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REVIEW

Global research priorities for historical ecology to inform conservation

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ABSTRACT: Historical ecology draws on a broad range of information sources and methods to provide insight into ecological and social change, especially over the past ~12 000 yr. While its results are often relevant to conservation and restoration, insights from its diverse disciplines, environments, and geographies have frequently remained siloed or underrepresented, restricting their full potential. Here, scholars and practitioners working in marine, freshwater, and terrestrial environments on 6 continents and various archipelagoes synthesize knowledge from the fields of history, anthropology, paleontology, and ecology with the goal of describing global research priorities for historical ecology to influence conservation. We used a structured decision-making process to identify and address questions in 4 key priority areas: (1) methods and concepts, (2) knowledge co-production and community engagement, (3) policy and management, and (4) climate change impacts. This work highlights the ways that historical ecology has developed and matured in its use of novel information sources, efforts to move beyond extractive research practices and toward knowledge co-production, and application to management challenges including climate change. We demonstrate the ways that this field has brought together researchers across disciplines, connected academics to practitioners, and engaged communities to create and apply knowledge of the past to address the challenges of our shared future.

KEY WORDS: Community engagement · Knowledge co-production · Ecological restoration · Conservation policy · Environmental management · Climate change

1. INTRODUCTION

Historical ecology is a field of research that addresses how human–environment interactions shape ecological change. This rather recent research approach (at least nominally) emphasizes quantifying environmental change and describing the historical context connecting biophysical and human processes (Szabó & Hédl 2011). Research in historical ecology focuses on the causes and consequences of changes caused by past human actions (Beller et al. 2020), as well as understanding natural variation before and after human intervention (Rick & Lockwood 2013). Although terrestrial ecosystems were initially empha-

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sized (Swetnam et al. 1999), marine and freshwater ecosystems later became prominent. Marine historical ecology has pioneered the development of more informed baselines over timescales relevant for management (Pauly 1995) and the documentation of severe impacts to coastal ecosystems due to chronic overexploitation (Jackson et al. 2001).

A central feature of historical ecology is employing a diversity of methods and connecting a range of disciplines — especially history, anthropology, paleontology, and ecology. As a result, historical ecology benefits from source materials that span decades to millennia, and frequently focus on changes from the Holocene to 1950 C.E. (Rick & Lockwood 2013). Historical ecology overlaps in theme with conservation paleobiology, with the latter drawing primarily on fossil and subfossil data and also emphasizing deeper time periods (Rick & Lockwood 2013). Archaeological and paleontological data provide insights from the fossil record, including bones, teeth, shells, and pollen, which can extend from recent to pre-human history (Dillon et al. 2022). Historical ecology also has strong overlap with studies of Indigenous and other local knowledge, and in that context often focuses on the relationship people have built and tended with the environment centered on reciprocal processes (Armstrong et al. 2017). Such local knowledge includes oral histories and community science data streams, which provide observations of ecological change and traditional practices for managing resources (Sullivan et al. 2009, Kittinger et al. 2013, Reif et al. 2021). Finally, historical ecology overlaps with environmental history, including a focus on archival sources, which can range from texts written in medieval times to paintings, newspapers, tax records, menus, as well as records from early natural historians and ecologists who documented their collections systematically (McClenachan et al. 2012). Now a highly transdisciplinary field, historical ecology frequently integrates qualitative and quantitative data (Pandolfi et al. 2003, Lotze et al. 2006, 2011a, Cramer et al. 2021, Paulson et al. 2021) and includes academic researchers and conservation practitioners.

Applications from historical ecology are relevant to conservation and restoration at the species, ecosystem, and landscape scales. Knowledge of multidecadal, centennial, or millennial processes can significantly modify conservation policies based on sub-decadal observations (Lyman 2012, McKechnie et al. 2014, Wolverton et al. 2016). Benchmarks and reference points, such as species recovery goals and other ecological restoration targets that are informed by longer-term records, can help to avoid the shifting baselines syndrome (Pauly 1995), or the gradual erosion of knowledge about the potential for ecosystem productivity or resilience. Knowledge of past faunal and floral abundances and ecosystem resilience has been used to understand nature-based solutions and develop well-informed conservation plans (Jackson et al. 2001, Balée 2006, Al-Abdulrazzak & Pauly 2017, Nicholson et al. 2024). As a result, historical ecology provides critical long-term context for the current global environmental challenges (Rost 2018, Lotze et al. 2022) and forms a strategic response to initiatives like the United Nations Decade on Ecosystem Restoration (Fischer et al. 2021).

Since early landmark analyses over 25 yr ago (Pauly 1995, Swetnam et al. 1999, Jackson et al. 2001), historical ecology has become a well-recognized field of research that integrates knowledge across disciplines, environments, and geographies. Over this time, multiple initiatives have endeavored to apply historical ecology to conservation, which requires both cross-disciplinary work and engagement with non-academic stakeholders. An increasing focus on diversity, equity, and inclusion, representation, and decolonization has also encouraged researchers to evaluate past methods and interpretations more critically. For historical ecology, this has meant reconciling extractive research practices with the need for co-production of knowledge and grappling with diverse views on historical change and management derived from Indigenous and other local knowledge-holders.

Given all of these developments, there is a strategic need to bring diverse perspectives together to evaluate the state of historical ecology, establish future priorities, and build effective conservation strategies in light of climate change and other anthropogenic perturbations. In this study, we review historical ecology as it applies to conservation, targeting both those already working in historical ecology, but also people that may not be familiar with the goals and aims of historical ecology. We gathered leading and emerging world experts to identify and define the top priorities that will help shape future progress in the field and build on previous syntheses by focusing specifically on conservation (e.g. Balée 2006, Szabó & Hédl 2011, Rick & Lockwood 2013, Armstrong et al. 2017, Beller et al. 2020, Crumley 2021). What have we learned? What persistent problems remain? Where are emerging opportunities? As our objective is to integrate a range of voices, we prioritized expert representation from diverse demographics, quantitative and qualitative perspectives, and alternative forms of knowledge and worldviews.

2. METHODS

We followed the form and process of a series of conservation-themed reviews focused on megafauna conservation published in this journal over the past decade (Lewison et al. 2012, Rees et al. 2016, Jorgensen et al. 2022). Specifically, a steering committee (K. S. Van Houtan, L. McClenachan, T. Rick, R. H. Thurstan, and A. Trant) established the scope of the study and created an initial list of international experts from terrestrial and marine ecology, history, archaeology, anthropology, and paleoecology. We then invited coauthors via email to join the project, using chain referral or snowballing (Biernacki & Waldorf 1981, Van Houtan & Kittinger 2014) to identify potential additional contributors, with a particular focus on increasing diverse participation and global representation.

Next, we employed a structured Delphi process (Linstone & Turoff 1975) to prioritize and select content topics for the review. For the latter, each coauthor submitted up to 4 questions they considered essential to applying the discipline of historical ecology to conservation. We grouped 93 such submissions into 4 category themes. The steering committee excluded questions that were too narrow in scope or not directly related to historical ecology and merged the remaining related submissions into 26 questions. Coauthor voting ranked and focused this list, with questions and category themes further merged by the steering committee where topics overlapped. Coauthors self-selected questions they might answer, with the steering committee then assigning 2 co-authors to each question. Contributors subsequently jointly drafted a response that aimed to summarize the scholarly advances to date, articulate remaining unresolved issues, and identify potential frontiers for future study. All responses were then made available to the full co-author list for comment and review.

To document a baseline of scholarly activity, we queried 3 academic search databases for historical ecology publications over time. To accommodate for differences in database indexing methodology, open-access, search algorithms, disciplinary focus, and literary sources (Martín-Martín et al. 2018), we queried 3 independent sources: Google Scholar (scholar.google.com/), Scopus (www.scopus.com/), and CORE (core.ac.uk/). From 1970 through 2022, we tabulated the number of annual publications containing either of the exact phrases 'historical ecology' and 'historical ecological,' separated by the Boolean operator 'OR'. We report the raw values from each search engine and perform summary statistics on their ensemble average. Due to the broadly defined, interdisciplinary nature of historical ecology, this search is a broad tool, is inherently imperfect, and does not capture all publications that may be considered to fall within the field.

As observational and cultural norms are framed and legitimized by historical contexts and social settings (Taylor 1992), throughout the process of this project we prioritized the representation of historically underrepresented communities — diverse voices and demographics, qualitative perspectives, and Indigenous knowledge. We particularly sought contributions from women, early-career scholars, and researchers from the Global South. To monitor and self-report our progress, we distributed a survey (available in the Supplement at www.int-res.com/articles/suppl/n054p285_supp.pdf) to all project coauthors and present the results from all respondents (n = 37).

A third-party repository at GitHub (bit.ly/477TePD) provides the data and scripts used in this study. All survey data were anonymized to remove any personally identifying information, and all visualizations were made in the R computing environment, v. 2022.07.2, Build 576 (R Core Team 2023).

3. RESULTS

We defined 18 questions as essential research priorities for the continued application of historical ecology to conservation, which were split into 4 subject groups: (1) methods and concepts, (2) knowledge co-production and community engagement, (3) policy and management, and (4) climate change (Box 1). Question responses aim to summarize the current state of knowledge, emerging opportunities, and recommendations for future progress. Many of the questions that emerged from our analysis focus on issues of colonialism and Indigenous knowledge. These topics are central to current discussions in historical ecology, but we recognize that not all areas of the world followed the same trajectories as regions with significant settler colonial histories. However, colonialism and associated extractive enterprises permeate all regions of the globe and as such, these issues are broadly relevant to the field of historical ecology.

In our review of historical ecology research, the Google Scholar, Scopus, and CORE search platforms identified an average of 17 374 publications containing 'historical ecology' OR 'historical ecological' from 1970 to 2022. From 1970 to 1989, there was comparatively minor activity, averaging 25 or fewer publi-

i. Methods and Concepts
Q1. What do qualitative and quantitative approaches contribute to understanding long-term change?
Q2. How do historical data help understand long-term ecological change?
Q3. How can diverse data types that span a range of time scales be meaningfully integrated?
Q4. How can historical ecology leverage quantitative methods, big data, and machine learning?
Q5. How does bias affect the distribution of knowledge in historical ecology?

ii. Knowledge Co-production and Community Engagement
Q6. What are best practices for knowledge co-production and community engagement for historical ecology?
Q7. How can natural history museums expand the relevance of historical ecology?
Q8. How can historical ecology encourage community participation in cultural heritage preservation?
Q9. What are equitable approaches to knowledge co-production with Indigenous communities?

iii. Policy and Management
Q10. In what specific policy and decision-making contexts is historical ecology most relevant?
Q11. How do we select baselines dates for use in conservation?
Q12. How can conservation baselines consider complex linkages between people and nature?
Q13. How did past Indigenous management result in outcomes providing insight today?
Q14. What unique challenges and opportunities exist for historical ecology in data-poor or colonized countries?

iv. Climate Change
Q15. What sources are available to document past climate drivers and impacts?
Q16. How can knowledge of ecological and societal responses to past warming inform conservation and adaptation in the face of future climate change?
Q17. How can management reference historical climate conditions, given that there may be multiple baselines?
Q18. How may historical knowledge be relevant for future ecosystem states that have no precedent?

Box 1. Global research priorities for historical ecology to inform conservation. The final list of 18 questions are grouped into 4 categories that we address in this review

cations annually (Fig. 1). The period 1990–2016 shows a rapid annual rate of increase (r = 0.114), followed by flat production (r = 0.001) thereafter. Though beyond the scope of the present study, the reasons for the recent production plateau may reflect the diversification of terminology into more specialized topics and phrases (e.g. Dillon et al. 2022). The 2017–2022 trend does not match the increasing research production seen in the environmental sciences (Davison et al. 2021) over a similar period, and is unlikely related to the decline in research production resulting from the COVID-19 pandemic (Riccaboni & Verginer 2022), whose impact began in late 2020. Further bibliometric or scientometric research in this area may produce additional important insights.

Our author group represents 6 continents, 12 primary languages, diverse career stages, and institutional sectors including academic, non-profit, government, and museum (Fig. 2). Despite this broad representation, many of this study's contributors self-identify as mid-career academic ecologists working in the USA or Canada, who are white and primarily speak English. While contributions across disciplines, geographic regions, ethnicities, genders and languages is more diverse, significant progress and opportunity remains to achieve greater representation, inclusion, and equity.

3.1. Methods and concepts

Q1. What do qualitative and quantitative approaches contribute to understanding long-term change?

Both quantitative and qualitative methods are essential to understanding long-term ecological change. Qualitative approaches can be used to describe human knowledge, perceptions, and decisions, while quantitative data can identify ecological patterns and processes (Clavero 2016). For example, qualitative ethno-

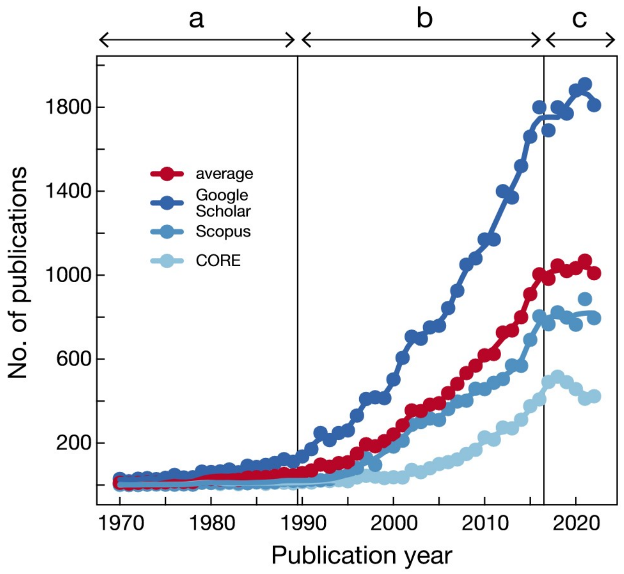

Fig. 1. Annual changes in historical ecology research publications from 1970 to 2022. A query for the whole phrases 'historical ecology' OR 'historical ecological' from the Google Scholar, Scopus, and CORE databases returned an ensemble average of 17 374 publications during the 52 yr record. These sources indicate (a) slow growth in scholarly production from 1970 to 1989, (b) a sharp rise from 1990 to 2016 (annual increase 11.4%), followed by (c) relatively flat production from 2017 to 2022 (0.1%). The most recent pattern (c) does not appear to reflect either the broad trends in research production or impacts arising from the COVID-19 pandemic

graphic and quantitative archaeological data on turtle consumption in Polynesia reveal distinct cultural patterns that contributed to different rates of decline over millennia (Allen 2007). Likewise, combining qualitative archival sources and quantitative DNA analysis have documented ancient introductions of non-native species, revealing long-term human influence on biodiversity (Forcina et al. 2015, Clavero et al. 2016).

Working across disciplines can produce new methods that bring analytical weight and narrative power to our understanding of long-term ecosystem change. In the Florida Keys (USA), for example, historical newspapers and photographs were used to quantify an order of magnitude decline in the size of recreational fish caught over 50 yr (McClenachan 2009a,b), while a range of archival sources were synthesized to describe the cultural and political forces motivating this overfishing (Alagona et al. 2023). In Baja California, Mexico, intergenerational knowledge of fishers, archival records, and archaeological data were incorporated to show long-term population trends from ~12 000 yr ago to the 1960s for green turtles *Chelonia mydas*, demonstrating sustainability until they became fungible or commercial goods (Early-Capistrán et al. 2018, 2020).

While not unique to historical ecology, the integration of qualitative and quantitative information is particularly relevant because there is often an expectation of quantification within ecological analyses of change, and in many instances, qualitative data are the only available information over long time frames. In such cases, qualitative observations (such as categorical or ordinal data) can be converted to semi-quantitative metrics including rankings of ecosystem state based on qualitative rules (Pandolfi et al. 2003) and binary measures such as presence–absence or dominance versus non-dominance of taxa (Cramer et al. 2021). Such methods have facilitated global analyses of ecosystem change over millennia and across ecosystems (Pandolfi et al. 2003, Lotze et al. 2006). Similarly, the use of archival data in ecological models reveals patterns and consequences of population extinctions (McClenachan & Cooper 2008), past food web dynamics and trophic structures (Lotze et al. 2011a), and historical habitat distributions that challenged established ideas on the distribution of tree species (Szabó et al. 2017).

In this effort, researchers must understand and employ best practices from specific techniques, fields, and subdisciplines. For example, a critical examination (and sometimes reformulation or transformation) of historical sources to be used under ecological analytical frameworks is necessary, and researchers endeavoring to use local ecological knowledge should be aware of ethical and cultural considerations inherent in these approaches (Szabó & Hédl 2011, Pooley 2013, McClenachan et al. 2015).

Q2. How do historical data help understand long-term ecological change?

Historical ecology has commonly focused on local changes in individual taxa or communities over past decades, centuries, and millennia driven by human activities (e.g. exploitation, habitat alteration, pollution, invasive species) and sometimes natural environmental fluctuations (Lotze & McClenachan 2013, Rick & Lockwood 2013). From the scale of species to landscapes, historical ecology is important for documenting past occurrences, abundance, distributions, demographics, habitat usage, and species interactions. For example, surveillance satellite data (Munteanu et al. 2020, Rizayeva et al. 2023), historical maps (Fuchs et al. 2015, Munteanu et al. 2015), and aerial photography (Lydersen & Collins 2018) can be used to reconstruct ecosystem structure and species habitat use at regional to global scales extending cen-

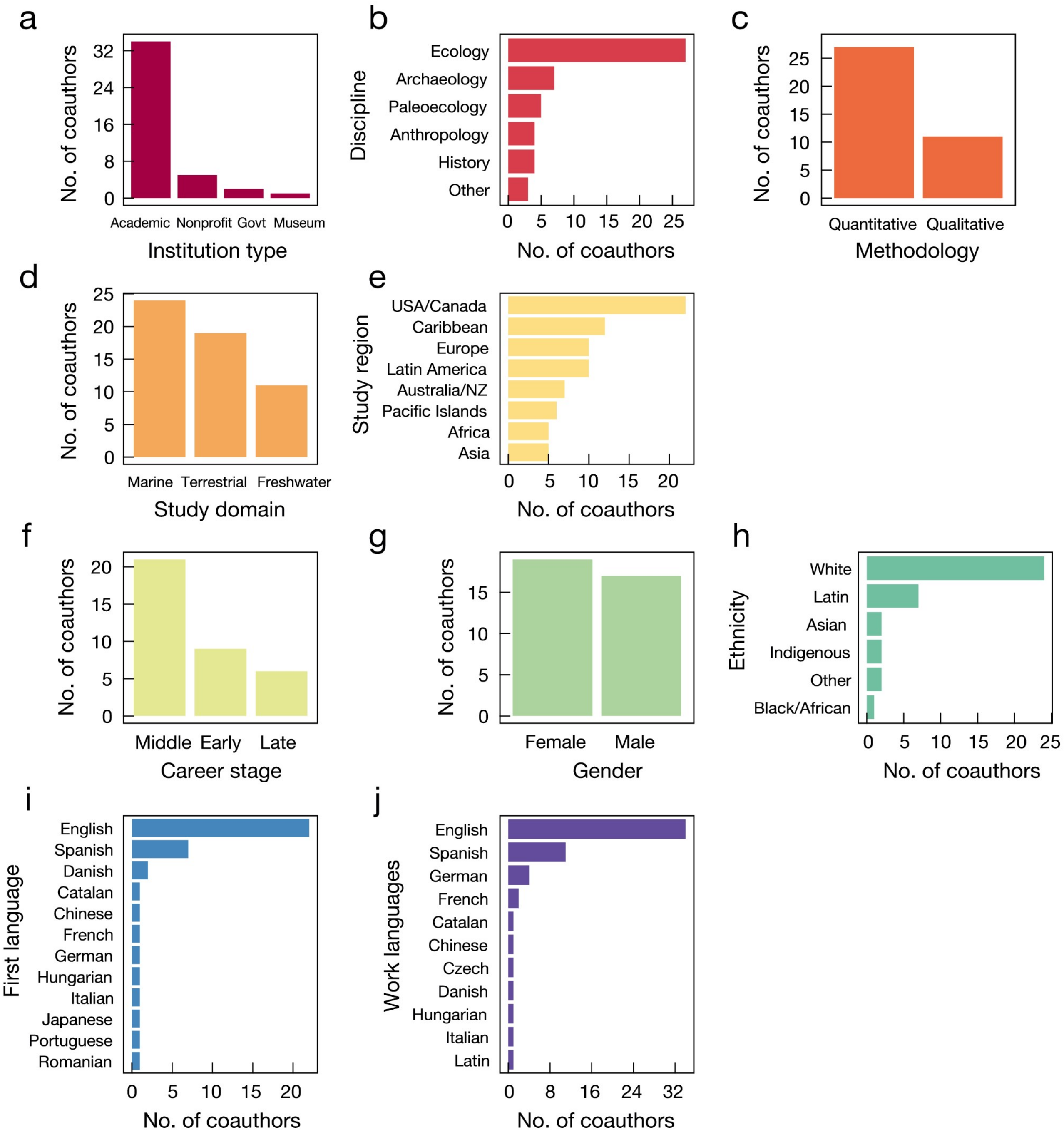

Fig. 2. Self-reported perspectives from the contributing authors of this study. Authors' responses to survey questions (questions available in the Supplement at www.int-res.com/articles/suppl/n054p285_supp.pdf) on (a–c) professional affiliation and approach, (d,e) geographic domain, (f–h) demographics, and (i,j) language use. Despite significant representation beyond these categories, most authors of this study are white, English-speaking, mid-career quantitative marine ecologists who conduct research at universities in the USA or Canada

turies in the past. Natural archives (Wolfe et al. 2013, Xu et al. 2016) can be used to quantify ecosystem productivity, community structure, and population sizes at millennial time scales via a large number of organic and inorganic proxies, such as pollen, bio-elements, stable isotopes, and ancient DNA (Emslie 2021, Palli et al. 2023).

When using historical information to understand ecological change, several challenges persist. Ecosystem variation over decadal to millennial scales is high

(Duda et al. 2023), and available historical sources may miss the full range of variation in ecosystems (Soga & Gaston 2018). Discriminating the effects of biophysical variability and anthropogenic activity remains difficult even if the range of variation is known (Swanson et al. 2009, Armstrong et al. 2017). Finally, when used in isolation, individual historical data sources may be difficult to validate, leading to interpretive errors (Stahl 2018). Several solutions exist. Integrating historical species records, modern observations, and modeling approaches, for example, allows for long-term range and population dynamic reconstructions. Developing more refined tools for integrating these different data sets should be prioritized. For example, specific biomarkers may lead to unambiguous conclusions on human- versus environment-driven changes, and more precise age determinations would shed light on the past at finer timescales, avoiding dating-induced biases (Bluhm & Surovell 2019, Zimmerman & Wahl 2020). Importantly, data on various scales and from different disciplines can help to validate results: population dynamics or vegetation coverage from pollen records can be spatialized using historical maps and remote sensing, and ecosystem dynamics from maps or aerial photographs can be validated using similarly timed literature entries, species records, or biomarkers.

Q3. How can diverse data types that span a range of time scales be meaningfully integrated?

In integrating diverse data, historical ecology researchers confront issues regarding the scale, resolution, and format of data. These can be addressed by standardizing metrics of interest (Lotze et al. 2011b). Oral history, archival, and fossil/subfossil data have been integrated to reconstruct timelines of ecological change, relative abundance of key taxa, and fisheries catch over thousands of years (Lotze et al. 2006, Kittinger et al. 2015, Early-Capistrán et al. 2018). In doing so, calibration across diverse data sets has been achieved by assessing the correlation between metrics, such as the accumulation of shark dermal denticles preserved in marine sediments and underwater surveys of modern shark abundance (Dillon et al. 2020), hunting rates for dugongs from archaeological middens and modern conservation assessments (McNiven & Bedingfield 2008), and information from oral history and commercial fisheries records (Sáenz-Arroyo & Revollo-Fernández 2016).

Several technological and methodological advances are accelerating the integration of data types across timescales. Increases in instrumentation and artificial intelligence capabilities are increasing the capacity to analyze ancient and environmental DNA, and isotopic, elemental, and histologic data that can be collected in the same manner across varying sources of data (paleoecological, archaeological, collections-based, and modern) (Kidwell 2015). High-precision chronologies from natural archives are available via radiometric dating, providing similar temporal resolution across historical and modern data (Clark et al. 2014). Several approaches would improve the capacity to integrate diverse data to understand long-term change. Using historical data to validate hindcasting based on modern data can help to understand ecological dynamics, such as if past impacts of climate change on species distributions were similar to those observed today (Dietl & Flessa 2011). Improved data integration may also arise from collaborating across disciplines to create standardized methods and deriving conversion factors for ecological metrics (Miller et al. 2019, 2020) by designing studies that allow for statistical comparisons of historical and modern data.

Q4. How can historical ecology leverage quantitative methods, big data, and machine learning?

The large-scale acquisition, storage, and analysis of ecological and related information provides conservation science with unprecedented resources and opportunities (Tuia et al. 2022). Researchers and institutions are responding by embracing new technology and methods in cloud storage and computing, artificial intelligence, automated systems, '-omics,' and community science (NOAA 2020). Similar initiatives are helping to increase the efficiency and productivity of historical ecology research programs, where the extraction and curation of historical data streams are often manual and logistically intensive. For decades, the humanities have focused on digitizing, processing, and publishing relevant historical texts, images, and cultural ephemera (Galla 2009, Van Houtan et al. 2013). Further enhancing accessibility and linking those efforts to the goals of historical ecology, such as the open publication of papers and data sets resulting from The History of Marine Animal Populations Project and Oceans Past Initiative (e.g. Starkey et al. 2012, Polónia 2020), will be fruitful. When standardized and attributed with metadata, open-access clearinghouses of historical data may also further advance the field in the mold of more established (Ratnasingham & Hebert 2007, Beck et al. 2014) and growing disciplines (Jung et al. 2018, Miller et al. 2022). In addition, techniques to advance automation and robotics in -omics methods (Sinclair et al. 1998, Searcy et al. 2022) will improve the efficiency of data acquisition and analysis across a range of historical ecology topic areas.

With new data come new analytical methods, such as artificial intelligence and machine learning methods. In ecology, these approaches have been used in remote sensing, genetics, climate, and biotelemetry, often by incorporating autonomous sensor networks into research workflows (Tuia et al. 2022). Applying machine learning to qualitative data such as text (e.g. natural language processing and large language models) is rapidly advancing (Shen et al. 2023), with significant potential for conservation (Van Houtan et al. 2020). Such approaches complement traditional historical ecology methods, where expert-trained data sets and advanced algorithms work together to automate learning from historical texts (Davidson et al. 2019) in multiple languages. Beyond removing barriers to historical data, adopting big data and artificial intelligence in historical ecology may help reduce geographic bias (see Q5 and Thurstan 2022), while increasing access and cultural representation (see Fig. 3, Q8–9). The reduction of such biases also requires addressing existing structural inequalities, for example, access and expertise gaps arising from the concentration of high-powered technological infrastructure in highly developed nations (Obermeyer et al. 2019, Jindal 2022). Assuming such inequalities are addressed, collectively these outcomes will advance a core goal of historical ecology — to increase knowledge for conservation practitioners across contexts and solutions.

Q5. How does bias affect the distribution of knowledge in historical ecology?

The availability of historical ecology data is affected by biases across space, taxonomy, and time. Most fundamentally, historical ecology has, like other Western scientific endeavors, been affected by colonial power

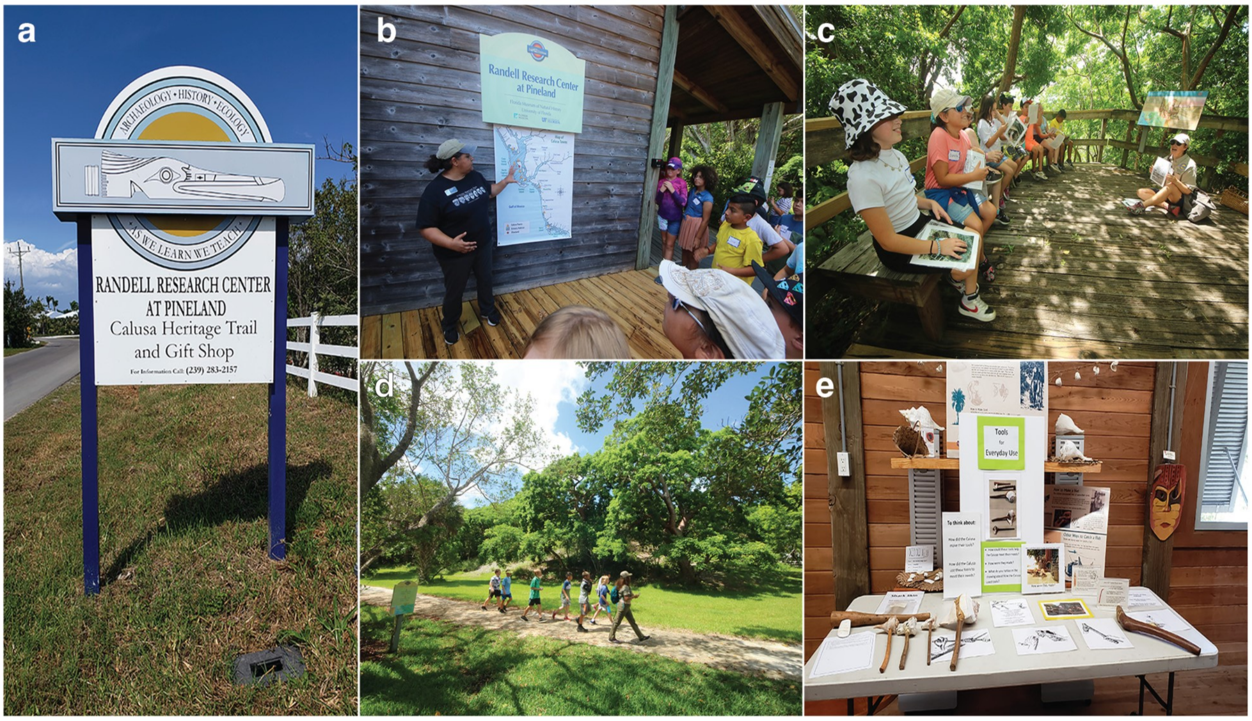

Fig. 3. The Florida Museum of Natural History's Randell Research Center and Calusa Heritage Trail. Located at the Pineland Site Complex on Pine Island, Florida, the museum center is explicitly dedicated to the research, preservation, and public education about the archaeology and historical ecology of the Calusa and Pine Island Sound estuary. (a) Welcome sign clearly naming archaeology, history, and ecology as the cornerstones of the center and trail. (b) Center operations manager and (c,d) museum educators leading Title I School fourth-grade educational programs across preserved Calusa shell mounds, middens, and canals. (e) Classroom display with replica artifacts for public education about estuarine historical ecology and 2000 yr of fishing. Photos provided by Annisa Karim and Charles O'Connor and used with permission

structures, which results in knowledge biases (Fernando 2022). For example, colonial administrations destroyed historical sources, while also producing documents that can help understand the historical ecology of many colonized regions. In using such sources, researchers must assess and account for those biases (McClenachan et al. 2015). Likewise, archaeological sources may contain biases that affect their use, and assessments of the so called 'cultural filter,' or the ways in which objects are biased by human actions such as transport, are needed (Peacock et al. 2012). Additionally, there are socio-economic and geographic biases in analyses of available sources (Trisos et al. 2021, Fernando 2022, Raja et al. 2022). Roughly 90% of historical ecology studies derive from North America and Europe (Beller et al. 2020), for example. Furthermore, biological and cultural objects held in museums or private collections, trapped behind paywalls, or written in languages not spoken by local communities, present significant barriers to equitable access (Meagher 2021).

These cultural biases result in an unequal distribution of records relevant for historical ecology, such as an overrepresentation of studies on environmental change and biodiversity in human population centers across the Global North (Gagné et al. 2020, Hughes et al. 2021), with large data gaps in the biodiversity-rich tropics (Felton et al. 2009, Davison et al. 2021, Spalding et al. 2023). Cultural biases for charismatic and commercially valuable species drive taxonomic biases regardless of time and location (Davison et al. 2021, Daru & Rodriguez 2023), while available data are also region- and taxon-specific and accompanied by taphonomic biases (Barnosky et al. 2017). Temporal biases emerge from technological advancement, accessibility, research interests, and socioeconomic factors changing over time (Stropp et al. 2016), and the tendency to collect historical sources and ecological data based on convenience, such as adjacent to research centers (Davis 2018), perpetuates global biases despite the growth of community science records in recent decades (Sullivan et al. 2009, Hughes et al. 2021, Daru & Rodriguez 2023). Biased ecological data distort our understanding of biodiversity gradients, species distributions, and predictions of their responses to human-driven change (Hortal et al. 2008, Gagné et al. 2020, Daru & Rodriguez 2023). Solutions include developing mechanistic models of ecological distributions (Reygondeau et al. 2020), addressing sources of cultural biases, and amplifying and broadening knowledge systems from developing countries, marginalized communities, and Indigenous and other local knowledge co-production (see Q6, Q8–9).

3.2. Knowledge co-production and community engagement

Q6. What are best practices for knowledge co-production and community engagement for historical ecology?

Community engagement in historical ecology ranges from knowledge dissemination to the public in the context of natural history museums (see Q7) to the co-production of research priorities with Indigenous knowledge holders (see Q9). Given this wide-ranging and often complex social setting, there is no single set of best practices for knowledge co-production and community engagement for historical ecology. Yet, several principles and practices are relevant in many contexts. First, accessibility of information is needed, because despite the transdisciplinary nature of historical ecology, information sharing remains restricted by factors including the disciplinary siloing of knowledge (Carmenta & Vira 2018), competition among researchers, and the privileging of specific types of knowledge and holders (see Q5) (Sidik 2022). Platforms for open-source data sharing (see Q4) and guidelines for ethical best practice (Wilkinson et al. 2016, Crystal-Ornelas et al. 2022) facilitate information sharing to meet global conservation challenges. Likewise, knowledge may be better shared through audio-visual tools such as infographics, videos, and the classroom, and relevant materials should be communicated in locally spoken languages (ISE 2006, Lawson et al. 2021).

While improved communication training and the implementation of wider dissemination strategies can enhance information sharing in historical ecology, they often remain unidirectional as they may host data 'from' researchers 'for' others to use. Instead, more fundamental changes are needed to ensure equitable representation of historically marginalized histories, voices, and knowledge systems. For example, 'community peer review' is a mechanism which supports research and knowledge co-production led by community groups. Community peer review includes steps to ensure that research outputs (papers, data, etc.) are accurate and consistent with community standards for data sharing (Liboiron 2021). This process helps to guard against parachute science or tokenism, where knowledge is extracted and misapplied without consent (de Vos & Schwartz 2022). Appreciating the deep entrenchment of local knowledge (Klenk et al. 2017) and recognition of oral traditions and knowledge systems (Reid et al. 2021) is essential in this process, as is taking steps to communicate the differences across knowledge forms and examine how such differences may influence their acceptance, application, and interpretation. Moreover, ethical engagement and community self-determination must be the foundation for collaboration (ISE 2006, Mistry & Berardi 2016, Schroeder et al. 2019).

Emerging models of information sharing could also be more broadly incorporated into historical ecology. For example, collaborative research learning networks (RLNs) promote more inclusive models of knowledge co-production and information sharing (Dalton et al. 2020), and are emerging as alternatives to traditional institutional and academic networks. RLNs, such as the current UN Ocean Decade (Singh et al. 2021), promote formal working groups with wide representation that aim to collectively build a comprehensive and accessible knowledge base while fostering collaboration and inclusivity (Gerhardinger et al. 2020). Blending RLNs with enhanced media and information literacy could further facilitate knowledge co-production and sharing, empower individuals and communities, and more effectively navigate complex environmental issues (Gerhardinger et al. 2020).

Historical ecology increasingly recognizes the pivotal role that communities play in the framing and prioritization of research questions, data curation, and conservation efforts (Evans et al. 2008, Greer 2010, Shackeroff et al. 2011). The focus of historical ecology on place and potential for powerful imagery can act as a catalyst to break down barriers to community participation (Astudillo et al. 2023). Additional expertise and training in inclusive community engagement, such as participatory or consensus-based techniques (Wells et al. 2019), may be required. Such relationship building requires significant time and resources from the beginning of research, and extends beyond typical project timelines (Mace 2014, Morgan et al. 2023).

Q7. How can natural history museums expand the relevance of historical ecology?

Although rarely nominally referenced, natural history museums have long featured some of the most prominent tenets of historical ecology in their research and public engagement. These include museum collections, exhibits, research, and educational outreach on climate and ecosystem change, evolution and biodiversity loss, and the dynamics of human–environment relationships. Such themes are often presented across multiple time scales represented by paleontological, archaeological, and historical natural history collections. Recently, however, the historical and societal relevance of natural history museums as collection repositories and bastions of public education have been critiqued (Dorfman 2017, Reid & Vail 2019). Natural history museums' long-professed interpretive neutrality when exhibiting natural and cultural history is now increasingly recognized as problematic and perhaps a disingenuous representation of the featured ecosystems and people (Evans et al. 2020, Shiraiwa & Zabalueva 2021). Rather, 'museum activism,' has emerged as the way of the future for relevant natural history museum practice and exhibits. This approach centers purposeful community engagement and co-production in research, exhibits, public education, and solutions to pressing societal challenges (Robinson 2017, Drotner et al. 2019, Janes & Sandell 2019, Sutton 2020).

It is within this spirit that natural history museums are well-positioned to expand historical ecology from the status quo, which is more of an underlying academic framework. Beyond increasing access to and diagnostic research on collections (see Q4), this transformation may move to more publicly recognized, community-accessible, applied science focused on understanding how the past can help address Anthropocene challenges (Miller et al. 2019). Doing so may help communicate how linked ecological and cultural histories have together shaped socioecological systems through time (Fig. 3). This work requires unpacking colonial structures through consultation and collaboration with the communities whose histories, legacy environments, and continuing biocultural heritage are represented in collections and exhibits. Engagement with local biological and cultural heritage stakeholders is essential. Natural history museums are often the public face of historical ecology, and bear responsibility for shaping and demonstrating its societal, scientific, and conservation relevance. At the same time, these principles also apply to local education centers and classroom settings, in particular in areas of the world where natural history museums lack access.

Q8. How can historical ecology encourage community participation in cultural heritage preservation?

Like natural history museums (see Q7), the preservation of cultural heritage is not always associated with historical ecology, but it can be a powerful mechanism for engaging communities. Cultural heritage is both tangible (e.g. cultural landscapes) and intangible (e.g. traditions) and intertwined with people's interactions with local environments (Silverman & Ruggles 2009, Hassan 2014). Historical ecology research can help identify cultural heritage and its significance to communities in time (Crumley 2021, Astudillo et al. 2023). Leveraging community knowledge via historical ecology research applying community-based approaches can empower communities to protect cultural heritage by engaging with drivers of heritage decline (Piñar & Sterflinger 2021, Curran & Zimmermann 2022), reconnecting with and redefining their heritage (Astudillo et al. 2023), reframing dominant discourses (Hill et al. 2011, Koslov 2016), and generating information for consensus-driven policy and practice (Hill et al. 2011, Armstrong et al. 2017). In aiding understanding of past environmental changes and their drivers, historical ecology can illuminate how heritage practices interacted with and influenced local environments. For example, the rediscovery of lost 'dreg' songs from the south coast of the Firth of Forth, which used a specific song pattern to maximize the efficiency of the oyster dredges in this particular environment, and which went extinct with the fishery, became the focus of a community effort to reintroduce these songs and subsequently illuminated the loss of the native oyster in the Forth (Bishop et al. 2013). Such understanding helps communities to reframe their priorities and build future visions that facilitate community adaptation and transformation in the face of environmental change and heritage loss (DeSilvey & Harrison 2020, Hassan 2021).

Q9. What are equitable approaches to knowledge co-production with Indigenous communities?

Indigenous and other local knowledge is valuable for generating a more holistic understanding of ecosystems and the human–environment relationship through time, which is central to historical ecology (Spalding et al. 2023). Combining Indigenous and scientific knowledge as complementary approaches (McKeon 2012, Hall et al. 2015, Marshall et al. 2015, Abu et al. 2020) is referred to as '2-eyed seeing' (Bartlett et al. 2012); this methodology values and amplifies the intellectual tool box that Indigenous peoples carry, and draws from daily activities and cross-generational factors when engaging in sociocultural and ecosystem-based activities (see also 'braiding knowledge'; Atalay 2020). Central to this methodology is ensuring that the research benefits all (Bartlett et al. 2012), and does not exploit Indigenous people.

A persistent challenge facing conservation practitioners is how to work with Indigenous and other local knowledge respectfully and ethically throughout the processes of conservation. Two related models for partnership with Indigenous and other local communities include equitable exchange (Harris et al. 2021) and 'boundary spanners' (Hatch et al. 2023). Equitable exchange focuses on 'currencies' within different communities, and proposes a framework for defining these currencies prior to formal partnerships with the goal of equal and self-defined benefit. The success of many mainstream-community partnerships is frequently dependent on a boundary spanner — a person or small team that is fluent in both community protocol and mainstream science. Unlike the concept of 'informant' in anthropological research contexts, the boundary spanner is often a member of both communities, and helps to ensure that equitable exchange occurs. Future progress may also be found in the Indigenous 'land back' and 'water back' movements (Fisk et al. 2021, Gray 2022, Leonard et al. 2023). These efforts are rooted in Indigenous peoples' sovereignty over their traditional territories, and focus on the use of local ecological knowledge to support Indigenous conservation methods (Simpson 2017).

Equitable approaches to knowledge co-production also integrate ethical data management, and acknowledge Indigenous authority over intellectual property rights. Methodologies that ensure data sovereignty and protect intellectual property rights are essential to knowledge sharing and co-production relationships. Strategies within this realm include community-controlled information databases such as Mukurtu (https://mukurtu.org), protocols for Indigenous intellectual property use, and memoranda of agreements (Buck & Hamilton 2011, Malsale et al. 2018, Carroll et al. 2020).

3.3. Policy and management

Q10. In what specific policy and decision-making contexts is historical ecology most relevant?

Historical ecology is relevant for policy and decision-making involving the management of species, populations, and ecosystems. Historical research has helped resolve the biogeography of priority species (Clavero et al. 2016), justify source populations for species reintroductions (Gessner et al. 2011), and challenge modern ideas of 'natural' ecosystem states (Jackson 1997, Szabó et al. 2017). One such case involves the 'American' Atlantic sturgeon *Acipenser oxyrinchus* and European sturgeon *A. sturio*. These species diverged at least 15 million years ago (Ludwig et al. 2002), and it was thought that Atlantic sturgeon did not exist in European waters. However, historical research documented that humans extirpated Atlantic sturgeon from European waters in the 1600s (Desse-Berset 2011), which supported enhancing Baltic sturgeon populations with the more abundant Atlantic sturgeon instead of the Critically Endangered European sturgeon (Gessner et al. 2011).

Historical ecology can help communities converge on shared goals for restoration (see Q8). In South Australia, for example, a multidisciplinary network of scientists, practitioners, and managers was successful in reaching out to a diversity of stakeholders to communicate the past (and potential future) social, ecological, and economic significance of oyster (*Ostrea angasi*) reefs. This helped to build political support for the establishment of a large-scale restoration initiative and a nationwide 'reef-building' agenda (McAfee et al. 2022). Pooled data from explorer histories, fisheries catch, archaeological records, and sediment cores contributed to a Critically Endangered listing of Australian oyster reefs on the IUCN Red List of Ecosystems (Gillies et al. 2020). Here, historical ecology motivated and legitimized government intervention, including customizing restoration for the current environment and paired social benefits (McAfee et al. 2021).

Finally, historical approaches are necessary to historicize and critique ideas like management itself, as Western scientific management exists within a specific set of cultural frameworks and biases. For example, in southwestern Ethiopia, fire plays a crucial role in the conservation of African savannas and as a tool for nomadic pastoralists to create pastures. The establishment of a national park in 1980 led to a fire ban for local communities, particularly the Mursi people (Turton 2011), as high-frequency fires were thought to cause bush encroachment and to reduce grass availability for wild ungulates. However, a combination of paleoecological indicators (Gil-Romera et al. 2010), Mursi oral histories (Gil-Romera et al. 2011, Turton 2011), and current-day plant ecology revealed that bush encroachment was related to fire suppression policies (Gil-Romera et al. 2010). This example demonstrates that by adding more voices to the field of historical ecology, it will become more complex, more meaningful, and allow more people to join a respectful community of practice.

Q11. How do we select baseline dates for use in conservation?

Baselines are ubiquitously, though often implicitly, used in conservation endeavors (Alagona et al. 2012). Such reference points from the past simultaneously provide targets to guide management actions and thresholds for assessing recovery progress or status (Grace et al. 2021). Poorly-chosen baselines — whether due to unacknowledged assumptions, cultural biases, or shifting baselines — can have negative consequences, such as the premature removal of protection (e.g. Yellowstone wolves; Sturges 2019) and misleading assessments of population trends (e.g. furbearer hunts, Collins et al. 2020; also see Q13, Q17].

Why are baselines selected, and by whom? The IUCN Green Status of Species (IUCN Species Survival Commission 2021), a recovery assessment, identifies species-relevant baselines between 1500 and 1950, recognizing that human impacts occurred outside of that period, but asserting that earlier baselines are too removed from the present (Stephenson et al. 2019). Policy baselines are often set later, within the past 50 yr (Burns et al. 2023). Choice of baselines is also vulnerable to cultural biases that render them value-laden. The initial objective of US National Parks, for example, was to maintain or re-create ecosystems 'in the condition that prevailed when the area was first visited by the white man' (Leopold et al. 1963, p. 3). Recognizing the biases inherent in this objective, it has since been updated to the more open-ended directive 'to preserve ecological integrity and cultural and historical authenticity.'

Another consideration is whether reference periods are selected *a priori* or emerge from a synthesis of historical data. *A priori* baselines include inflection points in humanity's relationship with the environment and each other, as occurred during the climatic shifts and megafaunal extinctions of the Late Pleistocene/Holocene transition (~11 000 yr ago and earlier), the onset of European colonization and the widespread dislocation of Indigenous communities (ca. 1500), in the Industrial Revolution (beginning ca. 1750), and the Great Acceleration (ca. 1950) (Ellis et al. 2016). However, not all species were affected equally by these shifts in human activity, so synthesis of species-specific historical data may be necessary to choose a meaningful baseline. It is also important to remember that not all conservation goals are backward-looking. In some cases, historical baselines are put aside or used as a menu of options when helping species, communities, and ecosystems adapt to a changing world (Barnosky et al. 2017, Coleman et al. 2020, Mychajliw et al. 2022).

Q12. How can conservation baselines consider complex linkages between people and nature?

One important recent shift in historical ecology is from a focus on informing conservation baselines with information before human impact (i.e. so-called 'pristine' conditions), to one that emphasizes the role of human societies in shaping both lasting ecological patterns and socially valuable outcomes. Historical ecologists have described human agency in landscape formation, even in seemingly pristine forests, where intermediate disturbances by people sometimes enhanced the biodiversity in landscapes (Denevan 1992, Balée 2006, 2013, Balée & Erickson 2006, Yasuoka 2013, Clement et al. 2015, Levis et al. 2017, Avtzis et al. 2018). People developed complex socio-ecological arrangements all over the world, many of which have been disrupted over past centuries by growth-centered capitalist (Rose 2004) and modernizing forces — including state-sponsored conservation, which is often based on the human–nature dichotomy (See also Q10) (West et al. 2006, Fletcher et al. 2021). Many protected areas overlap lands where Indigenous peoples and local communities historically lived (Garnett et al. 2018). Therefore, using 'pristine environments' as benchmarks for conservation baselines, while untenable as it is often embedded within colonial discourses (Early-Capistrán et al. 2018), causes normative, scientific, and practical problems (Hilding-Rydevik et al. 2017). For example, historical analyses are challenging views on management of keystone species, such as sea otters in British Columbia and Alaska, as evidence emerges that Indigenous communities managed otter populations in order to enhance shellfish productivity (Salomon et al. 2015). Coupled with justice-informed research, this work demonstrates that the recovery goals established for otters may benefit non-Indigenous stakeholders and harm historically disadvantaged Indigenous fishers (Levine et al. 2017). When discussing ecosystem restoration, historical ecology is increasingly demonstrating the need to acknowledge the ecological roles of people in ecosystem function (Bliege Bird & Nimmo 2018). Conservation can in fact become more effective by reinforcing the role, capacity, and rights of Indigenous peoples and local communities (Dawson et al. 2021). Such shifts in perspective can be controversial, as it challenges established knowledge priorities within conservation biology.

Baselines are socially constructed and thus influenced by political agendas, economic realities, preconceived ideas, and socio-cultural understandings of human impacts on nature (Hilding-Rydevik et al. 2017). Therefore, to share more appropriate baselines and collaborate with local peoples in a dynamic world, knowing the past, as well as ongoing, human–landscape interactions, even if imperfect, will be an indispensable guide (Alagona et al. 2012). Future work in historical ecology that combines scientific and Indigenous knowledge to focus on the complex material and cultural linkages between people and nature will help scholars, decision-makers, and community members articulate and attain support for ambitious conservation goals that seek to repair and conserve nature while respecting local knowledge and traditions and promoting environmental justice.

Q13. How did past Indigenous management result in outcomes providing insight today?

For millennia, Indigenous peoples throughout the world have directly and indirectly shaped ecosystem dynamics, resulting in a continuum of outcomes from enhancement to degradation. Habitat modification by Indigenous peoples includes structural changes, such as building stone walls in the intertidal, as well as changes in ecological processes like fire and propagating and hunting species (Boivin et al. 2016, Ellis et al. 2021, Hoffman et al. 2021). Bringing together historical ecology and Indigenous knowledge offers insight into the scale and scope of past management and stewardship activities. Importantly, these insights can empower Indigenous communities, guide place-based restoration, and help identify conservation priorities.

For example, in forest islands of the Llanos de Moxos, in the Bolivian Amazon, shellfish gatherers visiting seasonally flooded grasslands for more than 10000 years have built-up middens on higher ground, which transformed into islands supporting trees and other dense vegetation (Lombardo et al. 2013). These constructed soils provided nutrient inputs to support intensive traditional agricultural production starting around 5000 yr ago to present day (Lombardo et al. 2020). In the Western Desert of Australia, the Indigenous practice of deploying hunting fires buffers against larger-scale, and increasingly climate-driven, wildfire and creates more diverse landscape mosaics (Bliege Bird et al. 2008, 2016), increasing food and shelter for common wallaroo *Osphranter robustus* (Codding et al. 2014) and monitor lizards (*Varanus* spp.) (Bliege Bird et al. 2013), which are critically important food for Indigenous peoples (Bliege Bird & Bird 2021). On North America's Pacific Coast, the construction of clam gardens by coastal Indigenous peoples increased the available niche space for clams and secured a reliable food source for people (Smith et al. 2019, Toniello et al. 2019, Lepofsky et al. 2021). Clam gardens have had persistent indirect effects on soft sediment marine communities (Cox et al. 2019) and increased nearby forest productivity around village sites where clam shells and other materials were deposited after being consumed (Trant et al. 2016). Clam garden restoration is occurring today in many Indigenous territories (Wickham et al. 2022). While most commonly studied in settler colonial regions, similar lessons emerge from research in other parts of the world. For example, coppice management in premodern Europe maintained higher plant diversity in lowland forests than that found in unmanaged closed forests (Hédl et al. 2010).

Solutions gleaned from Indigenous stewardship and historical ecology include strategies that increase productivity and crop yields through the addition of soil amendments, enhance habitat conditions for culturally important foods through use of fire, and set conservation and restoration targets (Allen 2007, Evans et al. 2008, Lotze et al. 2011a, Colonese et al. 2023). While all of these practices are critical for Indigenous food security and food sovereignty, they may also shed light on contemporary conservation and restoration strategies more broadly.

Q14. What unique challenges and opportunities exist for historical ecology in data-poor or colonized countries?

Knowledge on the dynamics of populations and ecosystems on centennial and millennial scales has recently increased in low- and middle-income countries in the Global South. The unique challenges that these countries face in engaging with historical ecology research are that most were subjected to European colonial expansion, which led to the abrupt imposition of new elites and their languages and the silencing of the original surviving inhabitants (Palomares et al. 2007). As a result, much of the knowledge of colonized societies, including those with written records (e.g. the Maya, whose books were burned; Christenson 2007) was lost. Thus, while the time horizon that historical ecologists choose to work on tends to depend on the ecosystem they study and on the study's goals and outcomes, those working in countries that were colonized will be faced with information gaps related to the damage of the linguistic and cultural rupture that colonialism caused. Additional challenges include the maintenance of archives and colonial science which results in knowledge being controlled by outsiders.

Certain countries in the Global South face challenges such as political instability and limited funds, coupled with priority areas for fund allocation that may perceive disciplines related to historical ecology as less strategically aligned with economic development. For example, Brazil, despite being a biodiversity hotspot, has experienced substantial cuts in research and disciplines within the social and humanities realms. This issue is not exclusive to Global South countries, but increasing populism and political polarization have a more pronounced impact on low-income and less literate nations than countries in the Global North (Moutinho 2022). These political challenges underscore the importance of engaging with local communities, private sectors, institutions such as museums (see Q7), and the general public to enhance the visibility of historical ecology, and promote its application and training at both undergraduate and postgraduate levels.

Historical ecology also presents unique opportunities in data-poor contexts, particularly because ecological knowledge in most post-colonial countries is limited by the short duration of continuous instrumental records (e.g. atmospheric conditions) and observation records (e.g. fisheries statistics). In this context, historical, local knowledge, archaeological, and paleoenvironmental sources are vital, as they can provide quantitative evidence of ecological status for pre-instrumental periods (see Q4). In addition, such sources can help estimate ecosystem conditions before crucial historical turning points triggered by European contact, such as the establishment of a market economy (e.g. Fossile et al. 2023) or recent policy incentives promoting industrial exploitations (Herbst et al. 2023). The information gained can provide strong arguments for the protection and conservation of ecosystems.

3.4. Climate change

Q15. What sources are available to document past climate drivers and impacts?

Linking historical changes to underlying biophysical drivers at the millennial and basin scale has long been of interest (Swetnam et al. 1999), but progress has been limited, partly because of the mismatch of temporal and spatial scales and the resolution of available data (Lotze et al. 2011b, 2022, Harnik et al. 2012, Finnegan et al. 2015, 2024, Beller et al. 2020). With increasing coverage of historical, archaeological, and paleoecological data plus advances in modeling for hindcasting and mapping, integrating various data sources can help discern between drivers of change, and inform future projections (Lotze et al. 2019, Sandweiss et al. 2020). For example, in the Northwest Atlantic, future climate change may shift ecosystems towards conditions last seen >5000 yr ago, with warmer waters, red tides, and other algal blooms being much more prevalent than in recent centuries (Lotze et al. 2022). Similarly, synthesizing global paleoecological records during the past 21 000 yr illustrates that future warming will cause major changes to terrestrial ecosystem composition and biodiversity (Nolan et al. 2018).

To better resolve long-term (centuries to millennia or more) changes over larger special scales, additional historical records from terrestrial and aquatic inshore and offshore sources are available (e.g. marine sediments, mollusk shells, corals, animal bones and teeth, and phytoliths; also see Q2, Q4) (Sherwood et al. 2011, Sibert et al. 2017, Nolan et al. 2018, Lotze et al. 2022). Comparing patterns to local or regional ecological changes, often documented in historical and archaeological sources, will help address foundational questions about environmental drivers of change. For instance, integration of different environmental proxies (pollen from lake sediments, dendrochronology, historical maps, etc.) document the drivers of changing vegetation composition in the Mediterranean over the past millennium, with implications for understanding future vegetation change in an uncertain climate (Palli et al. 2023).

Q16. How can knowledge of ecological and societal responses to past warming inform conservation and adaptation in the face of future climate change?

The structure and composition of ecological communities are, to a large extent, driven by climate at millennial and global scales (Jackson & Erwin 2006, Zhang et al. 2007, Deutsch et al. 2015, Reddin et al. 2022). Historical environmental data are central to resolving models that seek to provide robust predictions of ecological responses to future climate conditions (Crowley & Berner 2001, Lotze et al. 2019, 2022). On land, records of past environmental and ecological dynamics reveal the thermal fragility of high mountain flora that are likely to be driven extinct along with their endemic fauna as temperatures rise (Flantua et al. 2019). In contrast, lowland tropical forests may be able to tolerate rising temperatures, but only if rainfall persists (Slot & Winter 2018), demonstrating the importance of modeling precipitation patterns as well as temperature to inform conservation. With enough spatial resolution, prior records are well suited to help resolve several key questions facing conservation, including the long-term threat of extinction debt (Jackson & Sax 2010) and the ability (or lack thereof) of ecological communities to persist under changing climates (Staples et al. 2022, Wang et al. 2023).

Due to its inherent extended chronology, historical ecology is uniquely situated to evaluate past societal responses and adaptations to major weather events and climate variability. A more accurate depiction of peoples' past responses to climate change cuts through assumptions and biases of peoples' knowledge, capabilities, success, and failures when mitigating socio-ecological risks from changing weather patterns, sea level, and climate variability (Schaan 2016). For example, people have been shown to exploit the expansion of fire-prone landscapes under changing climates (Hoffman et al. 2021). Mid-Holocene terracing and terraforming of the intertidal across the Pacific Northwest was a highly localized but broadly applied practice for dealing with sea level changes while increasing food production (Lepofsky et al. 2021). Pastoralism has been highly variable and adaptive over space and time, despite (incorrect) assumptions about its heterogeneous practice and regional impacts (e.g. overgrazing) (Boles et al. 2019). Local Indigenous knowledge is particularly valuable in understanding how communities have adapted livelihoods and cultures in response to climate change (Reyes-García 2024). Understanding the ways in which societies adapted to changing climates throughout history provides insights into societal responses to modern warming and can help to inform more equitable resilience planning (Crumley 1994, Degroot et al. 2021, Reeder-Myers et al. 2022).

Q17. How can management reference historical climate conditions, given that there may be multiple baselines?

As world temperatures continue to rise and affect ecosystems, multiple baselines may be beneficial and practical. Historical reference conditions, at least regionally, can be selected from records of past analogues of current climatic trends, such as the Last Interglacial (~110 000 yr ago), the mid-Holocene Climatic Optimum (~8000–4500 yr ago) and the late Holocene Medieval Climate Anomaly (MCA, ~1300–650 yr ago) (Jerardino 2012, Rick et al. 2020). Quantitative data derived from these records can be used to characterize ecosystem functions at that time and socio-environmental responses to climate change, providing insights into current warming trends (Meltzer 1999, Rick et al. 2020). Paired with recent written records of species and habitat occurrences and their use (e.g. fisheries records), these data can establish targets for ecological conservation (Braje et al. 2016). However, few studies have used data on specific past environments for projecting into the future (e.g. Rivera-Collazo & Perdikaris 2023), and while lists of taxonomic abundances are described for past environments, it is not always straightforward how they translate into baselines (see Q11). Therefore, close collaborations of historical ecologists and conservationists are vital for linking these disparate data sets.

Q18. How may historical knowledge be relevant for future ecosystem states that have no precedent?

Historical knowledge has significant value for guiding ecosystem restoration, resource management, and conservation under conditions that are unprecedented or novel in the recent past (Higgs et al. 2014). Historical knowledge in many forms (Higgs et al. 2014) can illustrate past variability to explain ecological legacies, contextualize unprecedented change, and provide a set of possible expectations for and responses to unpredictable climatic and ecological conditions (Grayson 2005, Millar et al. 2007, Crumley 2021).

For example, catastrophic marine heat waves threaten many fisheries, and North Pacific fisheries managers have called for the integration of a historical perspective into management strategies (Barbeaux et al. 2018, 2020). Historical data suggest there have been significant climate-driven periods of change in the Pacific herring *Clupea pallasii*, Pacific cod *Gadus macrocephalus*, and salmon (*Oncorhynchus* spp.) fisheries over millennia (West et al. 2022). Both managers and archaeologists (Barbeaux et al. 2020, West et al. 2022) have drawn on these data to develop a series of guiding questions that apply historical data to present fishery management: What were past conditions like under different climate regimes? How did broad-scale climate changes affect biophysical, biological, and social dynamics in the marine environment? Can the answers to these questions provide a range of possible responses to changing climate conditions in increasingly warm periods, and be used to frame a range of possible responses?

These questions underscore that increasing ecological novelty does not necessarily mean a separation from historically continuous functions and composition (Hobbs et al. 2014, Heger et al. 2019). Even in cases where thresholds produce novel ecosystems or alternative stable states, there is much to be learned from historical data (Whitman et al. 2019). With a rise in unprecedented ecosystem conditions, historical knowledge can yield insights into the pathways of change or analogs offering clues for managing new conditions.

4. DISCUSSION AND CONCLUSIONS

During the past few decades, historical ecology has grown from an approach used by just a few scholars primarily studying terrestrial forests, to a large community of researchers and practitioners working around the world on a wide variety of terrestrial and aquatic organisms and ecosystems (Szabó & Hédl 2011, Rick & Lockwood 2013, Beller et al. 2020). Synthesis of publications focused on historical ecology demonstrates a dramatic increase in research during the past 20 yr (Fig. 1). A variety of initiatives, training opportunities, and professional networks (such as the Conservation Paleobiology Network and Oceans Past) will help carry forward historical ecology and its application to conservation. Given this increase in research and growing list of collaborative networks, our group of historical ecologists from around the world worked to assess the current state of historical ecology and provide future directions by developing research priorities centered around key issues and questions. Four key research priorities emerged: (1) methods and concepts, (2) knowledge co-production and community engagement, (3) policy and management, and (4) climate change, covering everything from machine learning and open access data, to diversifying perspectives, Indigenous knowledge, integrating disparate data sets and information, and the place of museums, social media, and other forms of engagement in broader education and research efforts. Here we discuss each of these priority areas and their value to historical ecology, conservation biology, and science more generally.

From history to paleoecology and archaeology, historical ecologists aim to understand natural climatic and anthropogenic environmental change, drawing on a wide range of different data sets and intellectual frameworks (Beller et al. 2020). Consequently, historical ecology is inherently interdisciplinary and requires collaboration that breaks down traditional intellectual silos. This is a key perspective that emerged in our 5 research questions focused on methods and concepts (Priority 1; see Box 1). Advancements in historical ecology demonstrate that both collaboration among scholars from diverse fields and the transdisciplinary expansion of individual scientists' interests and skills are important to effectively integrate quantitative and qualitative approaches (Allen 2007, Dietl & Flessa 2011, Clavero 2016, Clavero et al. 2016, Cramer et al. 2021, Dillon et al. 2022). While progress has been made, a need for better integration of data sets across spatiotemporal scales and drivers remains. At the same time, there is a call to move beyond data to take a critical view of baselines, considering the ways in which these are socially constructed, and the power dynamics embedded in the selection and implementation of baselines (Bliege Bird & Nimmo 2018, Soga & Gaston 2018, Collins et al. 2020, Duda et al. 2023, Palli et al. 2023). Historical ecology must continue to embrace its interdisciplinary nature and seek partnerships across disciplines, including natural science, social science, and the humanities, when developing and interrogating baselines and other aspects of research.

One of the most significant aspects of our research is the need for engaging diverse communities, the co-production of knowledge and research, and diversifying perspectives (Priority 2; see Box 1). This includes expanding training opportunities that promote diversity in scholarship and practice, enchaining funding opportunities for projects that emphasize under-represented groups and co-production, and democratizing knowledge through equitable open-access publication and dissemination. Our work here emphasizes the critical need for greater equity and engagement in historical ecology, which will ultimately enhance, expand, and improve research. While historical ecology is in many ways a leader of this type of research, there are still many areas for improvement, particularly to help make research less extractive and dominated by Western scientific interests and knowledge systems and towards one that appreciates diverse knowledge systems and is done with, for, and by Indigenous and other local communities (Liboiron 2021, de Vos & Schwartz 2022). Such a transdisciplinary approach to historical ecology, based on knowledge co-production, fosters a holistic understanding of ecosystems and their dynamics, benefiting both scientific research and communities (Matarrita-Cascante et al. 2019, Dalton et al. 2020, Sidik 2022), and should be broadly incorporated in professional training, funding, and publication priorities. Continued recognition that people are not separate from ecosystems, not all human activities are negative, and people can be nested within ecosystems to promote long-term sustainability is important for better integrating distinct perspectives and knowledge systems to educate conservation practitioners, researchers, and the broader public. Knowledge co-production also seeks to break down traditional intellectual silos — a key goal of historical ecology — and one with significant opportunities for training, mentoring, and education. Finally, a more inclusive and equitable research framework offers a bridge between environmental justice, restoration, and ecological conservation with historical ecology poised to lead in these efforts (Douglass & Cooper 2020).

Historical ecology research priorities identified here also include the need for collaboration between academic researchers and practitioners (Priority 3). Curating data from the past that are relevant to conservation today demands collaboration with those implementing actions in relevant, applied management frameworks (Groff et al. 2023). Collaboration among researchers and practitioners overlaps with the previous research priorities by demonstrating another step in taking historical ecology from an academic pursuit to one focused on action and application to solving conservation and other environmental problems (Cavaleri Gerhardinger et al. 2023). Four of the questions identified in this priority emphasize the value of historical context as an integral part of the management decision-making process. Still, this is an area in urgent need of attention, especially investigations into how resource managers view findings from historical ecology and their application to decisions. Conservation efforts and application of historical ecological insights also draws from integrating diverse perspectives from different scientific communities and Indigenous communities into management decisions and priorities (Balée & Erickson 2006, Witter & Satterfield 2019).

Climate change is a central environmental concern of the 21st century, evidenced by 2023 being the hottest year on record, with a wide variety of climate-related perturbations, including massive fires in Canada and the Pacific, and extreme heat in American deserts and elsewhere, and marine heatwaves globally (Asner et al. 2022, Speare et al. 2022, Tanaka & Van Houtan 2022). Priority 4 (see Box 1) emphasizes the contribution of historical ecology to climate change, discussed in 4 questions. One of the opportunities and challenges in this area is integrating long-term records of climate change that are generally on a global scale, with historical ecological data that are often more locally focused (Lotze et al. 2022, Palli et al. 2023). Similarly, the integration of distinct data sets focused on past climate such as fossil and marine sediment records provide opportunities to compare past climatic change and ecological responses, both with and without people, to help forecast future change (Harnik et al. 2012, Finnegan et al. 2024). Although we increasingly live in a no-analog world, historical ecological records still offer an unparalleled source of information on the relationships between climate change, anthropogenic processes, and the responses of ecosystems and organisms (Higgs et al. 2014).

The 4 research priorities discussed here demonstrate tremendous opportunity and growth for historical ecology. These priorities are all synergistic, illustrating the need to increase collaboration and expand historical ecology's field of inquiry, community of scholars, and practice and heighten inclusion and co-production of knowledge. These expanding frameworks will undoubtedly drive novel insights and breakthroughs and enhance the application of historical perspectives to contemporary and environmental issues, all while emphasizing the links between social justice and environmental conservation. Even though we are living on a rapidly changing planet, we believe that now more than ever, historical perspectives are central to helping better prepare for and navigate environmental uncertainty.

As we conducted our research, a commission of scholars was poised to mark the onset of a new geological epoch, the Anthropocene, or Age of Humans, that recognizes the profound influence of people on our planet (Lewis & Maslin 2015). After considerable debate, the committee rejected the proposal to set the beginning of the Anthropocene around 75 yr ago (~CE 1950), citing the longer time frame of human impacts on planetary processes, traced to the Industrial Revolution, colonizing the Americas and Australia, or onset of agriculture (Witze 2024). Historical perspectives from the preceding 12000 yr of the Holocene and earlier demonstrate that people influenced our planet for much longer than 75 yr, making perspectives from historical ecology crucial for understanding both how we arrived at present day conditions and illuminating the path ahead.

Data and material availability. All data needed to evaluate the conclusions in the paper are present in either the paper, the Supplementary Materials, or the linked repositories. Data and source code used in this study are available in the open-access third-party repository at GitHub (https://bit.ly/477TePD).

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