et al., 2016a; Plaza et al., 2019).

In terms of the mitigation of greenhouse gases generated by dead animals, these population declines mean that considering all the species mentioned together (excluding *Gypaetus barbatus* due to a lack of detailed population estimates for Africa) have lost approximately 90% of their capacity to remove sources of emissions (carcasses). Before the catastrophic vulture population crash of fifty years ago, the maximum emission reduction potential of these birds was 0.22–4.48 Tg CO_2 eq. per year, depending on the disposal method implemented, and 0.96 Tg CO_2 per year considering the natural decomposition scenario (Table 3, Fig. 2). Currently, vultures in Africa can only remove up to 0.02–0.40 Tg CO_2 eq. per year, depending on the disposal method implemented, and 0.087 Tg CO_2 per year considering the natural decomposition scenario (Table 3, Fig. 2).

Africa has large numbers of wild herbivores (Hempson et al., 2017), but also a growing livestock sector that has increased their emissions over the last 25 years (Gilbert et al., 2018; Herrero et al., 2013; Moeletsi et al., 2017). Therefore, the extended permanence of carcasses in the environment (both wild and domestic animals) associated with declining vulture populations and the need to process dead animals by disposal methods should be considered an additional source of greenhouse gas for this continent.

3.3.3. Europe

In Europe, the situation is different from the scenario presented for India and Africa. The species that occur on this continent such as the griffon, Egyptian, bearded and cinereous (*Aegypius monachus*) vultures have suffered historical population decreases, but some are recovering due to conservation measures (IUCN, 2021) (Table 3). These increasing populations improve vulture capacity to mitigate GHG emissions. For instance, in Spain the population of griffon vultures increased from 5000 to 8000 birds in 1958 to 95,930–122,452 in the present (Del Moral and Molina, 2018) (Table 3). Before these population increases, griffon vultures in Spain removed 0.0004–0.009 Tg CO_2 eq. per year, depending on the disposal method implemented, and 0.002 Tg CO_2 per year considering natural decomposition (Table 3, Fig. 2). Currently, they can remove much more, up to 0.007–0.14 Tg CO_2 eq. per year, depending on the disposal method implemented, and 0.03 Tg CO_2 per year considering natural decomposition (Table 3, Fig. 2). Their capacity for removal of greenhouse gases has therefore increased 15 times over this time period. In contrast, Egyptian vulture populations have suffered declines over recent years (Table 3), reducing their capacity for removal of greenhouse gas sources by approximately 10% (Table 3, Fig. 2).

3.3.4. America

Two species from this continent, the California (*Gymnogyps californianus*) and the Andean condor (*Vultur gryphus*), have suffered marked population declines, associated with human disturbances (e.g., lead contamination, poisoning) (Finkelstein et al., 2012; IUCN, 2021; Plaza and Lambertucci 2020). In the Americas, however, black, lesser yellow-headed and turkey vultures are abundant. These three species could reduce the emission of approximately 2.91–58.34 Tg CO_2 eq. per year, depending the disposal method implemented, and 12.51 Tg CO_2 per year considering natural decomposition (Table 2). This represents approximately 96 % of the total emissions that vultures may currently be removing in the entire world. Therefore, as previously mentioned, the most abundant species are the most important in removing sources of greenhouse gases produced by dead animals, so maintaining large populations of these species is essential. In fact, our results suggest that currently the greatest impact of vultures as GHG emission reducers is in the Americas (supplementary material, Fig S1).

3.4. How much service have we lost?

Our estimates suggest that decreasing vulture populations in India and Africa (geographical areas where vultures are most threatened) have led to a loss of their capacity to mitigate the emissions generated by dead animals of up to 0.87–17.53 Tg CO_2 eq. per year, depending on the decomposition scenario (Table 3). This suggests that, in the last decades, vultures have lost approximately the 30% for GHG emission mitigation as they actually have today. If these trends do not change over the next years, we will have to face additional greenhouse gases emissions produced by dead animals that remain in the environment or are disposed of with alternative methods (e.g., burial, incineration). Alternatively, carcasses could be used by other problematic species such as feral dogs and rats, which are not as efficient as vultures and could have a negative impact on human wellbeing (Markandya et al., 2008; Plaza et al., 2020).

3.5. Future carrion scenarios

The livestock sector is constantly increasing in various parts of the world (Chhabra et al., 2013; Gilbert et al., 2018; Herrero et al., 2013; Patra, 2014). Global warming is expected to affect wildlife and livestock in different ways (e.g., heat stress, exposure to extreme climatic events, and infectious disease outbreaks), producing an increase in their mortality (Harvell et al., 2002; Sirohi and Michaelowa, 2007; Stillman, 2019). Moreover, wildlife mortality events associated with anthropogenic causes are increasing (emerging pathogens, toxins, etc.) (Fey et al., 2015). Therefore, this situation could lead to a chain of events (a vicious circle) resulting in the death of more animals (wildlife and livestock) and a consequent increase in carcasses that have to be disposed of or remain in the environment, thereby producing greenhouse gases or spreading pathogens. In this sense, the presence of healthy vulture populations could be key; if vulture populations continue in severe decline and this trend is not stopped, it could not only favor an increase in GHG emissions (our results), but also lead to disease outbreaks, affecting human health and the ecosystem (Plaza et al., 2020). Increasing threats from climate change could also negatively affect vulture populations (Simmons and Jenkins, 2007; Williams et al., 2012), which at the same time will impact on their ecosystem service of mitigating GHG emissions.

3.6. Caveats and future considerations

Our results show that vultures make an important contribution to humans and nature through consumption of dead animals, thus reducing sources of greenhouse gases. However, it is important to note that our estimates are somewhat limited. First, there are no precise estimates of vulture populations worldwide, only approximate numbers and most are discordant among the databases. Second, our estimates are based on the average weight of vulture individuals described in the bibliography; differences due to age, sex or region are not considered, and it is known these differences exist. Third, the methodologies used to compute emissions are in many cases based on theoretical approaches or experimental laboratory simulations. Fourth, our estimations are conservative since they did not include the GHG emissions generated by the transport of dead animals to disposal plants (see Morales-Reyes et al. 2015), thus underestimating the amount of GHG emitted if vultures are not present and carcasses have to be transported; this is why our results on emissions associated with natural decomposition are higher than two artificial methods of disposal (Fig. 1). Finally, the availability of livestock carcasses in the environment could be affected by sanitary and environmental regulations that could increase emissions (e.g., due to the mandatory use of disposal methods) regardless of the presence of vultures (i.e., because of legislation the service provided by vultures is replaced by artificial methods generating GHG gases) (Morales-Reyes et al., 2015). Despite these limitations, with the available information, this is the first attempt to quantify the contribution of vultures in reducing emissions generated by dead animals at a global scale.

It is also important to consider that when vultures are absent, or are present in low abundances, other facultative scavenger species (birds and mammals) could predominate in carcasses, thus reducing the emissions we estimated. For example, facultative scavengers (including top predators) could also be relevant in the removal of organic material from the environment, particularly the species that are gregarious at feeding (Sebastián-González et al., 2019, 2021; Selva et al., 2019). Prey items and carrion constitute part of the diet of these species, the percentage of carrion consumed possibly varying according to the species and environmental conditions. Therefore, species such as facultative scavenging birds could also be important in reducing emissions generated by dead animal decomposition, especially considering some highly abundant species such as gulls or crows (Callaghan et al., 2021). However, as mentioned above, vultures are more efficient in consuming dead animals than facultative scavenger species (birds and mammals), due their natural history characteristics (good vision, the ability of some to smell, ability to cover huge home ranges, etc.) (Ruxton and Houston, 2004; Sebastián-González et al., 2021). Further research is also necessary to evaluate the role that large and social facultative scavengers (e.g., top and meso-carnivores and reptiles, among others) are playing to maintain the efficient scavenging function in the ecosystem (Ćirović et al., 2016; Sebastián-González et al., 2019) and thus reducing emissions from dead animals together with vultures.

4. Conclusions

Our results show that vultures provide an important ecosystem service reducing emissions produced by carcasses at a global scale, which would otherwise remain in the environment or be disposed of using alternative methods (Fig. 3). Today, vultures remove a large number of carcasses and thus reduce GHG emissions in diverse geographical areas from the four continents where they inhabit (supplementary material, Fig. S1), especially related to a livestock sector that is currently increasing worldwide. However, the global decline of these birds in recent years has led to a marked loss of their previous capacity to reduce emissions from rotting carcasses. The most abundant species currently maintain the main ecosystem service. Although less abundant species have lost most of their capacity to provide this service, they could be making contributions in sites where the most abundant species are absent. Replacing this contribution to humans and the ecosystem with alternative methods of carcass removal would not only be expensive, but also harmful to the environment due to the consequent increase in greenhouse gas emissions. Moreover, although carcasses remaining in the environment produce a lower quantity of greenhouse gases than other disposal methods (e.g., composting), they may constitute a significant source of dangerous pathogens than can affect ecosystem and human health. Therefore, to preserve healthy vulture populations on all the continents where they occur is a clear win–win environmental strategy, producing several benefits for humans and the ecosystem.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2022.101455.

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