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# Animal capital: a new way to define human-animal bond in view of global changes and food insecurity

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We propose the concept of “animal capital” to acknowledge animals’ contributions beyond material value, essential for human survival. Despite humans relying on 50,000 species, interaction is limited to a few, destabilizing ecosystems and increasing risks like food insecurity and pandemics. Recognizing animal capital’s four components—material, natural, social, and cultural—can drive better investment in biodiversity, aiding in achieving United Nations Sustainable Development Goals and ensuring both human and animal survival.

Earth hosts approximately eight million animal species, yet humans primarily engage with around a dozen, mainly for food and companionship. This limited interaction poses risks. Concentrating resources on a few species harms biodiversity, destabilizing ecosystems<sup>1</sup> and elevating the threat of food insecurity and pandemics. This biodiversity decline is rooted in the global economic system’s failure to properly value biodiversity’s benefits, leading to inadequate animal protection<sup>2</sup>. With one million species potentially at risk of extinction among the eight million on Earth, safeguarding animal capital aligns with the United Nations Sustainable Development Goals and the IPBES Nature Futures Framework<sup>3</sup>. Recognizing animals’ multifaceted contributions to society is crucial, acknowledging their roles not just as food but as vital natural and cultural agents, paralleling past recognition of human contributions.

Human capacity for community contribution is often framed as ‘human capital’<sup>4</sup> in economics. Enhancing human capital, through measures like improved education and healthcare access, fosters long-term economic development. Nevertheless, an individual’s societal contribution is not confined to skills. Bourdieu emphasized the role of social and cultural activities in human well-being. While society acknowledges social and cultural capital for humans, there is a growing call to extend similar recognition to animals.

Animal contributions to human societies can be encapsulated as ‘animal capital.’ Past discussions have primarily focused on animals’ forced use in areas like food production and experimentation<sup>5</sup>. However, animals offer value beyond mere material gain; they contribute via natural, social, and cultural dimensions but also have intrinsic value. We propose a four-component framework for animal capital, aligning each component with the United Nations Sustainable Development Goals (SDGs, Table 1). Developed through interdisciplinary discussions among a biologist, an economist, and a philosopher specializing in animal ethics, this framework addresses contemporary global challenges and aims to shape a more desirable future.

## The Four Animal Capitals

**Animal material capital.** Animal material capital encompasses direct benefits humans obtain from animals as products, historically driven by extractive practices like meat consumption (SDG 1-3). Yet, their contribution extends beyond meat, including the sustainable use of resources

like milk, wool, and eggs, vital for some communities in harsh conditions as with severe droughts or living in deserts (SDG 1-3). Social and technological advancements, particularly in agriculture, have reduced the need for direct animal exploitation (SDG 8-9). Plant-based options, flexitarianism, and improved animal welfare laws reflect efforts to refine animal farming, akin to the 3 R principles in animal experimentation<sup>6</sup> (SDG 16-17). Cultured meat development showcases how we can harness animal material capital with minimal harm and environmental impact (SDG 11-15). However, we acknowledge, that further development of this technology is required before it would be able to contribute to any SDGs. Embracing sustainable practices optimizes animal material capital for long-term benefits without compromising animal welfare and environmental sustainability.

**Animal social capital.** Social capital, crucial for human well-being, extends to animals, especially pets, benefiting human health (SDG 3). Pets enhance human interactions by promoting physical activity, fostering social networks, and boosting emotional well-being, potentially reducing drug dependence and environmental pollution (SDG 6, 10, 11-15). Moreover, animals directly contribute to human development, nurturing children’s soft skills, fostering empathy, and aiding in education (SDG 4). Integrating animals into urban planning and policies enhances human-nature connectedness<sup>7</sup> (SDG 11, 16). Human-wild animal cooperation, inspired by native practices, promotes mutual benefit<sup>8,9</sup> (SDG 8, 10). Animals in our communities represent social capital, reducing agricultural and urban environmental impacts (SDG 12-15). Providing shelter, food, and healthcare to pets or farm animals creates a mutually beneficial relationship, where both humans and animals derive physical and emotional benefits from their social bonds.

**Animal natural capital.** Animals contribute significantly to human societies by providing ecosystem services, addressing climate change, and combating food insecurity (SDG 6-7, 11-15). For instance, rewilding predators offers socioeconomic benefits surpassing farming costs<sup>10</sup>, while elephants and whales aid in carbon storage<sup>11</sup> (SDG 6-7, 11-15). These services are challenging to quantify and likely underestimated<sup>12</sup>, leading to calls for human-free nature reserves like the Half-Earth project<sup>13</sup>. Studying wild animals yields insights into energy management and survival strategies<sup>14</sup>, benefiting human progress (SDG 3, 6-7, 11-15). Natural capital includes animals’ roles as bioindicators and pollinators, supporting local ecosystems and contributing globally to maintain planetary boundaries<sup>15</sup> (SDG 3, 6-7, 11-15). Biodiversity safeguards climate resilience and food security by limiting invasive species’ expansion. Species diversity mitigate issues like biogeochemical flows, freshwater changes, and ocean acidification (SDG 6, 11-15). Safeguarding animals’ natural capital is vital in

**Table 1 | How the four animal capitals advance food security and help meet the United Nations Sustainable Development Goals (SDGs)**

Sustainable Development Goals (SDGs)	How animal capital meets SDGs
SDG 1: No Poverty	By recognising animal material capital beyond immediate use for food, the framework encourages the development of sustainable products, such as plant-based alternatives and cultured meat. Sustainable material capital, such as cultured meat, releases space to grow vegetables. Social capital sets people free from costly engines through collaboration with animals. Natural and cultural capitals set humans free from expensive drugs and products.
SDG 2: Zero Hunger	The animal material capital dimension highlights the historical significance of animals in providing food, such as milk and eggs. By embracing sustainable practices and innovations in food production, as suggested in the framework, we can improve food systems' efficiency, resilience, and availability, ultimately contributing to achieving zero hunger and food security. These innovations can contribute to food security and affordability, potentially reducing poverty by making nutritious and environmentally friendly food options more accessible to low-income populations. Sustainable material capital releases space to grow vegetables. Integral protected areas contribute to sustainable material capital.
SDG 3: Good Health and Well-being	The animal social capital dimension recognises the positive impact of animals on human health and well-being, especially as pets. Studies have shown that owning pets can improve mental health, promote physical activity, and foster social connections, all of which contribute to better overall well-being and potentially reduce healthcare costs. Natural and cultural capital may reduce the use of drugs. Social capital increases health and prevents the need for medication.
SDG 4: Quality Education	The animal cultural capital dimension emphasises the importance of preserving animal behaviours, cultures, and knowledge, which can serve as valuable educational resources. Learning from animals can provide insights into sustainable practices, food innovation, and ecosystem management, enhancing educational opportunities for both current and future generations. Access to sustainable material capital, social capital, and natural capital can lead to better education about how to obtain and utilise these resources. This virtuous circle enhances the education quality.
SDG 5: Gender Equality	The framework's recognition of animal cultural capital extends to the preservation of local animal traditions, which can be linked to human cultures. Protecting local animal traditions is essential for ensuring cultural diversity and inclusivity, which can contribute to fostering gender equality and respect for diverse perspectives. Sustainable material capital, natural capital, and collaboration with animals may decrease climate change and gender inequality. In addition, working with animals involves fewer funds to buy tools or engines, making it more accessible to women.
SDG 6: Clean Water and Sanitation	The animal natural capital dimension highlights the significant role of animals in ecosystems, including their impact on freshwater systems. Preserving animals and their habitats helps maintain ecological balance, contributing to cleaner water sources and sustainable water management. Sustainable material capital decreases pollution. Natural capital is important as for animals filtering and cleaning water and allowing for ecosystem stability and biodiversity.
SDG 7: Affordable and Clean Energy	The animal natural capital dimension also highlights the role of animals in research, where studying their behaviours and adaptations can inspire innovations, such as temperature-resistant proteins. These discoveries may contribute to advancements in renewable energy and sustainable technologies. Working with animals instead of engines saves energy and is not harmful. Some animals, such as bioluminescent ones or symbiotic algae in corals, can also provide clean energy. While we are still far from illuminating cities, there are numerous applications, including the rapid detection of microbial contamination in beef and water, locating cancer cells, and mapping brain circuitry <sup>21</sup> .
SDG 8: Decent Work and Economic Growth	Working with animals can be more gratifying and healthier than working with engines to achieve the same goal. Animal capital creates new jobs or makes jobs accessible to everyone using for instance horse-drawn vehicle. The aim is not to replace all modern vehicles but to integrate this animal-friendly mode of transport for short distances within cities, such as driving children to school <sup>22,23</sup> .
SDG 9: Industry, Innovation and Infrastructure	Animal capital is an ecocentric way of living and leads to rethinking our habits with innovation. Insufficient exploration into biomimicry, cultured meat, and drawing inspiration from zoological observations of animal behaviour can hinder innovation and the emergence of new startups.
SDG 10: Reduced Inequality	Animal resources, regardless of the capital, are more equally distributed, reducing inequality. Non-private access to animal capital increases equality. Social capital enhances health and reduces inequality. Similarly, sustainable material capital and natural capital also help to decrease inequality. Additionally, cultural capital facilitates increased access to knowledge.
SDG 11: Sustainable Cities and Communities	The animal social capital dimension calls for integrating animals into urban design and politics, recognising their presence as part of the community. Such inclusivity fosters human-nature connectedness, which is linked to healthier and more sustainable urban environments. Natural capital, including higher biodiversity and some animal roles, leads to more sustainable cities with fewer pollutants. Social animal capital increases mobility and social networks.
SDG 12: Responsible Consumption and Production	Sustainable material capital leads to responsible consumption and production. Social capital decreases the production of drugs. Natural and cultural capital lead to sustainable societies with fewer short-term products.
SDG 13: Climate Action	The animal natural capital dimension emphasises the importance of protecting animals and their habitats to combat environmental degradation and climate change. By preserving biodiversity and ecosystem services, we contribute to climate resilience and sustainable development. Sustainable material capital fights climate change. Natural capital maintains the environment within planetary boundaries, as in the case of pollination, ecosystem stability, and limitation of invasive species expansion.
SDG 14: Life Below Water	Sustainable material capital contributes to the sustainable use of the ocean. Natural capital allows for ecosystem stability. Coastal and island communities often rely on marine life for their livelihoods, cultural identity, and social cohesion. Marine ecotourism, including activities like whale watching and coral reef exploration, fosters human-nature connectedness and supports local economies. Research on life below water will lead to an increase in cultural capital and natural capital. Stable terrestrial ecosystems play a vital role in maintaining the health of marine and freshwater systems. Healthy terrestrial ecosystems, such as forests, grasslands, and wetlands, act as natural buffers that reduce runoff and prevent soil erosion.
SDG 15: Life on Land	The entire animal capital framework aligns with SDG 15, as it emphasises the need to protect animals, their behaviours, cultures, and habitats, contributing to the conservation of terrestrial biodiversity and ecosystems. Sustainable material capital contributes to the sustainable use of land. Natural capital allows for ecosystem stability.
SDG 16: Peace and Justice Strong Institutions	Non-private access to animal capital increases equality and peace. Recognising animal rights and respect strengthen justice and makes society more respectful of both animals and humans. Animal social capital increases empathy, leading to peaceful and collaborative societies.
SDG 17: Partnerships to achieve the SDG	Animal capital strengthens domestic resource mobilisation. Endemic species should enhance international exchanges and diffusion of knowledge. Animal capital should increase macroeconomic stability and international policy coherence.

The animal capital framework draws links to Sustainable Development Goals (SDGs) through its multidimensional approach. It promotes sustainable food innovations (SDG 1, 2), recognises animals' positive impact on human health and well-being (SDG 3), promotes the preservation of animal knowledge for education (SDG 4, 5), and emphasises ecosystem preservation and clean water (SDG 6). By integrating animals in urban design and combating climate change (SDG 11, 13), the framework fosters inclusive, resilient, and sustainable societies (SDG 15).

combating environmental degradation and securing a sustainable future for all life.

**Animal cultural capital.** Cultural capital denotes knowledge, behaviours, and skills showcasing cultural competence and social status. Preserving local animal cultures has gained attention<sup>16</sup>, as the recent calls from UNESCO to safeguard ape cultural behaviour demonstrate. Animal traditions are vital, extending beyond economic benefits, fostering education, and innovation, including food by learning directly from observing animal cultures (SDG 4, SDG 9). Animal cultures hold both intrinsic and extrinsic value, aiding evolutionary research and that aims to understand human origins (SDG 4, 5). Animal observation reveals essential behaviours, from instinctive eating to employing plants for medicinal purposes based on ancestral knowledge<sup>17,18</sup>. For example, *Afromonum* fruits, which are ingested by chimpanzees, bonobos, and gorillas, contain antimicrobial properties and are sold for medicinal use in the Bwindi region. Animal behaviour and culture also play pivotal roles in ecosystem services, enabling food extraction, dispersal, and pollination. Native Navajos attribute knowledge of *Ligusticum porteri*'s properties to bears (SDG 3, 5, 10). Use of leaves of a liana (*Fibreurea tinctorial*) to treat a wound in Sumatran orangutan reveal antibacterial, anti-inflammatory, anti-fungal, anti-oxidant, and anticarcinogenic biological activities<sup>19</sup>. Learning from animals, as indigenous people have done for generations, can inspire sustainable food practices<sup>20</sup>.

### Advancing Food Systems Beyond Conventions

The animal-capital framework offers a more comprehensive perspective on animals than traditional food systems frameworks. While conventional frameworks focus mainly on food production, distribution, and consumption, the animal-capital framework takes a multidimensional approach, acknowledging animals' rich contributions to society and their intrinsic value. It transcends anthropocentrism, recognizing that animals' worth is not solely based on their utility to humans but involves the interests of both humans and animals. This approach highlights the importance of evaluating these interests case by case in human-animal interactions, as they vary across situations. Interests at play include 1. Human Interests: Humans value animals for roles in agriculture, entertainment, companionship, or research. The perceived value of an animal can differ based on whether it is seen as livestock, a pet, or a subject of study. 2. Animal Interests: Animals have their own interests, including well-being, freedom from suffering, and the ability to exhibit natural behaviors. These interests may conflict with certain human activities like factory farming or invasive research. 3. Mutual Interests: Some interactions are mutually beneficial, such as therapy animals providing emotional support to humans while receiving care and companionship in return. This nuanced perspective underscores the need to consider diverse interests in every human-animal interaction, moving beyond a one-size-fits-all approach to better address the complexities of our relationships with animals.

Interests in human-animal interactions are dynamic and context-dependent. Policies that consider these fluid interests include tailored animal welfare regulations, ethical treatment in animal industries, and species-specific conservation. The following components of the framework acknowledge animals as sentient beings, aiming for a balance that respects their worth, promotes ethical treatment, and fosters sustainable coexistence:

**Multidimensional Approach.** The framework outlines four dimensions of animal capital: material, social, natural, and cultural. It reveals animals' diverse contributions beyond mere material use, aiding in recognizing the

potential benefits of improved animal protection. It also helps identify trade-offs between these dimensions in our complex relationships with animals.

**Focus on Sustainability.** The framework promotes sustainability by protecting animals and habitats, preserving biodiversity, and combating climate change. It defines holistic sustainability goals, addressing human, animal, and mutual interests, proposing policies that would make the SDGs less anthropocentric.

**Recognition of Animal Welfare and Well-being.** Unlike conventional frameworks, the animal-capital framework prioritizes animals' welfare and well-being for their intrinsic value. It embraces the OneWelfare concept, addressing both animal and human well-being, beyond just their interconnected health in OneHealth.

**Integration of Animal Behaviour and Culture.** This framework pioneers valuing animal behavior and culture for both intrinsic and extrinsic worth. Unlike conservation policies focused on species, it appreciates the irreplaceable cultural value in animal and human communities, enriching human education, innovation, and evolutionary understanding.

**Holistic View of Human-Animal Interactions.** The framework promotes harmonious coexistence, recognizing animals' intrinsic value and interconnectivity, fostering ethical, sustainable, and interconnected relationships between humans and animals.

The animal-capital framework provides a multifaceted perspective on our relationship with animals, emphasizing the importance of evaluating their interests, which sets the stage for the following messages for the food systems community.

### Messages for Food Systems Community

The following messages are aimed at the wider food system community, urging them to reconsider their perspectives on animals and embrace the animal capital framework.

**Rethink Animal Contributions beyond anthropomorphism.** Move beyond viewing animals solely as food sources and acknowledge their multifaceted contributions to human societies. Recognise the significance of animals in social, cultural, and ecological aspects of food systems. First, we need to consider animals' contributions to society beyond their utility to humans, advocating for a broader perspective like ecocentrism. Second, we need to point out that only humans have moral principles towards other animal species, raising complexities in evaluating animal capital, maybe introducing the concept of vulnerability to redefine animal capital, highlighting the interdependence between humans and animals, transcending the traditional hierarchy between species and utility.

**Promote Sustainable Food Innovations.** Embrace sustainable practices and innovations, such as plant-based alternatives and cultured meat, to reduce direct exploitation of animals while ensuring food security and affordability (SDG 1, 2).

**Enhance Human Well-being.** Recognize animals' positive influence on human well-being, especially as pets. Encourage their integration into urban settings to enhance human-nature connection and promote healthier communities (SDG 3, 11). Note that this may vary by species, and it doesn't apply universally due to prey-predator dynamics.

**Preserve Animal Knowledge.** Recognise the value of animal cultures and behaviours as educational resources. Preserve local animal traditions, fostering respect for diverse perspectives and contributing to sustainable food innovation (SDG 4, 5).

**Protect Ecosystems and Biodiversity.** Preserve animal habitats and behaviours to maintain ecosystem services, clean water, and climate resilience. Recognise the vital role of animals in climate action and sustainable development (SDG 6, 13, 15).

**Collaborate for a Sustainable Future.** Unite scientists, policymakers, practitioners, and citizens to work together in protecting animal capital and achieving broader sustainability goals (SDGs).

**Consider all interests in case of conflicts.** When conflicts of interests emerge between humans and animals, consider all interests at stake, not only human ones. When conflicts are inevitable, think about the merits of respective interests (e.g., is a practice profitable to humans justified given the burden it imposes on animals?) and, if human interests prevail, find the least damaging options (e.g., sterilizing wild animals to avoid overpopulation instead of killing, vaccinate animals instead of culling them in case of zoonotic outbreak).

By adopting these messages, the food system community can foster a more inclusive, sustainable, and ethical approach to human-animal interactions, ultimately contributing to a healthier planet and more resilient societies.

## Conclusion

Today, the recognition of animal capital as only material, primarily meat, is diminishing as people realize animals possess diverse value beyond their utility to humans. To protect animal capital, four essential societal actions must be taken: 1. Enforcing or Establishing Legislation: Robust legal measures are crucial to safeguard animals, protecting their well-being and intrinsic value, both as species and individuals. 2. Preserving Animal Behaviors, Cultures, and Languages: Animals' unique behaviors, cultures, and languages contribute to human education, innovation, species conservation, and ecosystem sustainability. Efforts to preserve and respect these aspects of animal capital promote a deeper understanding of their roles. 3. Establishing Social and Economic Mechanisms: Developing policies prioritizing animal welfare and sustainable practices is vital. This includes reducing animal exploitation while ensuring sustainable food production and resource use. 4. Uniting Scientists, Practitioners, and Citizens: Collaborative efforts among scientists, practitioners, and citizens are essential to advocate for sustainable practices, protect animal habitats, and raise awareness about the significance of animal capital in achieving long-term ecological and societal stability. Working with animals is paramount to create a sustainable way of living and ensure the preservation of their multifaceted contributions to our and their world.

## Data Availability

No datasets were generated or analysed during the current study.

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## References

- Cardinale, B. J. et al. Biodiversity loss and its impact on humanity. *Nature* **486**, 59 (2012).
- Dasgupta, P. *The Economics of Biodiversity: The Dasgupta Review*. (Hm Treasury, 2021).
- Pereira, L. M. et al. Developing multiscale and integrative nature–people scenarios using the Nature Futures Framework. *People Nat.* **2**, 1172–1195 (2020).
- Bourdieu, P. The forms of capital. in *The sociology of economic life* 78–92 (Routledge, 2018).
- Shukin, N. *Animal Capital: Rendering Life in Biopolitical Times*. (U of Minnesota Press, 2009).
- Rault, J.-L., Binder, R. & Grimm, H. Rethink farm animal production: The 3Rs. *Science* **378**, 842 (2022).
- Barragan-Jason, G., de Mazancourt, C., Parmesan, C., Singer, M. C. & Loreau, M. Human–nature connectedness as a pathway to sustainability: A global meta-analysis. *Conserv. Lett.* **15**, e12852 (2022).
- van der Wal, J. E. M. et al. Safeguarding human–wildlife cooperation. *Conserv. Lett.* **15**, e12886 (2022).
- Cram, D. L. et al. The ecology and evolution of human–wildlife cooperation. *People Nat.* **4**, 841–855 (2022).
- Wang, L., Pedersen, P. B. M. & Svenning, J.-C. Rewilding abandoned farmland has greater sustainability benefits than afforestation. *npj biodivers.* **2**, 1–4 (2023).
- Schmitz, O. J. et al. Trophic rewilding can expand natural climate solutions. *Nat. Clim. Chang.* **13**, 324–333 (2023).
- Lehnen, L. et al. Rethinking individual relationships with entities of nature. *People Nat.* **4**, 596–611 (2022).
- Ellis, E. C. & Mehrabi, Z. Half Earth: promises, pitfalls, and prospects of dedicating Half of Earth's land to conservation. *Curr. Opin. Environ. Sustainability* **38**, 22–30 (2019).
- Pagano, A. M. et al. High-energy, high-fat lifestyle challenges an Arctic apex predator, the polar bear. *Science* **359**, 568–572 (2018).
- O'Neill, D. W., Fanning, A. L., Lamb, W. F. & Steinberger, J. K. A good life for all within planetary boundaries. *Nat. Sustain* **1**, 88–95 (2018).
- Brakes, P. et al. Animal cultures matter for conservation. *Science* **363**, 1032–1034 (2019).
- De la Fuente, M. F., Souto, A., Albuquerque, U. P. & Schiel, N. Self-medication in nonhuman primates: A systematic evaluation of the possible function of the use of medicinal plants. *Am. J. Primatol.* **84**, e23438 (2022).
- Huffman, M. A. Animal origins of herbal medicine. *From the sources of knowledge to the medicines of the future*. IRD Editions, Paris 31–42 (2002).
- Laumer, I. B. et al. Active self-treatment of a facial wound with a biologically active plant by a male Sumatran orangutan. *Sci. Rep.* **14**, 8932 (2024).
- Sueur, C. & Huffman, M. A. Co-cultures: exploring interspecies culture among humans and other animals. *Trends Ecol. Evol.* **39**, 821–829 (2024).
- Wilson, T. *Bioluminescence: Living Lights, Lights for Living*. (Harvard University Press, 2013). <https://doi.org/10.4159/harvard.9780674068025>.
- Senecal, K. & Leach, F. *Racing Toward Zero: The Untold Story of Driving Green*. (SAE International, 2021).
- Logan, K. G., Hastings, A. & Nelson, J. D. *Transportation in a Net Zero World: Transitioning Towards Low Carbon Public Transport*. (Springer International Publishing, Cham, 2022). <https://doi.org/10.1007/978-3-030-96674-4>.

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## Author contributions

C.S. developed the original concept and wrote the initial draft. RE and EF provided critical feedback, contributing revisions and refinements to the final manuscript.

## Competing interests

The authors declare no competing interests.

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