Trends in
Ecology & Evolution

CellPress
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Review

A horizon scan of global biological conservation issues for 2024

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We present the results of our 15th horizon scan of novel issues that could influence biological conservation in the future. From an initial list of 96 issues, our international panel of scientists and practitioners identified 15 that we consider important for societies worldwide to track and potentially respond to. Issues are novel within conservation or represent a substantial positive or negative step-change with global or regional extents. For example, new sources of hydrogen fuel and changes in deep-sea currents may have profound impacts on marine and terrestrial ecosystems. Technological advances that may be positive include benchtop DNA printers and the industrialisation of approaches that can create high-protein food from air, potentially reducing the pressure on land for food production.

Highlights

Our 15th annual horizon scan identified 15 emerging issues of concern for global biodiversity conservation.

A panel of 31 scientists and practitioners submitted a total of 96 topics that were ranked using a Delphi-style technique according to novelty and likelihood of impact on biodiversity conservation.

The top 37 issues were discussed in person and online in September 2023 during which the issues were ranked according to the same criteria.

Our 15 issues cover impacts from the development of new sources of hydrogen fuel to temperature changes in the mesopelagic ocean zone.

Other emerging technologies include benchtop DNA printers and the creation of high-protein food from air.

Horizon scanning for conservation

Horizon scanning is a well-established method for identifying emerging threats and opportunities that allows sufficient lead time to develop actionable solutions [1]. The inaugural horizon scan of global conservation issues took place in 2009 [2], and every year since we have sought to identify 15 issues before their substantive impacts are widely recorded. Examples include the use of environmental DNA (eDNA) for aquatic and air monitoring, and the promotion of biochar to enhance carbon sequestration. Inherent to horizon scanning is the understanding that some issues will never fully materialise because the participants misjudged the signal, other factors intervened, or perhaps occasionally because forewarning reduced the likelihood that the issues would be realised.

Technologies for reducing human impact on the environment caused by food production and consumption have featured regularly in our horizon scans (e.g., [2,3]). These issues are increasingly seen as a means to tackle both biodiversity loss and climate change. If, for example, global meat and dairy consumption is halved by 2050, greenhouse gas emissions from the agricultural sector could decline by a third, with over 653 million hectares of land being removed from production [4]. Restoration of these lands by 2030 could contribute 13–25% of the estimated area needed globally under Target 2 of the Kunming–Montreal Global Biodiversity Framework. Others have suggested that the food system could achieve net negative emissions by 2050 by adopting different technological solutions [5]. The likelihood of such impacts through more environmentally friendly food consumption, similar to other interventions in human behaviour and decision-making, is likely to depend on the success of targeted behavioural change approaches [6] and market dynamics.

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Innovations to reduce greenhouse gas emissions from industrial and energy systems have also regularly featured in our horizon scans (e.g., [7,8]). Investments in cleaner processes and technologies are currently affected by rising costs and by a lack of policies to stimulate demand and support investment or to control environmental impacts. For example, the International Energy Agency [9] highlighted that many governments have announced programmes to support low-emission hydrogen production and use, but most have not implemented them. One exception is China, which is projected to reach 50% of global hydrogen-producing capacity by the end of 2023 and is developing new infrastructure that is directly reliant on hydrogen [9].

Box 1. Horizon scanning methods

In March 2023, a panel of 31 scientists, practitioners, and policymakers accepted the invitation to participate in this year's horizon scan. Participants were required to submit two to five issues that were novel, largely unknown, and likely to impact biological conservation in the future. Participants canvassed their networks and colleagues in person or via email, social media platforms, and conferences, reaching over 1700 people (~20% from the Global South). We counted all direct contacts, whether in person or online, but considered social media posts or generic emails as a single contact unless multiple individuals responded. One participant, R.B.P., worked with W.E.P. to identify candidate issues by using artificial intelligence (AI) (discussed in the section ‘Identification of issues’).

Figure I provides an overview of the process used to identify and score issues. This year, 96 issues were submitted for consideration. Participants confidentially and independently reviewed and scored each issue from 1 to 1000 (low to high). Every issue was scored according to two criteria: (i) its potential positive or negative impact on biological conservation, and (ii) its novelty. Notes were added by participants to provide further information should a particular issue be retained for the second round. The effect of voter fatigue [13] was counteracted by randomly assigning participants to receive one of three lists of issues in different orders. Participant scores were converted to ranks (1–96), and issues with the highest 36 median ranks were reviewed against the qualifying criteria. We considered the suitability of all issues with which >50% of participants indicated they were familiar and removed two issues that were too well known. One issue that had been included in the final 2019 horizon scan was removed from further consideration. Participants had the opportunity to retain any issues ranked lower than 36. This year one issue was retained. Thirty-seven issues advanced to the second round and were discussed at the workshop.

We allocated each participant up to four of the 37 issues, none of which they were familiar with, to further investigate and bring additional information to the workshop. Twenty-six participants convened in person for the workshop in September 2023, and an additional five participated online. Each participant, whether online or in person, joined the meeting virtually so that all could access the chat function. Many contributed extra information, such as links to relevant publications, in the chat. Participants scored each issue on a scale of 1–1000 (low to high) at the end of its discussion, and considered it against the same criteria as applied in round one. Scores were converted into ranks at the end of the workshop, and the 15 issues with the highest median ranks were revealed. This year, three similar issues related to hydrogen were ranked in the top 15. It was proposed that these issues should be amalgamated. Participants voted by email on whether the three issues should be combined and, if so, which of the three should be the primary issue. This meant that the issues initially ranked 16 and 17 were included in the final list. The single issue generated by AI that progressed to the second round was ranked 24 after the discussion.

The issues are presented in thematic groups rather than rank order:

- New sources of hydrogen for energy production
- Decarbonised ammonia production
- Food and animal feed from autotrophic hydrogen-oxidising bacteria
- Acceleration of light-free artificial photosynthesis with indoor agriculture
- Extensive adoption of carbon mineralisation techniques
- Evidence of earthworm population declines over large regions
- Use of ecoacoustics to monitor soil ecology
- Wildfires affect climate oscillations
- Benchtop DNA printers
- Extrapolating chemical toxicity assessments
- NEOM (The Line) linear skyscraper city
- Sea urchin die-offs affect marine ecosystems
- Removal of carbon dioxide from the ocean
- Rising temperatures in the twilight zone affect the biological carbon pump
- Melting Antarctic ice affects deep sea ocean currents

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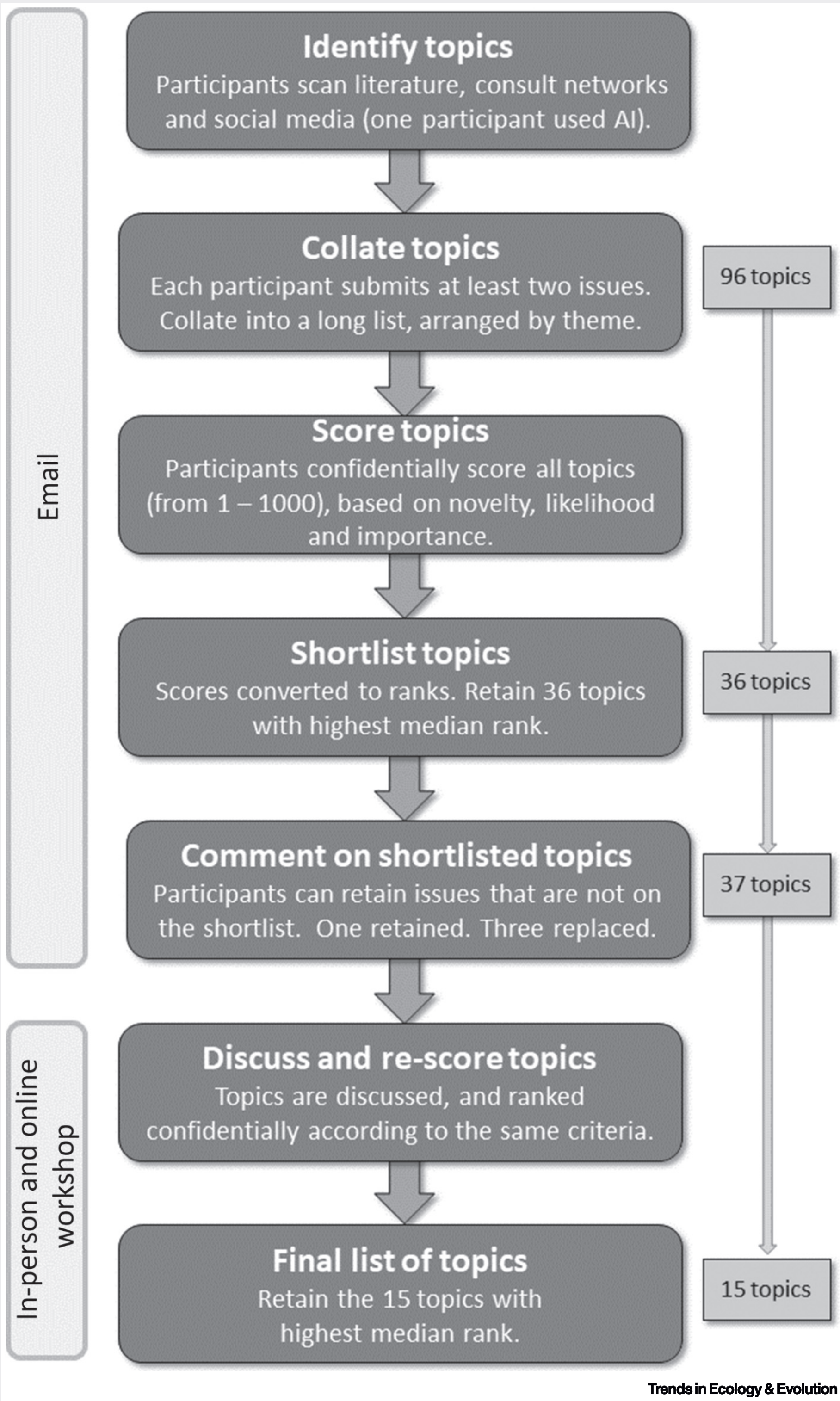

Figure I. Process for identifying and selecting issues for horizon scan 2024. Abbreviation: AI, artificial intelligence.

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Identification of issues

We followed standard methods, and applied a modified Delphi technique to select issues (e.g., [2,3]) (Box 1). This technique maintains the transparency, repeatability, and inclusivity of the process [2,10].

In 2016, we highlighted artificial superintelligence as a horizon issue [11]. During 2023, interest and concern about the potential and the risks posed by artificial intelligence (AI) surged [12]. Four of the original 96 issues submitted this year focussed on AI, but none was retained beyond the first screening step (Box 1). In addition, and with agreement from W.J.S., one AI expert (W.E.P.) used three AI models, GPT-3.5 (Open AI), GPT-4 (Open AI), and Claude (Anthropic), to generate 20 novel topics in ecology, conservation, and environmental science. W.E.P. used our selection criteria (issues must be novel, important, and relevant) to specify the format and general area of interest of the issues but not the exact research topic. W.E.P. then screened the AI-generated topics with respect to accuracy, novelty, and interest, and iteratively revised the initial prompt to exclude topics that were not relevant or toward which the AI models seemed biased. The 20 AI issues were submitted to W.J.S. and A.T., who selected five that they considered to be suitable for consideration. These five were added to the list of issues submitted by the other participants. One of the five was selected for discussion at the workshop but was not ranked among the top 15. To avoid potential bias, only the participants involved in the initial generation and selection of AI issues (W.J.S., R.B.P., W.E.P., and A.T.) were aware that any topics had been suggested by AI until all rounds of selection were completed.

The final 15 issues

In the following we present the 15 novel issues that could influence biological conservation in the future resulting of our 15th horizon scan.

New sources of hydrogen for energy production

The use of hydrogen as an energy source has grown considerably in recent years, creating demand for new sources, transport mechanisms, and generation methods. Currently, most hydrogen is produced by steaming natural gas (termed brown or blue hydrogen). Other production methods include production by electrolysis of fresh water (green hydrogen) or by extraction from natural subsurface sources in the Earth's crust (white hydrogen) where availability has recently been found to be orders of magnitude larger than was previously estimated [14]. Extracting white hydrogen requires drilling over large areas and potentially involves the development of transport infrastructures in relatively undisturbed ecosystems. Recent advances could favour the direct use of seawater in green hydrogen electrolysis, which would ease pressure on limited freshwater supplies [15] and increase the feasibility of offshore hydrogen production, but drawbacks include the production of hypersaline brines and excess oxygen that are probably harmful to marine habitats in particular [16]. Despite the potential for these new hydrogen sources to reduce greenhouse gas emissions, leakage from hydrogen infrastructure may increase with scale and influence the abundance of greenhouse gases such as methane and water vapour [17]. Construction of hydrogen-tight infrastructure will be critical to ensure that any transition to hydrogen economies mitigates climate change.

Decarbonised ammonia production

Ammonia (NH_3) has high energy density and is the precursor to many nitrogen-containing compounds. It is primarily used as a fertiliser and is produced with fossil fuels via the energy-intensive Haber–Bosch process. In 2021, 1.5×10^8 tonnes of ammonia was produced globally, releasing 3×10^8 tonnes of carbon dioxide (CO_2) into the atmosphere [18]. A novel and fast method of forming ammonia sprays water microdroplets (the hydrogen source) onto magnetic, iron oxide-coated graphite mesh, and uses nitrogen or air as the nebulising gas [18]. This simple, low-cost approach converts widely available materials into ammonia and could be deployed industrially, thus decarbonising ammonia production for fertiliser, transportable energy, and fuel [19]. Despite the potential benefit of emissions reduction, any increased use of such products via a distributed, decarbonised, low-cost, and ubiquitous supply of ammonia could have considerable negative environmental impacts. Human alteration of the global nitrogen cycle via combustion and fertiliser use is already a major contributor to global declines of species, eutrophication, and reduction of air quality. Associated emissions of nitrous oxide (N_2O), a potent greenhouse gas [20], could greatly exacerbate these problems.

Food and animal feed from autotrophic hydrogen-oxidising bacteria

The production of food remains a major driver of global biodiversity loss owing to land conversion, greenhouse gas emissions, unsustainable levels of fishing, and pollution. Increasing demand for high-protein foods, including meat and fed aquaculture in developing economies, will probably increase the environmental footprint of food production. Building on early research on extraterrestrial food production (e.g., [21]), a growing number of companies are working to produce protein economically with autotrophic hydrogen-oxidising bacteria. The bacteria are grown in bioreactors supplied only with hydrogen from the electrolysis of water, nitrogen from decarbonised ammonia, and carbon dioxide from direct air capture [22]. Biomass produced with these bacteria has a nutritional profile similar to that of soy or fish, is relatively tasteless, and can be integrated into many food and feed products [23]. The resulting protein products have been approved for human consumption in Singapore and will soon be produced industrially, with other regulatory applications pending. If industry can rapidly expand this generally fossil fuel-free method of food production, the growing demand for protein for human or animal consumption could be decentralised and decoupled from the substantial and growing environmental consequences of its production.

Acceleration of light-free artificial photosynthesis with indoor agriculture

The expansion of global agriculture for crop production is a major driver of global biodiversity loss. Plant-based food production is constrained by the energy-inefficient process of photosynthesis [24], and requires significant land area. Therefore, increases in photosynthetic efficiency would support sustainable food production [25]. Hann *et al.* [26] created artificial photosynthesis with an electrocatalytic process in which acetate made from water, electricity, and carbon dioxide replaces the glucose created and consumed during traditional photosynthesis. The acetate is added to vials in which plants grow hydroponically. Energy is provided by photovoltaics that power an acetate-producing carbon dioxide electrolyser, a process up to 18-fold more effective than biological photosynthesis [26]. The use of alternative energy sources, such as wind, would further remove the need for sunlight. This novel photosynthetic process has been demonstrated for several food crops in laboratories and has potential for significant efficiencies. Even when accounting for the space required for renewable energy infrastructure, this process uses considerably less land than traditional crop production because it allows urban production of food in multistorey buildings.

Extensive adoption of carbon mineralisation techniques

Widespread application of rock dusts, notably basalt, across agricultural land could exploit the elevated carbon dioxide and carbonic acid concentrations in soils to mineralise carbon. If applied across large areas, the method could mineralise 0.5–2.0 gigatonnes of carbon dioxide annually [27]. Recent evidence that this approach increases crop yields [28] is likely to accelerate uptake, leading to adoption in many regions. The wider environmental impacts of rock dust applications remain unclear. Ancillary benefits may include reduced acidity of agricultural soils and ocean water, increased diatom production, and reduced eutrophication [29]. However, application could also risk ecosystem-wide heavy metal contamination, especially if dust is produced via building materials or mining waste; it could also increase the siltation and turbidity of freshwater, coastal, and marine habitats, and negatively affect species adapted to low pH soils. Although potentially sourced from mining waste and industrial byproducts [27], the sourcing or application of rock dusts at unprecedented extents may increase mining and impact limestone ecosystems. Ultimate implementation of this approach will depend on the availability of rock dust, realisation of improvements in soil and crop yields, and government subsidies.

Evidence of earthworm population declines over large regions

Earthworms (phylum Annelida) are ecosystem engineers that play important roles in nutrient cycling, soil fertility, and ecosystem condition, and contribute significantly to global food production [30]. Although global insect declines are increasingly well documented, the status of soil invertebrates is not. Simple models suggest that pesticide use may have reduced global earthworm populations [31] but, as for many invertebrate taxa, data on trends in earthworm abundance were only available from studies in small areas (e.g., [32]). The first national-level assessment of earthworm trends collated almost 100 years of data on soil invertebrate densities and biomass from across the UK. This revealed evidence of 33–41% declines in earthworm abundance over the past 25 years, particularly in farmland (likely driven by agricultural intensification) and broadleaved woodland [33]. Although these data were not derived from systematic monitoring, they suggest that considerable loss has occurred across UK soils, and possibly in other countries with similar agricultural and other land-use practices. Such declines would likely have significant effects on soil health, ecosystem structure and function, and the provision of ecosystem services, with potential cascading effects on soil structure, species diversity, and chemistry.

Use of ecoacoustics to monitor soil ecology

Acoustic technologies are routinely used to assess the presence of animals above ground. Soil ecoacoustics is a relatively new use of the technology to monitor the presence, composition, or number of soil invertebrates in an effective and nonintrusive manner [34,35]. The sounds in soils range from water moving through soil pores to the distinct vibrations of different animals moving and communicating, which can be analysed with acoustic indices. Comprehensive information on soil invertebrates, including the diversity of target invertebrates in the soil of restored areas and the ecological processes they support, does not currently exist. Soil ecoacoustics has effectively assessed some restoration outcomes, such as the diversity of sounds in soils, in a temperate forest [36], and sound signatures may provide indicators of soil quality. However, for soil ecoacoustics to become ubiquitous for monitoring, particularly if members of the public are to provide data on the state of soils, methods need to be improved and standardised. A more comprehensive understanding of soil community structure and function may result from combining soil ecoacoustics with other monitoring techniques, such as eDNA metabarcoding which provides data on the composition of the soil microbiota.

Wildfires affect climate oscillations

Wildfires and land-use associated biomass burning produce aerosols that reduce the absorption of solar radiation and affect cloud and precipitation patterns [37]. Wildfires are likely to become more frequent and larger in many regions worldwide. Evidence is emerging that the aerosols produced from wildfires and biomass burning can affect climate oscillations or induce shifts in the position of high- and low-pressure systems, and thus influence the distribution of temperature and pressure over large oceanic areas. The intensity of the El Niño Southern Oscillation (ENSO), one of the best-understood climate cycles, may be sensitive to aerosols produced by biomass burning [38]. For example, an increase in biomass aerosol concentrations in one season may lead to sea-surface cooling and development of the La Niña phase of ENSO. Short climate cycles have major implications for biodiversity conservation through ecosystem consequences and wide societal effects from food production to human health and security. Wildfires in the tropics may reduce the effects of climate feedbacks on short-term climate oscillations [39]. If annual variability in aerosols from wildfires and biomass burning does affect climate oscillations, then the effects will likely cascade through ecosystems and affect species in numerous ways, from food availability to changes in the extent and quality of their habitats.

Benchtop DNA printers

Benchtop DNA printers can now produce double-stranded DNA. Within 5 years these devices may allow printing of sequences equivalent to that of a small viral genome on demand and in a distributed manner [40]. Given the lack of centralised regulation and oversight, and the lack of input from potential end-users and other interested parties in the development of genetic tools, the printers present new ecological and ethical risks. Potential indirect effects of benchtop DNA printing include the unintended transfer of genetic material to wild populations, the creation of new, invasive cultivated species, increases or decreases in conversion of natural areas to agriculture, and reductions in agrochemical applications [41]. Direct application of benchtop DNA printing could include the use of gene drives (increasing the likelihood that specific alleles are inherited) to enhance (e.g., coral thermal tolerance) or reduce (e.g., non-native invasive rodents) populations of interest, the development of heritable immunity to disease in threatened and endangered species [42], and the creation of proxies of extinct species. However, significant regulation by various United Nations bodies is likely to follow, as has been the case with earlier iterations of gene drives and similar technologies.

Extrapolating chemical toxicity assessments

Chemicals such as neonicotinoids often have major and unanticipated ecological impacts years after first use. New mechanisms may bridge this lag in knowledge by enabling identification of the potential toxicity of new chemicals before observations of their impacts accrue. Adverse outcome pathways (AOPs) have been suggested as a means to reliably extrapolate assessments of toxicity among taxonomic groups [43]. AOPs capitalise on knowledge of absorption, distribution, metabolism, and excretion of a particular toxicant and the effects of the toxicant from the molecular to the whole-organism level [44]. Implementation of AOPs may be facilitated by the development of tools such as the US Environmental Protection Agency 'SeqAPASS', which makes predictions across species on the basis of susceptibility to chemicals with known molecular targets, conservation of molecular targets, and molecular initiating events[i]. Advances in AI, machine learning, and deep learning methods may improve the effectiveness of AOPs and expand the feasibility of drawing reasonable inferences about toxicology among species, thus facilitating the effective application of agrochemicals with a lower risk of negative impacts on non-target species [45].

NEOM (The Line) linear skyscraper city

A 26 500 km^2 area in Saudi Arabia has been designated for the NEOM development. The development includes The Line, a linear skyscraper city that could house nine million people. Although marketed as being sustainable, its dimensions (500 m high, 200 m wide, and 170 km long), design (including mirrored façades and, potentially, roof-top wind turbines), and east–west orientation at the head of the Red Sea mean it is likely to pose a substantial risk to migratory species, particularly passerine birds. Collisions with buildings kill an estimated 365–988 million birds annually in the USA alone [46], and 16–42 million in Canada [47]. Higher collision risks are associated with lit windows [48] and with larger expanses of continuous glass. This would suggest that there may be some opportunities for mitigating impacts. However, the magnitude of The Line may pose a novel threat to the Eastern populations of the estimated 2.1 billion migratory birds of >100 species that migrate from Europe to Africa in autumn each year, for which this area forms a bottleneck [49], with downstream ecological consequences. No environmental impact assessment has yet been published, and site preparation has already commenced.

Sea urchin die-offs affect marine ecosystems

Extensive sea urchin die-offs in the Caribbean and Mediterranean in 2022 have highlighted potential ecosystem shifts in some of the most diverse seas across the world. Up to 99% mortality of *Diadema antillarum* (long-spined sea urchin) was documented in the Caribbean, similar to the mass mortality in 1983 and 1984 that led to coral reefs becoming overwhelmed by algal growth [50]. Across the eastern Mediterranean, considerable mortality of the non-native *Diadema setosum* (porcupine sea urchin) also occurred in 2022 over 1000 km of coastline [51]. The mortality appears to have spread into the Red Sea where *D. setosum* is native. The Caribbean mortality was associated with a scuticociliate protist pathogen [52]. The cause of the Mediterranean die-off is unknown, but the symptoms and extent are similar to those in the Caribbean. Given the known and substantial ecosystem impact of past sea urchin die-offs [50], these two new events may suggest an emerging threat to tropical ecosystems globally. Ciliate species are known pathogens of other marine species, including corals, crabs, and fishes. If mortalities are linked to environmental stresses such as heat, then extensive outbreaks of marine diseases are likely to become more frequent.

Removal of carbon dioxide from the ocean

There is growing consensus that limiting global warming to <2°C will require both dramatic emission reductions and removal of carbon dioxide from the atmosphere. Given that the oceans contain 50-fold more carbon than the atmosphere, attention has turned to ocean-based climate interventions including ocean fertilisation, macroalgal culture and sinking, enhancement of ocean alkalinity, and injection of carbon dioxide into marine rock formations. The efficacy of these technologies for long-term carbon removal and storage over large areas remains to be determined. Furthermore, the likelihood of harmful environmental consequences, including reduced oxygen concentrations, macronutrient depletion, entanglement of marine life, and increased trace metal toxicity in seawater, is unclear [53]. The potential social implications of deployment are also unknown, including conflicting ocean uses. Nonetheless, governments (e.g., [54]), researchers [55], and members of the environmental non-governmental organisation (NGO) community[ii] have begun advocating and are funding research to determine the potential costs and benefits of wide adoption of these approaches by 2030. Simultaneously, private investors and myriad start-up companies are seeking permits to deploy these approaches without delay, with the hope of accessing rapidly expanding carbon-offset markets despite continued uncertainty in ocean governance.

Rising temperatures in the twilight zone affect the biological carbon pump

The twilight or mesopelagic zone, at depths of 200–1000 m below the sea surface, accounts for about one quarter of ocean volume. The zone can be particularly rich in life, and harbours the largest stocks of fishes; recent studies suggest that fish biomass at these depths has been significantly underestimated [56]. The mesopelagic zone is also critical to global carbon fluxes through the biological carbon pump – the downward transport of organic matter and subsequent sequestration of carbon [56]. The efficiency of the biological carbon pump is predicted to decline with rising temperatures, leading to increased rates of remineralisation of organic matter and reduction in the availability and quality of food for deep-sea organisms [57]. The duration of carbon sequestration may also be affected by rising temperatures. Cooler temperatures in the mesopelagic zone maintain the integrity of organic matter and thus enhance its transport to deep water. Faster-sinking, larger organic matter (e.g., faeces and carcasses) can be sequestered for up to 970 years, whereas slower-sinking, smaller particles are sequestered for about 140 years [56]. If warmer temperatures lead to more rapid decomposition of the faster-sinking matter, this oceanic sequestration potential could be reduced.

Melting Antarctic ice affects deep sea ocean currents

Although the impacts of climate change on the Atlantic meridional overturning circulation are receiving increasing attention, the importance of Antarctic abyssal overturning has been largely overlooked [58,59]. Recent studies [59] suggest that reductions in water density caused by increased melting and reduction in the concentration of salts may reduce abyssal overturning by 40% by 2050. These changes may affect nutrient flows, ocean oxygen levels, and global climate, with consequences for terrestrial and marine environments. The impacts of many of the potential changes, such as reduced oxygen concentration and biogeochemistry in the deep ocean, are poorly understood [58]. These changes reduce the ability of the ocean to absorb carbon dioxide. However, changes in winds, especially easterly winds, may alter this process and potentially enhance overturning circulation [60]. Antarctic bottom water influences circulation patterns. Decreases in the density of salts and changes in wind patterns may have nonlinear and long-lasting effects on oceanic circulation and climate patterns.

Concluding remarks

Horizon scanning provides a neutral assessment of the potential positive or negative impacts of a particular issue. Inevitably, impacts of a single issue can be positive in some respects but negative in others. The issues highlighted this year fall into three broad categories related to their potential impact on biological conservation. Seven issues have positive impacts on one area but unintended negative impacts on another: new sources of hydrogen, decarbonised ammonia production, carbon mineralisation, benchtop DNA, wildfire impacts on climate oscillations, NEOM, and carbon dioxide removal from the oceans. Four issues have potentially positive effects: food and animal feed from bacteria, light-free photosynthesis, the use of ecoacoustics for soil ecology, and advances in identifying chemical toxicology. Four issues appear to have only negative impacts: earthworm decline, sea urchin die-off, rising temperatures in the twilight zone, and melting Antarctic ice.

Horizon scanning aims to identify issues that will have impacts in the future. In our 2020 horizon scan, a decade after the first, we examined how issues identified in 2010 had developed [2]. Some of the issues presented in the 2014 scan (Box 2) have had the potential impact we

Box 2. Ten-year retrospective

The 2014 horizon scan featured three issues relating to control of invasive or problematic species or diseases [61]. Global efforts related to the first – increasing scales of eradications of non-native mammals on islands – have been realised over the past decade. Although there has been a downturn in the number of eradication events, there has been a significant increase in the magnitude of the eradications [62]. Considerable laboratory progress has been made on the second issue – the development of self-sustaining genetic systems for the control of non-native invasive species [63]. Such development may be influenced further by the development of benchtop DNA printers (highlighted this year). Field applications of such systems remain limited, however, because of ethical concerns about potential unintended impacts (e.g., [64]). Emerging snake fungal disease (caused by *Ophidiomyces ophidiicola*), the third issue, has seemingly not emerged, as it was still categorised as an emerging infectious disease as recently as 2021 [65]. Other issues we highlighted, such as probiotics for amphibians, are still the focus of laboratory testing and have not yet been adopted in practice [66].

The search for sustainable alternatives to fossil fuel energy continues. In 2014, these included use of macroalgae as a potential biofuel [61], which remains a possibility [67]. Advances in the use of carbon-based nanomaterials such as graphene and carbon nanotubes for solar panels have been reported [68].

The impact of two issues in our 2014 horizon scan have undergone step-changes, and served as the basis of others presented this year. In 2014, we highlighted the redistribution of global temperatures among ecosystems given that increases in surface temperature appeared to be slowing [61]. We proposed that the rate of temperature increase was not decreasing, but other ecosystems, such as the Antarctic or mesopelagic ocean, could be warming at a greater rate. The consequences for the Antarctic ice sheet, including feedbacks as deep ocean warming leads to upwelling of warmer currents and further ice melt, are highlighted in one of the topics this year. Also in 2014, we noted the potential ecological and environmental impacts of Antarctic exploitation and threats to the mesopelagic zone posed by increasing temperatures. This year, the evidence was sufficient to highlight the effects of warming on the ability of the mesopelagic zone to sequester carbon.

described, some have not yet come to pass, and others have undergone a sufficiently significant step-change to warrant inclusion this year.

Many issues identified in this year's horizon scan concern direct or indirect impacts on marine ecosystems. The past 2 years have been transformative for marine environmental policy. New policy initiatives to better conserve biological diversity include the Biodiversity Beyond National Jurisdiction (BBNJ) or High Seas Treaty[iii] and the Kunming–Montreal Global Biodiversity Framework through the Convention on Biological Diversity[iv]. The BBNJ Treaty, signed in September 2023, fills a major gap in legislation related to areas beyond national jurisdiction. Commitments such as Target 3 under the Global Biodiversity Framework, which aims to conserve 30% of terrestrial, freshwater, and marine areas by 2030 through protected areas and other effective area-based conservation measures (OECMs), can only be achieved when there is a means to implement legislation on the high seas beyond national jurisdiction. New and improved area-based protections will greatly alleviate direct threats to biodiversity conservation. However, some of our issues, such as climate change impacts in the ocean, will not be affected by such protection measures.

The issues identified in this scan continue to reflect the juxtaposition between anthropogenic impacts on biodiversity and increasing technological capacity to mitigate those impacts. In some cases, new issues arise directly from efforts to mitigate other issues, as may be the case with the development of new fuel production systems to enable the reduction of greenhouse gas emissions or the expansion of efforts to sequester carbon dioxide in the ocean. Although major advances are being made in carbon capture, alternative fuel sources, and synthetic biology, exploitation and disruption of ecosystems remain prevalent. Significant step-changes in the adoption of more sustainable technologies, including those that could reduce the footprint of food production, combined with increased protection of species' habitats, will be necessary to halt global trends in the loss of biodiversity. Technological advances associated with AI may offer some opportunity to break the cycle of novel, unintended impacts of attempted solutions, as exemplified by the issue of avoidance of AOPs in assessing chemical toxicity. At the same time, many challenges are mounting. Although scientific consensus on the gravity of climate change has been reported for many years, and six of nine proposed planetary boundaries are judged to have been crossed already [69], few nations are reducing greenhouse gas emissions to the extent necessary to meet internationally agreed warming limits. We anticipate continuing to highlight novel emerging impacts of climate change, and technologies aiming to mitigate climate change and transition to more sustainable pathways, in future horizon scans.

Acknowledgements

This exercise was coordinated by the Cambridge Conservation Initiative and was funded by The Pew Charitable Trusts, the Natural Environment Research Council, and the Royal Society for the Protection of Birds (RSPB). We are grateful to everyone who submitted ideas to the exercise and to the following who suggested topics that made the final list: Bruce Liggitt (hydrogen), Jason Dinsdale (light-free artificial photosynthesis), Genevieve Hinchliff (carbon mineralisation), and Hannah Littler (extrapolation of chemical toxicity). W.J.S. and A.T. are funded by Arcadia; J.E.H-R. is supported by the Whitten Programme in Marine Biology; X.L.R. is supported by the French National Institute of Research for Agriculture, Alimentation, and Environment (INRAE, ECODIV Department). The results, conclusions, and opinions expressed are those of the authors and do not necessarily reflect the views of any of their organisations.

Declaration of Generative AI and AI-assisted technologies in the writing process

W.E.P. used GPT-3.5 (Open AI), GPT-4 (Open AI), and Claude (Anthropic) to source suitable issues to submit to the process. All submitted issues were checked and reviewed by W.J.S. and A.T. to determine their suitability; those deemed suitable were submitted to the voting process. None of the 15 issues presented here were generated using AI or AI-assisted technologies.

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Declaration of interests

The authors declare no conflicts of interest.

Resources

[i]www.epa.gov/sciencematters/epa-releases-seqapass-version-70

[ii]https://oceanconservancy.org/wp-content/uploads/2023/06/Precautionary-Principles-for-Ocean-Carbon-Dioxide-Removal-Research.pdf

[iii]www.un.org/bbnj/

[iv]www.cbd.int/gbf/

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