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Future-proofing Science: How to Provide for the 22nd Century Historical Ecologist

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Opinion

Equipping the 22nd-Century Historical Ecologist

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Historical ecology provides information needed to understand contemporary conditions and make science-based resource management decisions. Gaps in historical records, however, can limit inquiries and inference. Unfortunately, the patchiness of data that poses challenges for today's historical ecologist may be similarly problematic for those in the future seeking to understand what are currently present-day conditions and trends, in part because of societal underinvestment in systematic collection and curation. We therefore highlight the generational imperative that contemporary scientists and managers individually have – especially in this era of tremendous global change – to ensure sufficient documentation of the past and current conditions of the places and resources to which they have access.

Trends

Although historical records have proved invaluable in addressing myriad societal challenges, societal investment in systematic collection and curation is widely recognized to be insufficient.

Such underinvestment creates gaps in data that will limit the ability of future historical ecologists to understand present-day conditions and trends, which is especially unfortunate given the degree of global change currently under way.

Individual scientists, resource managers, and citizen scientists can play a critical role in filling the gap, by taking the initiative to sample and archive the contemporary conditions of the places and resources to which they have access.

A crowdsourced initiative can be instrumental in generating the records needed to inform a wide array of current and future societal interests, including biodiversity conservation.

Are We Setting Up Our Successors for Success?

Historical ecology seeks to understand how past conditions and interactions between people and their environment have shaped contemporary conditions [1]. Such understanding can provide critical context for the interpretation of environmental change and making science-based resource management and policy decisions, today and into the future [2]. From public health to food security, many interests in society have benefited from analyses using museum and herbarium collections and other historical records [3–5]. The value of archived data and materials only grows as technologies advance that can unlock information unimagined at the time of original collection [6,7]. Molecular techniques, for example, can now provide insights into the lives of preserved biological specimens ranging from their diet to their population structure [8,9]; population and environmental attributes revealed through analyses of preserved individuals can be compared with present-day patterns and help elucidate priorities for conserving biodiversity [10]. Long-term data series can be similarly valuable [11] and help guard against biases of contemporary experience [12].

Despite these values, investment in systematic collection, curation, and maintenance of museums, herbaria, and long-term datasets is widely recognized to be insufficient [5,13]. That this disparity coincides with an era of dramatic global change is especially unfortunate, given our growing understanding of the degree of human effect on – and connection to – the biosphere [14,15]. Observations of changes in species' ranges, phenologies, disease dynamics, and vulnerabilities are now ubiquitous (e.g., [16,17]). What is contemporaneously observed and documented, however, is likely to be only a fraction of the social, ecological, and evolutionary transition under way [1,2]. Although today's scientific enterprise will ensure a degree of knowledge capture and retention, the adequacy of efforts to document this pivotal moment of Earth's history is questionable, particularly for systems that are not a focus of active research. Ironically, our current era of 'big data' [18] largely overlooks the archiving of sources of data that have proved so valuable in past studies, such as biological specimens and natural history observations [3,19].

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Gaps in historical, archaeological, and fossil records can limit their scientific and management utility [20]. Indeed, the patchiness of data and collections often relegates historical ecologists to inductive inference [1]. In this light we consider the prospects of future historical ecologists looking back to our present time. They may face the same limitations as historical ecologists today, because they too will be reliant on archived material and data that were not originally collected to answer their specific question of interest. Thus, the sufficiency of the then-historical sample may be accidental. The general lack of a systematic approach to archiving modern material in existing collections, and time-series data in general, exacerbates this risk [21,22].

Future historical ecologists would be better equipped to undertake more deductive research and hypothesis testing if they had access to records from systematic surveys and focused curation of present-day conditions. We therefore echo calls for robust societal investment in institutional curation of diverse materials that document contemporary conditions (e.g., [3,23]). However, given the high stakes of the *status quo*, we also call on individuals directly, to ask what they themselves can do to better enable the historical ecologists of tomorrow. We specifically appeal to resource managers and field scientists because, unlike many of the other societal beneficiaries of historical archives, they often have the access to original materials and remote places required to undertake the collection. Motivating voluntary action can be more successful when it aligns with personal values and interests [24], so to strengthen our appeal we encourage scientists and managers to consider not just how enhancing collections would serve some unforeseen societal good, but specifically how it could benefit future practitioners in their field. In that regard we emphasize the contributions that historical ecology can make to a societal value that many natural resource professionals are likely to share: a desire to conserve biodiversity. Although we cannot predict with precision the ecological conditions of the future, or the research questions that will be of most interest to scientists, managers, and policymakers, or even which data or materials will be most valuable in answering them, we do know how historical data are currently being used in a diversity of contexts. Given that knowledge, today's managers and scientists have a clear generational imperative: to try to anticipate the information needs of their future colleagues and to take the initiative to secure – for them – the requisite archives.

A Look Back from the Future

At the turn of the 20th century, Joseph Grinnell and colleagues conducted biological surveys throughout California, USA with the intent of leaving specimens and detailed records for the 'student of the future', knowing that the value of their efforts may not 'be realized until the lapse of many years, possibly a century' [25]. A century later, resurveying those locations, reviewing those field notes, and analyzing those collections has indeed provided critical insights into the biological effects of climate and land use change (e.g., [26]).

Looking back, one might wish that scientific surveyors of past centuries left more comprehensive records of the conditions of that time. With that recognition, however, we also can look forward and expect the scientists and resource managers of the future to wish the same of our present time. For example, just as conservationists today want to have the information they need to make informed management decisions, they want the conservationists of the future to be similarly equipped. Thus, we encourage managers and scientists working today to undertake an inquiry in which they imagine themselves working at the turn of the next century and ask 'What would our future selves most want our present-day selves to be sure to do?' We suggest they would want present-day scientists and managers to answer three questions. (i) How could we better document the past? (ii) How could we better document the present? (iii) How could we better use historical and contemporary materials to improve understanding of current ecological conditions and make more informed resource management decisions? Below, we elaborate on this inquiry.

Defining the Focal Place and Resources of Interest

To keep their query from becoming unproductively expansive, those undertaking the inquiry we propose should first establish some geographic and thematic sideboards, by specifying the spatial extent and resources of their interest. Either can be the starting point. For example, resource managers may be interested in a specific place, such as a protected area, and use the boundaries of the place to define the resources of their interest and to hypothesize what environmental changes may be expected within and near that place over time. Alternatively, a manager may be interested in a specific resource (e.g., a species) and then seek to define its spatial extent (e.g., its past, present, and future range) and the environmental conditions of interest affecting it, today and in the future. Speculating about the research questions or management scenarios that future resource managers are likely to face is helpful; modeling and environmental horizon scanning methods can be used to generate hypotheses about future conditions [27]. Those scenarios, in turn, can help further define the places and resources that should be considered in this inquiry.

Documenting the Past

We posit that future historical ecologists would want present-day scientists and mangers to ensure that information pertaining to past conditions is secured and archived. Because we are temporally closer to that past than our future colleagues, we are likely to be in a better position to access and preserve historical data and materials, given that conditions change, memories fade, sites deteriorate, and records are lost. Many places and resources will have a considerable historical record already established and in further development by active researchers. Those undertaking this inquiry might first seek to identify those initiatives, as present-day historical ecologists, anthropologists, archaeologists, ethnobiologists, paleobiologists, historical societies, and natural history museums are ideal collaborators in this effort. Our emphasis here is to identify what would be needed to complement existing initiatives: what from past decades or centuries needs additional concerted effort to preserve?

To spur this portion of the inquiry, managers and scientists might find it helpful to identify questions important for resource management today that could be investigated using historical collections or data (Box 1). Priorities for better documentation might include processing already-collected materials that have yet to be properly accessioned, cataloguing private collections, including those of local scientists [28], digitizing historical documents such as field notes, and investigating sites or materials that are vulnerable to environmental change or degradation (e.g., Box 2). Particular attention might be paid to information that could be lost with generational transitions such as staff retirements. Providing interns to assist late-career researchers process and archive materials could reduce the risk of important data being forgotten or discarded. We also encourage managers and scientists to consider the seemingly ordinary or inconsequential. Ephemera and non-traditional data sources that pertain to the place and resources of interest – personal photographs, business records, diaries, video tapes, and oral histories – may be especially vulnerable to loss and yet prove useful to future scientists (e.g., [29]). For example, McClenachan [30] used historical photographs to document long-term declines in the size of trophy fish.

Documenting the Present

Although future historical ecologists will have access to products from the broad scientific enterprise currently under way, including a variety of increasingly automated environmental data streams such as satellite imagery, they would also be likely to benefit from a more concerted effort to document present-day conditions related to the focal place and resources. Managers and scientists could initiate this portion of the inquiry by identifying questions they believe might be important to colleagues of the future (Box 1). Survey priorities for a modern

Box 1. Guiding Questions to Examine the Sufficiency of Documentation Regarding the Past and Present Conditions of a Focal Place or Resources

We call on managers and scientists to imagine performing their job at the turn of the next century and to ask 'What do we need to leave behind today to position our future selves for success?' An interdisciplinary workshop may be a productive way of elucidating priorities. Below are questions to spur discussion.

Questions to Prompt Discussion about Priorities for Better Documentation of the Past and for the Use of Such Data

- What information regarding past species distributions, environmental conditions, and human environmental interactions should we collect and analyze to inform today's management of natural and cultural resources?
- Are initiatives already under way to capture and archive data regarding past conditions?
- What additional efforts are needed to secure knowledge about the past?
- What are important or interesting research questions that could leverage historical collections and data (e.g., by applying modern molecular technologies)?
- For the place and resources that are the focus of the inquiry, what are the best examples of insights gained using existing collections and historical data?
- Are information management systems in place to ensure long-term data security and accessibility?

Questions to Prompt Discussion about Priorities for Better Documentation of the Present and for the Use of Such Data

- How might conditions change over the near and longer term for the resources and places of interest?
- What kinds of data, specimens, and other objects should we gather in the years ahead to establish a baseline for future comparison?
- How could we analyze those materials to inform current resource management?
- Do past or ongoing systematic surveys exist that could offer a useful baseline (e.g., opportunities to create a longer-term time series)?
- What are the big questions colleagues in 2100 are likely to need to answer for effective resource management?
- What are the questions we need to address now that a contemporary systematic survey can inform?
- How could we systematize and streamline the collection of priority data streams?

series could be established with a gap analysis of existing collections [31]. A consideration of emerging technologies might catalyze other ideas (e.g., Box 3). Possibilities are as numerous as they are exciting, spanning microbiome analysis, genetic barcoding, and environmental DNA, to acoustic monitoring and portable weather stations, to frozen zoos and seed banks. We should be careful, however, not to undervalue traditional methods and materials. For example, systematically collected field observations can sometimes capture even more information than the original author was aware of (e.g., [26,32]) and help future historical ecologists avoid the conundrum of trying to distinguish between evidence of absence and absence of evidence (e.g., [29]).

Non-traditional data sources and ephemera may provide other helpful records, such as personal photographs and videos, harvest data for extracted resources, email and social media dialog, and oral histories [33]. Materials that may seem unimportant when addressing current research questions may become illuminating under a future lens. For instance, Van Houtan *et al.* [34] analyzed hundreds of seafood menus through time to infer changes in the availability and abundance of marine resources. Generating hypotheses of how the resources or places of interest might change could help determine which types of materials should be prioritized [35] and enhance the likelihood that the resulting archive will be useful and not merely a hoard of historical clutter.

In addition to prompting the identification of documentation priorities, this inquiry should encourage an examination of how data collection might be systematized to capture information regarding present conditions on an ongoing basis. For example, natural resource managers can incorporate record management protocols into site access and researcher permission processes. Permit conditions could stipulate metadata standards, with particular emphasis on collecting robust locational information for field observations [36], and require eventual public accessibility of physical materials and digital data. Managers and scientists might examine how

existing monitoring programs can be adapted or supplemented to better meet the needs of future practitioners [11,35]. Given the environmental dynamism expected in the century ahead, baseline datasets and systems for monitoring species arrivals (including pathogens) and phenological changes are likely to be especially useful [37,38]. Advances in mobile technologies, remote sensing, and citizen science offer promising means of efficiently creating valuable data streams [39].

As climates change and historical conditions become less practical or appropriate as management goals, resource managers will need to redefine their objectives and how best to achieve them [40,41]. We expect future scientists and managers to be interested in how today's managers are navigating this uncertainty, determining priorities, and intervening in the system. That information will help them understand why the place and resources of their interest have come to look the way they do. At the least, managers today should document decisions and actions. Better still, they should document the values, assumptions, and constraints underpinning those decisions, as that would provide future historical ecologists with important socioecological context. Overlooking the historical significance of present-day activity is commonplace. We encourage managers to recognize that by virtue of their everyday actions (and inactions) they are participants in what will become history, and to develop systems to memorialize what they do – and, importantly, why.

Box 2. Example of Documenting the Past to Inform Contemporary and Future Conservation

Archaeology provides a vehicle to reconstruct past ecosystems and the role of people in shaping ecological change. Animal and plant remains recovered from archaeological sites contain evidence of past abundance, ecosystem structure and function, the timing of introductions and extirpations, and other variables that can be used to provide baselines or reference points for restoration and conservation. Non-renewable archaeological sites are often threatened by a variety of processes, including development and landscape alteration, looting, and marine erosion, that can destroy or compromise archaeological sites before they are studied.

Some of these processes, especially erosion of coastal archaeological sites, are particularly apparent in coastal areas like California's Channel Islands. Native Americans lived on California's Channel Islands for at least 13 000 years, leaving behind a remarkable record of human–environmental interactions, including thousands of shell middens (Figure I) [48]. Shell middens – ancient refuse piles containing bones, shellfish, plant remains, and other materials – are crucial for the documentation of socioecological relationships through time and across space; they provide material that can be sampled for ancient DNA, proteomics, and stable isotope research. Like other coastal areas around the world, archaeological sites around the Channel Islands seacoast are being destroyed by marine erosion, which is intensifying due to sea level rise [49]. Geographic information system (GIS)-based predicative modeling and field assessment can help identify and prioritize the most vulnerable sites [50]. Focused sampling and recording of such sites can enhance our understanding not only of human cultural adaptations but also of past human–environmental interactions, which can inform current and future conservation [51,52].

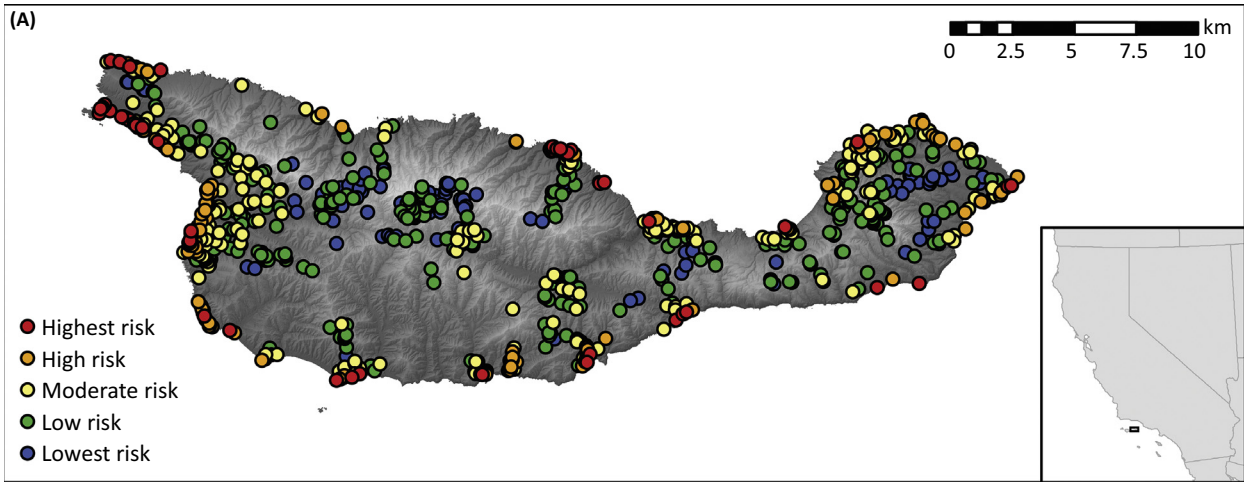

Figure I. Geographic Information System (GIS) Model of Archaeological Site Vulnerability to Marine and Stream Erosion on Santa Cruz Island (Inset Shows the Location of the Island in California, USA) (A), Eroding Shell Midden on the Island (B), and an Archived Sample of Shell Midden Awaiting Detailed Analysis and Identification (C). Map: Leslie Reeder-Myers; photographs: T.C. Rick.

Capitalizing on Historical and Contemporary Data and Materials

Our call to position future colleagues for success includes asking how we might better use the materials available today to advance science and apply it in resource management. That, in turn, should increase the likelihood that what we deem to be the most important natural,

Box 3. Example of Documenting the Present to Inform Contemporary and Future Conservation

Understanding the biogeographic distribution of species is a critical first step in conserving biodiversity [53], but the majority of species have gone undetected and undescribed [54]. Part of the reason for the poor understanding of biodiversity is that many species are cryptic: two or more species may be morphologically similar but erroneously classified as one species. Integrative taxonomy, which combines genetics, morphology, and other types of phenotypic data, has become a powerful approach in uncovering cryptic diversity [55].

Ecuador, a country the size of Colorado, has 523 described frog species – approximately five times as many as the USA and Canada combined (http://amphibiaweb.org). Many more may remain undescribed. For example, using an integrative taxonomic approach, one frog population thought to be the ornate rainfrog (*Pristimatnis ornattissimus*) was found to be a distinct species, the Ecuadorian rainfrog (*Pristimatnis ecuadorensis*; Figure I) [56]. Due to its extremely small range and rarity and habitat loss from agriculture and logging, the newly discovered species may be 'Endangered' [56] under criteria established by the IUCN (http://www.iucnredlist.org). The discovery of cryptic species using genetics is essential for contemporary conservation prioritization, providing species-specific genetic markers that allow conservation scientists to identify and monitor these species.

New genomic techniques that use thousands of loci allow a much richer inquiry than traditional genetic approaches, which typically use 1–20 loci. For example, they can help identify genes underlying adaptive differences among populations [8,57]. Characterizing adaptive genetic variation can help determine a species' potential for adaptation to environmental change, help identify appropriate source populations for assisted gene flow, and inform the design of reserve networks to maximize adaptive potential [58].

Genomics can be used to identify loci underlying adaptation to climatic variation. For example, a cross-latitudinal and elevational examination of lodgepole pine (*Pinus contorta*) and interior spruce (*Picea glauca*, *Picea engelmannii*, and their hybrids) in western Canada (Figure I) identified dozens of genes associated with spatial variation in temperature or cold hardiness, many of which were shared in both species despite their ancient divergence [59]. Such results can inform contemporary strategies to conserve spatial variation in adaptive genetic variation in key species and allow future conservation scientists to track how the geographic distribution of this variation shifts as climates change.

Trends in Ecology & Evolution

Figure I. Newly Discovered Cryptic Frog Species from Ecuador (*Pristimantis ecuadorensis*) (**A**) and the Lodgepole Pine (*Pinus contorta*) and Interior Spruce (*Picea* spp.) from Western North America (**B**). Photographs: Elicio Tapia, Sally Aitken.

cultural, and physical resources will be stewarded successfully into the future. Timely investigation and application of findings is especially critical in the context of biodiversity conservation; clearly, its aim is not just to preserve biological specimens and descriptions but to ensure the *in vivo* and *in situ* persistence of biological diversity. An important outcome of undertaking the inquiry we describe may be a heightened awareness of the assets that exist in archived materials that can be deployed to inform decision-making. Interdisciplinary discussion may reveal ways that collaborative research and emerging technologies can help generate knowledge needed to guide management (Boxes 2 and 3). When historical materials do demonstrate value in contemporary applications, we encourage broad dissemination of those examples, to highlight the relevance of such records and build a constituency for their upkeep.

Managing Records and Materials

Information management systems are essential to ensure that data and materials are not lost and opportunities to use them are not overlooked. Fortunately, increasing attention is being paid to archiving data used in published ecological studies [42]. However, many of the materials that future historical ecologists will need are physical objects and other data. Accredited research institutions have limited space and budgets and will not be able to prioritize many important materials. Consequently, it will be necessary to explore less traditional means of

Box 4. Ten Actions Managers and Scientists Can Undertake Today to Better Equip Future Historical Ecologists

- Use the inquiry framework outlined here to structure an interdisciplinary workshop focused on a place or resources of interest; collaborate to advance priority research needs.
- Integrate citizen science, crowdsourcing, and public education and outreach in the implementation of recommendations.
- Maintain a list of priority research needs; share with existing and potential research partners and students.
- Review existing collections of key taxa, artifacts, and historical documents; conduct gap analyses to identify priorities for augmentation of those collections; advance efforts to fill gaps.
- Foster partnerships to collect, receive, and curate specimens and samples from the place and resources of interest.
- Specify in research permits protocols for cataloguing field samples and for the disposition of data to ensure their security and accessibility.
- Institute salvage collection protocols (e.g., for roadkill), including cataloguing and preservation instructions.
- Develop guidelines for destructive uses of samples (e.g., blood, tissue) that consider their value over the long term.
- Ensure digital duplication of data and robust information management systems to guard against catastrophic loss.
- Build a constituency for further investment by publicizing examples of how archived materials have been valuable in resource management decisions.

securing some of the records generated by the inquiry we propose, and it may require managers and scientists investing in their own record retention and accessibility systems [43]. We recognize the risks and limitations associated with reliance on such decentralized and potentially *ad hoc* systems and reiterate how important some partnership with – and investment by – governmental agencies, research institutions, funding entities, and NGOs will be in ensuring that data are properly secured and discoverable. Research funders could foster greater discipline in information management by requiring an explanation of a researcher's record retention plans and providing funding for archivists.

Emerging mobile and networking technologies may offer means of streamlining the collection and management of digital data that are cost-effective and accessible. Digitizing records and effective use of web platforms can facilitate searchability and guard against catastrophic loss of original material. Computer technologies evolve rapidly, however, so vigilance will be required to ensure the durability of any data platform [44]. We hope our call to crowdsource better documentation will also spur creative solutions to the concomitant archiving challenge.

Concluding Remarks

Managers and scientists who undertake – and act on – the inquiry we propose would contribute to an archive with innumerable contemporary and future applications. They could also design their effort to produce additional collateral benefits. For example, the effort could be initiated as a facilitated conversation among researchers and managers to reveal documentation priorities and opportunities for collaboration (Boxes 1 and 4). Advancing the subsequent implementation as a programmatic initiative could enhance coordination among participating scientists and create opportunities to further crowdsource the effort. Events and activities such as field expeditions and the deployment of citizen scientists could advance the needed work while engaging the broader public [39]. All could be elements of an outreach strategy to focus media and public attention and foster a constituency for public and private investment in science and conservation. Funding for such an enterprise might be more forthcoming if it is marketed as an initiative evocative to the public: for example, under a banner of 'discovery' to secure a legacy for the future. Disseminating a portfolio of compelling insights gained through such initiatives could increase awareness of the myriad and invaluable societal benefits that robust historical archives provide.

One unquestionable beneficiary of such an initiative would be conservation. Even in the face of increasing ecological novelty spurred by global change [40], information about past conditions will remain an important input when setting priorities for ecosystem restoration and biodiversity conservation [20,45–47]. Records from today may well prove to be essential to the success of conservationists working in the future. However, that will only be the case if the scientists and managers working today step up to provide them. We – collectively – need to be deliberate about documenting this moment of extraordinary global change, before the opportunities to do so are lost. Although it may be challenging to anticipate what future generations would consider to be the best gift we could have left for them from our present day, we nevertheless must rise to that challenge and try to deliver it.

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