Integrating historical sources for long-term ecological knowledge and biodiversity conservation

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Abstract

Historical data sources are instrumental in biodiversity research because they provide historical and conservation baselines for species and ecosystems, and they contribute to a deeper understanding of long-term human-nature relationships and their sustainability (or lack thereof). Yet, historical sources are still underutilized in biodiversity research, in part due to the perceived difficulty in mobilizing, interpreting and using them. Their use often relies on collaborations where overcoming disciplinary silos requires time-intensive processes of mutual acculturation. Here, in an interdisciplinary effort to strengthen connections between historical ecology, biodiversity research, and conservation, we review historical sources, the variety of information they hold, and discuss how data on species, ecosystems, and socio-ecological systems can be mobilized. Drawing from case studies across the globe, we also illustrate historical data integration and its applications, as well as emerging tools and technologies that could improve data mobilization efforts. Lastly, we propose a 7-point strategy to improve the availability and use of historical data for biodiversity research and conservation.

1. Introduction

Centuries-old fur trade and whaling logbooks reveal that the historical distribution of beavers in Canada and humpback whales in the Atlantic were larger than what contemporary records indicate[1]. In contrast, 16th century documents show that a crayfish species traditionally considered and managed as native and threatened in Spain was in fact introduced from Italy, suggesting its past European distribution was more restricted than previously thought[2]. These examples illustrate how the use of historical sources can help shift temporal and conservation baselines[3,4], providing critical context to refine ecological assessments[5] and guide conservation actions based on a long-term assessment of species' status and population trends[6,7]. Researchers investigating past patterns, events, and processes to better understand contemporary ecosystems use an interdisciplinary toolkit, which provides theoretical and methodological guidance for synthesizing and integrating historical information about species, ecosystems, and

socio-ecological systems. Many of these tools have been developed within the field of historical ecology[8–10], drawing on disciplines such as archaeology, paleontology, history, geography, environmental science and ecology.

Historical-ecological approaches have been used to assess long-term interactions between species, ecosystems, the environment and human societies, with a focus on human-nature relationships and anthropogenic impacts[11–14]. These approaches provide a robust basis to model species' niches and habitat suitability, and to define conservation priorities[15–17]. Historical biodiversity information (i.e., records of species, genes, and/or ecosystems) is pertinent for contemporary ecological research on biogeography[18–20], community resilience[21,22], ecological memory[23] and evolutionary adaptations to environmental change[24,25]. This knowledge can in turn strengthen projections of biodiversity change under potential future scenarios[26]. By nature, many historical-ecological data document human uses of species and land, and allow the reconstruction of demand and supply of ecosystem services through time[14]. Lastly, historical-ecological approaches can provide fairer baselines for conservation and restoration[27,28] by accounting for long-term human pressures and ensuring that targets reflect historical impacts rather than recent trends alone[3,29,30]. Nevertheless, in practice, historical data predating the mid-20th century are often overlooked, arguably under the assumption that they do not exist or that they are difficult to access, interpret, and integrate. Additionally, the historical data mobilized is often qualitative in nature and may thus be devalued in conservation and biodiversity research[31]. As a result, historical-ecological data known by archaeologists, historians, and other scholars in the humanities and social-sciences often remain underutilized[18,32]. This contrasts the uptake of data contained in paleo-archives, which have been more widely used by ecologists and biogeographers[22,26].

Here, we review and characterize potential sources of historical-ecological information and explore how each can provide data for different layers of time, biological levels (i.e., genes, species and ecosystems), and (socio-)ecological processes. We assess historical sources from the early Holocene onward, a temporal scale that is appropriate for understanding how human activities have distinctly influenced the landscape, leaving traceable imprints over time[12,33]. We then discuss current and potential mobilization efforts for historical biodiversity data. Lastly, we

propose a strategy to improve historical data identification, mobilization, and integration for more rigorous use in biodiversity research and conservation.

2. A typology of historical sources and the data "hidden" within them

We build on previous work discussing historical sources[1,11,18,34] to identify eight broad source types (FIG.1), and systematically assess the relative amount of available material and biodiversity-relevant information each contains. Additionally, we distinguish whether such information can be extracted directly (e.g. direct observation of species occurrence from a photograph) or indirectly (e.g. inference of species traits from diaries and newspaper articles) (FIG.2). To the extent possible, we document historical data relevant to studying biodiversity change across all levels of organization – from genetic diversity to species, and ecosystems – and associated human uses, ensuring a comprehensive perspective on long-term ecological knowledge. This review builds primarily on research published in English but we acknowledge that there are numerous additional published resources on this topic in other languages.

A. Physical archaeological materials. These materials provide essential evidence for reconstructing past environments and human-nature interactions, and are available throughout the Holocene, though their coverage varies across world regions and time periods[35]. Preservation biases, particularly those related to taphonomic processes (*i.e.*, the processes affecting remains and their preservation or fossilization) must be considered when interpreting physical archaeological materials. Zooarchaeological and archaeobotanical remains can provide a rich source of information on species presence, their genetic diversity, their relative abundances, and their interactions with people in past ecosystems (FIG.1A)[29,36,37]. For example, DNA and stable isotope analysis of faunal remains have revealed shifting hunting practices and pressures on beluga whales by Inuvialuit and Thule Inuit in northeastern Canada over the past centuries, while also showing that subsistence harvests have had minimal impact on beluga populations[37]. Field evidence and physical living heritage, encompassing historical artifacts and sites, such as boundaries between fields and forests, or Culturally Modified Trees (CMTs, e.g. with signs of bark peeling or coppicing), also provide information about historical ecosystem

distributions and socio-ecological systems dynamics[38–40]. More recently, the use of LiDAR (Light Detection and Ranging) has enhanced the detection of archaeological landscape features — e.g., in areas covered by dense vegetation. For instance, it has been used to map historical processes, such as landscape anthropization[41].

B. Oral and linguistic sources. Historical biodiversity information and data can be ascertained from the collective memory and narratives of human communities[42–44](FIG.1B) which are documented and interpreted through oral history interviews and ethnographic methods[14,45]. Oral archives have, for example, been used to reconstruct deep-time geomorphological processes like deglaciation, and the resulting landscape changes, after the Late Glacial Maximum in the Pacific Northwest[46]. Linguistic analyses provide another underutilized source for evaluating medium- and long-term biodiversity and environmental changes. Ethnobiologists and environmental linguists evaluate the relationships between language (culture) and peoples' environment—documenting linguistic structures, and verbal practices (how things, places, and families are named, e.g., toponyms) — which conceptualize and encode long-term knowledge about the natural world[29,47]. Oral and linguistic information can constitute a historical source spanning several millennia, especially when cultural and geopolitical factors have supported their preservation. They can provide species/taxa and ecosystem records, and inform on the societal use of both species and land[14,43,48]. This knowledge can also contribute to detecting and quantifying biodiversity change, such as changes in population abundances, community composition and ecosystem conditions (e.g. Arctic freshwater diversity and habitats[49]; or bat colony densities and cave hydrology[50]). It can also help reveal changes in the use and demand of ecosystem services[14], and identify the drivers of such changes (e.g. drivers of landscape transformation[44,46]).

C. Structured written records. This source type encompasses structured compilations of information, including trade ledgers, and fishing, whaling, hunting, and forestry records[11], land surveys[14,51], cadasters and censuses[18], and gazetteers or geographic dictionaries[15,52] (FIG.1C). Taxation, colonization, land development, and more generally, state record-keeping often

motivated the original collection of some of these data, resulting in relatively standardized sampling protocols that facilitate data comparisons across space and time[11,51,52]. Some records, like the Domesday Book in medieval England[53], date back several centuries, though the collection of structured information became particularly frequent some 500 years ago. Structured records became increasingly relevant in contemporary times, especially with their digitalization (e.g. land cover and use in Europe[54]). These records often provide direct information on taxa or species occurrences, ecosystem distributions, and societal use of land and species, including the intensity of these uses[14]. For example, Spanish geographic dictionaries[52] have been used to produce conservation assessments and baselines for wolves[4] and the European eel[15]. Structured records can also be used to derive information on species traits such as body size and weight, as well as population abundances and biomass. Some written records, such as land surveys (e.g. Public Land Survey System in the USA since the late 18th century[51]) and cadasters[55] may also be accompanied by maps (see *spatial information* below).

D. Unstructured written material. Materials in this category are diverse, and range from ship logs to travelers' accounts, newspapers, private letter collections, judicial cases, and chronicles[1,56,57] (FIG.1D). It also includes technical documents which are narrow in scope, such as restaurant menus, cookbooks, and technical manuals for textile production, leathermaking, and basketry[58,59], as well as guild documents detailing tools and equipment specific to species or habitats, and laws regulating the harvest of wild species – such as restrictions on catch size and weight in fisheries[11]. Unlike structured records, these sources provide anecdotal and partial insights into historical contexts. Nevertheless, unstructured written materials are consistently available for the past thousand years, with higher abundance starting some 300 years ago, and can be mined for extensive information on species, ecosystems, their societal uses, and exploitation intensity[60]. Court records and diaries, for example, were mined to provide the longest time series on phenology, the 1200-year Kyoto cherry blossom record[61]. A medical treatise, the Brooklyn Papyrus, was used to map the paleo-distribution of venomous snakes in Ancient Egypt[62]. Restaurant menus and cookbooks have also been used to detect changes in local relative abundance[59], community composition[63], and the intensity of human use[58].

E. Pictorial representations. This category includes artwork, town and family emblems, and ground-based photographs and video recordings, in which the identity and characteristics of species and habitats can be extracted (FIG.1E). Pictorial representations of Indigenous and Local Knowledge, ranging from rock art to digital photography, may also be referred to as communal visual – or optic – histories[64]. In most cases, the location is known (e.g., town emblem) or can be interpreted using the identity of the artist and/or recognizable landmarks[1,11,65,66]. Historical artwork for instance includes paintings, mosaics, sculptures, decoration of dishes with animal molds, impressions with fish (Japanese "gyotaku"[67]) and any figurative art produced by artists and craftspeople. Historical artwork goes back tens of thousands of years and is found across all inhabited continents, with examples in Africa[68], Oceania[69], Asia[70], Europe[71] and the Americas[72]. It becomes particularly valuable as a source of historical-ecological information once figurative art begins to favor realism and a respect for colors that allow the recognition of species and landscapes[73,74], as was the case in Europe starting in the Early Modern Period (500 to 300 years ago)[65]. Such art can be used to derive species and ecosystems records, and information on species traits[75] and on the interactions between humans, species, and habitats[76]. Since the 19th century, ground-based photographs and videos complement artwork and provide benchmark data on species at the trait level—for instance, the body size of fished and hunted animals[77]—and at the ecosystem level—such as ecosystem structure and phenology. Illustrating the latter, decades of video archives of a yearly cycling race in Belgium were used to document changes in flowering onset, spanning more than three decades[78]. Importantly, georeferenced ground-based imagery provides raw (i.e. free of interpretation) information on landscapes that can be replicated to directly assess spatial and temporal changes of land-use and ecosystem distributions[66,79–81].

F. Spatial information. Explicit representations of the Earth's surface have been produced for at least a millennium but the usability of the information drastically changed in the past 250 years, with the advent of cartographic projections of maps[82–84], the development of aerial and spaceborne photography, and finally with the increased availability of digital remote sensing data[85,86]. Here we consider sources that contain geo-referenced two- or three-dimensional

spatial visualizations, including historical maps (e.g. the world map of the Catalan Atlas[87], and a map of 17th century England[88]) (FIG.1F), aerial photographs (since the mid-19th century), and more recently airborne imagery (since the 1910s) or spaceborne analogue and digital imagery (starting in the 1950s). These sources can be mined for data at the ecosystem and socio-ecological level[14] and indirectly for data at the species level (FIG.2). For example, historical cartographic material can be useful in assessing land-use and vegetation changes, as exemplified in Central and Eastern Europe[89–91], and in California[92]. It can also inform the spatial distribution and effects of infrastructure[93] or historical socio-political territories[94]. Aerial photography, along with historical remote sensing data, are valuable for understanding past ecosystem extents and their changes (e.g. vegetation cover, water surface area) and have potential applications in mapping species occurrences[95,96] as well as human pressures on ecosystems, such as fishing weirs, war damage, and urbanization[86].

G: Scientific collections and historical surveys. Natural history collections, herbaria, and curiosity cabinets hold specimens that represent a broad range of geographical regions and taxa and span several centuries, which make them a rich source of historical species-level information[13,97,98]. This category also includes pictorial representations of nature produced with a scientific purpose[99,100]. Beyond centuries-old data on species occurrences[13], scientific collections provide material for DNA extraction[101,102] as well as direct trait measurements[97,103,104]. For example, comparing the height of Tibetan snow lotus (*Saussurea laniceps*) – traditionally harvested for medicinal use - in herbarium samples and present-day populations revealed the dwarfing of this endemic species, driven by harvesting pressure[105]. Scientific collections can also be mined to assess relative population abundances[106], as well as changes in species interactions through time[107,108]. Preserved specimens can also serve as sources for studies of stable isotope composition, potentially yielding ecosystem-level information such as trophic composition[109]. Scientific surveys and legacy studies are another extremely rich (albeit relatively rare) source of historical ecological information which may allow for contemporary resurveys to assess biodiversity change over centuries[11,18]. Some of the most valuable historical survey data are biological data inventories, such as those produced by Alexander von Humboldt in Latin America

in the early 19th century (FIG.1.G)[110] and by Joseph Grinnell a century later in California[111] whose design and comprehensiveness allow for replicability today, enabling the tracking of long-term biodiversity changes. Scientific surveys can be mined to extract data on species occurrences, relative population abundances, traits and ecosystem distributions and structure[110,112,113]. They may also be accompanied by pictorial representations, and/or by the collection of specimens, such as Charles Darwin's Galápagos finches[114] and Alfred Russel Wallace's collections[115]. Both scientific collections and surveys are available throughout Modern History, particularly after 1800.

H: Paleo-archives. Paleo-archives refer to material of geological and biological origin that preserves evidence of past changes in species, communities, ecosystems, and climate[116,117]. Geological archives usually come in the form of stratified depositions, including ice, aquatic sediment[118–120] or speleothems (i.e. mineral deposits in caves)[121]. Biological archives are also diverse, encompassing packrat and hyrax middens[122,123], guano piles[50,124], tree rings, fire scars[125,126], and peat bogs[127]. Paleo-archives provide significant opportunities to reconstruct environmental change across centuries to millennia[12,26] and some contain biological remains often identifiable to the species level[19,20,123]. These remains include fossil or subfossil pollen and spores[12,128], soil charcoals[129], insect and crustacean microfossils, and invertebrate dormant stages[120,130,131] as well as ancient sedimentary DNA, or *sedaDNA*[132,133]. Together, paleo-archives offer insights into population abundances and community composition[131], disturbance regimes and ecosystem structures[134,135], along with land-use patterns and other human impacts[136,137]. For instance, pollen studies of the Mesolithic period across Europe indicate active disturbance regime, likely at least partially linked to anthropogenic fire management[138]. Furthermore, experimental work on dormant stages (e.g. seeds, eggs) resurrected from sediment archives has demonstrated evolutionary adaptation to environmental change[24,139] and provided insights into its genomic underpinning[25,140]. While data from paleo-archives cover a long time period (FIG. 2), the availability of various source types varies over time. In particular, the depth of environmental and biological information is limited by the preservation conditions of the archives, as well as chronological constraints and discrepancies in taxonomic resolution[141,142].

3. Integration of historical data

Historical sources and the data they hold are not exempt from biases, which complicate their interpretation (Box 1). However, they share many of these biases and reliability issues with widely-used contemporary biodiversity datasets and repositories[143–145]. Furthermore, while historical biodiversity data is valuable on its own, integrating several historical sources is a powerful approach that can address some biases. Integration is achieved by standardizing and/or correlating metrics extracted from different sources, including modern observations[104,146,147]. This approach expands the geographical and temporal scope of studies, and underpins sounder data interpretation and more robust analysis of historical dynamics and trends[34,50]. Furthermore, the combination of multiple historical sources allows mutual corroboration and sensitivity analysis of their interpretations[14,51,148]: alone, a single historical source may provide a patchy and incomplete picture of past ecological information, while integrated historical sources can support a more complete and meaningful picture (e.g.[110,149]). Integration is particularly instrumental for reconstructing natural baselines to determine what is 'natural' in a given system and assessing resilience by quantifying the legacy of past ecological states on contemporary communities[138]. Below, we showcase some studies that achieve such integration of various historical data and information types (FIG.3). These examples may provide insights for future works, but it is worth noting that integration approaches are case-specific and that universally useful recipes will not be available.

The integration of various historical data sources can reconstruct natural baselines and shed light on long-term patterns that otherwise may have been missed and that are relevant for conservation today[150]. This approach assumes that understanding historical ecosystem configurations can inform conservation efforts by distinguishing between human-induced shifts and natural variability. For instance, historical and contemporary periods of recovery in coral populations of Hawaii were revealed by integrating data on marine fauna from archaeological sites with data extracted from ethnographies and fishery reports (FIG.3K). Importantly, these results unmasked the resilience of the system, which has direct relevance for current conservation[151]. In north-eastern Africa, the traditional local knowledge of Mursi people

contributed to the interpretation of charcoal, pollen, and spore fossils contained in hyrax middens to document historical patterns of encroachment (FIG.3J). This interdisciplinary work highlights the long-term resilience of the system, the sustainability of historical human activity in the study area, and allowed for the identification of key species associated with encroachment, which is also relevant for current land management[152]. In Southern Guinea, aerial photographs, written materials and oral histories were integrated to reconstruct forest–savanna dynamics over the 19th and 20th centuries (FIG.3H), revealing forest expansion[148]. These findings contrasted sharply with colonial interpretations and narratives of deforestation, which (mis)guided land management policies. The integration of multiple sources can also clarify species' presence and origins. In Spain, this approach was applied to the case of the crayfish *Austropotamobius fulcisianus*, traditionally assumed to be native and still managed as such[153]. However, a range of evidence — including explicit and implicit absence in historical documents, the absence of commensal organisms and vernacular names, the timing of its appearance in cookbooks and records of crayfish imports matching the biogeography of the Italian species— collectively confirms and dates the introduction of the species in the country (FIG.3C)[154]. Similarly, combining DNA extracted from museum specimens with a review of historical written sources (literary, letters, regulations) helped elucidate the complex human-mediated biogeography of the black francolin (*Francolinus francolinus*) in the Mediterranean (FIG.3E)[102]. Lastly, archaeological and paleontological records dating back over 10,000 years confirmed the identification of several megafauna species from rock paintings, and the likelihood of historical interactions with humans in the Columbian Amazon (FIG.3G)[72].

The integration of cultural and natural archives can also be instrumental in attributing biodiversity change to specific drivers and pressures over long time periods, and in turn guide current conservation and restoration. This is framed within the broader concept of ecological memory—the extent to which antecedent states influence present-day community structure and function. For example, beyond documenting changes in Namibian rangelands, the integration of historical photographic evidence with written sources (diaries, reports), old maps, and local knowledge (FIG.3I) revealed how historical land-use practices, as well as socio-cultural context,

had influenced landscape dynamics through time, which is relevant for their conservation today[79]. Similarly, wetland management and drainage history over seven centuries in a forest in Czech Republic was reconstructed by integrating natural archives from organic sediments with field evidence, written records, and maps (FIG.3D)[155]. In British Columbia (Canada), field evidence, shell middens, archaeological records of settlements, and oral sources were used to demonstrate that fires in the region were mostly of human origin and used to manage the composition and resources of the landscape (FIG.3B). This study revealed the ecological legacies of the past fire regimes on the composition and structure of the area, information which can guide future conservation efforts[126]. Source integration is also important in studies at the individual species level. In China, Li and colleagues[156] consulted journals, annals, the *Er Ya* Encyclopedia, and government archives, which they combined with information obtained from fossil records to reconstruct both the population trend of the critically endangered Snub-nosed monkeys (*Rhinopithecus spp.*), and the human drivers of this dynamic over the past 400 years (FIG.3F). In Baja California, Mexico, quantitative and qualitative information from oral histories, written documents, and archaeological and historical scientific literature was integrated to reconstruct the nearly three centuries-long history of fisheries of the East Pacific green turtle, *Chelonia mydas* (FIG.3A). This data integration allowed the authors to overcome the scarceness of data on the species in the region to assess human pressure and impact over time, which can be used to establish recovery targets for the species[157].

4. Available data and tools

Mobilization, standardization, and sharing of large-scale historical datasets are already ongoing (Table 1). For instance, initiatives for the large-scale digitalization and geotagging of museum collections are now making information for millions of specimens searchable and available worldwide, including photographs[103,158,159]. Several historical vegetation surveys, dating back to the early 20th century, have also been compiled and standardized in digital databases such as ReSurveyEurope and the European Vegetation Archive[160,161]. Another notable example is the Neotoma Paleoecology Database, which provides not only standardized and open fossil data (e.g. pollen, diatoms, packrat middens), but also the infrastructure and tools to contribute, access, and/or analyze the data[162]. Heterogeneous historical source types can also be mined, mobilized, and integrated to produce comprehensive large-scale geodatabases. One example is the LONGWOOD database which brings together archaeological records, archives of cadasters and forestry, and palynological records of Eastern Czech Republic going back to the 11th century[163]. The Conservation Archive was also recently proposed as a catalogue with global scope aimed at documenting all available historical databases and repositories (including some discussed above) that can be used to set species conservation baselines[6]. Nevertheless, despite these advances, limitations persist—data and repositories are not always interoperable or openly accessible, and concerns regarding the transparency and ethics of data collection remain important challenges that need addressing.

In parallel to data mobilization efforts, new technologies are being leveraged to develop tools that enhance the mining and sharing of historical data. For example, computer vision has been used to create pipelines like *Mothra*[164] and *Skelevision*[165], which automatically derive morphological measurements and associated functional traits, from imaged and skeletal specimens of natural history collections (respectively). Similarly, computer vision has been applied to automated pollen identification and counting[166], sometimes down to the species level[167]. Image processing techniques originally developed for drone imagery have also been successfully adapted for processing historical remote sensing data[168] while machine learning and deep learning techniques promise to accelerate data extraction and classification from old maps

and aerial photographs[86]. There is for instance a rapid development of large-scale machine learning models, or "foundation models", that use deep-learning image-segmentation to group areas of images without specific training, and with minimal user input. A leading example is the Segment Anything Model (SAM) which has proven effective in classifying remote sensing data[169]. Workflows have also been proposed to apply deep-learning methods to classify and geo-reference ground-based photographs[170]. Artificial intelligence (AI) also holds great promise for automating the mobilization of biodiversity-relevant data from written historical sources such as collection labels, logs, or correspondence. This process involves transcribing handwritten and typed material using Optical Character Recognition (OCR) and Handwritten Text Recognition (HTR) tools[104,171] such as *Transkribus*[172], followed by the use of Natural Language Processing (NLP) and Large Language Models (LLMs) for subsequent data classification and mining[173]. Until the potential of these technologies is fully realized, and for oral data sources, qualitative methods to structure, extract and codify information may still be more appropriate[45,174]. AI is also increasingly being applied to paleo-archival data, enhancing species identification and paleo-environmental reconstructions. For example, convolutional neural networks (CNN) are applied to identify fossil species by analyzing morphological features, revealing patterns likely overlooked by traditional methods[175]. Machine learning models are also improving the accuracy of climate and environmental reconstructions by integrating datasets from proxies like ice cores, sediment layers, and tree rings, offering more precise insights into past climates[176]. While these technological advances offer exciting progress, important gaps remain in validating their outputs through collaboration with local knowledge holders and disciplinary specialists, as well as in documenting workflows for transparency and reproducibility.

5. A strategy for the mobilization and integration of historical information

The value of integrated historical information for biodiversity and its conservation is much larger than the sum of its parts. We therefore outline a 7-point strategy to leverage the value of historical sources for biodiversity and global change research (FIG.4) in which we identify the most directly concerned stakeholders, including scientists, funding agencies, and civil society.

1. **Protect historical sources and datasets.** Much like the species and ecosystems they document, historical sources and long-term datasets are often endangered, and the risk of losing valuable data before it is described or digitized is significant[13,103,127]. Conversely, when funding agencies and research institutes prioritize biodiversity data rescue projects[177], scientific research based on those data thrives, as exemplified by a Kenyan-Belgian collaboration that mobilized over 100,000 marine observations collected between 1873 and 1999 along the eastern coast of Africa[178]. This in turn can incentivize further funding for historical research. Moreover, the preservation of the historical biodiversity data sources themselves, including physical specimens, culturally modified trees, relict forest gardens, and other cultural-ecological phenomena, is intertwined with protecting cultural heritage[9,38,147], and these shared objectives should be leveraged across disciplines and beyond research (e.g., regulatory frameworks and policies). Lastly, long term datasets should be preserved for both their scientific and cultural values, with some researchers proposing a "world heritage" status for the most impactful ones[179].

2. **Expand and coordinate digitization efforts.** Institutions such as archives and museums should accelerate their digitization initiatives and ensure open access to their collections, prioritizing those historical sources that are at highest risk of physical deterioration. This applies across all categories of historical sources, from written archives to museum collections, slides produced from sediment cores, and historical maps[103]. These efforts could be prioritized across space, time, and species or ecosystems, as has already been suggested for herbarium collections[104]. In order to maximize efficiency, usability, and interoperability,

data holders should coordinate their efforts in digitization and geo-referencing[86], building on the examples of open archives such as the Neotoma Paleoecology Database([162]; www.neotomadb.org) and using open platforms that share protocols and good practices[159]. Funding could further incentivize digitization and standardization for data holders and enhance interoperability through catalogues and databases that are connectable e.g. by location, time period, by taxa and/or ecosystem, and by survey[108]. Pre-registering historical data mobilization efforts and potential applications in biodiversity research, as proposed for ecological research more broadly[180], could help ensure data collection meets diverse research needs. Importantly, digitization should complement, not replace, the preservation of physical sources. Protection and digitization efforts must be integrated to ensure the long-term persistence of the data and to maximize analysis potential, both analogously and digitally.

3. **Leverage new technologies.** Emerging technologies such as Computer vision and Large Language Models show tremendous potential for the mobilization and mining of biodiversity-relevant data from historical sources (see *Available data and tools* section). While the wealth of digitized scientific collections and remote sensing data has catalyzed the development of several tools[158], these technologies could also be applied to additional historical sources, such as pictorial representations and archeological remains[66,80]. Collaborations between historians, ecologists, and computer scientists should be encouraged to continue developing and applying these novel technologies. In particular, open algorithms, open workflows, and capacity building will be essential for the large scale adoption and application of these tools across data and knowledge holders[86,147].

4. **Engage citizen scientists in this global effort.** Citizen (or community) science is significantly contributing to global biodiversity data collection and can be instrumental in historical ecology. First, citizen scientists can contribute the historical material itself, for instance, oral histories, old family photographs or private hunting/fishing logs, or by cataloguing private collections, e.g., taxidermized specimens[102]. Second, they can participate in re-sampling and monitoring efforts, such as repeat ground-based photography of sites captured in old

455 photographs or postcards[181,182](e.g. https://paisajescentenarios.csic.es/). Lastly, citizen
456 scientists can help mine historical sources for relevant information, through platforms like
457 Zooniverse (zooniverse.org), successfully tested with electron microscope images[183] and
458 ships' logs (oldweather.org), but with mitigated results with paintings[75]. The design of
459 projects involving citizen scientists in the co-production and co-analysis of historical
460 ecological data —contributing material, participating in fieldwork, and mining sources—
461 could draw inspiration from research involving 'paraecologists', i.e. local experts
462 collaborating in ecological research[184]. Furthermore, involving the civil society in historical
463 ecology research could directly help address the shifting baseline syndrome and raise
464 awareness on biodiversity change and conservation[185].
465
466 **5.** **Prioritize standardization and interoperability.** Historical biodiversity data should adhere to
467 the FAIR principles (*Findable, Accessible, Interoperable, Re-usable*) which ensure that data
468 can be easily discovered, shared and repurposed by various users. To achieve this, metadata
469 standards like Darwin Core[186] and Humboldt Core[187] for species data, the ISO 19100 and OGC
470 standards for geographic data, or EAD for archival records should be consistently applied.
471 Developing tools like semantic search engines and new ontologies will facilitate crosswalks
472 between standards, disciplines and Research Infrastructures[117,188]. Large data infrastructures
473 such as the Global Biodiversity Infrastructure Facility (GBIF) can play a key role in facilitating
474 data sharing (e.g.[52]) and guiding data holders on appropriate standards and best practice. This
475 includes discussions on the minimum required information for data re-use, such as the "basis
476 of record" (e.g., preserved specimens, fossil or machine observation), coordinate uncertainty
477 and temporal grain and accuracy. Funding agencies and scientific publishers should further
478 incentivize the standardization and open sharing of historical data.
479
480 **6.** **Ensure ethical acquisition and use of data**, with full, prior, and informed consent of the
481 knowledge holders and communities involved[37,49,147]. Researchers can follow well-
482 established frameworks like the CARE principles (*Collective benefit*, *Authority to Control*,
483 *Responsibility*, *Ethics*) which complement the FAIR data principles, and the OCAP principles

(*Ownership*, *Control*, *Access*, *Possession*) for First Nations' data in Canada, more specifically. Ethical standards extend to material culture, such as artefacts and artworks found on Indigenous land. The use of historical Indigenous and local knowledge also implies the conscious integration, or weaving, of different knowledge systems[9,189]. Indigenous and local knowledge systems can be complementary, yet epistemically distinct from scientific discourses, and as such, they need to be utilized in rigorous, reflective, and informed ways[147,190]. Ethical engagement also requires acknowledging science's colonial legacy and treating Indigenous knowledge holders as collaborators in the design and use of research[191].

7. **Embrace inter- and trans-disciplinarity.** To implement the strategy effectively, and to address the perceived and objective challenges of using historical data in ecological research, it is essential to integrate concepts and methods from various disciplines (interdisciplinarity), and to go beyond disciplinary boundaries by involving non-academic actors (transdisciplinarity)[60,147,154,192]. For example, biodiversity data extracted from historical sources require socio-economic contextualization[14,58,63]. Historians can elucidate the context and motivations behind these sources, which, although not created for scientific purposes, contain valuable biodiversity data for interpretation by ecologists. This is evident in the interpretation of historical artwork, where collaborations between ecologists, historians and art historians assess the realism and reliability of species occurrences, traits, and landscape compositions[65,74]. Reciprocally, ecologists can offer insights into environmental changes that help historians understand their impacts on human societies[10]. Developing new tools and methodologies for data extraction requires collaboration among computer scientists, information scientists, remote sensing experts, historians, and ecologists[80,86]. Interdisciplinary collaborations — particularly between scientists and experts from the Global South and Global North — are key to ensuring accurate interpretation of historical and cultural contexts before undertaking historical ecological analyses[148]. Lastly, recognizing the contributions of diverse knowledge holders underscores the need for transdisciplinarity[189]. Funding schemes should also acknowledge and be adapted to the fact that inter-disciplinary research involving historical datasets can be particularly time-intensive.

6. Concluding remarks

Our review highlights the potential of historical sources to enrich our understanding of biodiversity and the human-nature relationship (FIG.1). These sources provide insights across all dimensions of biodiversity, from genes, to species, and ecosystems (FIG.2), spanning millennia, globally, albeit with varying degrees of interpretation and reliability. By integrating diverse sources, as shown in numerous examples (FIG.3), historical ecologists can cross-validate information, broaden the temporal, geographic, and thematic scope of studies, and reveal patterns and events that may otherwise be overlooked, challenging current assumptions and paradigms.

Enhancing the mobilization and sharing of biodiversity data from historical sources requires collaboration among a diverse group of actors – from curators and historians to ecologists, computer scientists, and citizen scientists (FIG.4) – as well as diverse knowledge-holders, to step-up data mining, standardization, and interoperability.

Intensifying human activities through the Holocene have shaped ecosystems across the globe for millennia[193]. This long history of impacts underscores the need for long-term perspectives to understand biodiversity processes and patterns and to inform decisions that address ongoing changes[10,60]. As awareness grows that spatially and thematically representative long-term data is key for biodiversity research, and for designing fair and effective conservation policies, as well as monitoring their progress[28,194,195], a concerted effort to leverage the wealth of biodiversity data contained in historical sources is needed. Doing so will not only enrich our understanding but also empower future conservation efforts and foster a deeper connection with our ecological heritage.

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9. Competing Interests

The authors declare no competing interests.

10. Box

BOX 1. Challenges of interpreting data from historical sources.

Historical sources and the extraction of data within them present some limitations and challenges. For sources produced or compiled by humans, the quality of the data and the extent of its reliability for biodiversity research depends on the context and purpose of production of the source material, as well as the author's knowledge of the subject and whether the information was obtained firsthand or not[60,74,174,196]. Historical surveys, exploitation records and pictorial representations are hence susceptible to either exaggerations or abridging[11,51,197]. Archival sources produced under colonial rule often reflect a partial—and at times distorted—view of historical human–nature interactions[148]. The spatial availability of historical sources is also not globally homogeneous, which may further lead to sampling biases in the data. Maps are typically available for historical territories of old empires and areas of military interest that have been more intensively surveyed than others (e.g. during the Vietnam War and Cold war)[86,89]. The surveys that underpin natural history collections, field photography and gazetteers can also be spatially biased by interest and/or accessibility[103,106–108,198]. In the case of species, sampling and

reporting bias can lead to taxonomic bias. Indeed, historical sources are by nature skewed towards species and ecosystems that have local cultural or commercial value, and towards species that technical development at a given point in time allowed to capture, preserve and transport so that it could be described (i.e. socio-cultural and technical sieves[65]). As a result, not all species will be described with the same level of detail, if mentioned at all[49,73] and cautious interpretation of the absence of a species in a record as a "true absence" is warranted[4,199].

11.Table

Table 1 – **Examples of repositories, databases and datasets mobilizing historical information and data**. For each entry, we identify the historical source type, the geographical and temporal extent, the primary information that can be derived from it and whether the data is standardized ("Stand."). *R: Repository; Db: Database; Ds: Dataset. Stand.: Standardized (Y = Yes, or N = No). Ref: see the corresponding number in the reference list. **Additional sources, not cited in the text: https://www.biodiversitylibrary.org/; https://inpro.csic.es/;https://www.sead.se/; https://www.ncei.noaa.gov/products/paleoclimatology/tree-ring; https://amunatcoll.pl/

Name	Type*	Historical source categories	Detailed source type	Spatial extent	Temporal extent	Biodiversity-relevant Information	Stand.	Ref.
Biodiversity Heritage Library	R	Scientific collections	Natural history literature	Global	1450-2023	Species occurrences, taxonomy, traits	N	**
European Pollen Database In Neotoma	R	Paleo-Archives	Pollen samples	Eurasia	Pliocene-Quaternary	Species/taxa occurrences; relative abundance	Y	162
International pro pluvia rogation database	Db	Structured written, Unstructured written, Pictorial representations	Official records, rogation dossiers, private diaries, newspapers, iconographic testimonies	Global	1333-1949	Date of droughts	N	**
Kyoto Cherry Tree Flowering Dates	Ds	Unstructured written	Diaries; Chronicles	Kyoto (Japan)	801 - 2010	Date of bloom	Y	61
Longwood	Db	Structured written, Unstructured written	Medieval charters, Urbaria, estate conscriptions, cadastral surveys, Forest Management Plans, court cases, chronicles	Moravia (Czech Republic)	1000-1950	Species/taxa & ecosystems occurrences; disturbance; use	Y	163
Relaciones topográficas de Felipe II	Ds	Structured written	Geographical dictionary	Central Spain	1574-1582	Species/taxa occurrences; use	Y	52
SEAD - Strategic Environmental Archaeology Database	R	Physical archaeological, Paleo-archives	Ceramic, fossils, tree rings, stable isotopes	Global	Quaternary	Species/taxa occurrences; use; geochemical soil properties	Y	**
International Tree Ring Data Bank	Db	Paleo-archives	Individual and site series of tree-ring width and wood density	Global	3000 BC - today	Radial growth indices of tree species. Maximum tree lifespan	Y	**
AMUNATCOLL	Db	Spatial information, Scientific collections	Botanical, mycological and zoological collections available in digital and georeferenced form	Global	XIX century - today	Species/taxa occurrences	Y	**
Historical Spy Satellite Imagery from the Cold War	Ds	Spatial information	photographs taken from space (2m to 150m resolution)	Global	1950s-1970s	Species occurrences; Land use; Human pressures on ecosystems	Y	86
Mountain Legacy Project	Db	Pictorial representations	Repeat ground-based photography from systematic surveys	West Canada	1880s-1950s + resurveys	Ecosystem occurrence; Land use	Y	81

12. Figure legends

Figure 1. Illustrations of historical sources types discussed in the text. A. *Physical archaeological material*: Seashell accumulation at Eland's Bay Cave, South Africa; B. *Oral and linguistic sources*: representation of Indigenous Perspectives based on youth input to the Canadian Climate Institute; C. *Structured written*: Town of Puertollano, extract of the "Relaciones topograficas" of Felipe II, Spain, 16th century; D. *Unstructured written*: pages of a Journal of a whaling voyage of the ship Charles Carroll, Nantucket, USA, 19th century; E. *Pictorial representation*: Fish Market by Frans Snyders, Flanders between 1618 and 1621. Oil on canvas; F. *Spatial information*: Region of Sisteron, France, Cassini's map (early 18th century); G. *Scientific collections*: A. von Humboldt's illustration of the Chimborazo volcano, Ecuador, 19th century; H. *Paleo-archives*: Freeze core from Store Saltsø (Greenland) with visible laminated structure of the sediment. Image credits from A to H (some original images were cropped for display): A. John Atherton (CC BY-SA 2.0); B. Tehatsistahawi (Tsista) Kennedy, Anishinaabe-Oneida artist C. F. Javier Campos & Fernández de Sevilla; D. Barbara Johnson Whaling Collection; E. Hermitage Museum; F. Cassini map, French IGN and BNF; H. N. John Anderson in[200] (CC-BY-4.0).

Figure 2: From historical sources to biodiversity data. Left panel. Relative temporal availability of the historical sources. The width of each shape in each period represents the amount of information provided by each source type (combining number of sources and the information contained in each of them). Note that the relative amount of information cannot be compared between source types, so each category should be treated independently. Right panel. Information that can be extracted from historical sources. This information is organized at the species, ecosystem or socio-ecological level. The two sizes of the circles indicate whether the quantity of information that can be extracted is high or low relative to the other information of the same source category. The color of the circles indicates whether the information can be extracted directly (black), or indirectly (grey). Note that for Paleo-archives the information on ecosystem disturbances can be extracted either directly or indirectly depending on the source material.

Figure 3: Examples of historical data integration in ecology, biodiversity, and global change research indicating the spatial and temporal scope, as well as the type of historical sources used. Historical source types are described in the text. References: A. Green turtle fisheries in[157]; B. Fire regimes in[126]; C. Historical crayfish invasions in[154]; D. Wetland landscape change in[155]; E. Black francolin biogeography in[102]; F. Snub-

nosed monkey population dynamics in[156]; G. Megafauna presence in[72]; H. Forest-savanna dynamics in[148]; I. Vegetation change in[79]; J. Savanna resilience in[152]; K. Coral reef composition in[151]. Icons obtained via FlatIcons: ©Freepik and ©max.icons

Figure 4. A strategy for the mobilization and integration of historical information. The long-term mobilization and integration of biodiversity data from historical sources can be enhanced by implementing a 7-point strategy. Its operationalization will rely on the involvement of multiple actors across scientific disciplines and beyond. See the main text for a detailed description of each point of the strategy. Icons obtained via FlatIcons: ©Freepik; ©SmashIcon; and ©Uniconlab