Trends in Ecology & Evolution

Cell Press REVIEWS

Review

Ten Years On: A Review of the First Global Conservation Horizon Scan

William J. Sutherland,[1,*] Erica Fleishman,[2] Mick Clout,[3] David W. Gibbons,[4,5] Fiona Lickorish,[6] Lloyd S. Peck,[7] Jules Pretty,[8] Mark Spalding,[9] and Nancy Ockendon[1]

Our first horizon scan, conducted in 2009, aimed to identify novel but poorly known issues with potentially significant effects on global conservation of biological diversity. Following completion of the tenth annual scan, we reviewed the 15 topics identified a decade ago and assessed their development in the scientific literature and news media. Five topics, including microplastic pollution, synthetic meat, and environmental applications of mobile-sensing technology, appeared to have had widespread salience and effects. The effects of six topics were moderate, three have not emerged, and the effects of one topic were low. The awareness of, and involvement in, these issues by 12 conservation organisations has increased for most issues since 2009.

Highlights

We review the first horizon scan of global conservation issues, conducted 10 years ago.

Five of the 15 issues identified have shown a major increase in importance since 2009.

Six other issues appear to have developed to a moderate extent.

The proportion of conservation organisations working on nine of the identified topics has increased, but for six topics has decreased.

We find little evidence for a relationship between the expertise of participants and the topics that were identified across 10 years of horizon scans.

We hope that this review article encourages more widespread adoption of horizon scanning, as well as further evaluation of its effectiveness.

Aims of Horizon Scanning

Horizon scanning identifies and scrutinises potential future opportunities and threats, with the aim of increasing preparedness, allowing hazards to be mitigated, and facilitating capitalisation on opportunities. By focusing attention on emerging issues that are not widely known, the process aspires to catalyse research and proactive adoption of policies [1].

Our first annual horizon scan of global conservation issues was conducted in September 2009 (and published in 2010 [2]). It aimed to identify potential new threats to, and opportunities for, conservation of biological diversity that were not then widely known. At the time, the potential benefits of such an exercise were suggested by phenomena such as the rush to grow large quantities of biofuels without thorough evaluation of the environmental consequences [3,4]. If the potential effects of extensive growth of biofuels had received sufficient attention from conservation researchers, practitioners, and policy-makers several years previously, the ultimate environmental costs might have been much lower [5]. By conducting an annual global horizon scan, we hope to increase the likelihood of identifying issues when they are within range of materialising but still are sufficiently distant that action to avert crises or to seize opportunities is possible. There is no objectively optimal frequency for conducting a scan on a given theme. We chose to conduct scans annually because we felt that we might miss rapidly emerging issues if the interval between scans was longer (e.g., 5 years).

As far as we are aware, evaluations of whether horizon scans meet their stated aims have rarely, if ever, been undertaken [6]. The effect of the horizon scan itself on the trajectory of a given issue is impossible to characterise, given that there is no counterfactual (i.e., development of the issue in the absence of a horizon scan). However, our aim is to identify issues that will become prominent at the point when awareness of them is low (i.e., they are the subject of few articles and discussions). Although the time period over which issues might become prominent is uncertain and therefore not explicitly specified, we generally anticipate some development of

[1]Conservation Science Group, Department of Zoology, Cambridge University, The David Attenborough Building, Pembroke Street, Cambridge CB2 3QZ, UK
[2]Department of Fish, Wildlife and Conservation Biology, Colorado State University, Fort Collins, CO 80523, USA
[3]Centre for Biodiversity and Biosecurity, School of Biological Sciences, University of Auckland, PB 92019, Auckland, New Zealand
[4]RSPB Centre for Conservation Science, Royal Society for the Protection of Birds, The Lodge, Sandy, SG19 2DL, UK
[5]RSPB, The David Attenborough Building, Pembroke Street, Cambridge CB2 3QZ, UK

most issues within a decade of identification. Therefore, an examination of the issues identified in 2009 now seemed timely and valuable.

In the present analysis, we first reviewed the 15 topics identified in 2009 to investigate whether they since have emerged and become higher priorities on worldwide conservation research and policy agendas. This was supported by a bibliometric search examining the trajectory of the number of references related to each topic in the scientific literature and news media from 2000 through 2017. We then compared the awareness of, and involvement in, each topic by conservation organisations from 2010 through 2018. In addition, we examined the relation between the topics identified and participants' expertise across all ten horizon scans undertaken since 2009.

[6]UK Research and Consultancy Services (RCS) Ltd, Valletts Cottage, Westhope, Hereford HR4 8BU, UK
[7]British Antarctic Survey, Natural Environment Research Council, High Cross, Madingley Road, Cambridge CB3 0ET, UK
[8]School of Biological Sciences, University of Essex, Colchester CO4 3SQ, UK
[9]Global Marine Team, The Nature Conservancy, Department of Physical, Earth and Environmental Sciences, University of Siena, Pian dei Mantellini, Siena 53100, Italy

*Correspondence:
w.sutherland@zoo.cam.ac.uk
(W.J. Sutherland).

A Review of the Issues Identified in 2009

Here, we give a brief overview of the development of each issue since it was identified in 2009.

Microplastic Pollution

Five trillion pieces of plastic are estimated to float in the oceans. Microplastics (<5 mm in diameter), the numerically dominant form, result either from items manufactured at small sizes, such as microbeads, or degradation of larger items, such as plastic bags [7]. Research on microplastic pollution has increased exponentially since 2009, and there is now extensive evidence of its negative effects on marine organisms [8]. Chronic exposure to microplastics is rarely lethal, but it can disrupt feeding and limit fecundity and growth of marine organisms [9]. Research since 2013 has demonstrated that microplastics also are widespread in freshwater and terrestrial ecosystems and interact with soil-dwelling invertebrates and fungi [8]. Legislative measures to reduce plastic bag use began in Germany in 1991 and have increased dramatically since 2006, whereas the first efforts to reduce microbead production began in 2014 [10]. Despite intensification of research, legislation, public concern, and activism since 2009, the amount of plastic in the oceans is projected to double from 2010 through 2025 [11].

Nanosilver in Wastewater

In 2009, we described the increasing use of nanosilver particles and the potential effects on bacteria and aquatic vertebrates when these products are discharged in wastewater. Since then, the number of medicinal, cosmetic, clothing, optical, and other products containing nanosilver particles has continued to increase [12]. As use rises, the release of particles into the environment increases, although direct quantification is difficult. In the past 10 years, research (much of it focused on fishes) has demonstrated a wide range of biological impacts of nanosilver, including effects on immune function, metabolism, and embryo development. There also is some evidence that nanosilver can bioaccumulate in fishes [12]; however, these findings are almost exclusively based on laboratory studies, and whether such effects occur in the field remains unclear. Effects of nanosilver in terrestrial environments are increasingly being considered, with high concentrations documented in soil treated with sludge, and negative effects on soil bacteria and plants [13]. Overall, the increase in the use of nanosilver and research on its effects has increased since 2009, but does not appear to have undergone a step change.

Synthetic Meat

In 2009, synthetic meat was extremely expensive (US$2.7 million/kg), available in small strips, and generally considered to taste unpleasant. However, the potential for changes in production methods led to identification of synthetic meat as a major protein source for the future. The first synthetic beef burger was cultured and cooked in 2013. In 2016, the first cultured meatball was developed, followed by cultured poultry in 2017. The main stumbling block to widespread consumption has been price. Nevertheless, the cost of producing a synthetic meat burger has dropped from £215,000 in 2013 to £8 in 2018 [14]. Research on environmental effects of widespread consumption of synthetic meat is equivocal. Production may be more benign than traditional meat production, given that less land is required, greenhouse gas emissions are 96% lower, and use of veterinary products such as antibiotics and growth promoters is reduced [15]. In addition, there is potential for widespread human-health benefits and improvements in food safety. However, one anticipatory life cycle analysis suggested that although synthetic meat production could require smaller quantities of agricultural inputs and land than traditional meat production, more energy may be required for production [16]. One US survey suggested that if prices continue to drop, and taste and environmental issues are overcome, most individuals may be willing to try synthetic meat [17].

Artificial Life

Our 2009 scan identified the advent of novel artificial life forms, the potential risks of these organisms interacting with genes and species in natural communities, and the possibility of malicious use. Since then, there have been significant advances in *in vitro* research into artificial life, such as the incorporation of natural and artificial DNA into new semi-synthetic life-like structures. Another development towards artificial life is the potential to engineer new proteins with a combination of four natural and two novel base pairs [18]. Further areas of progress include creation of life-like features, such as replication, mutation, and death, *in silico* [19]. A third application simulates artificial life computationally. These developments open many opportunities for information carriage, transfer and storage, and synthesis of new compounds, but they could also create systems with traits and attributes not found in nature. The risks identified in 2009 have not yet come to pass but, given developments in semi-synthetic organisms and artificial life, they may have increased.

Stratospheric Aerosols

The possibility of injecting particles into the upper atmosphere to mitigate climate change leads to questions about the trade-off between greenhouse gas concentrations and solar radiation and about potential immediate effects on local precipitation and other aspects of climate. Since 2009, there has been considerable research and debate on stratospheric aerosol injection, ranging from models of potential effects to discussion of the political, economic, and ethical implications. Despite this growing research and interest, society does not appear to be significantly closer to implementing atmospheric geoengineering in 2019 than it was in 2009. The origins of the concept of stratospheric aerosol injection remain relevant, given little sign of dramatic global action to curb carbon emissions [20], but geoengineering was not mentioned as an approach for meeting the temperature goals of the Paris Agreement of the United Nations Framework Convention on Climate Change [21]. High levels of scientific and political uncertainty about the effects of solar geoengineering also remain [22], and there is debate about the ethical aspects of continued research [23].

Promotion of Biochar

Biochar is a carbonaceous material obtained by pyrolysis of organic waste materials. It has been proposed as a soil management strategy for mitigating climate change and improving crop productivity. The 2009 topic focused on the use of biochar as a soil amendment that could mitigate greenhouse gas emissions by sequestering carbon for long periods [24]. The use of biochar for sequestration of carbon, while potentially improving soil fertility and removing biological waste, now appears to be widely accepted [25]. However, much recent research has concentrated on biochar's ability to improve soil health and promote plant growth, with particular attention on the positive effects of biochar on soil microbial communities, nutrient availability, and soil characteristics [26]. A review of the effects of biochar on ecosystem functions suggests that it may offer a solution to carbon storage, ecosystem function, and energy, but uncertainty about how biochar interacts with the environment remains high [27].

Mobile-Sensing Technology

Given how commonplace mobile-sensing technology has become, it seems remarkable that just 10 years ago the idea of using mobile phones (also known as smartphones or cell phones) to observe the environment was still on the horizon. Awareness of this issue has risen rapidly since 2009, and mobile phones are now widely used for environmental monitoring in a conservation context [28], with better geographic coverage, more memory, and higher speeds. As we described in 2009, most mobile devices now have links to global positioning systems; have compasses; have tilt, yaw, and altitude sensors; and can record video, images, light, and sound. These features can be used with online mapping services via fast mobile networks. Additional environmental sensors can also be connected to mobile phones. Fuel cell packages are available for remote power at moderate cost, and solar cell arrays and storage batteries are becoming cheaper and more practical for low-power devices. Provision of real-time data depends on cellular coverage, which still is poor in many remote areas. However, with emerging technologies, small data networks will support low-power monitoring and remote-control conservation applications in such areas. Given the development of applications, including automated identification of species and easy collation of field data, continued growth in the use of mobile-sensing technology for environmental observation seems highly likely.

Deoxygenation of the Oceans

Deoxygenation here refers to the reduction in the concentration of oxygen in seawater that has occurred during the past 50 years and is predicted to intensify in coming decades. The causes of deoxygenation are climate warming and industrial and domestic contaminant inputs into coastal waters. Research on ocean deoxygenation has accelerated rapidly in recent years, leading to improved understanding of key drivers and mechanisms, such as warming, biological consumption, and stratification or reduced vertical turnover of deeper ocean waters. Quantification and modelling of deoxygenation have improved, yielding estimates of a 2% global decrease in oxygen content of the oceans since 1960 and spatial data illustrating global variation in deoxygenation [29]. Understanding of regional variation, beyond the warm-water regions that were a key focus of much initial work, is also increasing. There remain considerable challenges in building models that better match observations, understanding local drivers of regional variation, and modelling the social and economic consequences of deoxygenation [30,31]. Despite the threats of ocean deoxygenation to biodiversity and society, there is little awareness of this topic beyond the research community, and it is rarely mentioned in concert with ocean acidification or warming in discussions of global change [32].

Changes in Denitrifying Bacteria

In 2009, we raised the issue of disruption to nitrogen cycles due to the discharge of anthropogenic nitrogen into the oceans, with evidence that an estuary in the United States had changed from a nitrogen sink to a nitrogen source [33]. These changes in denitrifying bacteria were suggested to be a response to climate change, with the potential to increase the quantity of anthropogenic nitrogen reaching the open ocean. However, despite some new data demonstrating the existence of nitrogen sinks, such as the Chukchi Sea [34], we have not found further evidence of the changes hypothesised in the original horizon scan. It therefore appears that changes in denitrifying bacteria may not have materialised as an issue of global importance; it is also possible that the effects may accrue over a longer time period, with widespread impacts that have not yet been detected.

High-Latitude Volcanism

Less than a year after we highlighted that the decline in high-latitude ice could increase volcanic material in the atmosphere, the Eyjafjallajökull volcano in Iceland erupted, causing serious disruption to air traffic across Europe. The timing of this eruption relative to our horizon scan clearly was coincidental. Our aim was to highlight medium-term thinning of polar ice, which exposes areas of relatively limited volcanic activity, and the long-term possibility that extensive eruptions will break through ice sheets. Research on high-latitude volcanism has increased since 2009, with some evidence that the largest field of active volcanoes on Earth may exist in Antarctica. There are up to 138 volcanoes in West Antarctica alone [35], and there may be a magma plume beneath Antarctica [36]. Recent papers also discuss the potential for volcanic activity to contribute to melting of polar ice sheets. Major past melting of the ice sheet in the Arctic has been associated with volcanic activity in the polar regions [37], suggesting that over the coming decades and centuries, high-latitude volcanism could have substantial environmental effects.

Invasive Indo-Pacific Lionfish

As identified in 2009, the colonisation of the Atlantic Ocean by Indo-Pacific lionfish (mainly *Pterois volitans*) could change predator–prey relations and the structure of fish communities. Extensive research published since has traced many aspects of this issue, including modifications of population and spatial dynamics and ecological interactions [38]. Lionfish have spread relatively quickly across the warm temperate and tropical waters of the eastern seaboard of the United States, the Gulf of Mexico, and the Caribbean, and the first record from Brazil was published in 2015 [39]. Negative effects on local fish populations have been quantified in many settings, with high densities of lionfish in northern parts of the invaded region increasing predation on juvenile fish [40]. High awareness among researchers and the public has led to support for lionfish control in some areas [41]; Sutherland *et al*. [42] raised the possibility of using automated robots to address invasions. In some invaded areas, lionfish abundance may have stabilised naturally or be decreasing, with corresponding amelioration of ecological effects [38]. At the same time, lionfish are spreading south, with potential negative effects on endemic fishes in South America [39]. Lionfish are also colonising the eastern and central Mediterranean [43], most likely resulting from migration through the Suez Canal.

Trans-Arctic Dispersal and Colonisation

Movement of species into the Arctic Ocean from the Pacific and Atlantic oceans, and subsequent colonisation of lower latitudes by species previously blocked by Arctic ice, is increasingly likely. There has been much research on this subject since 2009, with the first phase, the colonisation of the Arctic allowed by increases in global temperature, now well documented. Ranges of some species, such as snow crabs (*Chionoecetes opilio*), have expanded naturally. Other species, such as red king crabs (*Paralithodes camtschaticus*) that now are present in the Barents Sea [44], were purposely introduced for economic reasons (e.g., fisheries). In the past 9 years, countries bordering the Arctic have expended much effort in identifying both the magnitude of the potential colonisations and the likely vectors into the Arctic as they seek to identify mechanisms to minimise undesirable impacts [45]. Scientists have also been attempting to identify future periods when conditions may allow ecosystem engineers, such as cuttlefishes, to cross the Arctic and colonise North America for the first time [46]. No cases of movement between oceans across the Arctic have yet been documented. However, given the dramatic sea ice losses in the Arctic Ocean in the past decade and increasing ship traffic, trans-Arctic dispersal and colonisation seem more likely now than in 2009.

Assisted Colonisation

Assisted colonisation, the movement of species by humans to areas where they do not occur or have not recently occurred, has continued to develop as a conservation strategy since 2009. Although assisted colonisation in response to climate change, the focus of our original scan, remains relatively rare globally, overall awareness has increased, and debate has continued over the value, feasibility, and potential risks of translocating species beyond their current range [47]. Recent research has included detailed modelling to inform decisions about facilitating range expansions for species threatened by climate change [48]. In 2013, the International Union for the Conservation of Nature published guidelines for reintroductions and other translocations that define assisted colonisation as ‘the intentional movement and release of an organism outside its indigenous range to avoid extinction’ [49]. This definition is not restricted to responses to climate change; it also covers other threats such as habitat loss and non-native invasive species. In the context of these latter threats, assisted colonisation is an increasingly relevant tool for species conservation, especially in Australia and New Zealand [50].

Possible Impact of REDD on Non-Forest Ecosystems

In 2009, we suggested that enhanced forest protection, driven by the United Nations’ Reducing Emissions from Deforestation and Forest Degradation (REDD) initiative, might increase pressure to convert or modify other ecosystems, some of which themselves contribute greatly to carbon regulation [51]. Since then, land optimisation models demonstrated that forest conservation schemes, such as REDD, could drive cropland expansion in non-forested areas [52]. However, despite implementation of more than 500 REDD+ pilot projects worldwide, it remains unclear whether REDD+ actually has driven cropland expansion or other forms of ecosystem conversion. One region where such expansion may be occurring is the Brazilian Amazon, where a dramatic reduction in deforestation from 2005 through 2015 may have increased conversion to cropland of the neighbouring Cerrado, a savannah ecosystem with high species richness [53]. However, some authors even argue that conversion of the Cerrado to pasture and cropland is necessary to protect the Amazon [54].

Large-Scale International Land Acquisitions

In 2009, we identified the main risks of spatially extensive land acquisitions as the expansion of agricultural monocultures or plantations that threaten local biodiversity, usually in the tropics and sub-tropics. The main hypothesised agents were a few countries with domestic food-security concerns or inadequate water supplies, such as the Persian Gulf states, China, and India. Large-scale acquisitions or land rushes, especially in Africa, have continued since 2009. However, the primary drivers have not been countries seeking to protect their own food security but instead the emergence of new markets (e.g., jatropa or other agrofuels) or the expansion of existing markets as a result of growth in global consumption. Some acquisitions have been promoted by national governments, such as the Ethiopian government, as a source of revenue [55]. Otherwise, the main agents of acquisition are transnational corporations, which often deploy narratives suggesting that barren or degraded lands can be improved by acquisition and conversion to agriculture [56]. A study of 38 operations in Ethiopia, Ghana, Nigeria, and Zambia showed that investments in large tracts of agricultural land have often been synonymous with displacement, dispossession, and environmental degradation [57].

Change in Importance of Issues Identified in 2009

Trajectory in the Scientific Literature and News Media

We searched both the scientific literature and news media on each topic from 2000 (9 years before the first scan) until 2017 (8 years afterwards) inclusive. Our aim was to provide an indication of the change in level of awareness of, and development and interest in, each topic among researchers and the public before and since the topic's identification in 2009. Our sources of scientific literature and news media were the Web of Science Core Collection and NewsBank, respectively. Both are indexing services rather than definitive catalogues, and their content varies temporally and among organisational subscriptions. The Web of Science Core Collection is a citation index that includes scholarly abstracts, books, more than 20,000 peer-reviewed journals, and other types of media. NewsBank aggregates content from newspapers, newswires, blogs, periodicals, and other media worldwide.

We experimented with search terms, ultimately selecting terms that seemed to retrieve the greatest number of results that were relevant to the original intent of the topic (Table 1). We were unsuccessful in obtaining any results for one topic, changes in denitrifying bacteria, with all search terms we tried. For two topics, mobile-sensing technology and trans-Arctic dispersal and colonisation, we applied slightly different search terms to the scientific literature and news media because initial searches suggested that descriptions of these topics differed between the two bodies of literature.

We recognise that the searches were not exhaustive. Not every result relevant to each topic was retrieved, and not every result retrieved was relevant to the topic. Therefore, we examined

Table 1. Terms Used to Search the Scientific Literature and News Media on Each Horizon Scan Topic Identified in 2009

Topic	Search term(s)
Microplastic pollution	Microplastic*
Nanosilver in wastewater	Nanosilver AND wastewater
Synthetic meat	'Synthetic meat' OR 'lab-grown meat' OR '*in vitro* meat'
Artificial life	'Synthetic biology' AND genet* OR 'synthetic life' AND genet*
Stratospheric aerosols	'Stratospheric aerosol*' AND ('climate change' OR 'global warm*')
Promotion of biochar	Biochar AND 'climate change' OR biochar AND 'global warming' OR biochar AND 'carbon sequest*'
Mobile-sensing technology	News media: 'mobile *phone' AND app AND conservation AND (species OR wildlife) Scientific literature: 'mobile *phone' AND conservation
Deoxygenation of the oceans	Deoxygen* AND 'climate change' AND (marine OR ocean) OR deoxygen* AND 'global warming' AND (marine OR ocean) OR 'dissolved oxygen' AND 'climate change' AND (marine OR ocean) OR 'dissolved oxygen' AND 'global warming' AND (marine OR ocean) OR hypox* AND 'climate change' AND (marine OR ocean) OR hypox* AND 'climate change' AND (marine OR ocean)
Changes in denitrifying bacteria	No search terms successful
High-latitude volcanism	Volcanism AND 'climate change' OR volcanism AND 'global warming' OR volcanism AND Antarctica OR volcanism AND polar OR volcanism AND glaci* OR volcanism AND 'ice sheet'
Invasive Indo-Pacific lionfish	Lionfish AND Caribbean OR lionfish AND invasi* OR '*Pterois volitans*' AND Caribbean OR '*Pterois volitans*' AND invasi*
Trans-Arctic dispersal and colonisation	News media: ('trans-Arctic') AND (dispersal OR colonisation OR invasion) AND 'climate change' AND ocean Scientific literature: ('trans-Arctic' OR Arctic) AND (dispersal OR colonization OR invasion) AND 'climate change' AND ocean
Assisted colonisation	'Assisted colonization' AND species OR 'assisted migration' AND species OR 'species translocation' OR 'assisted colonisation' AND species
Possible impacts of REDD on non-forested ecosystems	REDD AND 'reduced emissions'
Large-scale international land acquisitions	'Land grab' AND (international OR investor OR foreign) AND 'developing country'

a subset of the scientific results (generally title and abstract) to determine whether they were relevant to the topics as described in 2009. We considered a result to be relevant if it described new research, developments, methods, or applications of the topic, or if it discussed the known or potential effects, ethical elements, or likelihood of realisation of the topic. We screened the first 100 results (or all results for topics that yielded fewer than 100 results) for each topic to estimate the proportion that were relevant. We then used this proportion to determine the sample size for each topic that was necessary to screen in order to estimate the total proportion of relevant results with 5% precision and 95% confidence intervals. We present the total number of results for each topic, adjusted by the proportion of our sample that was relevant (Figure 1). Although the data are quantitative, we suggest that they be interpreted as relative and qualitative trends.

We attempted to also examine the results of the searches of the news media for relevance, but NewsBank did not allow downloads of the volume of content that was necessary. Therefore,

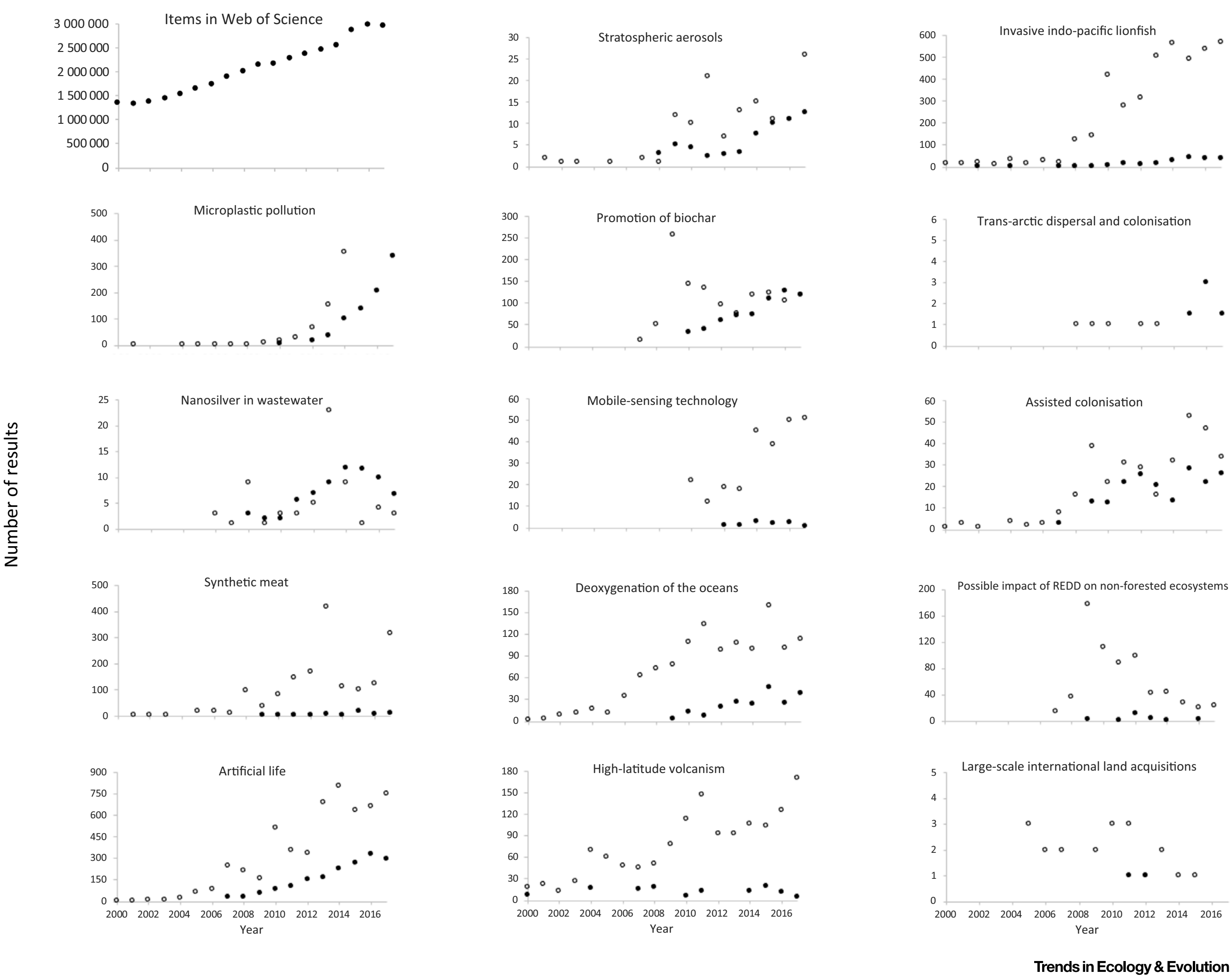

Figure 1. Number of Relevant Results on Each Topic Returned from Searches of the Scientific Literature (Web of Science, Closed Circles) and the News Media (NewsBank, Open Circles) for the 9 Years before and 8 Years since the 2009 Global Horizon Scan for Conservation. The scale of the y-axis differs among topics. No results were returned for searches on changes in denitrifying bacteria.

we report raw results (Figure 1) but, given the likelihood that a high proportion are not relevant and that this proportion will vary among topics, underscore that they should be interpreted as relative trends only.

The total number of peer-reviewed journal articles published annually has increased substantially since 2000 [58]. To consider whether this trend could be responsible for any observed increase through time in the apparent number of results on a topic, we present the total number of citations published in each year that currently are indexed in Web of Science. The results from Web of Science suggest an increase in total number of publications from approximately 1.3 million in 2000 to 2.3 million in 2009 and 3 million in 2017 (Figure 1). Therefore, if the increase in the apparent number of scientific citations on a given topic exceeds this rate, the increase in attention is likely to have been real. Similarly, if the apparent number of results for a topic has increased by less than 130% since 2009, the level of scientific awareness is likely to have changed little or may have declined.

Assessment of Change in Importance of Each Topic

We qualitatively assessed the change in importance of each topic since 2009 on the basis of the information provided in this review article. Each author read the review paragraph describing each topic and examined the trends in the relevant scientific literature (Figure 1). Each author then independently and confidentially scored each topic with respect to its change in importance since 2009 as follows: major increase (1), some increase (2), little or no change (3), some decrease (4), or major decrease (5). A summary of the number of authors that attributed each score to each topic was then circulated, after which the authors met in person and discussed each topic and its rate of development in turn. The authors also discussed the characterisation of change in importance at this meeting, to ensure relative consistency in scoring. Importance could describe either the levels of research activity, the number of articles discussing a topic, or the intensity or likelihood of a threat or opportunity (caused by either social or ecological factors). After each topic was discussed, the authors again confidentially scored its change in importance. We used these scores to calculate the median score for each topic (Table 2). The median score for 14 of the 15 topics fell within a single category: five topics were assessed as having undergone a major increase in importance, five had shown some increase, one had undergone little or no change, and three were scored as having undergone some decrease. The median score for one topic (artificial life) fell between major increase and some increase.

Change in Involvement and Awareness of Conservation Organisations

In 2010, 12 global conservation organisations were questioned about their awareness of, and current and anticipated involvement in, each of the topics identified in 2009 [59]. In July 2018, we surveyed individuals from the same 12 organisations to investigate whether their interest in these topics had changed since they were identified in the first global conservation horizon scan. If the first horizon scan had successfully identified important emerging issues for conservation, we would expect the proportion of conservation organisations working in these areas or recognising the issue as important to have increased in the intervening decade.

We asked the head of science or ecological research (or equivalent role) from each organisation (in consultation with colleagues from within their organisation if necessary) to assess, for each issue identified in 2009, whether they had heard of the topic and whether their organisation had actively worked on the issue since then. Given staff turnover, the person we approached in 10 of the 12 organisations was different from the person questioned in 2010. We did not ask the two people whose role had not changed whether they had heard of each topic because their awareness may have been affected by the 2010 exercise. Instead, in one organisation a new

Trends in Ecology & Evolution

CellPress REVIEWS

Table 2. Change in Importance of Each Topic (as Assessed by the Authors), and in Awareness and Involvement by 12 Conservation Organisations, of the Issues Identified in 2009

2010 issue	Change in importance[a]	Conservation organisations				
		% heard of in 2010[b]	% heard of in 2018	% involved in 2010[b]	% intending to be involved in 2010[b]	% involved in 2018[c]
Microplastic pollution	↑	23	100	25	25	50
Nanosilver in wastewater	→	31	55	8	17	0
Synthetic meat	↑	46	100	0	0	8
Artificial life	↑↗	77	100	0	8	8
Stratospheric aerosols	↗	54	82	8	42	0
Promotion of biochar	↘	85	91	50	92	33
Mobile-sensing technology	↑	69	100	33	75	92
Deoxygenation of the oceans	↑	54	82	8	50	25
Changes in denitrifying bacteria	↘	15	64	8	33	0
High-latitude volcanism	↗	31	36	0	8	8
Invasive Indo-Pacific lionfish	↑	31	82	8	0	8
Trans-Arctic dispersal and colonisation	↗	54	100	17	42	25
Assisted colonisation	↗	92	100	42	92	67
Possible impact of REDD on non-forested ecosystems	↘	85	100	58	67	58
Large-scale international land acquisitions	↗	77	91	17	58	8

[a]↑, major increase; ↗, some increase; →, little or no change; ↘, some decrease. Note: artificial life fell in between the major increase and some increase categories.
[b]Data from 2010 taken from Sutherland *et al*. [59].
[c]Represents whether an organisation had been involved in actively working on a topic between 2010 and 2018.

colleague (the Director of Science and Nature) scored whether they had heard of each issue; in the other organisation, nobody else in an appropriate role could score this; therefore, this result (percentage heard of in 2018) is presented for only 11 organisations. We compared the proportion of respondents that had heard of each topic or whose organisation had worked on each topic from 2010 through 2018 (Table 2).

Awareness of all topics increased; the largest increases were associated with microplastic pollution and synthetic meat. Similarly, the proportion of organisations that were involved in work on microplastics and mobile-sensing technology rose significantly from 2010 through 2018, but the increase in the level of work on most other topics was smaller.

Focus of Topics and Participants' Expertise from 2009 to 2018

A question frequently asked of our horizon scanning process is the extent to which the topics that are prioritised are affected by the composition of expertise among the participants that score them. In other words, how much does the inevitable variation in the knowledge and interests in the group of 18–28 experts that score the issues each year affect selection of the final set of topics? To investigate this question, we examined the distribution of expertise of participants in relation to the distribution of topics that were prioritised across the ten annual conservation horizon scans that we have undertaken. In total, 70 different experts participated in the ten horizon scans from 2009 through 2018, and they prioritised 150 topics (15 per year). We used our knowledge of the participants and their work to place both topics and participants' expertise into 12 categories: above- and below-ground terrestrial ecology, marine ecology, freshwater and ice ecology, vertebrate conservation, invertebrate conservation, plant conservation, toxicants, technology, climate change impacts, strategic foresight methods, social values and behaviours, and biodiversity and conservation policy. We assigned three categories of expertise to each participant and placed each topic in a single category. Although we recognise that individual expertise often has more than three dimensions and that not all topics are likely to be one dimensional, we decided this was a pragmatic approach that captured sufficient information. We then examined the relationship between the percentage of expertise in each topic with the percentage of topics in the same category across the ten annual scans.

Of the 70 participants, 50% identified as female and 50% as male. Accounting for participation of some individuals present for more than 1 year, weighted gender representation across all years was 45% female and 55% male. Other factors relating to expertise, such as age or the countries people have worked in, might also have been relevant, but they were not so readily assessed.

There was no correlation between participants' expertise and the focus of the issues ($R^2 = 0.016$; Figure 2). The 150 issues presented across the decade of horizon scans were reasonably evenly distributed among categories, with the greatest number of issues relating to technology (Figure 2). Strategic-foresight methods was an outlier: a moderate number of participants had expertise in these methods, but strategic foresight was not a focus of any topic. Other topics that were represented more strongly among participants' expertise than among topics were biodiversity and conservation policy and vertebrate ecology. Categories that were more highly represented within topics compared to within expertise included technology, above- and below-ground terrestrial ecology, and marine ecology.

Discussion

We took several approaches to examine whether our first horizon scan in 2009 was successful in identifying topics that were subsequently realised, with substantial effects on global conservation of biological diversity. The range of trajectories of topics over the past decade varied considerably, and it is not necessarily clear what an ideal trajectory for a horizon scan topic would be. An increase in interest and research following the identification of an issue may not always be the desired outcome. Arguably, highlighting the negative or harmful effects of an issue could be seen as successful if doing so causes rapid behaviour change that leads to desirable outcomes. For example, if an invasive species was predicted to colonise a new area, and implementation of a practical response prevented establishment of the species, the levels of research and popular interest might wane.

Of the topics identified in 2009, the most dramatic increases in priority on the conservation agenda were associated with microplastic pollution and the use of mobile-sensing technology for environmental observation (Figure 1 and Table 2). Pollution, particularly of marine environments, by microplastics increased suddenly. Few were aware of microplastic pollution in 2009, but by 2018, the issue was widely known among the general public and scientists, with a corresponding increase in the number of publications on the issue (Figure 1). Although many of these articles describe the magnitude of the issue and its impacts (e.g., the concentrations of microplastic pollution in different regions and ecosystems; effects on a range of species and taxonomic groups), others have started to address potential mitigation (e.g., methods for removing plastics from waste streams). Similarly, it now seems difficult to comprehend that in 2010, 31% of scientific heads of the conservation organisations we sampled had not heard of mobile-sensing technology, although other members of their organisations may have been

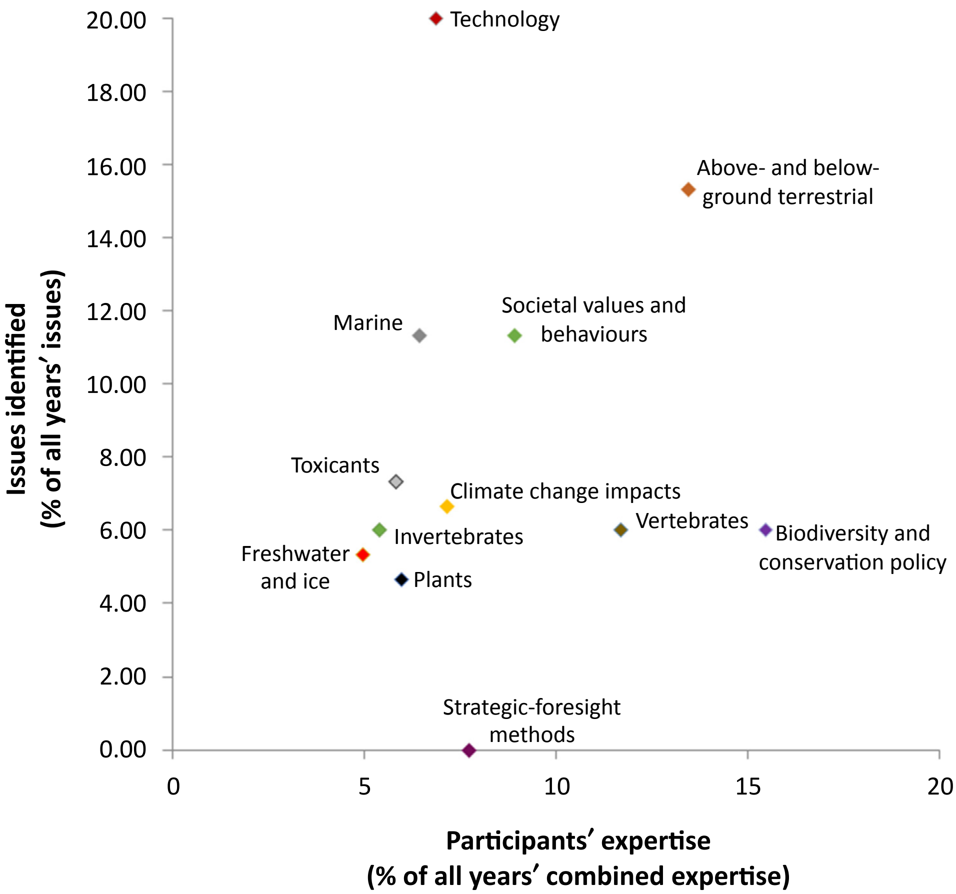

Figure 2. Relation between the Proportional Expertise of the Participants and the Proportion of Issues Identified in Each of 12 Focus Areas, On the Basis of Data from Ten Horizon Scans from 2009 through 2018. Each person's expertise was attributed to three focus areas, and each topic was assigned to a single focus area.

familiar with the technology. The current ubiquity of this technology has allowed an exponential increase in the number of conservation-related applications provided by mobile phones and associated devices. However, this increase was not reflected in the scientific literature, demonstrating the value of using a range of approaches to track issues.

A majority of the other topics, including the potential use of stratospheric aerosols and consumption of synthetic meat, have become higher priorities on the conservation agenda since 2009. By contrast, topics such as nanosilver in wastewater, the impacts of REDD on non-forested ecosystems, and, in particular, changes in denitrifying bacteria have not yet become prominent in the conservation community.

Trends in the number of scientific publications and news articles are broadly reflected in the difference in the proportion of conservation organisations that are working on each topic area. Considerably more organisations in 2018 than in 2010 are working on microplastic pollution, mobile sensing technology, and assisted colonisation (the latter likely enhanced by its applicability for conservation practice). However, the percentage of organisations working on promotion of biochar, stratospheric aerosols, and international land acquisitions in 2018 is substantially lower than organisations predicted in 2010. All of our metrics suggest that use of biochar as described in 2010 has not become a major mechanism for capturing carbon in soils. Despite high engagement and even higher intention to engage in biochar in 2010, the level of involvement by conservation organisations had dropped considerably by 2018. Similarly, the use of stratospheric aerosols for geoengineering solutions to climate change has not developed much since 2009. Regardless of whether geoengineering becomes more prominent, we suspect that it is unlikely to become more relevant for the conservation organisations we questioned, many of which primarily are concerned with conservation of species and their habitats. It also seems that the issue of international land acquisitions evolved in ways that we did not predict.

This review highlighted the challenges of horizon scanning, including many associated with quantifying the changes in interest or importance of each issue through time. The variability in the types of topic areas (some new technologies with associated environmental opportunities and risks, others with conservation challenges that are directly or indirectly caused by human actions) and in their degree of specificity meant that the ease of identifying relevant search terms varied substantially (Table 1 and Figure 1). It should also be noted that an increase in the number of results through time does not always equate with progress in research or problem solving. It also is likely that different topics will have different time horizons and trajectories, with the main impacts of high-latitude volcanism and artificial life unlikely to be understood for several decades. We hope that this review article will catalyse further research into approaches for evaluating the effectiveness of the horizon-scanning process, and the impacts of its outputs.

It is also difficult to gauge the impact of identifying issues through horizon scans. We believe that the method has been valuable for highlighting the risks and opportunities associated with topics such as microplastics and synthetic meat, allowing researchers and policy-makers to be better prepared as these issues are realised. In some cases, our work directly may inform these groups, but even our core audience is likely to be informed from multiple sources. We accept that not all issues that we identify will become important, as it is intrinsic to the process that we identify issues at a time when their future development is reasonably uncertain. Therefore, it is inevitable that some issues, such as denitrifying bacteria and promotion of biochar, are not realised.

A key question for all horizon-scanning exercises is whether the expertise of the participants biases the prioritisation of topics. Our analysis suggests that little such bias is evident across our horizon scans, perhaps because our method, described in full in the published versions of the annual scans, is designed to minimise bias. Given that the expertise of a finite group of participants necessarily is limited, we seek contributions of issues from many sources and use iterative, confidential assessments and scoring to select issues for retention. The consistent participation of a core group of individuals ensures some standardisation of the process; of the eight authors of this review article who participated in the first horizon scan, all participated in at least seven of the subsequent nine scans.

Concluding Remarks

We believe that horizon scanning continues to be a valuable and informative process, and we expect it to continue in the future (see Outstanding Questions) and extend to new disciplines, with the integration of advances in methods (Wintle *et al*. [6]). In particular, we believe that artificial intelligence will increasingly be applied to identification and prioritisation of issues. Although artificial intelligence may not surpass humans' ability to understand natural language in the short term, automated searches of the internet are already common for identification of

Outstanding Questions

How can the process of identifying new questions be improved?

How can government, organisations, and businesses be encouraged to use horizon-scanning outputs?

What determines whether concepts are adopted?

new topics and emerging trends [60]. As machine learning improves the ability of programmes to identify novel and important issues, automation may also become applicable to filtering and prioritising issues. Automation has the potential to massively increase the number of articles, reports, and webpages that can be scanned, including those written in languages other than English, and to make scanning methods more transparent and systematic.

Acknowledgements

We thank all of the participants in horizon scan exercises between 2009 and 2018. We are grateful to Nick Atkinson (Woodland Trust), Nigel Bourn (Butterfly Conservation), Pete Brotherton (Natural England), David Bullock and Rosie Hails (National Trust), Neil Burgess (UNEP-WCMC), Stuart Butchart (Birdlife International), Steve Gibson (JNCC), Martin Harper (RSPB), James Pearce-Higgins (British Trust for Ornithology), Mike Rands (Cambridge Conservation Initiative), Des Thompson (Scottish Natural Heritage), and Matt Walpole (Fauna & Flora International) for responding to questions about their organisation's work on these topics. We thank Murray Douglas for advice relating to mobile-sensing technology. We thank the Natural Environment Research Council and the Royal Society for the Protection of Birds for continuing to fund these annual exercises. W.J.S. is funded by Arcadia.

References

1. Könnölä, T. *et al.* (2012) Facing the future: scanning, synthesizing and sense-making in horizon scanning. *Sci. Public Policy* 39, 222–231
2. Sutherland, W.J. *et al.* (2010) A horizon scan of global conservation issues for 2010. *Trends Ecol. Evol.* 25, 1–7
3. Eggers, J. (2009) Is biofuel policy harming biodiversity in Europe? *GCB Bioenergy* 1, 18–34
4. Dauber, J. *et al.* (2010) The impact of biomass crop cultivation on temperate biodiversity. *GCB Bioenergy* 2, 289–309
5. Koh, L.P. and Ghazoul, J. (2008) Biofuels, biodiversity, and people: understanding the conflicts and finding opportunities. *Biol. Conserv.* 141, 2450–2460
6. Wintle, B.C. *et al*. Scanning horizons in research, policy and practice. In *Making a Difference in Conservation: Linking Science and Policy* (Sutherland, W.J., *et al*., eds), Cambridge University Press (in press)
7. Eriksen, M. *et al.* (2014) Plastic pollution in the world's oceans: more than 5 trillion pieces weighing over 250,000 tons afloat at sea. *PLoS One* 9, e111913
8. Machado, A.A. de S. *et al.* (2017) Microplastics as an emerging threat to terrestrial ecosystems. *Glob. Chang. Biol.* 24, 1405–1416
9. Galloway, T.S. *et al.* (2017) Interactions of microplastic debris throughout the marine ecosystem. *Nat. Ecol. Evol.* 1, 0116
10. Xanthos, D. and Walker, A.R. (2017) International policies to reduce plastic marine pollution from single-use plastics (plastic bags and microbeads): a review. *Mar. Pollut. Bull.* 118, 17–26
11. Dauvergne, P. (2018) Why is the global governance of plastic failing the oceans? *Glob. Environ. Change* 51, 22–31
12. Massarsky, A. *et al.* (2014) Predicting the environmental impact of nanosilver. *Environ. Toxicol. Pharmacol.* 38, 861–873
13. McKee, M.S. and Filser, J. (2016) Impacts of metal-based engineered nanomaterials on soil communities. *Environ. Sci. Nano* 3, 506–533
14. Hollywood, J. and Pirie, M. (2018) *Don't Have a Cow Man: The Pospects for Lab Grown Meat,* Adam Smith Institute
15. Tuomisto, H.L. *et al.* (2011) Environmental impacts of cultured meat production. *Environ. Sci. Technol.* 45, 6117–6123
16. Mattick, C.S. *et al.* (2015) Anticipatory life cycle analysis of *in vitro* biomass cultivation for cultured meat production in the United States. *Environ. Sci. Technol.* 49, 11941–11949
17. Wilks, M. and Phillips, C.J.C. (2017) Attitudes to *in vitro* meat: a survey of potential consumers in the United States. *PLoS One* 12, e0171904
18. Zhang, Y. *et al.* (2017) A semisynthetic organism engineered for the stable expansion of the genetic alphabet. *Proc. Natl. Acad. Sci. U. S. A.* 114, 1317–1322
19. Alvarez-Rodriguez, U. *et al.* (2016) Artificial life in quantum technologies. *Sci. Rep.* 6, 20956
20. Rogelj, J. *et al.* (2016) Paris Agreement climate proposals need a boost to keep warming well below 2 C. *Nature* 534, 631
21. Unites Nations Framework Commission on Climate Change (2016) *Decision 1/CP.21 Adoption of the Paris Agreement, 29 January 2016. FCCC/CP/2015/10 Add. 1, Annex* (Paris Agreement)
22. Barrett, S. *et al.* (2014) Climate engineering reconsidered. *Nat. Clim. Change* 4, 527
23. Frumhoff, P.C. and Stephens, J.C. (2018) Towards legitimacy of the solar geoengineering research enterprise. *Philos. Trans. R. Soc. A* 376, 20160459
24. Qian, K. *et al.* (2015) Recent advances in utilization of biochar. *Renew. Sust. Energy Rev.* 42, 1055–1064
25. Smith, P. (2016) Soil carbon sequestration and biochar as negative emission technologies. *Glob. Change Biol.* 22, 1315–1324
26. French, E. and Iyer-Pascuzzi, A.S. (2018) A role for the gibberellin pathway in biochar-mediated growth promotion. *Sci. Rep.* 8, 5389
27. Biederman, L.A. and Stanley Harpole, W. (2013) Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis. *GCB Bioenergy* 5, 202–214
28. Teacher, A.G.F. *et al.* (2013) Smartphones in ecology and evolution: a guide for the app-rehensive. *Ecol. Evol.* 3, 5268–5278
29. Schmidtko, S. *et al.* (2017) Decline in global oceanic oxygen content during the past five decades. *Nature* 542, 335
30. Shepherd, J.G. *et al.* (2017) Ocean ventilation and deoxygenation in a warming world: introduction and overview. *Philos. Trans. R. Soc. A* 375, 20170240
31. Breitburg, D. *et al.* (2018) Declining oxygen in the global ocean and coastal waters. *Science* 359, eaam7240
32. Levin, L.A. (2018) Manifestation, drivers, and emergence of open ocean deoxygenation. *Annu. Rev. Mar. Sci.* 10, 229–260
33. Nixon, S.W. *et al.* (2009) The impact of changing climate on phenology, productivity, and benthic–pelagic coupling in Narragansett Bay. *Estuar. Coast. Shelf Sci.* 82, 1–18
34. Brown, Z.W. *et al.* (2015) Aspects of the marine nitrogen cycle of the Chukchi Sea shelf and Canada Basin. *Deep Sea Res. II Top. Stud. Oceanogr.* 118, 73–87
35. Van Wyk De Vries, M. *et al.* (2017) A new volcanic province: an inventory of subglacial volcanoes in West Antarctica. In *Exploration of Subsurface Antarctica: Uncovering Past Changes and Modern Processes* (Siegert, M.J., ed.), pp. 231–248, Geological Society
36. Seroussi, H. *et al.* (2017) Influence of a West Antarctic mantle plume on ice sheet basal conditions. *J. Geophys. Res. Solid Earth* 122, 7127–7155

37. Muschitiello, F. *et al.* (2017) Enhanced ice sheet melting driven by volcanic eruptions during the last deglaciation. *Nat. Commun.* 8, 1020
38. Côté, I.M. and Smith, N.S. (2018) The lionfish *Pterois* sp. invasion: has the worst-case scenario come to pass? *J. Fish Biol.* 92, 660–689
39. Ferreira, C.E.L. *et al.* (2015) First record of invasive lionfish (*Pterois volitans*) for the Brazilian coast. *PLoS One* 10, e0123002
40. Ballew, N.G. *et al.* (2016) Invasive lionfish reduce native fish abundance on a regional scale. *Sci. Rep.* 6, 32169
41. Peiffer, F. *et al.* (2017) Ongoing removals of invasive lionfish in Honduras and their effect on native Caribbean prey fishes. *PeerJ* 5, e3818
42. Sutherland, W.J. *et al.* (2017) A 2017 horizon scan of emerging issues for global conservation and biological diversity. *Trends Ecol. Evol.* 32, 31–40
43. Bariche, M. *et al.* (2017) Genetics reveal the identity and origin of the lionfish invasion in the Mediterranean Sea. *Sci. Rep.* 7, 6782
44. Fernandez, L. *et al.* (2014) *Marine Invasive Species in the Arctic,* Nordic Council of Ministers
45. CAFF and PAME (2017) *Arctic Invasive Alien Species: Strategy and Action Plan*, Conservation of Arctic Flora and Fauna and Protection of the Arctic Marine Environment Akureyri
46. Xavier, J.C. *et al.* (2016) Climate change and polar range expansions: could cuttlefish cross the Arctic? *Mar. Biol.* 163, 78
47. Thomas, C.D. (2011) Translocation of species, climate change, and the end of trying to recreate past ecological communities. *Trends Ecol. Evol.* 26, 216–221
48. Ferrarini, A. *et al.* (2016) Planning for assisted colonization of plants in a warming world. *Sci. Rep.* 6, 28542
49. International Union for Conservation of Nature (IUCN) (2013) *Guidelines for Reintroductions and Other Conservation Translocations,* IUCN Species Survival Commission
50. Seddon, P.J. *et al.* (2015) Proactive conservation or planned invasion? Past, current and future use of assisted colonisation. In *Advances in Reintroduction Biology of Australian and New Zealand Fauna* (Armstrong, D. *et al.*, eds), pp. 105–126, CSIRO Publishing
51. Miles, L. and Kapos, V. (2008) Reducing greenhouse gas emissions from deforestation and forest degradation: global land-use implications. *Science* 320, 1454–1455
52. Popp, A. *et al.* (2014) Land-use protection for climate change protection. *Nat. Clim. Change* 4, 1095–1098
53. Noojipady, P. *et al.* (2017) Forest carbon emissions from cropland expansion in the Brazilian Cerrado biome. *Environ. Res. Lett.* 12, 025004
54. Cerri, C. *et al.* (2018) Reducing Amazon deforestation through agricultural intensification in the Cerrado for advancing food security and mitigating climate change. *Sustainability* 10, 989
55. Moreda, T. (2017) Large-scale land acquisitions, state authority and indigenous local communities: insights from Ethiopia. *Third World Q.* 38, 698–716
56. D'Odorico, P. *et al.* (2017) New frontiers of land and water commodification: socioenvironmental controversies of large-scale land acquisitions. *Land Degrad. Dev.* 28, 2234–2244
57. Schoneveld, G.C. (2017) Host country governance and the African land rush: 7 reasons why large-scale farmland investments fail to contribute to sustainable development. *Geoforum* 83, 119–132
58. Bornmann, L. and Mutz, R. (2015) Growth rates of modern science: a bibliometric analysis based on the number of publications and cited references. *J. Assoc. Inf. Sci. Technol.* 66, 2215–2222
59. Sutherland, W.J. *et al.* (2012) Enhancing the value of horizon scanning through collaborative review. *Oryx* 46, 368–374
60. Reardon, S. (2014) Text-mining offers clues to success: US intelligence programme analyses language in patents and papers to identify next big technologies. *Nature* 509, 410–411