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Organising evidence for environmental management decisions: a '4S' hierarchy

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Making decisions informed by the best-available science is an objective for many organisations managing the environment or natural resources. Yet, available science is still not widely used in environmental policy and practice. We describe a '4S' hierarchy for organising relevant science to inform decisions. This hierarchy has already revolutionised clinical practice. It is beginning to emerge for environmental management, although all four levels need substantial development before environmental decision-makers can reliably and efficiently find the evidence they need. We expose common bypass routes that currently lead to poor or biased representation of scientific knowledge. We argue that the least developed level of the hierarchy is that closest to decision-makers, placing synthesised scientific knowledge into environmental decision support systems.

Use of science for environmental decisions

The use of relevant scientific evidence to inform decisions in policy or practice is an aspiration widely shared by private and public institutions, and strongly advocated by scientists and science funders. In the environmental field, 'evidence-based conservation' or 'evidence-informed conservation' has been discussed in the literature for almost 15 years [1–10], and evidence-based policy is often claimed in other areas, such as energy and climate change [11]. Yet, recent studies show that scientific information is still not widely used in environmental policy and practice [8,11–19]. In this opinion article, we argue that this is because the infrastructure needed to incorporate scientific evidence into decisions is largely missing. Evidence-informed decision-making for environment and natural resource management is best achieved through a hierarchical framework that channels unbiased synthesis of research findings through systematic reviews (see Glossary) and summaries into decision support systems. The basic structure is emerging, but coverage of important environmental issues is poor at every level. The costs of developing this infrastructure could be met within existing investments in science and science–policy interactions.

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The limited use of scientific information in environmental decisions has been attributed partly to decision-makers' lack of access to relevant scientific literature [12,16,17,19,20], and to a lack of effort to incorporate the growing evidence base into decision frameworks [6]. This contrasts with the situation in medicine, where evidence-based clinical practice is now routine [21]. The methods used to make scientific research usable and relevant to clinical decision-making have been conceptualised in what was initially called a '4S' hierarchy [22], and subsequently developed into a '6S' hierarchy [23–25].

Introducing a 4S framework for environmental science

The 4S hierarchy shows the relation between different means of presenting science for use in environmental decisions (Figure 1, Table 1). Primary research is collated

Glossary

Advice or guidance: recommendations, either written or provided verbally to a decision-maker. In our 4S framework (see main text and Figure 1), these result from interpreting synthesised evidence or the output of a decision support system in a given context.

Decision support system: a tool, usually software-based, designed to assist decision-makers with a particular decision, often by illustrating different possible outcomes visually or numerically, or leading users through logical decision steps.

Experience: information gained from trial and error, or undocumented experiential knowledge about a particular location, environment, or management target. In our 4S framework, experience informs decisions and the design of individual studies.

Study: a report of a single scientific investigation testing the effect of a particular intervention or variable. For the purpose of synthesis, studies should be broken down into individual experiments or comparisons. They can be qualitative or quantitative.

Summary: a standardised, concise description of results provided by the best-available studies and systematic reviews, across a whole area of environmental practice, regularly updated and usually with recommendations based on evidence. Summaries cover a range of possible options or effects, and preferably use an explicit review process.

Synopsis: a brief, plain language description of the results of either a study or systematic review. Synopses are often available in databases or journals for practitioners. When collated across an area of practice, and assessed to extract messages or recommendations for decision-makers, they can form the basic units of summaries.

Systematic map: a catalogue or database of available evidence in a defined area of environmental science, derived using a peer-reviewed search and selection protocol. Systematic maps do not extract and analyse data to answer a specific question, but can provide semi-quantitative or qualitative appraisal of evidence quality and results if the full text of selected studies has been read.

Systematic review: a review, critical appraisal, and analysis of quantitative or qualitative scientific results relating to a specific question, based on a peer-reviewed search and appraisal protocol. Extracted data can be synthesized quantitatively, quantitatively, using narrative synthesis, or a combination of these.

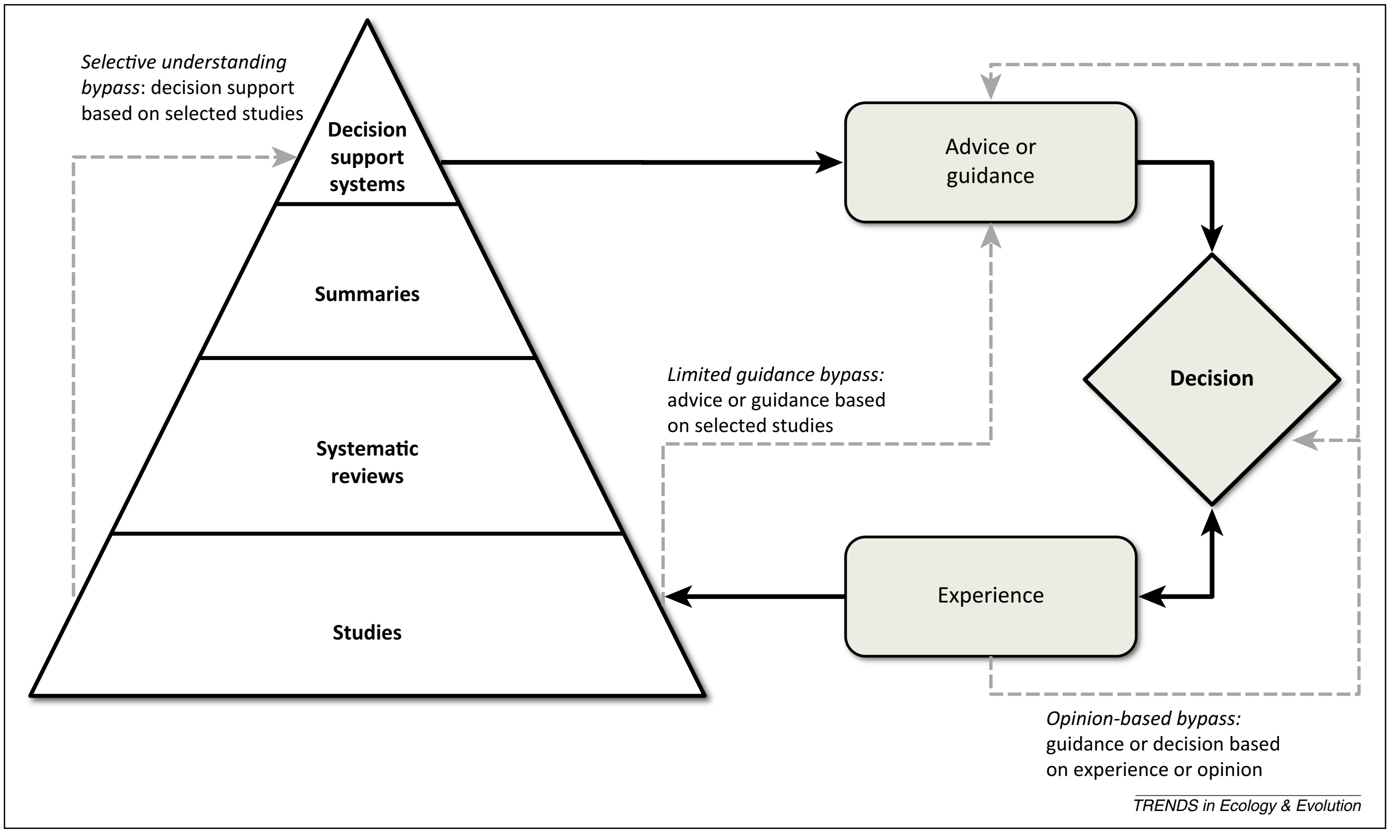

Figure 1. A schematic showing how scientific information could feed into environmental decisions. The triangle on the left is a simplification of the '4S' or '5S' hierarchy proposed by Haynes [22,24] in which summaries integrate evidence from studies and systematic reviews, and are used as the basis for information flowing into decision support systems. In this scheme, environmental decisions are based on the best-available evidence, combined with the expertise and local knowledge of the practitioner or policymaker (described by the 'Experience' box). Broken lines illustrate bypass routes currently taken to inform environmental decisions (see main text for details).

into systematic reviews, both studies and systematic reviews are presented in summaries, and decision support systems place the evidence into a decision-making context. The triangle shape illustrates the number of items at each level that could feed into a given decision. There might be hundreds of relevant research papers, several systematic reviews, one or a few summaries and one decision support system that accurately reflects the decision-making context. At each stage of ascent, the original scientific information is condensed, summarised, and becomes more accessible to decision-makers.

The 4S hierarchy is particularly useful for diagnosing threats, selecting management actions, or deciding how to monitor environmental outcomes, areas where available scientific information is disparate, variable in relevance, quality, and extent, yet critical to success. It is less suitable for finding contextual information, such as species or ecosystem ecology, status, distribution, or local conditions, where only very specific information is relevant.

We have not included two 'synopsis' levels from the 6S hierarchy [23], which refer to individual descriptions of either studies or systematic reviews, not collated or assessed to extract messages or recommendations for decision-makers. These levels exist in environmental science (for example, policy briefs summarising systematic reviews: http://www.environmentalevidence.org/policy-briefs), but they are most useful when collated and regularly updated to form the basic units of summaries.

We have modified the figure developed for evidence-based medicine into a framework that shows how decisions refer to compiled scientific evidence via experience and advice. Our 4S framework combines quality, rigour, and critical appraisal with easy routes for decision-makers to find the best-available scientific information. It also illustrates common bypass routes, through which environmental decisions can appear to be evidence-based without incorporating unbiased synthesis. Below, we explain each component of the framework.

Individual studies – the basis of scientific knowledge

There are millions of scientific studies to be found as peer-reviewed papers in scientific journals, in published or unpublished reports, in books, or student research theses. For a given environmental management decision, a small subset of these will provide relevant information. For example, a summary of global evidence on bird conservation [26] included 1237 individual studies, each testing the effects of one or more specific actions to conserve birds.

Published environmental studies are often not focussed on the needs of decision-makers, so they do not reliably supply information that is relevant and useful [27]. For example, a recent review showed that most published research on 'leopard conservation' was not relevant to leopard management, while practical leopard conservation projects tended not to publish their findings [28].

Table 1. A guide for environmental researchers or decision-makers on when and how to develop the different levels of evidence synthesis in the 4S hierarchy

Level of evidence	Type of question	When to develop	Number of specific questions addressed	Cost[a]	Time required	Renewal period
Study	A specific question about how an environmental system functions, how it is changing, or the differential effects of management. For example: how do carbon dioxide emissions change during wetland restoration on lowland peat?	When existing research or data are scarce, or the effect varies with context and requires repeated experimental tests; the results will not be broadly applied.	Few: often one main question	Highly context dependent; individual research grants from the UK Natural Environment Research Council range in value from US$3600 to US$21 million[b]	Anything from less than 1 year to decades	Studies should be replicated in different contexts to increase certainty
Systematic review	A specific question about how an environmental system functions, how it is changing, or the differential effects of management. For example: how are carbon stores and greenhouse gas fluxes affected by different land management on temperate and boreal lowland peatland ecosystems?	When multiple studies have asked similar questions and their results can be compared; the issue has strong political or community interest, or is controversial; the results will be broadly applied.	1–6 (mean 2.5)[c]	US$30 000–300 000 per review[d]	0.5–3 years[d]	Every 5 years[d]
Summary	A broad question relevant to managing the environment or natural resources, with many alternative options or aspects. For example: how can we reduce greenhouse gas emissions through land management?	When multiple sources of relevant evidence exist, including studies and systematic reviews; the issue has strong political or community interest, and presents a current challenge for decision-makers; the results will be broadly applied.	59–457[e]	Initial cost of collating synopses of evidence: US$70 000–750 000 per subject. Update cost: approximately 20% of initial cost[f]	1–5 years for initial collation of evidence[f]	Annual or biennial updates
Decision support system	A broad or specific question, applied in a specific institutional and environmental context. For example: what should the land management authority of a particular country or region do to reduce greenhouse gas emissions?	When multiple sources of relevant evidence exist; if there are systematic reviews and synopses, they should be incorporated at the design stage; the issue presents a current challenge for decision-makers; the results will be applied in a specific context.	Could address between one or several hundred questions, depending on the context and breadth of the overall question	We found no literature data on comparative costs of environmental decision support systems. Based on recent examples, costs can range from US$540 000[g] to US$5.6 million[h]; in medicine, a systematic review of cost-effectiveness provided costs ranging from US$3600 to US$45 000[i]	Usually several years	Modification as appropriate

[a]Costs converted to US$ on the basis of exchange rates on 22 June 2014, rounded to two significant figures where necessary.

[b]Results of a search for Natural Environment Research Council (NERC) on the UK Gateway to Research database (http://gtr.rcuk.ac.uk/).

[c]Number of primary and secondary objectives in the completed systematic reviews in the Collaboration for Environmental Evidence library (http://www.environmentalevidence.org/), calculated 22 June 2014.

[d]Information from [29].

[e]Range in the number of interventions covered by completed Conservation Evidence Synopses (http://www.conservationevidence.com).

[f]Estimates made by Conservation Evidence project (unpublished; http://www.conservationevidence.com).

[g]The cost of developing a decision support system for nitrogen fertiliser management on grasslands (Defra project NT1603; http://randd.defra.gov.uk/).

[h]The cost of BRIDGE – a European Seventh Framework Programme project to build a decision support system for urban planning (http://cordis.europa.eu/projects/rcn/88630_en.html).

[i]Calculated from the number of patients and total cost per patient reported for five studies in [68].

Systematic reviews – the primary method of synthesis

Systematic reviews analyse findings across all existing studies about a specific question, usually about the effectiveness of an intervention or the effect of exposure to a particular variable. They use transparent, unbiased search and appraisal methods, avoiding the vague methods or cherry picking of well-known studies that can make standard literature reviews unreliable or open to bias [29–31]. The process generates better outcomes when there are multiple, well-designed relevant studies [32].

The Cochrane Collaboration, which publishes medical systematic reviews, has over 8300 reviews in its database (http://www.cochrane.org). The Campbell Collaboration oversees the production of systematic reviews in social policy areas such as crime and education (http://www.campbellcollaboration.org/) and has a library of over 250 reviews or review protocols. Following this model, several centres have been established to incorporate systematic review methods into environmental decision-making [5]. There are guidelines and training on how to conduct environmental systematic reviews [30] and 62 completed reviews are currently published in the online library of the Collaboration for Environmental Evidence (www.environmentalevidence.org/completed-reviews).

A study completed in 2012 assessed the contribution of systematic reviews included in online databases since 1945 to environmental management decisions [33]. Of the 43 published at that time, 23 provided concrete conclusions relevant to conservation management. Many were too narrow in geographic scope or too broad in taxonomic scope to provide useful recommendations. The process of developing and framing appropriate questions for systematic reviews is key to ensuring they produce meaningful results [34].

A similar, more exploratory technique called systematic mapping has recently been adopted for environmental questions (for examples, see [35–37]). Systematic maps use the rigorous search methods of systematic review to build a database or catalogue of evidence, which represents an unbiased picture of scientific information in a given area. They do not set out to answer a specific question, and do not always include analysis of results. If the full text of studies included in the map has been read, it might be accompanied by an appraisal of the quality of evidence and its results, based on author judgement rather than in-depth data extraction and analysis (demonstrated by [36]). Systematic maps have an important role in the hierarchical synthesis of evidence, because they are able to cover the breadth of science often needed for policy-relevant questions. They can form the basic evidence-gathering phase for scoping a systematic review [38], or provide the set of studies and reviews to be described in a summary (as in [39], for example).

Summaries – integrating evidence-based information

Summaries are regularly updated descriptions of evidence across a range of possible solutions or approaches relevant to a particular type of decision. They integrate evidence-based information, preferably using an explicit review process to identify all relevant systematic reviews, and studies where systematic reviews are lacking. Summaries are written in simple, nontechnical language, suitable and sufficiently concise for a busy practitioner or policymaker to understand quickly. They can be organised collections of short synopses, each providing enough information about a single systematic review or study to use it in support of an environmental decision, without the decision-maker needing to read the whole article or review. Summaries often include recommendations about what practitioners should do, based on the evidence. In medicine, Clinical Practice Guidelines are an example [21], as is Clinical Evidence (http://www.clinicalevidence.com), an online database of systematic overviews that assesses benefits and harms of medical treatments.

For environmental science, at least one set of resources has been developed that is moving towards offering the summary level in our 4S hierarchy, for management of biodiversity and ecosystem services (http://www.conservationevidence.com). These resources, called 'Conservation Evidence Synopses', include collations of global evidence from systematic reviews and studies on bird conservation [26] and amphibian conservation [40]. They have been applied in several contexts to inform policy or set research priorities [9,41,42] and used directly in the development of UK policy on agriculture and pollinators (cited in [43] for example). So far, none has incorporated practical recommendations based on the evidence, or been updated.

A key element for both systematic reviews and summaries in environmental science is the involvement of practitioners and policymakers in framing the question and choosing the interventions or variables covered. This ensures that the scope remains relevant to environmental management or policy, regardless of what is covered in the scientific literature, and makes systematic reviews, maps, and summaries valuable tools for identifying gaps in knowledge [9].

Decision support systems

The final step in the 4S hierarchy links the full body of evidence, synthesised from the bottom up, into decision support systems operating at the point of decision. In medicine, these have been described as 'point-of-care evidence-based services' [44,45].

In environmental management, decision support systems, sometimes called 'decision support tools', are increasingly being used to help decision-making [46]. They are usually software based, and assist with decisions by illustrating possible outcomes visually or numerically or leading users through logical decision steps. Some are complex models, only reliably operated by their developers. Others have simple interfaces designed to be used by non-experts.

While challenging, this range of system types is probably necessary. Translating scientific information into real natural resource management decisions demands integration of different models, scales, disciplines, and stakeholder groups [47,48]. Most decision support systems use a selected subset of research studies, data sets, or one or more mechanistic or conceptual models to represent the environmental system in question [49]. Many also incorporate factors beyond environmental science, such as socio-economic, financial, or institutional elements of a specific decision-making context [50]. Participatory involvement of stakeholders throughout the design process is important [48,51–54].

The growing popularity of such systems results partly from their capacity to incorporate scientific evidence into the decision context [55]. From a practitioner's perspective, the completeness and reliability of the information provided by a decision support system is just as important as its usability [56]. There is likely to be an underlying body of science, and a range of uncertainty, for almost any element of an environmental model being used as the basis of a decision support system, whether it is conceptual or mechanistic.

Yet, the literature on environmental decisions support systems is largely concerned with improving their usability or likelihood of uptake. There is very little discussion of how well these systems represent scientific knowledge.

This is why we judge decision support systems as the least developed level of the 4S hierarchy. We know of no protocols or established mechanisms for linking them with summaries of evidence, and no guidelines on how to assess their quality, relevance, or scientific content. These areas should be an urgent focus of collaborative effort between researchers, research synthesizers, and users of environmental science.

One sensible starting point would be to incorporate synthesised evidence into decision support systems that quantify environmental impacts based on the expected effects of alternative management actions. Carbon accounting tools are a good example. Those designed for agriculture have recently been shown to produce widely varying results according to their underlying scope and assumptions [57].

The role of advice and experience

Evidence-informed environmental management integrates the best-available scientific information with the expertise, local knowledge, and values of environmental practitioners [1,10]. Although decision support systems often incorporate other elements of decision-making, such as costs or specific circumstances, there is still an important role for the individual expertise of decision-makers, stakeholders, and experts providing them with advice or guidance, in interpreting scientific information generated by the 4S hierarchy. The 'Advice or Guidance' box in Figure 1 represents a step where experts assess the outputs of a decision support system, generic evidence-based recommendations, or the best-available evidence for their relevance to a particular situation, and interpret them to develop sound, evidence-based advice for decision-makers.

The 'Experience' box in Figure 1 is the personal experience of a decision-maker, which is often essential for effective action. This anecdotal evidence is valuable, but its quality is difficult to assess, making it less reliable than evidence gathered using scientific methods. Experience is often relied upon heavily in developing guidance and in decision-making (Figure 1 'Opinion-based bypass'). This can lead to the propagation or entrenchment of poor or untested practice, a risk that is reduced if the sources of evidence and experience used to inform decisions are transparently recorded.

Bypassing the evidence hierarchy for a quick fix

In this section, we present examples of the common evidence bypass routes identified in Figure 1. Using these routes, decisions can appear to be evidence based, while not being based on carefully synthesised evidence from the 4S hierarchy.

The 'Selective understanding bypass' is when decision support systems use selected research studies that do not represent the full scientific understanding. One example is the representation of green roofs in the Storm Water Management Model (SWMM; http://www2.epa.gov/water-research/storm-water-management-model-swmm#Capabilities). In 2009, this widely used model incorporated 'bioretention cells', allowing planners and policymakers to model the effects of green infrastructure elements on urban water flow rates. The new function was based on a single mechanistic model of infiltration and runoff over natural surfaces. It has been shown to generate poor or inaccurate predictions of water flow rates over green roofs [58,59], because important details, such as orientation and plant communities, were not included. A 2011 review of environmental effects of green roofs [60] illustrated the range of relevant scientific findings that existed before the SWMM green infrastructure module was built.

The 'Limited guidance bypass' is when advice or guidance is based on some research studies, but not a full synthesis. Guidance documents on how to manage ecosystems or wildlife are typically based on a mixture of nonsystematic literature review and expert opinion. These do not always accord with advice that might be generated by a more thorough synthesis of evidence. For example, a guidance document on habitat management for amphibians in the USA [61] recommended installing culverts along roads and regular burning of grasslands. A summary of evidence on amphibian conservation [40] described ample evidence of reduced amphibian deaths as a result of road culverts, but the small amount of evidence on the effects of grassland burning suggested it could be more likely to cause amphibian numbers to decline.

The 'Opinion-based bypass' is when guidance documents, advice, or decisions themselves are based on experience or expert opinion [62], rather than scientific information. It is easy to find guidance documents promulgated by environmental nongovernmental organisations (NGOs) or government agencies that do not provide a clear link to scientific evidence (e.g., [63]). Government guidelines on how to protect the Siberian flying squirrel in Finland while harvesting timber were recently shown to be based on no scientific evidence, and entirely ineffective [64]. Without ongoing openly accessible synthesis of evidence, it has been necessary to develop guidance in this way.

Improving the use of science

We have shown that a 4S hierarchy for environmental science is poorly populated at present, and frequently bypassed when informing environmental decisions. Organising evidence synthesis according to this 4S framework should improve the use of scientific evidence in environmental management decisions, simply by making relevant evidence accessible.

Where synthesized evidence is not yet available, and a bypass is necessary to make a timely decision, we urge decision-makers to make it clear to people affected by that decision that it was not based on a full consultation of the best-available evidence, to explain which bypass route was taken, and to report the sources of evidence or opinion used.

Of course lack of access to science is not the only reason why decision-makers do not use scientific information. Some studies show that environmental managers have good access to scientific literature [65]. There are two other important reasons for the disjunct between environmental management decisions and science. First, science does not always address the right questions [27,28,66]. Second, a lack of dialogue between scientists and decision-makers can lead to management recommendations that are unachievable because of financial or institutional constraints [13,19]. The 4S framework will not solve these problems, but it can contribute to addressing them, by clearly identifying gaps in knowledge and by demanding collaboration between scientists and decision-makers in its three upper levels.

Environmental decision-making has many inputs other than scientific evidence, such as economic and political contextual factors [11]. In Figure 1, there could be a wide range of additional arrows feeding into the 'Decision' diamond. Our focus here is on devising a route for clear translation of the body of scientific information into decisions, so that it can be taken account of without susceptibility to bias.

Who should pay?

Constructing the 4S framework for the core areas of environmental management entails investment and collaborative effort (see Table 1 for cost estimates), but it does not require new investment or money diverted from basic research. The large-scale institutions that fund research and aspire to be evidence-informed already invest heavily in improving interactions between science, policy, and practice. They frequently fund expensive decision support systems (example costs in Table 1) and large-scale reviews or scientific assessments [67] that do not follow clear protocols to reduce bias or facilitate use in real decision-making contexts. The Intergovernmental Panel on Biodiversity and Ecosystem Services, for example, is expected to spend US$43.5 million on its first 5-year work programme (http://www.ipbes.net). The challenge is not to find the money, but to demand and enable appropriate rigour in activities that are already taking place.

Concluding remarks

In this opinion article, we have brought together the collective experience and knowledge from a range of contexts where there is a need to base decisions on sound science: medicine, environmental resource management, evidence-based conservation, and social policy. We outline a hierarchical framework for informing environmental management decisions with science, reliably and without bias. We advocate that building this framework, particularly its upper levels, becomes an aspiration for investment in key environmental policy areas over the next 10 years.

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