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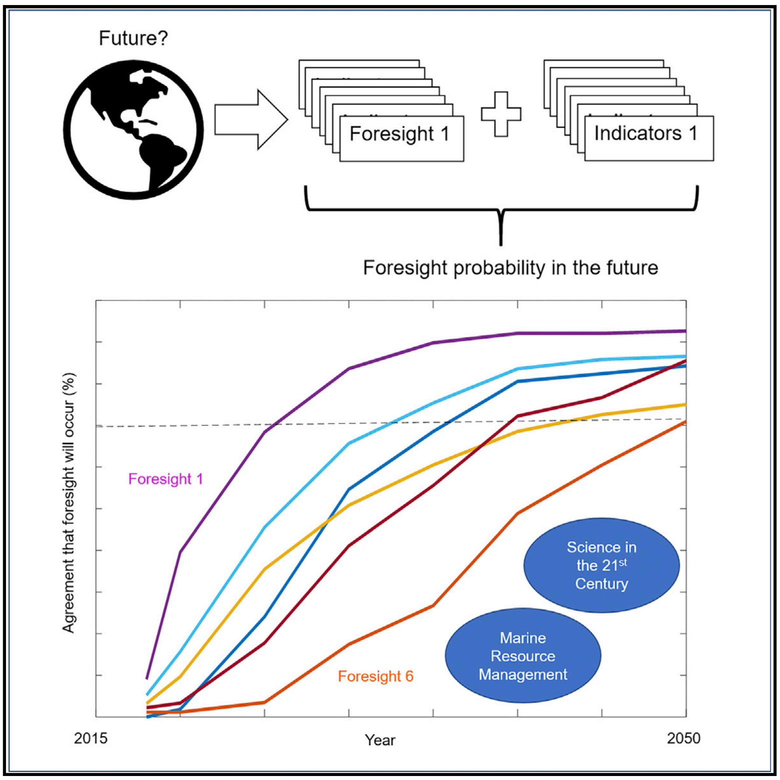
Quantitative Foresighting as a Means of Improving Anticipatory Scientific Capacity and Strategic Planning

Graphical Abstract



Highlights

- Fourteen foresight scenarios developed and ranked for general and marine science domains
- Repeat assessments by scientists in two consecutive years showed scoring consistency
- Quantitative foresighting can help build capacity to anticipate an uncertain future

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In Brief

In a rapidly changing world, scientists and research institutions need to plan for the infrastructure, skills, and policy engagement that will help society navigate social-ecological challenges. Here, Hobday et al. show that foresighting—an approach used to inform thinking about future conditions—can be used as a quantitative approach to motivate and guide strategic planning and investment decisions by scientific institutions in response to different anticipated futures and build skills in futures thinking.

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Quantitative Foresighting as a Means of Improving Anticipatory Scientific Capacity and Strategic Planning

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SCIENCE FOR SOCIETY Decisions about the future are necessarily uncertain, and increasing social-political change and technological disruption compound this uncertainty. Despite this, scientists and scientific organizations must still plan for the future. Foresighting is one approach used to inform thinking about future conditions. We describe a quantitative foresighting approach for a range of general science and marine-specific foresights. Repeat assessment over a 2-year period showed that the time-specific likelihood futures were consistent between years. Our approach can be used to prepare scientists and their institutions for possible futures, and to prioritize among these choices.

SUMMARY

In a rapidly changing world, scientists and research institutions need to plan for the infrastructure, skills, and policy engagement that will help society navigate social-ecological challenges. Foresighting draws on approaches used in strategic and long-range (>10 years) planning and participatory futures studies. Here, we describe a new quantitative approach to develop and rank 14 foresight scenarios across a range of general and marine-relevant science domains. Indicators for each foresight were used to assess the time-specific probability of each scenario being realized. Assessments by scientists in 2 consecutive years showed foresight scoring consistency and revealed surprises. Despite high variation among scientists in scoring the year that each indicator would occur, there was overall consistency across the foresights between years. We show that foresighting can be quantitative and that individual performance and changes in likelihood can be evaluated. This approach can motivate and guide strategic planning and investment decisions by scientific institutions in response to different anticipated futures and build skills in futures thinking.

INTRODUCTION

Scientists and scientific organizations are facing methodological and conceptual challenges associated with system uncertainty and rapid change. This is, in large part, due to rapid and pronounced ecological change including faster-than-anticipated rates of climate change,[1] ocean warming,[2] and increasing frequency of extreme events such as storms and terrestrial and

Table 1. Definitions of Strategic Planning, Foresighting, and Related Concepts

Concept	Definition (and Example Reference)
Strategic planning	planning is a structured process to integrate information and to conceptualize. Strategic planning involves creating a vision, setting goals, and determining resource allocation and other actions to pursue those goals;[31] planning by organizations or sectors aimed at improving the long-term effectiveness of operations; commonly based on some form of macro-environmental analysis of social, technological, and political trends, or scenarios which narrate internal and external drivers for future development[32,33]
Foresighting	foresight is the process involved in systematically attempting to look into the longer-term future of science, technology, the economy, and society with the aim of identifying the areas of strategic research and the emerging of generic technologies likely to yield the greatest economic and social benefits;[34] the purpose of foresight is to imagine different futures and their consequences and, on that basis, to engage in informed decision making. Foresight thus rests on two key assumptions: (1) that the future is not laid out and (2) that decisions made and action taken today can affect the future[26]
Visioning	"a tool to envisage the most desirable future, and commitment to create that future"[24]
Narratives	"narratives follow a particular structure that describes the cause-and-effect relationships between events that take place over a particular time period that impact particular characters";[35] narratives may be highly imaginative and visual (e.g., "science-fiction prototyping")[36]
Scenarios	"plausible, challenging, and relevant stories about how the future might unfold"; because scenarios are stories, they do not necessarily include numerical projections;[37] "a coherent, internally consistent, and plausible description of a potential future trajectory of a system"[38]
Forecasting	"to calculate or predict (some future event or condition) usually as a result of rational study and analysis of available pertinent data"; forecasting is the estimation of the short-, medium-, or long-term future in a specific research area or according to the questions posed by means of scientific methods;[31] forecasting requires both broad and expert knowledge and is often model based[39]
Projections	numerical estimates of the likely or possible future values of one or more indicators of a system's behavior. For example, projections can be described numerically either as a plot or as growth rate[40]
Horizon scan	an expert-based elicitation approach to identify emerging issues, widely used for business and scientific purposes[41]

marine heatwaves.[3–5] Concomitant with these ecological changes are increasing social-political change,[6] rates of technological progress and connectedness (e.g., Jouffray et al.[7]), and most recently, unprecedented disruptions to society resulting from the coronavirus disease 2019 (COVID-19) pandemic.[8] There is an increasing need for science that can underpin decision making to support societal wellbeing in the face of change, especially anticipatory science that can imagine change that is not obvious now.[9] Scientists also need to "expect the unexpected" to inform decision making associated with important topics such as tipping points,[10] planetary boundaries,[11,12] and desirable trajectories.[13]

One way to prepare for the future is to plan ahead.[14] Whereas most organizations (including research organizations) are familiar with and employ concepts of strategic planning, those processes tend to deal with relatively small modifications to the status quo or "business as usual."[15] Strategic planning generally looks at obvious opportunities building on the current landscape and existing strengths. It does not normally look far into the future to consider the unexpected. Indeed, there are psychological studies indicating that it is often hard for people to project far into the future without structured help.[16,17] Faced with change of the magnitude that has been suggested by the Intergovernmental Panel on Climate Change (IPCC) reports,[1,18] the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services,[19,20] and organizations such as the Food and Agriculture Organization[21] and the World Economic Forum,[22] it is essential to implement methods that allow investigation of the unexpected using more proactive approaches that are capable of anticipating plausible changes.[9] McDonald et al.[9] illustrate a spectrum of potential responses by scientists to the challenges from climate change that range from inactive and reactive to proactive. This in turn illustrates a range of advantages expected in proactive compared to reactive approaches. Given the amount of information about possible future environmental and societal changes,[1,21] failure to consider more forward-looking approaches could be considered negligent and undermine public confidence in the scientific community and scientific agencies.[23]

Foresighting is a structured process for creatively identifying alternate future options.[24,25] Foresighting has been defined and used in a variety of ways in the literature but usually aims to confront decision-makers with a set of contrasting, alternative, plausible, and coherent future scenarios that are intended to challenge assumptions that the future will be much like the present or follow a "business as usual" trajectory.[9] We contrast foresighting with related concepts in Table 1. Foresighting is concerned with futures that are usually at least 5–10 years away and is action oriented. It rests on two key assumptions: (1) that the future is not determined and (2) that decisions taken today can affect the future, and hence, action can change outcomes.[26] Foresighting exercises may lead to development of multiple non-exclusive scenarios and a set of corresponding responses. It most often involves a systematic, participatory, vision-building process to capture existing knowledge to uncover possible future paths for discussion.[25] Foresighting draws on approaches used in long-range and strategic planning,[27,28] horizontal policymaking, democratic planning,[29] and participatory futures studies.[30]

Foresighting and scenario generation require imagination, broad knowledge, and a propensity toward intellectual adventure.[42–44] Feedback is provided mostly in terms of intellectual counter arguments. "Data" mostly come in the form of trends and are often imprecise and may be contradictory.[45,46] Evidence, mostly in terms of indicators, is never conclusive and often amenable to alternative interpretation.[47] This may be contrasted with even more general visioning that is usually accompanied by informal, qualitative narratives,[30,41] and formal forecasts with projections that are usually based on empirical data and require underlying assumptions about model behavior and for which evidence and feedback are observed (e.g., biophysical forecasts[39]).

In this paper, we describe how we developed a quantitative foresight approach that can be used by research institutions to guide strategic planning and investment decisions. We developed a range of diverse marine-related scenarios in two areas—Marine Resource Management (fisheries, aquaculture, and conservation) and Science in the 21st Century. We were interested in both methodological development and skill development among scientists. We develop and use methods that advance our approach beyond the typical "imagining" phase of foresighting to provide strategic value for decision making and allocation of research resources.[48,49] This repeatable, measurable, and participatory approach is supported by the development of indicators to assess progress and likelihood of the futures emerging to support strategic planning in scientific research. We evaluated the scoring behaviors of the project team over a 2-year period to expose biases and identify surprises. Finally, we describe how foresighting may influence the process of investment by science research and funding agencies.

RESULTS

Approach Overview

The group developed a total of 14 foresights (Table 2). Seven foresights were related to Science in the 21st Century and seven to Marine Resource Management (fisheries, aquaculture, and conservation). While we do not review each of these foresights in detail, descriptions of each foresight indicator can be found in Experimental Procedures, and further descriptions are available on the project webpage.[50] The process of iteration was considered both critical and challenging, as discussed below. Between five and ten indicators for each foresight were developed and then scored by 18 participants in each of 2 years (2018 and 2019). Different numbers of indicators reflected the complexity of some foresights. A total of 3,034 indicator scores were compiled across the 2 years.

Considerable effort was spent to refine indicators, including a pilot trial prior to scoring, but discussion among the project team still revealed challenges with scoring some of the indicators, with some participants finding them imprecise, ambiguous, or poorly defined. Others reported little difficulty, which could mean comfort with ambiguity, tolerance for the goals of the approach, or superficial thinking. Overall satisfaction with the indicator scoring varied among the participants, and a range of improvements was suggested as part of the learning process in this study. This component highlighted how difficult development of indicators can be and the difference in how participants approached the scoring process.

Collective Patterns

The year for which participants felt each indicator was 90% likely was distributed across the full range of years in both 2018 and 2019 (Figure 1). The most common year for all indicators was 2025 and 2030, which was expected by design because we focused on foresight scenarios that would be likely within the next 10−20 years. A total of 8% of indicators was considered "unlikely before 2050" for both 2018 and 2019, and 11% and 10% were scored as "never likely" in years 2018 and 2019, respectively (between 3%–19% of indicators were scored as "never likely" across individual foresight scenarios, Figure S1B).

The years selected by participants for each indicator varied, with some selecting a particular year and others, "never," for the same indicator (Figure 2). In every scenario, some indicator scores included "never." Despite this spread of choice, most participants scored a set of indicators within a limited range of time periods in both 2018 and 2019. For example, indicators for the foresight "rationing of air travel" were generally chosen as likely to occur between 2030 and 2040, while indicators for "rise of ocean protection" were chosen as likely to occur between 2040 and 2050. Foresights were generally scored as likely to occur in the same year for each foresight in 2018 and 2019 (Figure 2, triangles from each year show mean scores occur close in time).

The overall scoring pattern across foresight scenarios showed variation in the likelihood pattern over time (Figure 3) —some scenarios were more or less likely than others. However, in terms of temporal ranking of which scenarios come earlier or later, there was reasonable consistency between the years 2018 and 2019 (Figures 3A, 3B, and S1). Foresights that were considered likely to occur early or late in each category were the same in each year. The linear correlation (R^2) between scores for each scenario in each year ranged from 0.41 to 0.06 (Figure S2).

Within the Science in the 21st Century category of foresights, 70% of participants considered that the foresight scenario "social media as truth" was likely by 2025, while in 2018, the foresight scenario "artificial intelligence" was considered only 68% likely by 2050 (Figure 3A). While 2019 scores suggested a delay in the likelihood of the onset of "privatization of science" and the "gig economy," overall, the 2019 scoring of the Science in the 21st Century foresights saw the same or higher likelihoods for most foresights. For the Marine resource management category of foresights, 70% of participants considered that the foresight scenario "aquaculture divided" was likely by 2025, while foresight scenario "blue revolution" was considered only 65% likely by 2050 (Figure 3B). Once again, the majority of foresight scoring in 2019 suggested that the foresights would be as likely or more likely. Exceptions to this were "aquaculture divided" (which saw a small drop in likelihood) and "rise of ocean protection," which was thought to be much less likely by 2050 in 2019 than in 2018. In both categories, the maximum likelihood of any foresight scenario by 2050 was around 90%. Other likelihood levels (e.g., 50% likely and 20% likely) could also be determined from these plots and used to inform risk-based decision making. We recommend that any such threshold should be used as a guide rather than a hard-wired decision rule.

Individual Patterns

Investigating the spread of scoring by each participant revealed individual differences that may offer additional insight. In particular, we investigated three questions:

Table 2. Summary of Foresights in Two Broad Categories

#	Foresight Name	Foresight Scenario	Implication
Science in the 21st Century			
1	rationing air travel	science agencies join national initiative to reduce air travel by scientists	proactive preparation will maintain scientific networks
2	privatization of science	reduced support for government-funded science and increase in private sector science	increasing contest between government-funded and industry-funded science; management agencies rely on science undertaken by private providers
3	participatory governance	government imposes more participatory management structure involving greater range of stakeholders	research community wrestles to maintain credibility in less objective stakeholder driven management system; other groups get privileged voice
4	artificial intelligence	science becomes dominated by autonomous instruments, robotics, and artificial intelligence	research users bypass traditional science providers and processes to source information
5	social media as truth	politicians, bureaucrats, and advisors rely on fast media as major source of information	expert commentary is marginalized or ignored
6	rise of populism	governments increasingly influenced by "populist" views and promote industrial development without critical review	reduced value of scientific research and advice; sustainability is compromised by emphasis on industrial development with short-term gain
7	gig economy	declining investment in governmental science necessitates outsourcing of science to casual suppliers	diminished institutional science infrastructure and capacity
Marine Resource Management (Fisheries, Aquaculture, and Conservation)			
8	precision fishing	fully automated fishing operations that require less human oversight	changes in economics, social structure, and management of fisheries as a result of automation
9	blue revolution	large increase in amount and types of human activities at sea, including "sea steading" communities on floating mega-platforms	increased human influence on the ocean; development of novel ocean uses
10	coastal segregation	government imposes ambitious coastal planning that includes resettlement of people in areas is permitted only according to marine activity	creation of "mono-cultural" communities and reduced conflict among competing uses at the expense of freedom of choice
11	aquaculture divided	aquaculture either gains or loses community support and acceptance	very different employment and economic outcomes in relation to community support
12	rise of ocean protection	societal pressure for increased marine conservation leads to reduction of extractive industries	increased emphasis on scientific advice for conservation, innovation in food production, and improved trust in and use of science
13	rapid climate change	human population and fossil fuel consumption continue to rise or there is a jump in the rate of warming	the most extreme IPCC scenario eventuates earlier than anticipated, perturbing marine ecosystems and disrupting human-ocean interactions
14	astronaut effect	increased space tourism revitalizes appreciation for the blue planet by all citizens	effective global efforts to mitigate climate change, introduce green technologies, and ultimately slow and reverse anthropogenic climate change

Full descriptions and indicators for each foresight are on the CSIRO Oceans and Atmosphere Project webpage.[50]

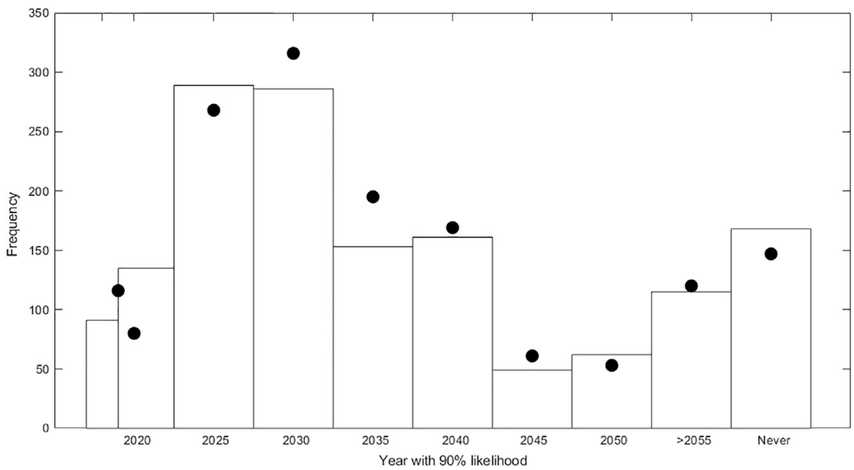

Figure 1. Frequency Distribution of Years Selected by Participants in Scoring Indicators for All Foresights

The year 2018 is represented as bars and the year 2019 as dots.

(1) Do a participant's selected years for each indicator reveal a propensity to imagine events to occur sooner or later in the future?
(2) Do a participant's selected years reveal a propensity to imagine foresight scenarios to occur sooner or later than other participants?
(3) Given the selection of years by all participants across all foresight indicators, does a participant's score of a specific indicator look particularly surprising?

Across participants, the year selected as the point at which a particular indicator was assessed as being 90% likely varied widely for each foresight (Figure 4). Within individual foresights, scores were often spread across 20 years. Similarly, across foresights, the range seen in the average year selected ranged by around 20 years (Figure 4; i.e., spread of filled magenta or blue dots was about as broad as the spread of open dots within any one foresight scenario). The consistency in scoring between the years 2018 and 2019 averaged 0.30 (R^2) for all participants combined, while at an individual level, it ranged from 0.56 to 0.12 (Figure S3). That is, some participants were more consistent in selecting the same indicator year than others.

Indicator and Foresight Entropy

Individual differences in the tendency to imagine indicators to occur sooner or later in the future is revealed by the indicator entropy, calculated across all foresights for both year 2018 and 2019 (Figure 5A). The values for all participants are closer to one (maximum value) than zero, indicating that they selected a wide range of available years (see Figure 4). The mean value for year 2018 (horizontal dashed line) indicates that participants selected around six of the nine available years, on average. This is roughly equivalent to three of the year options having a zero probability and an equal probability for the remaining options. The minimum value of entropy ($\sim$0.7, player 19 in 2019) is roughly equivalent to assigning zero probability to half of the year options and equal probability to the remaining options. The indicator entropy scores for a participant show that some participants were consistent between years (Figure 5A; e.g., participants 4, 6, and 12), some scored a wider range of years in 2019 versus 2018 (Figure 5A, participants 9 and 14), and some scored a narrower range of years in 2019 compared to 2018 (Figure 5A, participant 19). The mean indicator entropy value decreased slightly from year 2018 to 2019, indicating fewer of the available years were selected, which may be a result of an increase in confidence or knowledge in scoring the foresight indicators.

An individual's propensity to imagine foresight scenarios to occur sooner or later than other participants is revealed by the foresight entropy (Figure 5B). Participants with scores closer to zero were those that consistently scored foresights as occurring relatively earlier or later than others. Participants with scores close to one do not have a tendency to consistently score foresights as occurring sooner or later than other participants. The foresight entropy scores for a participant show that some participants were consistent between years (Figure 5B; e.g., participants 14 and 16), while some did score foresights as occurring relatively earlier, or later, to a greater degree in 2019 compared to 2018 (Figure 5B, participants 5, 8, and 10), and some became less specific in the choice of early or late foresight occurrence in 2019 compared to 2018 (Figure 5B, participant 19). The mean foresight entropy value also decreased slightly from year 2018 to 2019, indicating more participants scored foresights as either occurring relatively early or late in 2019 compared to 2018.

Overall, the mean entropy values in Figure 5B are lower than in Figure 5C, which suggests that, despite the spread of indicator scores (Figure 4), participants on average display some consistency in expecting foresights to occur sooner or later relative to other participants. These patterns could be explored in more detail to understand individual scoring behaviors and a subset of participants selected for additional foresight activities.

Surprises

We were interested not only in the similarity of individual scoring, but also in the differences, or apparent anomalies (or "surprises"), which may indicate particular insight held by a participant. As an example of this analysis, we explored one of the surprises in Figure 6. Focusing on the year 2018, 13 indicator scores from 9 participants share the largest surprise with a value of 1.93. From these nine participants, we selected the participant displaying the largest indicator entropy value (participant 10), as large values imply that the participant would be less likely to produce a highly surprising score. Only one score from this participant displays the largest surprise value of 1.93. The participant answered "never" to one indicator ("number of fisheries managed by individual transferable quotas [ITQs], catch shares, or individual quota entitlements [IQEs] reaches 80% in Australia") from the "precision fishing" foresight. This was an outlier compared to the other indicator years selected. Based on the years selected for the other indicators for this foresight, the average year for the scenario was calculated as 2026. In a

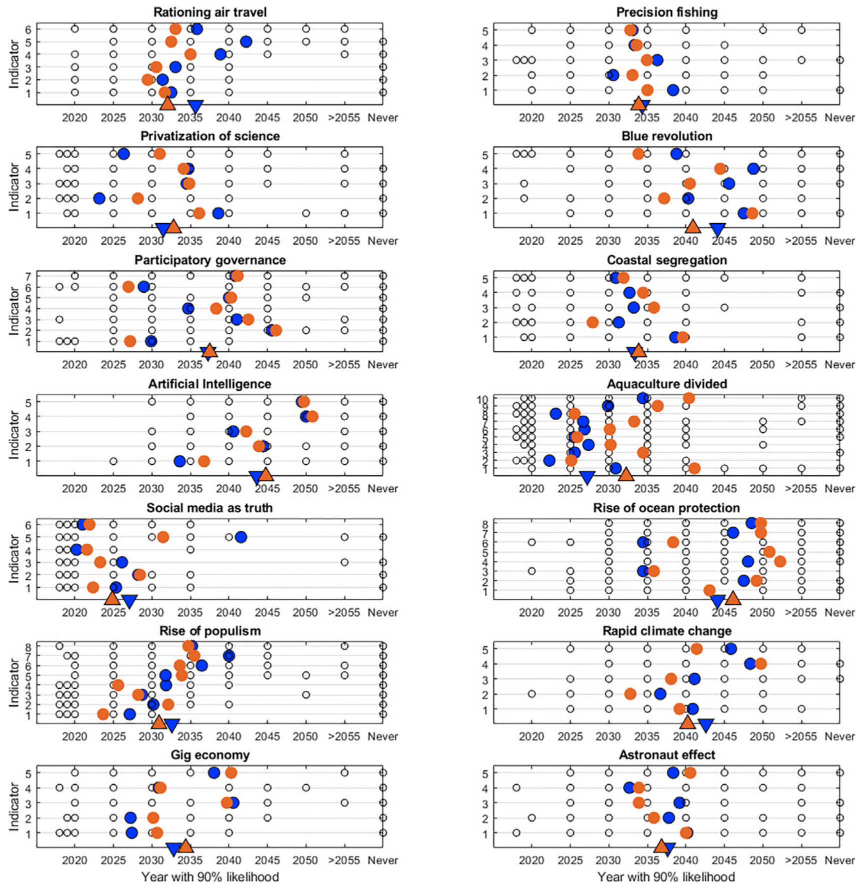

Figure 2. Participant Scoring of Foresights in 2018 and 2019

The years selected for each indicator by participants (open circles, multiple selections are possible for each year) for each of 14 foresight scenarios. Left column: Science in the 21st Century; right column: Marine Resource Management foresights. The mean year for each foresight is indicated at the base of each panel for 2018 (blue triangle) and 2019 (orange triangle). Blue (2018) and orange (2019) dots on each dashed indicator line are the mean for the indicator based on all participants. Where only an orange dot is visible on an indicator line, it falls on top of a blue dot, indicating the same value for both years.

similar way, each of the other surprising scores in Figure 6 could be explored to determine if there was extra information to be obtained.

DISCUSSION

Quantitative Foresighting

Strategic planning, while challenging due to climate and social-political change, is necessary, especially if science is to contribute to proactive approaches to potential futures.[9] Foresighting improves planning by promoting creative exploration of alternate futures and incorporating a systematic look into the longer-term future with the aim of identifying strategies likely to yield the greatest benefits.[24,51] A limitation of most foresighting approaches (and indeed of most future visioning and scenario planning) has been the focus on qualitative, narrative-based scenarios, without subsequent evaluation of likelihood or development of indicators. Indicators often are used in quantitative modeling approaches and in complex situations to judge progress or performance against an objective.[52] As here, a range of values for each choice (e.g., 2,030−2,035, 2,035−2,040, etc.) might be more appropriate when an exact measurement is not clear.[53] Foresighting often is used to explore two alternate visions of the future (e.g., scenario A versus scenario B) or to develop views in a mutually exclusive four-quadrant space.[54–56] We considered multiple and non-exclusive foresights for the two categories (Science in the 21st Century and Marine Resource Management), but the methods developed in this paper could be applied to binary foresight comparisons to specifically evaluate mutually exclusive futures or to undertake a structured horizon scan. An approach that was not comprehensive to the range of future relevant issues could limit the power of a foresighting effort. This potential bias can be limited by comprehensive discussions about the set of foresights being developed.

In the 14 foresight scenarios investigated in this paper, we first articulated a range of futures, which on their own could form the basis for improved decision making. Our quantitative scoring of the likelihood of these foresights (some were judged as likely occurring earlier than others, and likelihood was relatively stable across 2 years) provides additional information for risk-based decision making. Agencies can choose to defer action for foresights that are estimated as emerging later and increase focus for futures that are emerging earlier. For example, issues associated with two early emerging futures, "aquaculture divided" and "social media as truth," are already challenging society (e.g., dividing communities[57]) and science (e.g., combatting misinformation[58]) around the world. In response to these or any other early emerging foresights, a research agency can choose to commission projects, recruit expertise in these areas, undertake additional communication, etc. For foresights with longer lead times, there may still be a need to prepare for the future, but decisions can be sequenced to manage limited resources.

Our approach widens the scope of a traditional foresight exercise by including five additional components, which can add value to management and decision-making approaches:

(1) emphasis on reflection of what a pathway may look like with and without adaptive responses;
(2) a selection of indicators capable of monitoring whether or when the foresight might eventuate (where appropriate, distinguishing between the different response-dependent pathways);
(3) a collection of participant-based estimates on when the indicators will eventuate, which provides a semi-informed

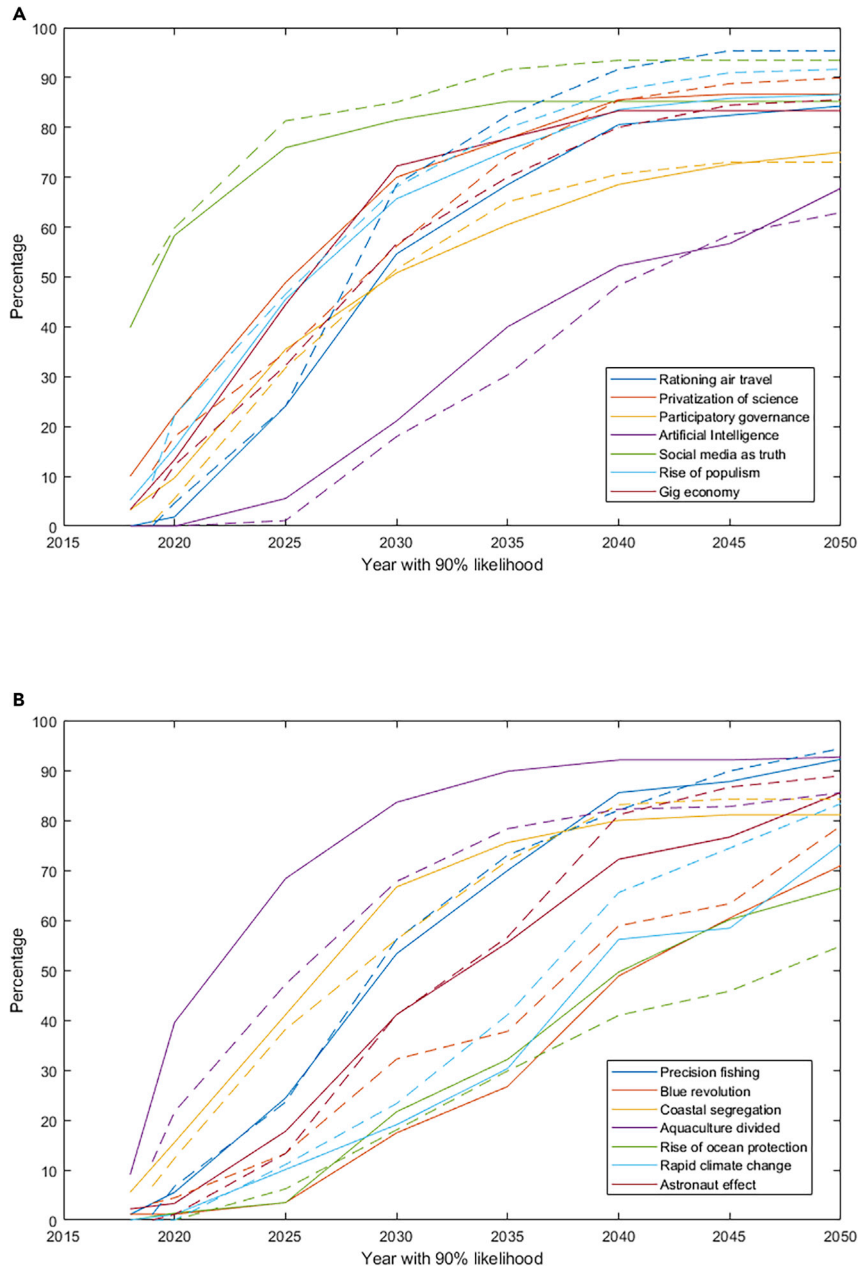

Figure 3. Cumulative Frequency Plots for the Year in Which the Participants Considered Each Foresight Scenario to be 90% Likely

Scenarios for (A) Science in the 21st Century and (B) Marine Resource Management are shown for 2018 (solid) and 2019 (dashed).

assessment of the probability of the foresights to eventuate at different times in the future (conditional on the opinion and expertise of the participants);

(4) a characterization of each participant's estimation signature, based on detecting patterns in each year's choices over time (iterative foresighting), and

(5) the detection of surprises, or unusual estimates, which deserve further attention because they have the potential to be informative compared to the average estimates of a group.

Previous work carried out by project members[16] shows that actively thinking about issues pertaining to the future can change personal perceptions of the future itself; i.e., it can make participants reflect on their own thinking and behavior and change how they act (double-loop learning[48]). In particular, it stretches the time horizon that receives active consideration. While an organization may not want, or be able, to change the temporal scope of its planning cycles (usually 1 to 5 years), a foresighting approach can help by placing this cycle within a longer time horizon.[59] The next 5 years naturally will look shorter in the context of a stretched time horizon. This stretching can help people or organizations to better prepare for the future, particularly when the lead time to develop scientific responses, prepare managers and policy makers, or advise funding agencies is relatively long (e.g., 5 or more years).

Repeated evaluation over several years can be used to examine consistency and changes in the likelihood of a foresight scenario (iterative forecasting, *sensu*[31]). Revisiting our estimates over a 2-year period allowed insight into participants' behaviors in order to understand their consistency and the natural ranges of variability in their estimates. In general, participants scored the foresights similarly between years, with some signs of increased specificity in selecting from the choice of years, as seen in the entropy scores. Selection of a subset of participants for future assessments could be based on aspects of performance once foresighting behaviors are understood (e.g., consistency, accuracy, and surprises). Sub-setting represents a balance between the "wisdom of the crowd" and reliance on a smaller group of experts.[60] Revisiting the forecasts also allows for adjusting participant belief about the likelihood of the foresight exercise to eventuate. The selection of well-performing participant subsets, and the adjustment of the likelihood in iterative foresighting, is consistent with super-forecasting guidance provided from geopolitical literature.[59,61] We note that while we have not commented on the accuracy of foresights here (as the future has not yet arrived), members of the group are now aware of the indicators and incidentally collect relevant information as part of their own scientific planning. A focus on a set of indicators does not limit additional assessment of the future, and we expect that alternative indicators may emerge

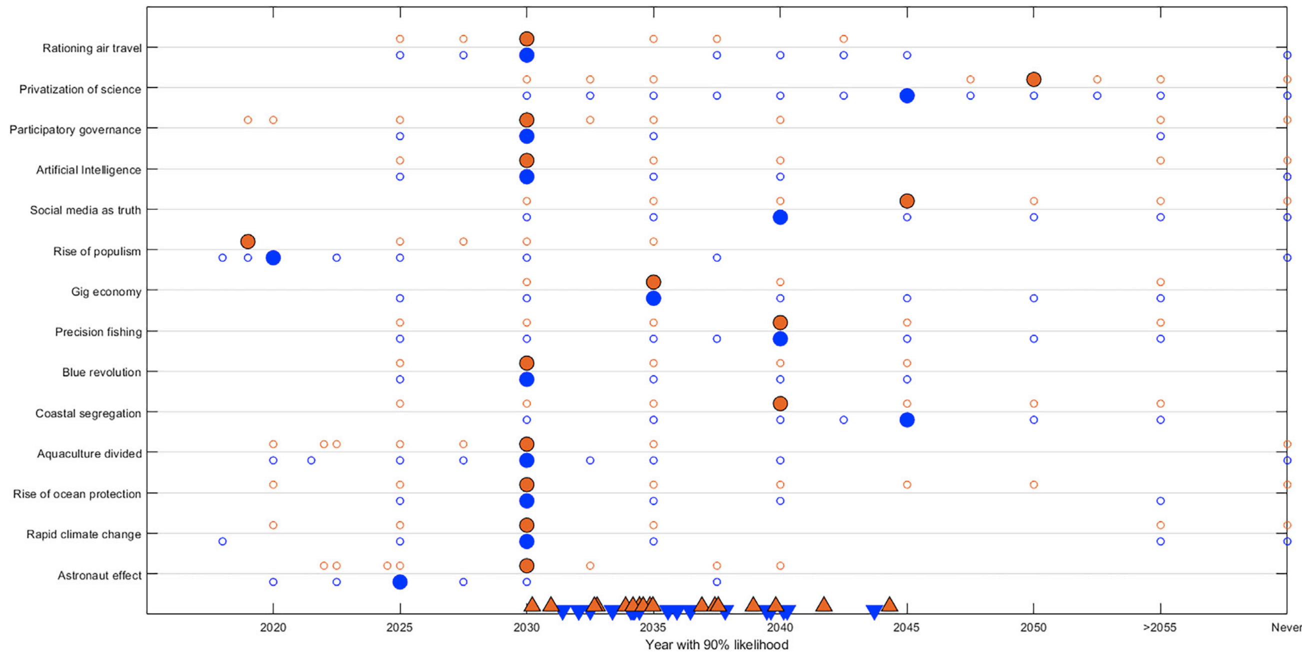

Figure 4. Foresight Scoring in 2018 and 2019

The foresight order from top to bottom on the y axis is the seven Science in the 21st Century, followed by the seven Marine Resource Management foresights. Circles represent the participant mean year (blue, 2018; orange, 2019) based on the set of indicators for each foresight. Blue (2018)- and orange (2019)-filled dots indicate the mean year for each foresight, based on all responses. Blue (2018) and orange (2019) triangles at the base of the plot indicate the mean year selected across all foresights by each participant.

in the future and could provide more useful insight. It will be important to consider these alternatives and not ignore other signals about an emerging future. In due course, time will allow for some assessment of the accuracy of the scoring process and potentially provide insight on the forecasting skill of specific individuals. While not the focus of analysis presented here, it is possible to undertake exploration of factors that could be driving individual differences in how participants viewed the future (e.g., based on age, level of experience, political views, gender, research field, expertise in a given topic, etc.). In the future, scoring of the "level of confidence" for each of the indicators or foresights could allow identification of participants with different perceived expertise.

The identification of surprises is useful in foresighting to overcome biases associated with using average responses. Using the so-called wisdom of the crowd to evaluate foresight likelihood can obscure individual knowledge. Outliers, in terms of the year selected for an indicator, can represent a warning. They can indicate that the foresight likelihood is changing (i.e., if some indicator years are far from the others), that the participant knows something special or is missing particular information compared to all others. As these options cannot be determined from the identification of an outlier, a subsequent step should be to look at outliers in more detail to determine if they come from a single foresight, come from a single participant, or are just features of a distribution. Such examination is an important element when planning responses to foresights.[60] A next step could include interviewing the participant to find out what motivated the surprising score.

Foresighting Skill Development for Scientific Agencies

> Foresighting requires time, extensive reading, deep thinking, and intellectual speculation.
>
> —Participant 17, foresight group

An organization (or any group) interested in implementing the approach we described here will need to consider a range of foresighting design aspects, including the investment in effort (time and money). A choice also needs to be made whether the available investment should be distributed among a large team with small individual effort or among a small team with higher individual effort. These choices may depend on the specific purpose of the task. A small team may work best if the purpose is to collect a number of well-crafted foresights and to use the best available expertise to assess their likelihood and then make subsequent strategic choices. It requires thinking outside, but not too far outside, the box, since the foresight needs to be realistic, useful, and credible.

Alternatively, the purpose of a foresighting exercise may be to shape an organizational culture and expose and train a large set of staff to future thinking. In this case, it may be important to make the exercise attractive to a large number of staff. Some staff may have a short time horizon and perceive long-term considerations as irrelevant. Other, particularly senior, staff may think they "have seen it all already" and feel less inclined toward speculation about novel futures. The experience described in Mellers et al.[61] suggests an

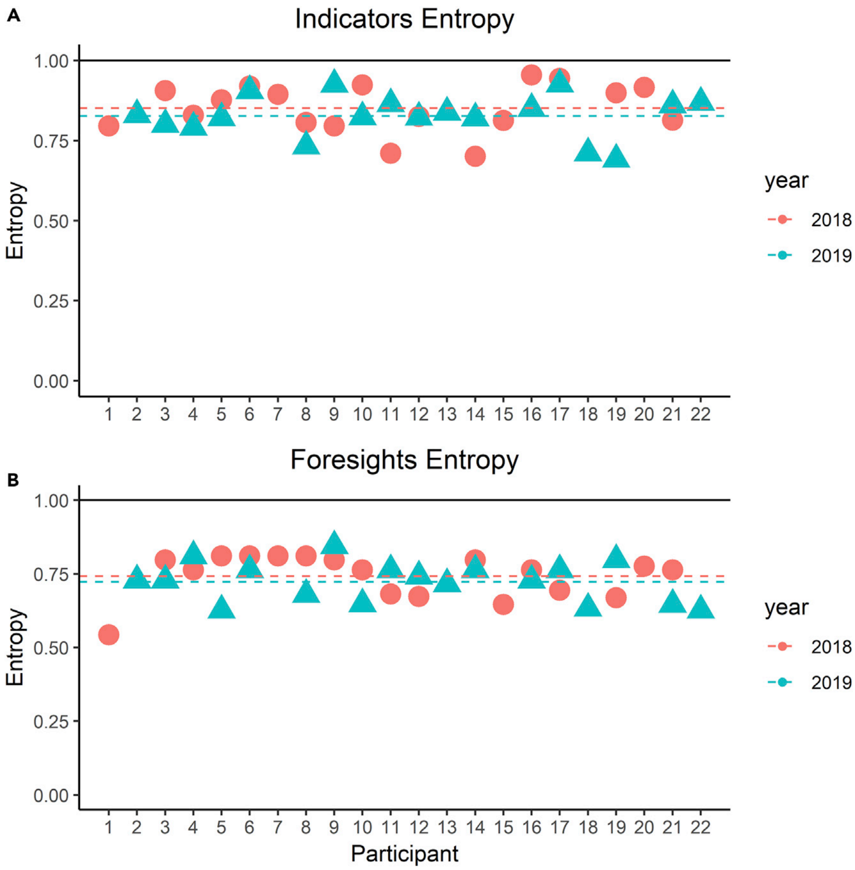

Figure 5. Indicator and Foresight Entropy Scores

Indicator entropy (A) and foresight entropy (B) are shown for each participant scoring in 2018 (circles) and 2019 (triangles). Participants with scores close to one provide little discrimination on the occurrence of future events. Note that of the 22 participants, 18 participants scored in each of the years, and 14 of the 22 scored in both years. Dashed horizontal lines show mean values for years 2018 and 2019.

alternative two-stage approach in which a large team is exposed to the experience first and a smaller team of skilled individuals is selected within the larger team for further, more in-depth work.

Whatever choice is made, dramatic changes in participant skills should not be expected within very short time frames. Feedback is slow as it involves future projections, and there is a lag time before these can be validated. Our experience is that some individuals can find this type of thinking challenging and that several iterations may be needed to agree on the choice of the indicators and the details of the scoring. The approach we propose may appear relatively straightforward, but dealing with foresights, speculations, choice of indicators, cumulative probabilities of indicators occurring at different times in the future, and probabilities of foresight to occur conditional on the occurrence of the indicators is challenging both from a cognitive and a communication perspective. Any group approaching foresighting needs time to absorb these ideas to carry out the task effectively. In our case, we allowed participants to self-select ideas to develop into foresight scenarios, which served to generate enthusiasm and motivated participation and learning. While untested, we felt that study participants are now better prepared to work on foresight topics nominated by leaders or others in our research agency, and have improved their interest and approach to future challenges.

Foresighting exercises reportedly work best when carried out by multidisciplinary teams because they can provide more diverse perspectives and avoid discipline-based bias.[62,63] Literature also indicates that at times, individual thinking, possibly perceived as eccentric, can be effective in resisting the constraints imposed by group thinking and the search for consensus. As a result, a balance needs to be found between encouraging teamwork, exchange of information, and provision of feedback, as well as individual speculations and the right to disagree. We showed how outliers, or surprises, can be identified to value these contributions. Estimates that differ significantly from group thinking may result from lack of knowledge, limited thinking, problem-specific knowledge, or brilliant insight. The latter may make the difference between a useful and a mediocre foresight exercise and are worth further investigation. Team members with different backgrounds may have very different attitudes toward quantitative approaches, especially when applied to highly speculative events. Unfortunately, true probabilities for such events cannot actually be defined.[64] Our experience is that requiring participants to define probabilities, in this case by selection of indicator years, is useful. The mental discipline that is required in formulating probabilities and the increased sense of accountability which may arise from this task has been shown elsewhere to improve the overall outcomes in foresighting exercises, including the reliability of the estimated outcomes.[60,61,65]

The most challenging component in our approach was the selection of appropriate indicators. This was somewhat surprising given the scientific background of the team members, who were well aware of the need for indicators to be measurable and time bound. We needed to resolve a range of issues, including the following: should indicators have causal influence on the foresighted events or merely be correlated with them? Should they lead or lag the events? How specific or unique should they be to the foresight? To what extent are ambiguous indicators (which can occur under different scenarios/foresights) useful? How do we decide that an indicator has eventuated? How do we combine multiple indicators to

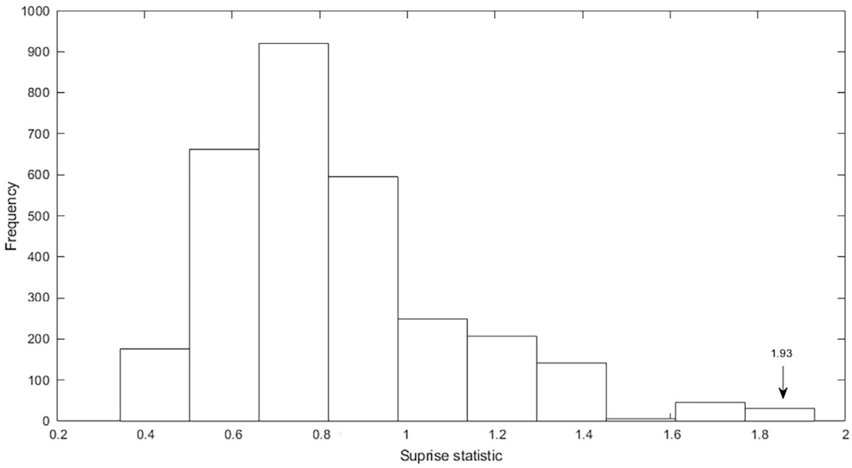

Figure 6. Frequency Distribution of Surprise Measures for All Participants Based on All Selected Indicator Years

Results are shown for both 2018 and 2019 scoring, with the maximum surprise score indicated with an arrow.

reveal the occurrence of a foresight? Discussions and decisions on these issues required a considerable amount of time even for team members with extensive expertise developing and using physical, biological, and socioeconomic indicators. This resulted in refinement of jargon and ambiguity, substitution, and tolerance for different interpretations. We believe indicator development requires particular focus for the successful application of foresighting as a quantitative strategic planning tool. Our use of leading indicators, by definition, anticipates the foresight scenario and thus can also be considered as an early warning, or the minimum time for the foresight to emerge. If indicators were too leading, they would be less informative, and may be less reliable as other factors can change in the interim.

Generality of the Approach—Portable for Real Use

We have described and tested a method for developing and evaluating the futures that may confront scientists in research organizations. The results can allow us to act differently and to prepare or even influence particular futures. While not all scenarios require or allow a response, as some are outside our sphere of influence, in some cases, participants can act in response to the foresights they have explored. Our insights have influenced the capacity for futures thinking (e.g., aided the development of early career scientists) and contributed to the research strategy within our research agency from individuals with now broader views through to more informed leaders who can effect institutional change. For example, we have encouraged more scientists to engage and learn good practice when using a range of social media (foresight: "social media as truth"), such that we are more literate and discriminating. With regard to the "gig economy" foresight, we considered that outsourcing of science was not desirable given the years that are needed to develop expertise in a subject. Thus, our research agency has now sought to offer continuing appointments over short-term contracts and casual staff use. A third example is the wide recognition of the potential for the use of artificial intelligence in fishing (precision fishing) and a strategic investment in development of capability within the research agency.

These approaches are useful beyond scientific organizations—any group seeking to consider the future and plan for alternatives can benefit. Different elements of the recipe we have described could be used, depending on the need and purpose. Simply developing a range of foresight topics may be useful for some purposes, including exposing a group to futures thinking. Development of indicators requires additional rigor and may be used to allocate resources in a defensible manner. Finally, the identification of individuals with particular capability and interest in an area can be used to develop more detailed research ideas or responses, or address individuals' knowledge gaps in selected research areas. While we have developed a repeatable approach, an adverse outcome would be to constrain free thinking when considering the future. Our approach should be considered as a complement to existing approaches, and care should be taken not to stifle the creativity of participants in consideration of unlikely events or perspectives. A diverse and deliberative process should accommodate these aspects.

In summary, this repeatable and quantitative approach is supported by development of indicators to assess likelihood of the futures in two areas—general scientific issues that may emerge in the rest of the 21st century and domain-specific issues for marine fisheries, aquaculture, and conservation. Tracking foresight likelihood over time with repeated assessment, based on approaches described here, might be used to check research agency investment decisions and the need for new information. This form of quantitative foresighting can serve as an approach for building a stronger capacity to anticipate a highly uncertain future. We argue that this approach will improve strategic planning and investment decisions and improve the skills of the group of participants in futures thinking, as has been proposed in the business sector.[66] These skills will be critical for scientists and their employers in a fast-changing world.

EXPERIMENTAL PROCEDURES

Resource Availability

Lead Contact

Further information and requests for resources should be directed to and will be fulfilled by the Lead Contact, Alistair Hobday (alistair.hobday@csiro.au).

Materials Availability

This study did not generate new unique materials.

Data and Code Availability

The datasets and code supporting the current study have not been deposited in a public repository because of privacy (individuals are identified), but code is available from the Lead Contact on request.

The Project Team

This foresighting effort evolved over a period of 4 years (2015–2019), supported as a strategic project by the Australian CSIRO Oceans and Atmosphere division, and involved investigating potential futures of marine research, conservation, and sustainable resource use. The project team comprised marine scientists representative of a range of disciplines, career stages (post-doctoral to post-retirement fellows), and gender (40% identify as female). The senior members of the team had deep experience in research on ecosystem change and challenges,[67,68] modeling of socio-ecological futures,[69,70] use of IPCC model class projections,[71] engagement in management,[72] and participation in other futures approaches (e.g., Australia 2050 work[16,73]). Early career researchers (ECRs), defined here as those with less than 5 years post-PhD experience, were included and paired with a senior researcher to develop many of these foresights. In a limited number of cases, we expanded the project team by pairing an existing member with another experienced scientist who had not previously participated in foresighting, but who had particular domain knowledge for the foresight topic. The project team met formally between 6 and 12 times per year over the 4-year period, with considerable electronic exchange and discussion outside these meetings.

Foresight Topics

One goal was to encourage and train a group of scientists to use foresighting techniques to inform our own agency's research strategy. The foresight topics were self selected within a broad mandate of relevance to general science or marine science, represent a major change potentially within the next 10−20 years, and likely by the year 2050. This relatively free topic selection fostered enthusiasm around the topic of choice. The idea for each foresight was presented and agreed upon by the project team. The foresights were then drafted by teams of two, as noted above. Drafts were discussed with the whole project team and refined, and indicators were developed. The set of foresights we developed could be classified in a number of ways, but here we present them as members of two broad categories; Marine Resource Management and Science in the 21st Century. The Resource Management category of foresights considered futures relevant to the management of fisheries, aquaculture, and biodiversity, while the Science category was relevant to the wider context of scientific research endeavors. Each of the foresights was developed by following a consistent recipe.

Foresight Recipe

We followed a consistent format for writing each of the foresights, which in total were three pages or less. The first short section (Background) established the contemporary context to the foresight and was followed by the Scenario section, which described the plausible future, as well as potential responses to that future. As a third step, each team suggested a likely time frame for the scenario to emerge (e.g., likely by 2030). The fourth section contained a set of five to ten indicators, which were expected to occur if the foresight scenario was becoming likely. We sought indicators that were independent (i.e., avoiding conditionality), leading (rather than lagging), and clearly measurable.[74] Thus, the indicators will occur in advance of the foresight becoming a reality; however, in this paper, we simply refer to the emergence of the foresight. The indicators were developed iteratively, with substantial feedback between authors and the rest of the project team. We attempted preliminary scoring of the indicators (pilot trial), then revised a final set of indicators based on group discussion and feedback (Experimental Procedures). The fifth section of each foresight document was a set of implications for (1) policy, (2) science, (3) society, and (4) our organization.

Assessing when the Foresight Scenario May Occur

After the foresights had been discussed and revised and the final indicators were developed, all project participants privately identified the year in which they considered that each indicator would be 90% likely to occur for each foresight. An online scoring system allowed each participant to select one of the following options for each indicator: the current year (2018), one of the 5-year periods between 2025 and 2050, after 2050, and never.

After a year (i.e., in 2019) and without reference to their evaluation from 2018, each participant provided a second set of selected years for each of the foresight indicators. We were interested to (1) see if any foresights had changed in likelihood, (2) evaluate the consistency of participants, and (3) illustrate how repeat scoring over time (iterative forecasting, *sensu*[58]) can be used to track progress or otherwise toward a particular future. We reviewed the results as a group after all participants independently completed scoring of the foresights and noted challenges with scoring particular indicators and foresights. Analysis was then completed at two levels, collectively and individually.

Collective Patterns

Frequency plots were used to examine the patterns in data across scenarios and participants. These diagnostic plots are used to indicate spreads in scoring of indicators and can indicate bias, outliers, and precision in scoring. The selected year was averaged across all indicators by participants to generate cumulative probability curves for the year in which the scenarios were considered likely to occur. For ease of analysis, in cases where the average score was "after 2050," we allocated a score of 2055; similarly, an average score of "never" was allocated a score of 2060. We considered the consistency in relative position and likelihood between the 2 years of scoring (2018 and 2019). The time period at which a foresight was considered likely to emerge (thresholds could be set based on an organization's risk tolerance) can be used to rank the set of foresights, the results of which could be used to inform research priority setting.

Individual Patterns

We considered the spread of scoring by each participant and looked for trends (e.g., persistently early and late selection of years by participants) and outliers (i.e., surprises) in the scoring patterns that could be used to identify individual differences that may offer additional insight. In particular, we investigated three questions:

(1) Do a participant's selected years for each indicator reveal a propensity to imagine events to occur sooner or later in the future?
(2) Do a participant's selected years reveal a propensity to imagine foresight scenarios to occur sooner or later than other participants?
(3) Given the selection of years by all participants across all foresight indicators, does a participant's score of a specific indicator look particularly surprising?

We answered the first question by calculating the entropy of the probability distribution of a participant selecting a given year for an indicator to occur. We call this Indicator entropy, defined as

$$Ent^i = -\sum_y p_y^i \log_b \left(p_y^i\right) \qquad \text{(Equation 1)}$$

where i is a participant, y is the year, p_y^i is the probability that participant i chooses year y in the scoring exercise, and b (the base of the logarithm) is equal to the number of options available for the choice of the year. The latter choice scales the entropy values between 0 and 1. Entropy is a natural choice for this purpose since it measures how uniform the distribution is and thus its information content: the entropy is maximum (=1) when a participant chooses all possible years with equal probability, thus providing no discrimination on the occurrence of future events. On the contrary, the entropy is minimum (=0) when a participant chooses the same year for all indicators.

We answered the second question by (1) computing the average year when a participant believes a foresight is likely to occur (based on all indicator years selected for the foresight), (2) for each foresight, ranking participants in chronological order according to (1), (3) for each participant, computing the probability of occupying each of the rank positions, and finally, (4) computing the entropy of this distribution according to Equation 1. We call this foresight entropy. It measures the tendency of a participant to believe that the foresights will occur sooner or later than other participants.

We answered the third question by computing how the probability of choosing a specific year contributes to the calculation of the participant's indicator entropy. This measures the amount of surprise (technically, the amount of information) contained in each of these choices, and is calculated as

$$surprise_y^i = -\log_b\left(p_y^i\right) \quad \text{(Equation 2)}$$

For example, if a participant chooses year 2025 very frequently, their choice of 2025 is not surprising, but the choice of year 2050 would be identified as surprising and thus deserve additional attention.

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.oneear.2020.10.015.

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AUTHOR CONTRIBUTIONS

Conceptualization: A.J.H., F.B., C.M., R.L.S., C.B., C.M.B., S.C., C.C., J.M.D., L.X.C.D., E.A.F., A.L., L.R.L., B.M., K.S.M., E.E.P., H.P., P.R., J.S., P.A.T., and I.v.P.; Formal Analysis: A.J.H. and F.B.; Writing – Original Draft: A.J.H., F.B., and R.L.S.; Writing – Review and Editing: A.J.H., F.B., C.M., R.L.S., C.B., C.M.B., S.C., C.C., J.M.D., L.X.C.D., E.A.F., A.L., L.R.L., B.M., K.S.M., E.E.P., H.P., P.R., J.S., P.A.T., and I.v.P.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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One Earth, Volume *3*

Supplemental Information

Quantitative Foresighting as a Means of Improving Anticipatory Scientific Capacity and Strategic Planning

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Supplemental Experimental Procedures

Indicators for each foresight. Participants selected the earliest year for which the indicator is considered 90% likely.

Group 1: Science in the 21st Century foresights

Foresight 1: Rationing air travel

1. Australian government signs up to an ambitious emissions reduction program, which could be air travel-specific, or overall and inclusive or air travel.
2. Australian government signals it will require this emission reduction for departments and science agencies.
3. An Australian science agency begins restricting staff air travel on the basis of emissions reduction
4. 25% of scientific societies sign international agreement to limit international conferences
5. Social pressure on scientists from other sectors leads to publication of personal carbon footprints by at least 25% of scientists
6. 25% of formerly face-to-face conferences become online only conferences

Foresight 2: Privatization of science

1. Decrease in discretionary funding to government research agencies of 50% relative to current levels.
2. Internal prioritization within government research agencies pushes scientific organizations towards an increasing 'consultant' role, increasing competition with private consultants.
3. Increase in deregulation at government level (policy and management).
4. Decrease in metrics of public confidence in government research agencies (below 75% trust scores).
5. Migration of scientists out of government research agencies and into roles as private sector consultants (fewer overheads and administrative burdens, better pay, more freedom).

Foresight 3: Participatory governance

1. Public activism leads to political interference that over-rides established scientific approval processes for marine resources (fisheries, oil and gas, ports etc) at least twice per year.
2. An anti-industry, truly Green, agenda wins in national elections
3. Australia faces international sanction related to poor performance in marine sustainability

4. Research agencies are merged in order to facilitate stakeholder involvement for fisheries and other marine resources.
5. Government departments are merged in order to facilitate stakeholder involvement for fisheries and other marine resources.
6. Major national initiative to control marine pollution is implemented (specifically plastics)
7. Major scientific journals demand a video clip for each accepted paper.

Foresight 4: Artificial intelligence

1. The proportion of scientific data obtained from autonomous, intelligent sensors and robots constitutes more than 80% of marine observations.
2. Scientific hypotheses and experimental designs are generated by smart algorithms in 50% or more of scientific papers.
3. Fifty percent or more of model applications rely on scientific models which are self-defining and refining, data-assimilating, widely accessible online and user friendly.
4. Twenty percent or more of scientific papers are generated by AI, with little or no human input.
5. Online providers of AI-directed, largely automated research services are responsible for 50% or more of applied scientific research.

Foresight 5: Social media as truth

1. Major issues driven by inaccurate and misleading statements accepted without critique.
2. Experts fail to engage in debate because of reticence to simplify information for social media
3. Institutional barriers prevent rapid-fire responses by experts.
4. Decisions made at odds with research but allegedly based on science.
5. Research perceived as irrelevant to most social issues
6. Public use conspicuously spurious 'facts' or 'science' argument to challenge research advice.

Foresight 6: Rise of populism

1. Political statements are later contradicted 20% of the time (where the contradiction reflects the influence of dogmatism views).
2. Increase in representation (reaching 20%) by minor parties that offer dogmatism assertions.
3. Increase in funding (by more than 20%) for things that accord with dogmatism views (e.g. a coal mine)
4. Number of 'ethical' resignations decreases (e.g. when politicians fall on sword for mistakes) to less than 10% of the time
5. Defunding of management agencies which leads to 25% decrease in staff

6. Increase in concentration and centralization of capital (e.g. in larger or monopoly companies) with more than 50% annual growth in wealth held by the top 1% richest Australians
7. Potentially environmentally damaging developments (e.g. canal estates, ports, oil and gas platforms, dredging shipping lanes, etc.) initiated more than 90% of time when proposed
8. Use of marine spaces and resources shifts from local, small-scale fisheries (e.g. self-employed or family operated, often operating small vessels) to more than 50% in large-scale commercial fishing, coastal tourism, and recreational, bio-prospecting and military uses.

Foresight 7: Gig Economy

1. Increase in use of casual staff on projects (50% of project staff)
2. Individual research businesses offering 'gig' services, such as editing, data entry, collection, and design used on more than 25% of science projects.
3. Payment demanded by citizens for involvement in citizen science projects (25% of projects)
4. Business offering the matching of workers to jobs advertised by agency scientists (>5 businesses)
5. Project leader is the only permanent staff member on a project (25% of projects in a portfolio)

Group 2: Marine resource management foresights

Foresight 8: Precision fishing

1. Number of fisheries managed by ITQs, catch shares or IQEs reaches 80% in Australia
2. Nominal fishing effort (fishing power increases). Number of vessels declines by 25%.
3. Nominal wild capture in Australia will not decrease but maintain between 0-20%, 170,000t to 200,000t (ABARES)
4. Employment in the wild capture fishing industry declines 33% (from current 5600 in 2016 to 4000 - ABARES)
5. Number of real-time (RT) of near-real time (NRT) fisheries with data acquisition or assessments will exceed 50%.

Foresight 9: Blue revolution

1. Number of major industry types harvesting operating in the oceans (e.g. exploiting oceanic resources [minerals, fish, pharmaceuticals] or transporting good, housing etc etc] is as diverse as on land (or more so)
2. Total value of marine industries in Australia exceeds 100 billion
3. Total employment in marine industries in Australia exceeds 1 million

4. Cover or linear length of built infrastructure (rigs, ports, walls, platforms etc) in the oceans exceeds 10% of the coastline
5. Increasing tension around uses of the oceans and the impacts/benefits of those uses sees the first lawsuit over the exclusion of an entire industry from a region (e.g. fisheries)

Foresight 10: Coastal segregation

1. New strict planning rules limiting people's residence choice and movement
2. Coastal real estate prices rise exponentially due to planning and building restrictions (creating scarcity) thus pricing some demographics completely out of the market
3. Fishers can no longer work and live in small coastal communities due to comparative high costs (only 'retired' fishers remain if they have already paid off their housing and fishing assets)
4. Coastal towns change their nature completely forcing lower paid professions and less wealthy demographics out
5. New marine industries, such as offshore wind farms, have to fight to find a spot in an increasingly busy and 'planned' ocean and rigidly structured coastal communities

Foresight 11: Aquaculture divided

- Scenario 1 (harmony and cooperation)
    1. Reduced conflict between aquaculture industry and community, as evidenced for example by reduction in media and advocacy focused on the conflicts and disagreements, and refocussed instead on supporting development
    2. CSIRO encouraged to play an objective trusted science role in credible knowledge co-production affecting other development initiatives
    3. CSIRO in its role as Australia's trusted advisor, develops an independent SLO fact checker for Aquaculture in Tasmania, providing clear unbiased information that addresses the concerns of stakeholders and generates a trusted platform for further dialogue.
    4. Evidence of compromise and ecofriendly, clean green adaptations in aquaculture ventures
    5. Regional growth of aquaculture industry and jobs
    6. Criticism of need for SLO shifts to other industries
    7. Increased cooperation in constructive dialogue and partnerships
- Scenario 2 (conflict and decline)
    1. Escalating conflict between aquaculture industry and community
    2. Stalemate in terms of industry growth and job creation

3. CSIRO not perceived as playing the role of trusted source for supporting objective decision-making regarding whether or not SLO should be granted

Foresight 12: Rise of ocean protection

1. Large no-fishing protected areas exceed 20% of Australia's coastline (currently <2%)
2. Global voluntary reduction of fisheries and catches of 25%
3. Sale of aquaculture products is considerably higher (75% higher) than wild-caught seafood
4. A global ban of wild-caught seafood in >25% "developed" (MEDC) countries.
5. Recovery of >50% pelagic species previously threatened by fishing (e.g. oceanic whitetip shark, leatherback turtles, etc)
6. Commercial production of synthetic meat and seafood for a wide range of flavours and textures
7. Sales of synthetic fish exceed wild caught (by value)
8. Sales of synthetic fish exceed wild caught (by volume)

Foresight 13: Rapid climate change

1. Global mean temperatures exceed 2C from the pre-industrial - i.e. exceed the Paris Agreement (COP21)
2. Loss of coral reefs - more than 80% of coral reefs impacted annually
3. Sustained decrease in food production impacting long-term food security at the regional/global scale
4. Abandonment of coastal development due to prohibitive costs (e.g. insurance) - 80% major coastal cities impacted
5. Permanent migration of climate refugees - larger than 50% of the population from individual countries e.g. the Pacific

Foresight 14: Astronaut effect

1. Booming space tourism and space development businesses globally
2. Increased funding (at least triple 2018 level) offered for space science and technology
3. Australia increases engagement and participation in space science (triple 2018 current levels)
4. Rise in popularity of early space explorers and tourists, with increased media coverage and some of these individuals in influential positions
5. Call from space tourists for more environmental protection on Earth

Supplemental Figures

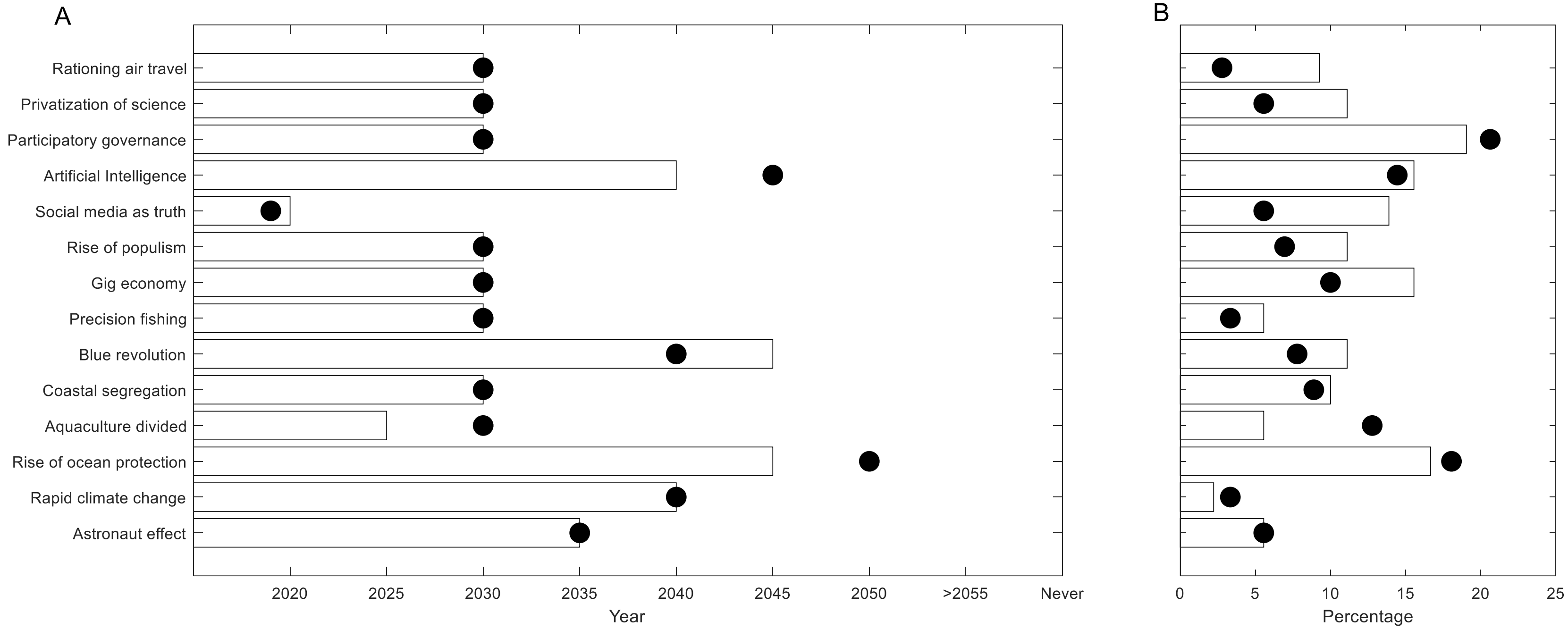

Figure S1. Foresight summary showing difference between survey years. The first seven listed are the Science in the 21st Century foresights, the second seven are the Marine Resource Management foresights. **A.** Median date selected for each foresight for 2018 (bars) and 2019 (dots). **B.** The percentage of times the choice "never" was selected by participants across all indicators for each foresight for 2018 (bars) and 2019 (dots).

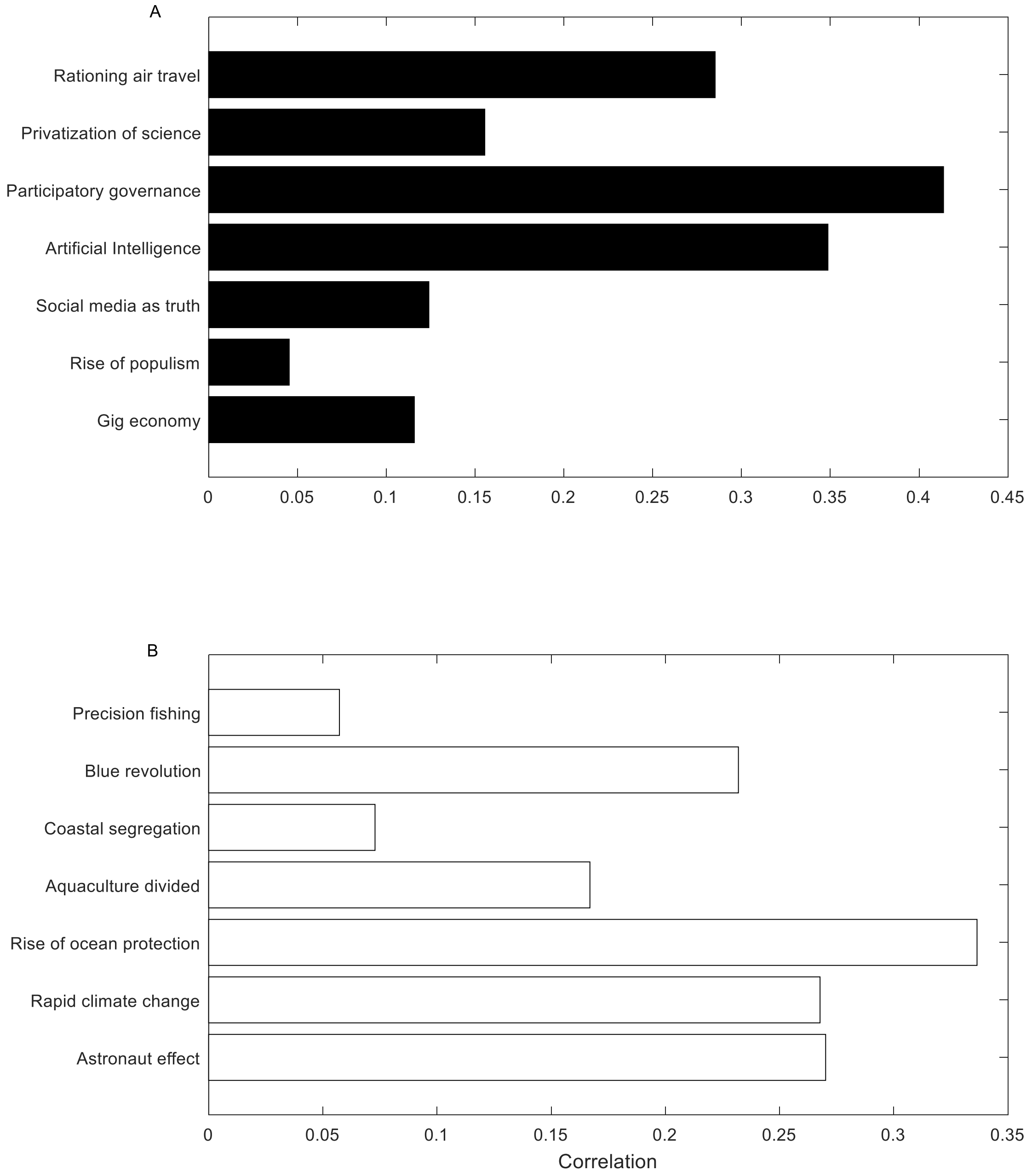

Figure S2. Correlation coefficient (R^2) between indicator years selected for each foresight across all participants (i.e. 2018 vs 2019). **A**. Science in the 21st Century foresights, **B**. Marine Resource Management foresights. The most consistently scored scenarios have the highest correlation.

A.

B.

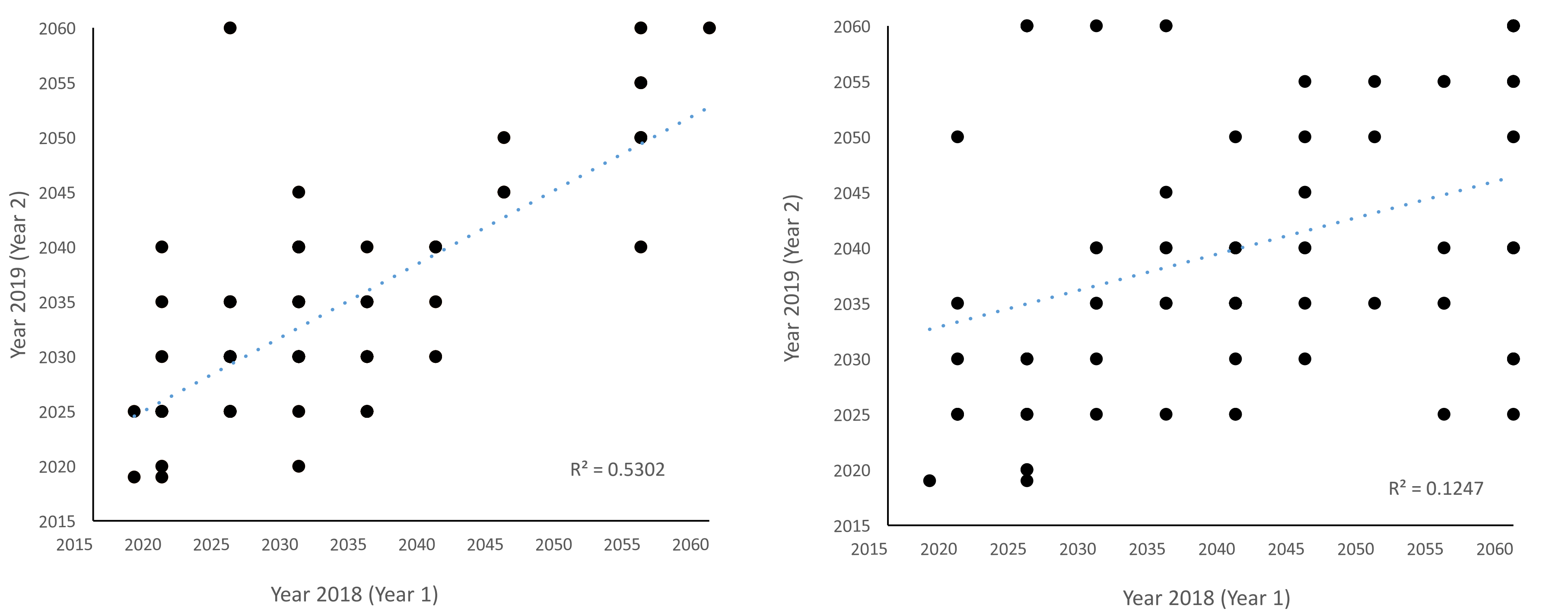

Figure S3. Comparison between indicator years selected by two participants in 2018 and 2019 across 14 foresights. The highest correlation (R^2) among the 14 participants who scored indicators in 2018 and 2019 was 0.56 (**A**) and the lowest correlation was 0.12 (**B)**. On each axis, 2055 indicates “>2055”, and 2060 indicates “never”.