Addressing priority questions of conservation science with palaeontological data

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Summary

Palaeontologists often ask identical questions to those asked by ecologists. Despite this, ecology is considered a core discipline of conservation biology, while palaeontologists are rarely consulted in the protection of species, habitats and ecosystems. The recent emergence of conservation palaeobiology presents a big step towards better integration of palaeontology in conservation science, although its focus on historical baselines may not fully capture the potential contributions of geohistorical data to conservation science. In this essay we address previously defined priority questions in conservation and consider which of these questions may be answerable using palaeontological data. Using a statistical assessment of surveys, we find that conservation biologists and younger scientists have a more optimistic view of potential palaeontological contributions to the field compared to experienced palaeontologists. Participants considered questions related to climate change and marine ecosystems to be the best addressable with palaeontological data. As these categories are also deemed most relevant by ecologists and receive the greatest research effort in conservation, they are the natural choice for future academic collaboration.

Keywords: Conservation biology; deep-time palaeontology; priority questions; biodiversity; survey

Introduction

Palaeontology has long aimed to contribute to the understanding and forecasting of climate change impacts, and to provide baselines from ecosystems undisturbed by anthropogenic

impact. Although many palaeontological publications mention the implications for these topics only in passing, attempts to improve the attribution of organismic changes to climate change and human impacts are increasing in palaeontology. Conservation palaeobiology has emerged some 10 years ago as a new discipline to address specifically conservation questions using palaeontological approaches. Numerous review papers and books provide case studies and best-practice examples from the field [1-8].

The key messages from these papers are (i) near-time fossil observations can contribute substantially to conservation, and (ii) the most relevant contribution of these data is providing baseline information from undisturbed communities and ecosystems. Once such baselines are established, practitioners can assess the degree of change that has since occurred and potentially estimate the cost and feasibility of restoring this baseline [4, 9]. Given that a "critical mass" of practitioners in conservation palaeobiology has now been reached [3], one needs to ask why palaeontologists are not consulted more regularly for defining priority questions and in modern-day conservation efforts. For example, the recent 10-year assessment [10] of the widely-cited paper that posed 100 priority questions in conservation [11] did not include palaeontologists among the 45 authors, nor the terms "palaeo" or "paleo" in the paper. This omission was likely unintentional but nevertheless reflects a community that considers palaeontology (abbreviated as "palaeo" below) as irrelevant to conservation endeavours that are "applicable to the practice of conservation and organizations" [11, p. 559]. The psychological distance of geological time may contribute to this mindset [12].

Given the enormity of temporal scale, research on "deep time" (conventionally, the record older than the Pleistocene > 2.58 Ma) necessarily has a harder time being perceived as relevant for conservation compared to "near time" (Pleistocene-Holocene) and historical studies. Near-time data are often seen as more pertinent to conservation, primarily in the context of providing baselines of past ecological conditions [1]. Baselines are not as directly applicable in deep time, although natural variability can be explored at multiple scales, providing the opportunity to define baseline envelopes. The primary contribution of the deep-time fossil record to conservation biology is perhaps in providing novel perspectives on general extinction risk [13]. A major theme in deep-time studies is the detection of organismic traits, environmental conditions, and biogeographic realms that responded most strongly to climate-change-driven biotic crises in the past. This theme has greater relevance for the conservation of marine environments, where the effects of warming are more severe than on land [14].

Beyond constraining extinction risk, palaeontology may be able to contribute to the field of conservation in several additional areas. Although vast differences in time scales and an incomplete fossil record remain obstacles, we hypothesise here that the potential of the deep-time fossil record for conservation is still underexploited [see also 7]. We first analyse a survey by colleagues asked to judge whether they deem deep-time palaeontology able to answer 100 priority questions in conservation [11]. We then discuss conservation-relevant contributions that have been made, or that could be made, to answer the questions with highest percentage of positive replies (termed support from here).

What are the needs of conservation biology?

The formal identification of research gaps and research priorities has evolved into an established and highly-successful method of advancing a discipline [15]. Priority questions are usually defined by consensus in disciplinary or cross-disciplinary workshops attended by tens or even hundreds of participants [16], and may therefore reflect the needs of the broader community.

Bearing in mind that priority questions reflect the experience and opinions of participants, we focus on the "100 questions of greatest importance to the conservation of global biological diversity" assembled by a large group of conservation biologists [11]. Although priority questions were also defined for specific systems [e.g., 17], we limit our analysis to the cross-system priority questions of Sutherland et al. [11]. The 43 authors of that paper are scientists with conservation experience representing international organisations as well as university departments covering various disciplines and all continents. Each representative submitted a list of questions generated from their organization via workshops, discussions, or e-mail requests. A list of 2291 submitted questions grouped by themes was reduced to 1655 questions by the representatives and their organisations. During a workshop divided into topical sessions, the list of questions was reduced to 100 in a process of discussions and voting. To our knowledge, no palaeontologists were involved in the process identifying these priority questions, and none are included among the paper's authors.

Assessing the impact of a scientific paper is difficult [18], but the impact of Sutherland et al. [11] is likely high among scientists and conservation organizations. This assessment is based on (i) the wide acceptance and popularity of Sutherland et al. [11] (443 citations in Google Scholar, 20 July 2019), (ii) the reliance of conservation organisations on policy-relevant

research questions [19, 20], (iii) the reproduction of Sutherland et al.'s approach to identify priority questions in other conservation fields [17, 21, 22], and (iv) roughly one third of the works citing Sutherland et al. do so to justify their research [10]. Underscoring further the impact of the 100 priority questions is the study of Juker et al. [10], which provided a 10-year assessment of these questions and quantified their relevance and research effort.

Methods

We developed a questionnaire based on the 100 priority questions of Sutherland et al. [11], which we asked both the palaeontological and conservation communities to complete. Specifically, we asked people to assess whether the questions could be answered using palaeontological approaches. The questionnaire included two fields for assessments. The first referred to deep-time palaeontology, and the second addressed the near-time fossil record. The near-time record offers a larger suite of geohistorical approaches than the deep-time record (e.g., long-term monitoring and archaeology). We therefore expected that the community would deem the near time record better suited for addressing conservation-related questions than deep-time data. Only yes/no answers were allowed, where a "yes" (termed a positive response) could also mean that the relevant question could be only partially answered. We did not ask participants to suggest how particular priority questions could be answered.

We asked participants for background information, including their professional specialisation, level of professional experience, gender, and whether they had previously attempted to use palaeontological data in conservation biology. These meta-data were used to evaluate potential biases in the self-assessment. To increase sample size, we aimed at a limited number of categories for this background information. Professional background was categorised into "palaeo" and "conservation". This categorisation was based on participants' self-assignment or our best-fit assessment (e.g., two participants self-identifying as global change biologists were assigned to the conservation background). Experience was categorised into student, postdoc, and experienced. "Student" refers to Master and PhD level, "postdoc" applies to those individuals with a PhD and up to seven years of professional experience, and "experienced" relates to individuals with greater than seven years of experience after their doctorate. A binary categorisation of gender was considered although participants could refrain from providing this information.

We approached communities in three ways. First, we sent mass e-mails to 146 colleagues in conservation biology and palaeontology (75% with a palaeontological background; referred to as "mass mail"). Second, we developed an online form that was advertised via Twitter (targeted at followers and @ConBiology, @PaleoSociety, @ThePalAss) (referred to as "online form", https://docs.google.com/forms/d/e/1FAIpQLSfD3lOEgwsCTp7i_0YQJ-5B544JBto2V0-ibIOE8-LWM5Qx7g/viewform?ts=5c86aa1f). Third, we sent e-mails to lab members in the Palaeobiology section at GeoZentrum Nordbayern (referred to as "lab mails"). We are aware that our outreach may have missed some individuals with highly relevant perspectives and may also be biased towards more positive assessments.

We used binary plots and generalised linear models (GLMs) to analyse the survey results. Specifically, we evaluated to what degree the likelihood of a positive response was influenced by experience, background and gender. All analyses were conducted in R [Version 3.5.1, 23].

In addition to a gross-evaluation of the responses, we evaluate the responses by the 12 themes provided by Sutherland et al. [11]. These themes (Fig. 1) represent a convenient grouping of the 100 priority questions. We assess how the proportion of positive answers in the different themes relate to their relevance and research effort score as quantified by Jucker et al. [10]. Relevance refers to questions that, if answered, would have the greatest impact on global biodiversity conservation, and was assessed by Jucker et al. [10] based on a subjective assessment of 222 experts who responded to a community-wide call. Effort was quantified by Jucker et al. [10] based on the number of review papers on the respective questions. We focus our analyses on deep-time responses. This focus was chosen because deep-time palaeontology appears especially neglected in conservation. The full list of responses is available as electronic supplementary material.

Survey results

Overall, we received 71 completed questionnaires (12 from mass e-mails, 11 from lab mails, and 48 through online forms, Table S1). The return was strongly biased towards palaeontological backgrounds, as might be expected from our intention to learn about the potential contribution of palaeo to conservation (Table 1). A majority (53%) of the participants have used palaeontological approaches in conservation research.

The overall assessment was positive. On average, 52% of the questions (range 13-100%) were deemed answerable with palaeo data (deep or near time). Support was substantially lower for

deep time (median = 20%, mean = 26%, range 3-100%) compared to near time approaches (median = 46.5%, mean = 50%, range 12-100%). Variation among participants was moderate for deep-time assessments (median absolute deviation, mad = 10.4%) but large for near-time assessments (mad = 28.9%).

From here on, quantitative statements refer to deep-time responses. Basic results, however, were similar for near-time responses (see 'Near-Time Palaeontology' section). Questions related to climate change (52%) and marine ecosystems (52%) received the greatest support, whereas questions related to conservation interventions and societal context had the lowest support (6 and 8%, respectively, Fig. 1). Questions related to terrestrial systems also received low support (16%), potentially because terrestrial questions pertain to systems strongly modified by recent anthropogenic activities such as "impacts of biofuel production", "forest governance", "urban reserves", "grazing of domestic livestock" and "agricultural practices".

Support was negatively associated with professional experience (chi-square test, $X^2 = 114$, df = 2, $p < 2 \cdot 10^{-16}$). In all themes, experienced researchers were more conservative than postdocs, who in turn were more conservative than students (Fig. 2). Colleagues with a conservation background were more positive about the use of palaeo data for conservation than were researchers from a palaeo background ($X^2 = 12.6$, df = 1, $p = 0.0004$) (Fig. 3). Gender also seemed to influence responses, with researchers identifying as women being more positive about palaeo's contribution to conservation than men ($X^2 = 39.2$, df = 1, $p = 3.7 \cdot 10^{-10}$). This effect is partly attributable to a stronger representation of young, potentially more optimistic researchers among women participants (85% of women were students or postdocs as opposed to 67% of males in these categories). However, a multiple logistic regression allowing for an interaction between gender and experience [R syntax: glm(deep.time ~ background + experience * gender, family="binomial")] still identified males as significantly more strongly associated with negative responses than females. The lower support from palaeo backgrounds and higher career stages remained significant in this multivariate context, which overall explains 2% of deviance among responses. The themes that received the greatest percentage of positive answers were also the ones deemed to be of highest relevance and receiving the greatest research effort by Jucker et al. [10] (Fig. 4).

Addressing specific questions

Positive responses to individual deep-time related questions varied profoundly among themes (Fig. 5a). No question received unanimous support from all 71 participants in terms of being answerable with deep-time palaeontology, and only one question was agreed by all participants to not be answerable ("social impacts of conservation inventions"). The 10 questions with the greatest support were distributed among four themes (Fig. 5b). We discuss questions with > 80% support (the top six) for deep-time palaeo below, ordered from strongest to weakest support in the questionnaires. The discussion reflects our opinions, which other participants and researchers may view differently. We focus both on contributions already made to the respective questions, and the likelihood that the questions may be answerable in the future. The information in brackets refers to the overarching theme of priority questions [11], the relevance and effort scores of Jucker et al. [10], and the percentage support from the questionnaires from this study.

Q46: How will ocean acidification affect marine biodiversity and ecosystem function, and what measures could mitigate these effects? (Marine Ecosystems, relevance score = 0.91, effort score = 0.61, 96% support)

In spite of its strong community support, answering this question will likely be difficult with deep-time palaeo approaches. Ignoring mitigation, the palaeontological community would first need to provide unequivocal evidence for ocean acidification in past systems, and then disentangle its impacts from other climate-related or environmental stressors. Although estimates of pH decline across some ancient hyperthermal events are now available [24, 25], evidence for ocean acidification is still meagre in deep time [26].

Q51: What will be the impacts of climate change on phytoplankton and oceanic productivity, and what will be the feedbacks of these impacts on the climate? (Marine Ecosystems, relevance score = 0.78, effort score = 0.71, 94% support)

A deep-time answer to this question may be closer at hand than in the previous example. Several key studies have established feedbacks between oceanic productivity and climate in the Quaternary, specifically regarding the links between the biological pump and CO_2 variations in glacial and interglacial intervals [27]. In deep-time studies, biodiversity rather than productivity is usually studied when trying to understand the impacts of climate change on phytoplankton. The fossil record of phytoplankton is exceptionally good, providing high-

resolution data, especially over the Cenozoic era [28]. Beyond diversity, suitable techniques also exist to determine absolute abundance data [29, 30], which together with high-resolution age models can be transformed into accumulation rates and hence indices of productivity. Geographically variable productivity responses have been established for the Palaeocene-Eocene Thermal Maximum (~56 Ma), the most recent hyperthermal event [31], providing baseline expectations for the future. Combining fossil phytoplankton occurrences, geochemical proxy data, and ecological modelling is an obvious route to address this question in deep time.

Q1: Do critical thresholds exist at which the loss of species diversity, or the loss of particular species, disrupts ecosystem functions and services, and how can these thresholds be predicted? (Ecosystem Function and Services, relevance score = 0.56, effort score = 0.49, 92% support)

Although this question was deemed of relatively low relevance by conservation biologists, forecasting potential tipping points and identifying keystone species is intuitively of high importance. Identifying keystone species is difficult today [32] and perhaps impossible in fossil assemblages. However, identifying critical thresholds of ecological collapse is within reach, particularly in the context of climate-driven biodiversity crises. Research increasingly reveals that such crises are less abrupt than previously thought. At least two deep-time extinction pulses, associated with wholesale losses of tropical reef systems (the end-Permian and the Toarcian crises) were preceded by community changes, minor extinction pulses, and declining body sizes of marine organisms [33-36]. Improved constraints on the patterns that signal early warning of ecosystem collapse is thus an obvious route to address this question. Of course, a disconnect will remain between the modern anthropocentric view of ecosystem services and the palaeo perspectives focusing on functional diversity [37, 38] and productivity [39].

Q10: Which elements of biodiversity in which locations are most vulnerable to climate change, including extreme events? (Climate Change, relevance score = 0.94, effort score = 0.84, 92% support)

This question, ranking in the top five by relevance [10], is perhaps the one to which palaeontology can make unique contributions. Assessing the vulnerability of species to

climate-related stressors is a key question in palaeontological endeavours. Species vulnerability in palaeontology is assessed primarily in terms of global extinction [e.g., 40, 41], but a few studies also highlight regional extirpation [e.g., 42, 43, 44]. Modern ecology can usually only assess population declines and estimate extinction risk at short time scales, whereas palaeontology provides direct evidence of extinctions. On the other hand, deep-time fossil data cannot inform about the effects of direct human impacts.

A rich literature exists on how lifestyles, habitats and organismic traits affected extinction risk under past climate change [45-52]. A pressing question is, of course, how well these ancient vulnerabilities reflect modern vulnerabilities, that is, to what extent are they conserved over time. While near-time studies suggest variability through anthropogenic impacts [53, 54], patterns in deep time are more contingent. Investigation of individual- and population-level (e.g., abundance) traits has provided evidence for a good match between fossil and recent extinction risk [55], and newer studies support this claim [40, 56, 57].

Palaeontological studies have also confirmed that habitat breadth and geographic range are major predictors of extinction risk, but the relationship may break down during intervals of high extinction rate [41, 58, 59]. Occupancy trajectories also have great potential to improve the assessment of extinction risk [60]. The latter observation is important, because only fossil and historical data provide direct evidence of long-term changes in geographic range, whereas the status quo of geographic range is better assessed in the Recent.

Establishing coherent geographic patterns of vulnerability across ancient warming intervals would perhaps be of great benefit to conservation biologists. Unfortunately, latitudinal extinction selectivity varies profoundly over time, even across hyperthermal events [49, 61]. More work is required to better predict geographic hotspots of climate-related impacts.

Mapping biodiversity hotspots in which vulnerable taxa are concentrated is a successful strategy to define conservation priorities [62-64]. For example, Finnegan et al. [13] combined (i) ancient extinction rates of taxa to establish general vulnerabilities, (ii) the spatial distribution of those vulnerabilities, and (iii) their overlap with current and predicted human impacts. The authors found that the tropics are most at risk, supporting neontological assessments [65, 66]. No conservation action has yet resulted from this and similar palaeo-informed maps [e.g. 67].

'Extreme events' in Q10 refer to events that are days and months in duration, whereas the palaeontological record typically captures events spanning thousands to hundreds of

thousands of years. This mismatch of time scales is an issue, especially when trying to compare rates of change. However, it is possible that the extinction mechanisms are not very different. For example, several marine mass extinctions are likely the result of multiple stressors that today jeopardise modern marine systems: warming, ocean acidification, and deoxygenation [45, 49, 68, 69]. The mechanistic links bridging organismic physiology and deep-time palaeontology are beginning to emerge [57], and a closer collaboration among disciplines is clearly the way forward

Of course, species richness is just one of several elements of biodiversity. Other elements, such as phylogenetic, functional and ecosystem diversity are also (partly) accessible in fossil data [70-74]. The most promising endeavour is perhaps functional diversity, for which studies suggest limited loss across mass extinctions among marine invertebrates [37, 38] but substantial turnover of functional richness across the Pliocene-Pleistocene boundary for marine megafauna [75].

Q32: What was the condition of ecosystems before significant human disruption, and how can this knowledge be used to improve current and future management? (Ecosystem Management and Restoration, relevance score = 0.27, effort score = 0.46, 86% support).

This question, related to baselines, is a core strength of conservation palaeobiology, with many successful case studies in near-time palaeo (see introduction). Deep-time palaeontology cannot provide baselines with direct relevance to contemporary ecosystems. However, deep-time palaeo may be able to provide important information on the natural variability of ecosystems over multiple time scales. This question was deemed of low relevance (bottom five) by the conservation community [10], demonstrating a possible disconnect between the self-perception of conservation palaeobiologists and the (potential) actual needs of the conservation community.

Q12: What factors determine the rates at which coastal ecosystems can respond to sea-level rise, and which of these are amenable to management? (Climate Change, relevance score = 0.47, effort score = 0.58, 85% support)

Sea-level changes are well characterised in the geological record [76], and the response of coral reef systems to rapid sea-level change has been explored intensely since Schlager's [77] seminal paper. Sea-level rise alone has rarely caused reef drowning, but exceptions exist, such

as during rapid meltwater pulses in the terminal Pleistocene [78] that also influenced reef morphology and community composition [79]. Similar deep-time examples cannot be provided, but it is well known that coastal ecosystems have changed substantially with sea-level rise. How exactly communities are expected to change and what this means for apparent versus real extinctions is explored thoroughly in the subdiscipline of stratigraphic palaeobiology [80, 81]. In sum, there is great potential to answer this question with deep-time observations, but this potential is somewhat underutilised.

Near-Time Palaeontology

Although we focused on deep-time palaeontology, some commentary on near-time assessments is relevant. Besides greater overall support for near-time palaeo (see section Survey Results), little difference exists in assessments. All basic tendencies (experience, gender and background) are the same, except that professional background had a non-significant contribution to support ($X^2 = 3.4$, df $= 1$, $p = 0.06$). The rank-order correlation in the number of positive assessments is high (Spearman's rho $= 0.90$, p $< 2 \cdot 10^{-16}$). Only three of the top ten positive assessments in the near time evaluation (Q55: "vulnerability of freshwater species to human impacts"; Q5: "strategies for distributing material benefits of biodiversity to conservation"; Q9: "impact of polar ice melting on high-latitude ecosystems") are not among the top ten in the deep-time evaluation.

Discussion

We used a novel approach to assess the potential contribution of palaeontology to conservation science. Previously, authors have provided examples of palaeontological studies and assessed how these studies may contribute to conservation [e.g., 1, 2]. We instead asked first, what the actual priority questions of conservation biology are, and then evaluated how deep-time palaeontology may contribute to answering these questions. Although community support for some questions may not necessarily mean that an answer is within reach (e.g., Q46 on ocean acidification), strong support existed for several highly relevant questions, for which deep-time answers seem to be attainable.

We found that increased experience makes researchers more conservative in their assessment of the ability of palaeontology to contribute to conservation-related questions. Increased experience may reduce naivety towards a more pragmatic assessment. Alternatively, younger

researchers may be more open minded and think more about novel, interdisciplinary research than established researchers. Naivety may also be responsible for the more positive assessment of conservation biologists compared to trained palaeontologists. Neontologists may know less about the limitations of palaeontological approaches, especially concerning biases introduced from taphonomy—the post-mortem fate of organisms [82]. If this interpretation is correct, reservations about the quality of the fossil record are not a likely cause for the lack of integration of palaeontological and neontological approaches.

Our results may be biased to some degree. For example, colleagues not responding to our survey may have done so because they have a more negative view on the answerability of priority questions. However, sample size does not appear to be an issue, because all basic results (ranks of support for questions, differences between gender and experience) were consistent between our initial draft with 42 completed questionnaires and the final 71.

Previous palaeo work on conservation-related topics rarely addressed priority questions directly, which led to discrepancies between actions and needs. For example, the question to which conservation palaeontology has traditionally contributed most (Q32 on baselines), was deemed of low relevance by conservation scientists [10]. Rather than reflecting a disregard of palaeo research by the conservation community, this mismatch is probably due to a general divergence between researchers and practitioners leading to a well-known research-implementation gap in conservation biology [83]. Regardless, the focus of conservation palaeobiology on establishing baselines is perhaps too narrow given the rich toolkit exemplified above and in Dietl and Flessa [7].

The poor match between priority questions and palaeontological action is obvious for terrestrial systems. Given the long list of "success stories" for conservation palaeobiology in terrestrial systems [2], the poor community support of this theme using both deep-time and near-time palaeo appears odd. If the Sutherland et al. [11] questions are truly key conservation questions in terrestrial systems, the previous approaches of conservation palaeobiology may have been, at least partially, misguided.

Perhaps the most common issue with deep-time palaeo that challenges its ability to inform conservation is the vast time scale over which patterns are observed (Fig. 6). Deep-time patterns differ by orders of magnitude from the decadal changes in which conservation science are most interested. However, physiological studies, conducted over hours to weeks, are also log-scales apart from the conservation time scale of interest, yet experience fewer obstacles in their integration into climate-impact related research [84]. Questions of scale

need to be a major research focus for palaeontology to become truly relevant for conservation science. This is a precondition for reducing the psychological distance of palaeontology in the conservation community [12].

Three strategies may help improve the integration of palaeo in conservation work: (i) Convince conservation researchers and practitioners that questions highly relevant to conservation goals can be answered using near-time and deep-time palaeontological information; (ii) adapt palaeo approaches to the most relevant priority questions in conservation biology; (iii) combine neontological and palaeontological approaches into a transdisciplinary conservation science.

Conclusions

Palaeontology can best show its relevance to applied science through actively contributing to the conservation of biodiversity and ecosystem health. As demonstrated above, the self-assessment of conservation palaeobiology is not perfectly matched to the needs of conservation biology. There are many conservation questions that palaeontological approaches can contribute to, either with existing data and methods, or in principle with targeted research in the future.

Assessing the impacts of climate change remains the best candidate for marrying palaeontological and neontological approaches in conservation science [85], and marine systems are better suited for a contribution to conservation biology than terrestrial systems. Because existing priority questions are highly influential in shaping research agendas and distributing funding [10], palaeontologists should carefully check them before designing new conservation-related projects.

In our opinion, the way forward is transdisciplinary, uniting both palaeontology and conservation biology. None of the priority questions in conservation biology can be answered uniquely with palaeo approaches, but palaeo's unique perspective on past extinctions and ecological changes without anthropogenic influence offer a potential that can be fully exploited only when combined with a neontological toolkit.

Additional Information

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Figure and table captions

Table 1. Matrix of experience vs. professional background among returned questionnaires (seven were missing relevant metadata).

	Conservation biology	Palaeontology
Experienced	6	21
Postdoc	5	16
Student	5	11

Figure captions

Fig. 1. Percentage of positive responses in surveys to the 100 priority questions in conservation biology [11], organised by themes. The replies in this and the following figures refer to deep-time responses, but near-time responses show the same basic trends.

Fig. 2. Percentage of positive responses by theme and experience level. Overall support is significantly greater among young scientists (see text for statistics).

Fig. 3. Percentage of positive responses by theme and professional background. Overall support is greater among conservation biologists.

Fig. 4. Mean relevance and effort scores [based on 10] within the themes of ref. [11]. The percentage of positive answers in each theme is indicated by the size of the circles.

Fig. 5. Positive responses to individual questions organized by themes as in ref. [11]. (a) Bubble chart of responses to all 100 questions. Area of circles is proportional to the number of positive responses and some individual questions are numbered. (b) The 10 top-ranked questions sorted by rank. Colours match the themes in (a).

Fig. 6. Time scales over which questions within the themes of ref. [11] can be potentially addressed.