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Unknown Germany - An integrative biodiversity discovery program

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Biodiversity knowledge, from genes to ecosystems, is crucial for addressing the biodiversity crisis. However, even in well-explored countries like Germany, much biodiversity remains unknown. Therefore, several research institutions are joining forces to conduct a comprehensive biodiversity inventory, combining broad taxonomic expertise with advanced technologies. By consolidating data across many organismic groups, the *Unknown Germany* initiative will significantly enhance conservation strategies and may serve as a model for similar efforts worldwide.

The Convention on Biological Diversity (CBD 2022)¹ defines biodiversity as “the variability among living organisms from all sources (...) within species, between species, and of ecosystems” (Article 2), emphasizing its genetic, taxonomic, and ecological dimensions. This definition includes species traits^{2,3}, thus linking species with their drivers, functions, and the ecosystem services they support. Furthermore, it encompasses ecosystem diversity as the variety of habitats, communities, and ecological processes within broader landscapes.

However, even for the most basic descriptor of biodiversity, the number of species on Earth, we are far from having reliable counts. While the Catalog of Life currently lists 2.3 million extant species⁴, estimates of the total global species richness range from the widely cited number of nearly 9 million^{5,6} to several billions, considering that the majority of life on Earth is composed of microbial species^{7–9}. Much of this microbial biomass is concentrated in largely inaccessible subterranean systems¹⁰. A realistic estimate of the total global species richness may be in the two-digit million range, given that Mora et al.⁵ grossly underestimated fungal richness by approximately 4–5 times^{11,12}. Yet, only a minute fraction (21,239 bacterial and archaeal species¹³) of the estimated 1.75 billion bacterial species⁷ have been validly described to date. For protists, a dominant eukaryote group, crude global estimates range from 300,000 species¹⁴ to more than 160 million species⁷, and metabarcoding of environmental samples confirms their high taxonomic richness^{15–17}. In

contrast, only around 74,400 protist species are cataloged, according to the CBOL Protist Working Group¹⁸.

Knowledge gaps in species richness are not limited to microscopic taxa. Recent studies suggest that each insect species delimited morphologically may conceal, on average, 3.1 cryptic species¹⁹. The global number of insect species is estimated at 5.5 million²⁰, with only about one million insect species named thus far, implying that more than 80% remain to be described. Regardless of continent, climatic region, and habitat type, just twenty insect families (half of which belong to the order Diptera) account for more than 50% of the local insect species richness. However, precisely these families (so-called “dark taxa” sensu Srivathsan et al.²¹) suffer the most from taxonomic neglect. The current global rate of about 10,000 newly described insect species per year²² is far too low, meaning that it would take approximately 450 years to describe and name the estimated 5.5 million insect species.

This starkly illustrates the extent of our knowledge gaps, even regarding the best-known species diversity. Far less is known about the roles these species play in ecosystem functioning, or about their genetic diversity. The fact that the functions of most soil-relevant prokaryotic species remain unknown is a major barrier to linking biodiversity and ecosystem services²³. This lack of basic information and knowledge is not confined to remote or inaccessible regions; it persists even in well-explored countries with a long tradition of natural history research, such as Germany.

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Here, we present the *Unknown Germany* initiative: a consortium of research institutes, natural history museums and collections, and independent experts. This alliance will integrate cutting-edge technologies with wide-ranging taxonomic expertise, citizen science projects, and public education, aiming to achieve a comprehensive biodiversity inventory within a foreseeable timeframe.

Unknown biodiversity: importance, implications, and threats

All species—known and unknown—contribute to ecosystem functioning and the provision of ecosystem services. For example, insects provide vital services such as pollination, decomposition of organic matter, and biological control²⁴. Fungi play indispensable roles in nutrient cycling, act as pathogens, form mutualistic symbioses with most vascular plant species, and are widely used in industry and pharmaceuticals²⁵. Lichens and their symbionts contribute to rock weathering, soil formation, carbon and nitrogen fixation, and support other organisms by providing food, habitat, shelter, camouflage, or nesting material²⁶. More broadly, soil biodiversity underpins many essential ecosystem functions, including nutrient cycling, carbon sequestration, water regulation, and biomass production for food and energy²⁷. Although certain ecosystem functions may be maintained by a subset of species, preserving species-rich communities is crucial for sustaining ecosystem resilience, particularly in the face of global change, including land- and sea-use change, direct exploitation, pollution, climate change, and invasive species²⁸.

Our knowledge gaps regarding biodiversity and its role in ecosystem functioning are particularly worrisome given that biodiversity is rapidly declining. Worldwide, up to 58,000 species are estimated to go extinct each year²⁹, and 28% of all assessed species are threatened with extinction²². This ongoing mass extinction is clearly human-driven, with current extinction rates approximately 35 times higher than the natural background rate that prevailed over the past million years in the absence of human influence³⁰. The extinction of each species may have cascading effects including the loss of host-specific organisms that form part of its microbiome and symbiont community. Indeed, many species are likely to disappear before ever being discovered.

Biodiversity loss poses a major threat to planetary health and human well-being³¹, and the consequences of species loss for ecosystem resilience and functioning are difficult to predict but potentially catastrophic³². Germany, in particular, is experiencing a dramatic loss of biomass and species diversity across several insect taxa, a trend that has attracted international attention^{33,34}. An estimated 60% of the country's 93 habitat types, spanning grassland, forests, agricultural and urban areas, as well as inland and coastal waters, are currently in inadequate or poor conservation status³⁵.

Scientists have repeatedly stressed the urgent need for intensified and focused biodiversity and conservation research^{36–38}. Detailed knowledge about biodiversity, its distribution, its roles in ecosystem functioning, and the direct and indirect drivers of its decline, is a precondition for an informed assignment and management of protected areas³⁹. The European Union's Biodiversity Strategy for 2030 aims to designate 30% of its land and sea as protected areas—the so-called “30 by 30” agenda. Although Germany has formally met this target⁴⁰, key questions remain: Do existing protected areas have adequate size and shape to support biodiversity? Are they located in areas with highest concentrations of threatened species⁴¹? Are all natural habitat types adequately represented⁴²? Which challenges beyond reaching the 30% target may emerge⁴³?

Current conservation policies are largely based on known biodiversity and use tools such as Red Lists to guide protection. However, for many taxonomic groups Red Lists are unavailable or incomplete (see below). Long-term datasets on species abundance, diversity, and biomass are required to assess temporal trends, perform risk analyses, and develop conservation strategies for vulnerable, threatened, or endangered species⁴⁴. Historical distribution data, going back to the 18th century in some cases, can provide valuable baselines for assessing change since the onset of the industrial revolution. Standardized, high-quality long-term biodiversity

data are also necessary for understanding the relative contributions of different drivers on species decline and for evaluating the effectiveness of restoration and conservation measures. These assessments are impossible when large portions of biodiversity remain undiscovered.

In addition, regular large-scale biodiversity assessments are essential for the early detection of invasive species, which can disrupt native ecosystems, displace or extinguish native species, and deteriorate ecosystem functioning, often with substantial economic and socio-cultural costs⁴⁵. The most recent list of established non-native species in Germany includes 1962 species. However, aquatic taxa and non-pathogenic microorganisms (e.g., viruses, bacteria, protists, and fungi) remain vastly underrepresented, primarily due to data bias⁴⁶. Regular national biodiversity surveys would accelerate early detection efforts, potentially reducing the effort and costs required for mitigation.

Germany is a signatory to international and regional frameworks, including the Convention on Biological Diversity (CBD 2022)¹, the Kunming-Montreal Global Biodiversity Framework, the EU Biodiversity Strategy 2030 (COM)⁴⁷, and the Nature Restoration Regulation⁴⁸. The country is also preparing its own German National Strategy on Biodiversity 2030 (NBS), with the overarching aim of “bending the curve” of biodiversity loss. However, these efforts are severely constrained by the limited knowledge of Germany's own biodiversity, and further complicated by the ongoing decline in taxonomic expertise^{49,50}.

Biodiversity in Germany—What we know and what we do not know

Germany is a medium-sized country in Central Europe, encompassing most major temperate biomes: from high mountains in the south, through various central middle mountain ranges, to lowlands and the sea in the north. According to species lists and German Red List assessments, Germany is home to approximately 48,000 animal, 9500 plant (<https://www.bfn.de>), and 16,000 fungal species (<https://www.pilze-deutschland.de/organismen/>), but these numbers are by no means complete. While vertebrates and vascular plants are relatively well documented, large gaps remain for insects and other invertebrates, protists, fungi, bacteria, and archaea—groups that currently lack species inventories and Red List assessments. The extent of unknown diversity becomes even more apparent when cryptic species are considered.

Taxonomic revision for these groups is particularly challenging, as many underexplored taxa are hyperdiverse, such as Diptera, parasitoid Hymenoptera, Nematoda, Copepoda, Medusozoa, and numerous fungal groups. Documenting them will require long-term, collaborative efforts by many taxonomic specialists. For example, the number of known freshwater diatom taxa in Germany increased by 46% (from 1437 to 2103 taxa, including varieties, forms, and subspecies) over the past 20 years as a result of focused taxonomic work⁵¹. Similarly, the number of lichens, lichenicolous and allied fungi rose by 14% (from 2300 to 2626 species) between 2011⁵² and 2021⁵³. However, such progress is still pending for many taxa.

In a recent study, Buchner et al.⁵⁴ identified 10,803 insect species in Germany using metabarcoding data from 75 Malaise traps set up across the country. They estimated that another 21,043 plausible species either lack a reference barcode or are undescribed, mirroring similar findings from Bavaria and Sweden^{55,56}. For taxa where species discovery depends primarily on molecular data, such as bacteria, fungi, and protists, species numbers can only be roughly estimated. Using the commonly applied fungi:plant ratio of 5:1 for temperate regions^{11,12}, Germany may host approximately 48,000 fungi species, indicating that 65% of them remain yet undocumented. To our knowledge, no estimates exist for the number of bacterial or protist species in Germany. A complete and timely inventory of these groups remains unfeasible. However, identifying key taxa, including their traits and functional diversity, offers a meaningful starting point⁵⁷.

Many unknown species inhabit hidden habitats that are difficult to access, such as soils, aquatic sediments, and tree canopies. The same is true for interconnected subterranean systems like caves and groundwater, which harbor rare subterranean species with narrow distribution ranges^{58,59}. The

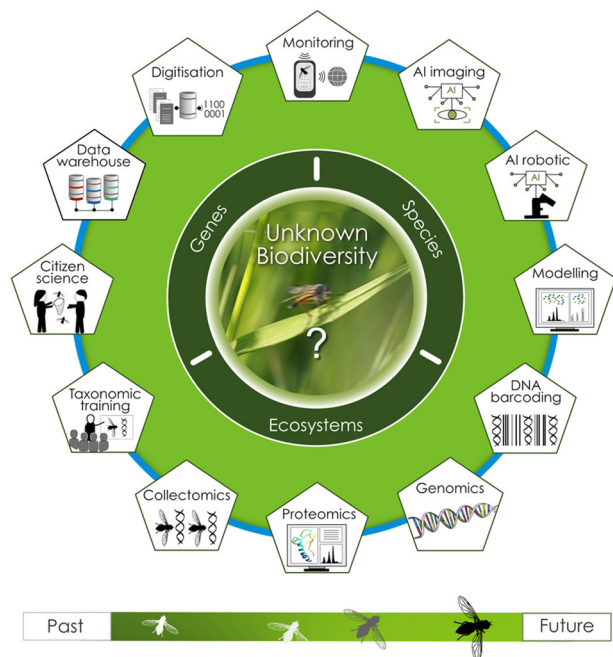


Fig. 1 | Approaches for recording the unknown biodiversity from genes to ecosystems in the *Unknown Germany* initiative. A combination of recent and well-established methods, grounded in broad taxonomic expertise, will be employed in the “*Unknown Germany*” initiative to uncover and describe unknown biodiversity, from the past to future predictions.

largest fraction of terrestrial biodiversity occurs in soils^{60,61}, yet much of it remains poorly understood, even in a well-studied country such as Germany^{62,63}. Mega-diverse soil microflora and microfauna, in particular, contain a large number of undocumented species⁶⁴. Sturhan and Hohberg⁶⁵, comparing the few available checklists with more comprehensive surveys from the Netherlands and Hungary, estimated a minimum of 2000 soil nematode species in Germany, though the true number is likely much higher⁶⁶. For abundant taxa within the soil mesofauna, such as Collembola (548 species: www.edaphobase.org) and Oribatida (560 species⁶⁷), species lists are available, but Red List assessments are lacking due to sampling gaps and a shortage of long-term data. Currently, only about 5% of soil biodiversity is included in Red Lists³⁵. Even for earthworms—arguably the best-known soil invertebrates—data on distribution and population trends were insufficient to assess Red List status for almost 10% of the 46 German species⁶⁸. Remarkably, a species new to science was described from Germany as recently as 2024⁶⁹.

River and lake sediments are similarly underexplored. Although benthic invertebrates from running waters are often assumed to be well-studied due to their importance in biomonitoring, their biodiversity—particularly of aquatic Diptera and Oligochaeta—remains poorly understood. Even in well-known groups like caddisflies (Trichoptera), intensive taxonomic studies have revealed significant underestimations: for example, the number of recognized Drusinae species in Europe nearly doubled from 56 in 2008 to 107 in 2021^{70,71}. Benthic fungi, fungal-like organisms such as oomycetes, as well as many other protists and bacteria, are even more underexplored, despite recent advances in global microbial diversity research in lake sediments⁷². In marine sediments of the North and Baltic Seas, many species also remain undiscovered. For example, around 20% of observed North Sea benthic Copepoda species—generally the second most abundant meiofauna group after Nematoda—are new to science⁷³, with even greater diversity likely hidden in cryptic species complexes. Species lists for marine benthic flora and fauna are available only for certain localities, such as Sylt^{74,75}, while a comprehensive national inventory is still missing.

How to tackle the unknown biodiversity—The *Unknown Germany* initiative

Germany has a long tradition in natural history research and hosts about 147 million natural history collection items (www.dnfs.de). This rich heritage makes it an ideal setting to demonstrate how a collaborative and targeted approach—integrating taxonomic expertise, natural history collections, citizen science, advanced technologies, and public education—can facilitate a rapid and comprehensive biodiversity inventory.

With this objective in mind, nine German biodiversity research institutions have joined forces in the *Unknown Germany* (*Unbekanntes Deutschland*) initiative, aiming to discover, describe, characterize, and promote Germany’s still unknown biodiversity. The consortium includes research centres, natural history collections, independent experts, as well as research museums with strong experience in science communication and knowledge transfer (www.unknown-germany.org). Furthermore, the initiative spans a wide taxonomic range—from bacteria and archaea to fungi, protists, plants, and animals—across terrestrial, freshwater, and marine environments, and addresses biodiversity from the molecular to the ecosystem level. Its collective taxonomic expertise is further strengthened by experience in cutting-edge techniques, such as genomics, machine learning, robotics, and ecosystem modeling (Fig. 1). Additional institutions and researchers with relevant expertise are invited to join and contribute to this ambitious initiative.

The *Unknown Germany* consortium aims to significantly advance knowledge of Germany’s biodiversity through the following objectives (Fig. 2):

- (1) Complete species lists
 1. Discover and describe unknown species through large-scale sampling campaigns, high-throughput species discovery methods, automated sorting, and expert taxonomic work.
 2. Contribute to global taxonomic syntheses.
- (2) Monitor biodiversity trends at multiple scales
 1. Map current species distributions using large-scale environmental genetic sequencing.
 2. Reconstruct historical species distributions from literature records and from specimens in natural history collections (data mobilization).
 3. Assess intraspecific genetic diversity using population genomic and metagenomic approaches.
 4. Predict future biodiversity dynamics using species distribution modeling and apply these insights to inform conservation planning.
- (3) Understand functional diversity
 1. Define ecological and biological traits to link organisms to ecosystem functions and drivers.
 2. Identify functional groups and key species among bacteria, fungi, and protists.
 3. Investigate how genetic, species and ecosystem diversity influence ecosystem functioning.
- (4) Develop standardized tools for biodiversity research
 1. Create illustrated, flexible and updatable identification keys.
 2. Develop software tools to automate species descriptions.
 3. Complete reference libraries of molecular species markers (DNA barcodes or genomes), linked to curated voucher specimens.
 4. Share standardized data via a publicly accessible data repository.
 5. Develop digital tools, including AI-based technologies, for biodiversity data collection, identification, and interpretation.
- (5) Information and training
 1. Develop educational outreach programs to promote public understanding of biodiversity.
 2. Provide integrative training for a new generation of taxonomists and biodiversity researchers.
- (6) Transfer into policy, conservation, and sustainable land use
 1. Improve the representation of German biodiversity hotspots within protected areas, particularly those of IUCN categories 1 and 2.



Fig. 2 | Objectives of the Unknown Germany initiative. The Unknown Germany initiative will discover and monitor biodiversity and its functions, accompanied by the development of new research tools and taxonomic training. The gained understanding of biodiversity change will be translated into practical recommendations for policy makers and conservation.

2. Identify key drivers of biodiversity loss to inform legislation and redirect subsidies accordingly
3. Expand the German Red Lists to include additional taxonomic groups

The idea of creating complete species inventories is as old as taxonomy itself, as reflected in the titles of historical works such as “Species Plantarum”⁷⁶, “Index Kewensis”⁷⁷, and “Conspectus Fungorum”⁷⁸. Today, with the advent of AI-driven robotics^{79–81}, novel image recognition techniques, accessible and cost-efficient high-throughput techniques for sorting, storage, and both molecular and morphological identification, we are witnessing a paradigm shift in modern biodiversity research^{82–85} (Fig. 1). These emerging technologies complement existing tools such as genomic sequencing, Matrix Assisted Laser Desorption/Ionization Time-of-flight mass spectrometry identification (MALDI-TOF MS)^{73,86}, molecular identification of interactions⁸⁷, and turbo-taxonomy⁸⁸. Species descriptions can now be automated and accelerated through rapid assessment of a few unambiguous morphological traits, software-assisted automated generation of species descriptions, and the integration of high-quality illustrations alongside molecular, biological, and distributional data⁸⁹. The combination of new high-throughput species discovery methods, such as large-scale DNA (meta-) barcoding⁹⁰ and efficient taxonomic assignment techniques^{91,92} is significantly speeding up the completion of species inventories.

To obtain comprehensive data and information on current species distribution, including those from neglected habitats, nationwide sampling efforts are required. Citizen science projects and biodiversity information platforms (e.g., iNaturalist, observation.org, Flora Incognita, Insekten Sachsen; see Table 1) facilitate large-scale geospatial sampling and rapid acquisition of distribution data, while simultaneously raising public awareness of biodiversity and its importance. These platforms increasingly combine machine learning with expert validation to continually improve automated species recognition. Environmental samples are processed more efficiently when robotic or semi-automated imaging and specimen handling are used, providing data to train convolutional neural networks^{79–81,83}. Environmental sequencing enables rapid diversity assessment, even in species-rich communities⁹³, provided that sufficiently complete genetic reference libraries are available^{85,94}.

Table 1. | Projects, initiatives, online tools, and education, already contributing to the investigation of the “Unknown Germany”

Related projects	Online tools
German Barcode of Life (GBOL I, II, GBOL III: Dark Taxa)	Edaphobase
iBOL Europe	LAND
NFDI4Biodiversity	iNaturalist
Trends in hidden taxa and habitats (TrenDiv)	observation
Faktencheck Artenvielfalt	Insekten Sachsen
Soil biodiversity baseline survey	neobiota-nord
Translational Biodiversity Genomics (TBG)	ARAMOB
Biodiversity Genomics Europe (BGE)	naturportal südwest
Biodiversity Decline's Genomic FOOTprint (BIGFOOT)	
Initiatives	Education
Leibniz Research Network Biodiversity	FörTax
FEa BMBF Research Initiative for the Conservation of Biodiversity	KennArt
Biodiversity Exploratories	KomBioTa
Taxon-Omics	Taxonomie Initiative
	EU TETTRIs taxonomic training

Natural history collections represent an unparalleled source of primary biodiversity data, offering multi-dimensional insights into historical species distributions and serving as baselines for biodiversity conservation⁹⁵. Furthermore, new species are often discovered within historical collection material^{96,97}. Advances in digital imaging, genomics, and artificial intelligence are accelerating data mobilization from natural history collections, a field now often referred to as “collectomics”⁹⁸ or with slightly different focus as “next-generation natural history”⁹⁹. Mass-digitization initiatives (e.g., NFDI, OSIRIS, and at the European scale DiSSCo) are making these data broadly and freely accessible through integrated platforms such as GBIF and OBIS. Citizen scientists are helping to digitize collections (e.g., WeDigBio¹⁰⁰) and contribute to the production of high-quality taxonomic datasets by measuring and annotating photographs of specimens¹⁰¹.

For effective nature conservation, comprehensive, yet simple species lists are not sufficient. Rather, it requires an in-depth understanding of the functions, interactions, and spatial and temporal patterns of biodiversity, from genes to ecosystems. High-throughput methods and extensive sampling of various environments can illuminate the functional role of taxa in ecosystems¹⁰². New molecular and isotopic tools make it easier to assess species interactions and ecosystem functions^{103–105}. Food-web models represent a powerful tool to link organisms on multiple trophic levels to ecosystem processes such as organic matter transformation and nutrient cycling (summarized in Potapov et al. for soil habitats¹⁰⁴). Multidimensional niche modeling provides ample information on ecological adaptations of bacteria¹⁰⁶. Another way of learning about species functions in the ecosystem is through functional traits. Existing automated image analysis pipelines may be adjusted to automatically recognize morphological functional traits of specimens or even communities to speed up this process^{107–109}.

While valuable taxonomic and ecological data are already digitally available (e.g., www.aramob.de), much of it remains scattered across different databases and is frequently not interoperable¹⁰. To model species distributions, predict population dynamics and ecosystem functions, and guide conservation efforts, biodiversity data must be integrated into standardized formats and combined with geographical, environmental, and methodological metadata in a publicly accessible data warehouse^{111,112}. Furthermore, a central platform is needed to enable efficient exchange and integration of knowledge from the numerous independent programs and projects already contributing to the goals of the *Unknown Germany* consortium (Table 1).

Taxonomic expertise remains the foundation of all biodiversity research. The methods and approaches described here can only deliver meaningful results if they are grounded in robust taxonomic knowledge. To accelerate biodiversity inventories and make newly described species and taxonomic revisions widely accessible, the taxonomic work must be systematically integrated into global expert networks in a structured and participatory way^{113,114}. Moreover, taxonomic education and training are vital to ensure the continuity of biodiversity expertise across generations. The European Red List of taxonomists recommends significantly increasing taxonomic capacity, for example, through dedicated training programs⁴⁹ like FörTax and KennArt (Table 1). These efforts, together with the fact that many species have wide geographic distributions, means that the *Unknown Germany* initiative will also contribute to biodiversity knowledge well beyond Germany's borders.

Summary

In Germany—as in every other country in the world—tens of thousands of species remain undescribed. A comprehensive biodiversity inventory must go beyond naming species: it must uncover the role of all levels of biodiversity in ecosystem functioning, document spatial and temporal trends, and provide robust baselines for nature conservation. Discovering, describing, functionally characterizing, and promoting the yet unknown biodiversity of Germany is an enormous task, but one that is essential if we are to halt biodiversity loss.

Relying on conventional methods alone, it would take centuries to complete this work. However, advances in high-throughput sequencing, artificial intelligence, machine learning, data integration, and ecosystem modeling now provide the tools to accelerate the process. Citizen science and biodiversity platforms play an essential role in supporting the substantial taxonomic, ecological, and conservation work envisioned. The *Unknown Germany* initiative integrates these modern approaches with deep taxonomic expertise and public engagement to achieve a comprehensive biodiversity inventory within a foreseeable timeframe. The first steps have already been taken. In a joint workshop, the consortium members identified knowledge gaps, explored funding opportunities, and developed concrete projects. A website was launched (www.unknown-germany.org) and the first funded project “Trends in hidden taxa and habitats (TrenDiv)”, has started. This project resamples sites previously studied 25–45 years ago to assess changes in biodiversity across multiple levels, using advanced methods such as large-scale (meta)barcoding, metagenomics, proteomics, compound-specific stable isotope analysis, scanning electron microscopy, and ecological modeling. The focus of TrenDiv is on underexplored habitats like soils, marine sediments, and groundwater. The next crucial step is to secure additional funding to reduce the currently unaccounted biodiversity in Germany. Given the ever-accelerating rate of biodiversity loss, time is of the essence.

Data availability

No datasets were generated or analyzed during the current study.

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Competing interests

The authors declare no competing interests.

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