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Is seeking certainty in climate sensitivity measures counterproductive in the context of climate emergency? The case for scenario planning

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ABSTRACT

Climate emergency is fast becoming the overriding problem of our times and rapid reductions in carbon emissions a primary policy focus that is liable to affect all aspects of society and economy. A key component in climate science is the "climate sensitivity" measure and there has been a recent attempt using Bayesian updating to narrow this measure in the interests of "firming up the science". We explore a two stage argument in this regard. First, despite good intentions, use of Bayes sits awkwardly with uncertainty in the form of known unknowns and surprise. Second, narrowing the range may have counterproductive consequences, since the problem is anthropogenic climate change, and there are asymmetric effects from under-response in the face of irreversible and ampliative effects. As such, narrowing the range using Bayes may inadvertently violate the precautionary principle. We take from this that there is a case to be made for scenario focused decision frameworks.

1. Introduction

Tackling climate change has become one of the most important policy issues of our time. Article 2 (1a) of the 2015 Paris agreement negotiated at COP21 aims to restrict the increase in global mean average temperature above the pre-industrial level to below 2 °C and ideally targets 1.5 °C (UN, 2015). As the UNEP emissions gap 10-year summary report states, total annual global emissions of carbon dioxide and equivalents (CO_{2e}) have increased rather than decreased over the last decade, remain stubbornly high and carbon budgets are rapidly being exhausted (Christensen and Olhoff, 2019). The 2018 IPCC *Global Warming of 1.5 °C* report suggests a need for a reduction in global annual CO_2 emissions of 45 % on 2010 levels by 2030, with the ultimate goal of "net-zero" by mid-century (IPCC, 2018: 12; but see Dyke et al., 2021). An assessment of "nationally determined contributions" (NDCs) released by the Secretariat of the UNFCCC just before COP26 in Glasgow states that despite 116 new or updated NDC targets covering 143 of the 191 Parties to the Paris agreement, total global GHG emission levels in 2030 are "expected to be 15.9 % above the 2010 level" (UNFCCC, 2021: 4–5). Even with full implementation of NDCs, combined cumulative emissions 2020–2030 would use up 89 % of the remaining carbon budget for the 1.5 °C target (leaving just an estimated 56 $GtCO_2$ to expend) and would use 39 % of the 2 °C target (UNFCCC, 2021: 6; however, see IPCC, 2021 later). This "implies an urgent need for either a significant increase in the level of ambition of NDCs between now and 2030 or a significant overachievement of the latest NDCs or a combination of both" (UNFCCC, 2021: 6). While COP26 provided some limited progress, Climate Action Tracker continues to maintain that even best case implementation of current pledges, commitments and plans remains woefully inadequate.[1] One can expect a continual improvement in NDCs (and a recent paper in *Nature* provides an optimistic best-case, Meinshausen et al., 2022), but there is a need for action now and according to UN Secretary General António Guterres in April 2022 the situation was one where "Some government and business leaders are saying one thing – but doing another. Simply put, they are lying. And the results will be catastrophic."[2]

We have then, entered a period of ecological and "climate emergency" (Ripple et al., 2021, 2020) and the UN has renewed its efforts to encourage countries, corporations, and regions to rapidly and urgently reduce emissions. At the heart of the climate science is the concept of "climate sensitivity", defined as the expected increase in global mean average temperature (typically global surface temperature or GST) per

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[1] Visit: https://climateactiontracker.org.
[2] Visit: https://youtu.be/EaZRvli9fgQ.

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doubling of atmospheric CO_2. The standard range for this measure was established in 1979 by the "Charney Report" from the U.S. National Academy of Sciences (NAS, 1979). That range was 1.5 °C to 4.5 °C and this has been reproduced since then despite that climate modelling has become more sophisticated and a great deal of evidence has accumulated. The IPCC is a UN mandated organization founded in 1988, and it collates climate science. It operates in cycles and each is assigned a number for its assessment reports (AR1 and so forth). Contributors to a cycle form working groups each with a designated focus and their work is ultimately combined and published at the end of the cycle as a synthesis report. The IPCC collates models and all five synthesis reports published so far – 1990, 1995, 2001, 2007 and 2014 – work with the Charney values, though more needs to be said about what this means later. The synthesis report for the sixth cycle (AR6) is due in 2022, but the indication given by working groups is that AR6 reflects a narrowing of the climate sensitivity range and it is issues arising from this narrowing that concern us in this paper (rather than AR6 per se).

While the climate sensitivity measure does not affect whether in fact decarbonisation must occur (since this is ultimately necessitated by the sum of emissions not the variation expressed by the climate sensitivity range), sensitivity does have an impact on the degree and rate at which heating is induced by emissions. It thus influences the kinds of claims made in the reports referenced in our opening paragraph, behind which sit probabilistic estimations. As such climate sensitivity has potential implications for emissions reduction policy. One might argue then, that "firming up the science" by narrowing the climate sensitivity range represents a constructive development. As the highly respected on-line site Carbon Brief, which specialises in encouraging public understanding of climate change, puts it, narrowing the range might allow "fine-tuning" of policy (Carbon Brief, 2018). However, though there is some merit in this claim there are several further considerations and we set these out as a two stage argument in this paper.

First, the major initiative used to narrow the climate sensitivity range uses Bayesian updating (Sherwood et al., 2020). This classical approach to probability requires numerical values to be assigned to beliefs and does not allow for what lies outside the decision set. We argue that this creates a methodological problem in so far as it does not allow for some types of uncertainty and uncertainty is intrinsic to the subject matter of climate science. Second, despite good intentions, narrowing the climate sensitivity measure may have counterproductive consequences. What lies outside the range may not now be under consideration for the purposes of decision-making, and in some cases this may lead to an under-response. Given the problem under scrutiny is *anthropogenic* change to the climate, this is an important tension. Moreover, given the potential grave consequences of under-responding (the catastrophic impacts that will be experienced as temperatures rise), seeking improved certainty along Bayesian lines may be in tension with the precautionary principle when applied to climate change. It may then, be more appropriate in policy terms to seek an evidence-informed approach to managing uncertainty, since such approaches may be better able to address the need to overweight urgent prudential responses. Moreover, given that uncertainty itself can have different effects on policy and behaviour and these depend in part on how evidence and argument are framed, we would argue there are multiple reasons to develop a scenario focused decision framework (SFDF) (Derbyshire, 2022, 2020a; Derbyshire and Giovannetti, 2017). Unlike standard predictive approaches, SFDF have the great advantage of being exploratory, deliberative, inclusionary, diverse and developmental and this can encourage integrative problem solving policy as well as empowerment and persuasion of stakeholders, which in the case of climate emergency is everybody (for work that emphasizes aspects of this see Workman et al., 2021, 2020; Sharmina et al., 2019; Moallemi and Malekpour, 2018). We illustrate this using the Intuitive Logics approach. We develop the argument in 7 sections.

In Section 2 we first provide some background on the meaning and significance of climate sensitivity measures in order to provide context for the recent high-profile Bayesian updating project that seeks to narrow the climate sensitivity range. We then address our two stage argument. In Section 3 we set out the methodological problem of uncertainty reduction via Bayesian updating. In Section 4 we address the subsequent problem of what the findings might convey and how firming up the science may have counterproductive consequences. In Section 5 we introduce scenario building and begin to make the case for Intuitive Logics Scenario Planning and in Section 6 we provide an illustration, prior to concluding in Section 7. To be clear, our argument might best be categorised as awareness building in the context of climate emergency, and as introductory rather than comprehensive in its exposition of scenario planning, since we do not have the space to develop the material in a detailed fashion.

2. Making sense of climate sensitivity as a precursor to the application of Bayesian updating

As noted in the introduction, in 1979 the U.S. National Academy of Sciences established a "range of uncertainty" related to the expected increase in average temperature from climate change of 1.5 °C to 4.5 °C per doubling of atmospheric carbon dioxide (NAS, 1979; Kellogg, 1987; Carbon Brief, 2018). The standard measure is parts per million (ppm) atmospheric CO_2 by volume concentration and the pre-industrial benchmark is typically put at 280 ppm. As such, 560 ppm constitutes doubling. In 2021 the global average approached 417 ppm (and by some reports 419 ppm). This is around 50 % higher than the pre-industrial level. According to the UK Met Office it took 200 years for the figure to increase by 25 % but just the last 30 for it to increase by 50 %. Current trends indicate we will reach CO_2 560 ppm by around 2060 unless rapid decarbonisation occurs. Two issues can be usefully clarified in order to make sense of the climate sensitivity measure. First, why there is a range rather than a definite figure. Second, in what sense the range has remained relatively wide despite that we have had over forty years of climate science since 1979.

Regarding the first issue, basic physics indicates a doubling of atmospheric CO_2 should induce heating of slightly >1 °C. However, as of the beginning of the decade, the Earth has already experienced an increase of about 1.1 °C (and in some measures 1.2 °C) in average global temperature compared to the pre-industrial level. The Earth is not a laboratory where relations can be isolated and studied. It is a complex of active and interacting processes operating across regions and different durations. Factors such as anthropogenic carbon emissions constitute sources of "forcing" which place pressure on existing processes and these take time to feed through. Some processes and changes induce "positive feedback" effects which augment and reinforce heating and some involve "negative feedback" which dampen effects. In general, over the Holocene epoch (the eleven and half thousand years since the last glacial period) the Earth has acted as a relatively stable system and this includes its climate system i.e. different processes and positive and negative feedback have maintained fairly consistent climate patterns, punctuated by natural events such as volcanic eruptions.

As Earth and climate system scientists note, the epoch has been highly conducive to the development of human civilization, but our effects on basic processes (and not just climate ones) put this in jeopardy

(Rockström et al., 2009; Steffen et al., 2015; Lenton et al., 2020). Some Earth system scientists suggest we have entered a new epoch, the "Anthropocene" in which we are the dominant influence on a whole range of Earth system processes (Steffen et al., 2011; Crutzen and Steffen, 2003). In terms of the climate system they suggest that heating is not just occurring in some simple additive fashion based on forcing. Changes to processes are interdependent and this too can amplify or accelerate and be self-reinforcing. Changes to processes thus have the potential to push the climate system out of its current state into another one. The augmentation of positive feedback effects may lead to a runaway transition to a "Hothouse Earth" state (Steffen et al., 2018; see also Hansen et al., 2017).

Ultimately, effects are irreversible within any timeline that is meaningful from the point of view of human lifespans and with the longer term implications in mind as the Earth becomes increasingly hostile to the kind of complex civilization we have built. At the extreme there is a possibility of a mass extinction event (Bradshaw et al., 2021). According to the IPCC Fifth Assessment Report:

> A large fraction of anthropogenic climate change resulting from CO_2 emissions is irreversible on a multi-century to millennial time scale, except in the case of a large net removal of CO_2 from the atmosphere over a sustained period. Surface temperatures will remain approximately constant at elevated levels for many centuries after a complete cessation of net anthropogenic CO_2 emissions. Due to the long time scales of heat transfer from the ocean surface to depth, ocean warming will continue for centuries. Depending on the scenario, about 15 to 40 % of emitted CO_2 will remain in the atmosphere longer than 1000 years.
>
> (IPCC, 2014: 28)

Clearly then, there are numerous reasons why there is a degree of uncertainty regarding the eventual effects of anthropogenic carbon emissions. To reiterate, the Earth is not a laboratory. There are numerous sources of change (and these include not just greenhouse gases but aerosols for example), and of interaction and interdependency in systems whose effects are contingent. There is a continual process of learning and climate science is continually developing and responding to updated evidence. There is gradual accumulation of instrumental evidence (changes in the measurement of various metrics from around the world, such as ppm, measurements from satellites etc., creating a data map that is continually updated) and other observational evidence (changes to particular features in given places, such as ice sheets) and there is growing innovative extraction of evidence from other sources – notably tree rings, geologic traces, ice cores, and a whole range of other paleoclimate sources. Moreover, the last forty years or so has seen major improvements in computer power and the scope to create models and run simulations.

This brings us to the second issue i.e., in what sense the climate sensitivity range has remained relatively wide despite that we have had over forty years of climate science since 1979. There are several aspects to this. The various studies undertaken since 1979 have been based on different premises: some seek to extrapolate the recent historical record of instrumental measurements, some seek to work from and match the paleoclimate evidence, some build models based on the physics, some models use the instrumental data to "constrain" the choice between simulations, some combine all of these sources. To be clear, however, all approaches require some assumptions about how climate systems work (a model of the world) and all produce a range of possible pathways of temperature change for the future based on the contingency of these conditions and the method of extrapolation or simulation used. Moreover, studies have several standard measures of sensitivity. Climate sensitivity can measure the amount of heating estimated to occur *at the time* CO_2 doubles. This is termed Transient Climate Response (TCR). However, at that time not all of the processes initiated by that level of CO_2 will have worked through different parts of the climate system (atmosphere, oceans etc.), so there is also an estimation of the amount of heating that will occur *from that level* of CO_2 over an extended duration and once the impacts reach an "equilibrium". This is termed Equilibrium Climate Sensitivity (ECS). This too has its limits since the focus is typically on how the emissions work through the climate system (changes to cloud cover at different altitudes, circulation patterns, water vapour levels, radiative forcing from albedo effects etc.), but excluding further changes to forestation, ice sheets and so on that may provide "slow forcing". Finally, there is also a longer term approach that explores feedback effects via changes to forestation, ice sheets and other processes. This is termed Earth System Sensitivity (ESS).

The perpetuation of a range from 1.5 °C to 4.5 °C is for ECS. However, the perpetuation is in part attributable to the findings of different studies focused on different properties using different evidence and different methods. But there are also differences between similar studies. For example, in the case of paleoclimate approaches, different studies may treat past differences in topography, continental location, levels and types of vegetation etc. in different ways. More generally, otherwise similar studies can have slightly different conditional assumptions underpinning ECS. In any case, taken collectively instrumental based studies have tended to produce a range starting at lower values (<2 °C) while paleoclimate and physics models typically start at higher values (at or above 2 °C) and extend further in range. It is across the full panoply of studies that the average range remains around 1.5 °C to 4.5 °C and so within the progress made there remains considerable diversity.

As noted earlier, the IPCC collates the findings of different studies and brings together models in its periodic synthesis assessment reports

Table 1
The simple Intuitive Logics scenario-planning approach.

Stage	Description
1 Setting the scenario agenda	Defining the issue of concern and process, and setting the scenario timescale.
2 Determining the driving forces	Eliciting a multiplicity of wide-ranging forces.
3 Clustering the driving forces	Clustering causally-related driving forces, testing and naming the clusters. Selecting higher-level factors, which are those most pertinent to the focal issue defined in stage 1.
4 Defining the cluster outcomes	Defining two extreme, but plausible and hence possible, outcomes for each of the higher-level factors over the scenario timescale.
5 Impact/uncertainty matrix	Ranking each of the higher-level factors to determine the critical uncertainties; i.e., the clusters that have most impact and the highest degree of uncertainty.
6 Framing the scenarios	Selecting two initial critical uncertainties to create a scenario matrix, framing the scenarios by defining the extreme outcomes of the uncertainties.
7 Scoping the scenarios	Building a broad set of descriptors for each of the four scenarios.
8 Developing the scenarios	Developing scenario storylines, including key events, their chronological structures, and the 'who and why' of what happens.

Reproduced from Derbyshire, 2020a: 717.

(AR). These have also varied in sensitivity range (narrower for AR4 than AR5, partly because AR5 was published after a series of high-profile instrumental studies, which tend to push the lower threshold downwards, since these studies likely do not fully account for offsetting factors and ingrained effects that may accelerate later) and it is with the working groups of the sixth cycle of the IPCC and the sixth synthesis report in mind that there has been an attempt to narrow the climate sensitivity range through an application of Bayesian updating to the many existent studies. This brings us to the first step in our two-stage argument, Bayesian updating creates a methodological problem in so far as it does not allow for some types of uncertainty and uncertainty is intrinsic to the subject matter of climate science.

3. Climate sensitivity and the methodological problem of uncertainty reduction via Bayesian updating

Following a workshop in Bavaria, Germany in 2015, a team of high-profile climate scientists, geophysicists and modelers came together under the auspices of the World Climate Research Programme's "Grand Science Challenge on Clouds, Circulation and Climate Sensitivity" in order to assess the state of the field. Specifically, the project asked what the scope was to reduce uncertainty in relation to the 1.5 °C to 4.5 °C range that had remained standard since the Charney Report (and as, at the time, was reflected in IPCC AR5). Is it possible to firm up the range by assessing evidence against low values and high values of that range and what scope is there to assess the likelihood that values lie outside the range? The study brought together three approaches: modelling of climate systems (using a new and innovative "process" approach), the historical record from instrumental work and the paleoclimate record. It should be noted that the team use a slightly different definition of sensitivity than has been standard for Equilibrium Climate Sensitivity since the Charney Report. They use "effective climate sensitivity" (termed S), which is defined as system behaviour over the first 150 years after a *quadrupling* of CO_2, but provide various arguments for equivalence.[3] Probability density functions (PDFs) of S are then derived and Bayesian updating is applied. PDFs of S form priors used to relate one approach to the others. For example, expert judgment on PDFs become the basis for priors that then form comparisons with historical evidence leading to modified posterior PDFs. The study was eventually published in the *Review of Geophysics* (Sherwood et al., 2020).

The study finds that it is now possible to be more confident that climate sensitivity is near the middle to upper part of the previous range. Their "baseline" is a range of 2.3 to 4.7 °C bounded by 2.0 to 5.7 °C, but with a central finding of 2.6 to 3.9 °C (in the 66 % confidence range) (Sherwood et al., 2020: 93–95). It is in this sense then that the study narrows the climate sensitivity range and the central figure was quickly picked up by the media. The study concludes that it is unlikely that climate sensitivity could be low enough to avoid substantial climate change well in excess of 2 °C per doubling of carbon emissions on average. They further state in their "plain language summary" that they are "*unable to rule out that the sensitivity could be above 4.5 °C per doubling of carbon-dioxide level, although this is not likely*." (Sherwood et al., 2020: 1, emphasis added).

Before outlining our argument it is important to stress that we are not intent on denigrating the expertise of those involved in this project or similar initiatives. It is not possible here to do justice to the tremendous sophistication of the original work, nor the amount of work required over several years to bring this collaborative project to fruition. As the authors note, one of the major impediments to progress on the climate is that the problem spans several Earth science disciplines and numerous specialisms and it is unusual for any given person to have expertise in more than one or two of these. Collaborative work of this kind is thus an attempt to overcome this hurdle and that in itself is of value and a great deal of the argumentation which situates the use of evidence is highly plausible.[4] Our purpose, however, is to look through this sophistication and consider the constraints imposed and the unintended consequence created by methodology and to suggest that alternatives are also worth considering.

The primary methodological question that concerns us is how does Bayesian updating treat uncertainty? Bayesian updating places emphasis on what is presently *known*, even though that is just a small fraction of what might be revealed over time, but which is presently *unknown*. Subjective probability, on which Bayesian updating is based requires a complete *ex-ante* listing of all possibilities so as to establish a set of priors that fully capture all eventualities (Feduzi and Runde, 2014). As such, it treats known unknowns (such as the contingent and as yet unobserved potentials for changes in and through interdependencies of aspects of some system and for amplification, acceleration and transition in processes) as tameable according to current expert assessment of available evidence and understanding and this essentially denies the

[3] For example: "Our S is not the true equilibrium sensitivity ECS, which is expected to be somewhat higher than S due to slowly emerging positive feedback. Values are similar, however, because we define S for a quadrupling of CO_2 while ECS is defined for a doubling, which cancels out most of the expected effect of these feedbacks." (Sherwood et al., 2020: 95).

[4] The study for example is highly plausible insofar as it contextualizes itself according to (Sherwood et al., 2020: 93–95)A very low sensitivity (S ~ 1.5 K or less) would require all of the following:

- Negative low-cloud feedback. This is not indicated by evidence from satellite or process- model studies and would require emergent constraints on GCMs to be wrong. Or, a strong and unanticipated negative feedback from another cloud type such as cirrus, which is possible due to poor understanding of these clouds but is neither credibly suggested by any model, nor by physical principles, nor by observations (Section 3).
- Cooling of climate by anthropogenic aerosols over the instrumental period at the extreme weak end of the plausible range (near zero or slight warming) based both on direct estimates and attribution results using warming patterns. Or, that forced ocean surface warming will be much more heterogeneous than expected and cooling by anthropogenic aerosols is from weak to middle of the assessed range (Section 4).
- Warming during the mid-Pliocene Warm Period well below the low end of the range inferred from observations, and cooling during the Last Glacial Maximum also below the range inferred from observations.
- Or, that S is much more state-dependent than expected in warmer climates and forcing during these periods was higher than estimated (Section 5).In other words, each of the three lines of evidence strongly discounts the possibility of S around 1.5 K or below: the required negative feedbacks do not appear achievable, the industrial-era global warming of nearly 1 K could not be fully accounted for, and large global temperature changes through Earth history would also be inexplicable.A very high sensitivity (S > 4.5 K) would require all of the following to be true:

- Total cloud feedback stronger than suggested by process-model and satellite studies (Section 3).
- Cooling by anthropogenic aerosols near the upper end of the plausible range. Or, that future feedbacks will be much more positive than they appear from this historical record because the mitigating effect of recent SST patterns on planetary albedo has been at the high end of expectations (Section 4).
- Much weaker-than-expected negative forcing from dust and ice sheets during the Last Glacial Maximum (Section 5). Or, a strong asymmetry in feedback state-dependence (significantly less positive feedback in cold climates than in the present, but relatively little difference in warmer paleoclimates).
- Thus, each of the three lines of evidence also argues against very high S, although not as strongly as they do against low S. This is mainly because of uncertainty in how strongly "pattern effects" may have postponed the warming from historical forcing, which makes it difficult to rule out the possibility of warming accelerating in the future based on what has happened so far. Indeed, we find that the paleoclimate record (in particular, the Last Glacial Maximum) now provides the strongest evidence against very high S, while all lines provide more similar constraints against low S (paleo slightly less than the others).

possibility for surprise.[5] Yet all those working on the anthropogenic climate problem recognize that it is by definition about *change* i.e. non-stationary effects to a complex system, and the significance of this becomes more apparent the more one's approach seeks to approximate the full nature of the Earth system as a complex system that can be pushed out of stable states. As one of the originators of the planetary boundaries framework, Will Steffen, notes:

> We know, with a high degree of certainty, that many positive feedback processes exist, but we don't know - with a high degree of certainty - where the tipping points for these processes might lie. That is, where is the level of forcing (e.g., temperature rise) beyond which permafrost melt becomes self-reinforcing and thus unstoppable? Even more uncertainty surrounds the interactions among these feedback processes, interactions that could lead to a global tipping cascade. In effect, this is the process that would drive the Earth System from one stable state - the Holocene - into another stable, but much hotter, state, sometimes called 'Hothouse Earth'. Large uncertainties remain regarding the point at which such a global tipping cascade, if it exists, could be initiated. (Steffen and Morgan, 2021)

Consider, for example, recent reports of the Pine Island Glacier in the West Antarctic (Joughin et al., 2021). An ice shelf has served to hold back the gradual flow of this glacier into the sea and based on gradual melt-driven subsurface effects it had previously been estimated it could take a hundred years or more for the ice shelf to be lost. However, the shelf has recently started to fragment and break apart rather than merely reduce and the glacier's advance into the sea has greatly accelerated. This, in turn, will have consequences for climate change since the Earth's albedo effect will be reduced faster and sea levels rise quicker than expected. Of course, one might respond that this is yet another source of evidence based on observation and this will facilitate better understanding of the climate problem and its interdependencies. This is true, but from the point of view of expectations of systems this is *ex post* and thus reveals the continuous problem of a Bayesian approach to reconciling issues of uncertainty.

In general, changes to average temperature and the upper range of temperature observed in the Antarctic (as they have been in the Wandel Sea off Greenland in the Arctic circle) have recently been much greater than anticipated and if one pays attention to recent reports then a whole host of effects on processes that in turn will feedback into climate change are happening earlier than previously anticipated. Again, this is starting to be reflected in the latest climate work, but this merely confirms the *ex post* problem. For example, the recent well-publicised sixth cycle IPCC Working Group 1 ('physical science') report highlights that the Earth may reach and exceed the 1.5 °C goal of the Paris Agreement much earlier than previously forecast – up to twenty years earlier in the worst case, when compared to the special report of 2018 (IPCC, 2021).[6] Moreover, in all 5 of its scenarios, it is now likely that global warming reaches or exceeds 1.5 °C regardless of how radically governments and corporations now cut greenhouse gas emissions – albeit with scope for decarbonisation to moderate changes to 1.4 °C by end of the century in the best case scenario. This finding, moreover, is reached with a narrower sensitivity range broadly along Sherwood et al. lines and while there may be value in the concern the report has induced it still creates the potential to underestimate the scope for outcomes to be outside the range. As a recent paper in *Earth System Dynamics* highlights, even the best science we have can continually underestimate effects because of problems inherent to the modelling, which cannot cope effectively with uncertain 'domino' effects (Wunderling et al., 2021). A complex system is not merely 'complicated', its components are interdependent and self-organizing, which gives rise to emergent properties and powers that place severe limits on anticipation of future outcomes, despite some understanding of system behaviour and stylised simulations.

Our point then is not that processes are inexplicable – this is not the case and one still looks to Earth science experts for explanations – our point rather is what this suggests about the application of Bayes. To reiterate and elaborate, for Bayes to apply the expert (the decision-maker) must know in advance all the possible decision outcomes relevant to the decision. It is a pre-requisite of applying Bayes' rule that a decisionmaker is prepared to attach numerical values to their prior beliefs and beliefs about the strength of the evidence. Bayesian updating then, assumes one "washes out" inaccuracies in priors by *successive* updating. This conception of improved accuracy entails convergence on the objective state of the world, which stands behind the probability and this implicitly suggests there is a learning process captured by Bayes. But in situations of rapid change or of emergence (such as phase transitions to new states not yet represented in data for the system) we do not necessarily have stable objective probabilities "out there" to be

[5] There are numerous ways in which the relevant issues here might be decomposed, stated and analysed. For example, one might distinguish what *is not* known (by an individual, group or everyone) and what *cannot be* known, for example, due to indeterminacy of the future, which may, in turn, involve complex contingency of outcomes, some of the basis of which has yet to be adequately theorised, some of which has yet to be adequately apprehended and some of which has not yet been manifest or realised (e.g. changes of state in reality). There is then, scope for uncertainty on the basis of surprise. Faulkner et al. (2017), for example, decompose Rumsfeld's famous statement regarding unknowns and later extend discussion to Taleb's Black Swans and the standard distinction for theory of probability between risk and uncertainty.In terms of its conceptual underpinning, the concept of uncertainty has various articulations and contrasts with numeric probability. Frank Knight (1921) distinguishes risk and uncertainty, Chapter 7 of *Risk, Uncertainty and Profit*, which turns on the difference for a decision-maker between situations guided by known chance (assigned numerically to events) and situations where it is not possible to assign numerical probabilities. He terms the former risk and the latter uncertainty. As Jochen Runde notes (Runde, 1998), however, the distinction is not a simple dichotomy. His concept of risk encompasses a priori probability (complete and homogeneous classes equivalent to propositions in mathematics – probability can be computed from principles) and statistical probability (derived from empirical evaluation of frequency), and he distinguished 'estimates' with no valid basis of any kind for classes. For Knight, there is a continuum based on groupings. Estimation echoes John Maynard Keynes' well-known statement that there are situations with 'no scientific basis on which to form any calculable probability' (roulette is not uncertain, the weather is moderately uncertain but the prospects of a war in twenty years' time is fundamentally uncertain). The classic statement is made in 1937 (Keynes, 1937), but the primary work is Keynes' *Treatise on Probability* (Keynes, 1973 [1921]), though Keynes does not define uncertainty here, one must infer it, where he explores probability as a measure of the individual's belief in a proposition or event but with an objective basis in empirical knowledge of the experienced real world (leading to discussion of evidential weight as well as a critique of frequency probability, which restricts adequacy to rare occasions where statistical frequencies can be validly measured). Keynes also objected to the subjectivist approach in so far as it requires unique real numbers be assigned to beliefs (and few decisions can be left until the conditions for this pertain or until all the evidence is in – if this is even possible in the given or general case).And as Faulkner et al. (2017) note: "Proponents of the subjectivist Bayesian interpretation of probability have argued that, if subjective degrees of belief are 'rational' in the sense of conforming to the strictures of something like the Savage axioms, all probabilities become numerical and the distinction between risk and uncertainty evaporates. However, there is considerable empirical evidence that people often do not behave 'as if' they are assigning numerically definite probabilities to the things they are uncertain about even in relatively straightforward situations, and a large amount of theoretical work, much of it by people working within the subjectivist Bayesian tradition, aimed at modelling these cases." (Faulkner et al., 2017: 1293, fn 14, references omitted).

[6] The expectation is that 1.5 °C will be reached by 2040 at latest compared to 2052 previously but the band overlap allows for 20 years; and the report begins from a current averaged heating figure of 1.09 °C, which as some of the previous material indicates, less than some datasets (placing it at 1.2 °C to 1.3 °C).

uncovered and for decision situations to converge to. Moreover, if the system manifests an unknown and/or emergence springs a surprise, then a Bayesian approach must start again. Priors must be re-specified, the outcome space reformulated and sampling resumed to reinitiate updating.

Constructing priors thoroughly in order to take full account of uncertainty, surprise and complexity *as these are perceived* at the point of their creation does not assist with the problems invoked in relation to convergence to objective probabilities that eventually accurately reflect reality. This is so even if based comprehensively on all available scientific evidence with the intention of reconstructing them when over time new evidence is revealed. There are four points one might make here that speak against recovering Bayes through alternative interpretations or framing of its use. Firstly, if a possibility was not included as a prior *ex ante*, it must have zero posterior probability (see Footnote 7). Secondly, notwithstanding this technical problem, even if it were possible within the Bayesian framework to add more possibilities over time as they are revealed, this would anyway at some point require the downgrading of the probability of *ex ante* included possibilities due to the finite amount of likelihood available and the requirement that probabilities sum to unity (the so-called problem of "additivity"). This downgrading of probability may contribute to highly impactful and extreme outcomes being overlooked or dismissed by policymakers (Derbyshire, 2022). Thirdly, reserving a portion of probability for these possibilities revealed over time, which is then "consumed" as these possibilities are revealed so that downgrading of the probability of *ex ante* included possibilities is avoided, does not help because the amount of reserve needed is unknown *ex ante* (Derbyshire, 2017; Shackle, 1955). Fourthly and finally, an eventual convergence with objective reality through successive updating based on information revealed over time is of no use in circumstances in which decisions must be taken now to head off what might be an extreme outcome in the future. If the convergence to objective probabilities eventually reveals that an extreme outcome has a high probability it is at that point already too late to prevent it and this seems to be the most pertinent point to make regarding attempts to apply Bayes to the climate problem.[7]

To be clear, the authors of the Sherwood et al. study are aware of basic limitations of Bayes. However, as they note in concluding, they consider that the overwhelming weight of cumulative evidence across the three approaches is sufficient to justify the approach i.e., the weight of evidence provides confidence that any consequences of unknowns and surprise is likely to be limited and so the derived climate sensitivity measure is a reasonable inference from the formal application of Bayes. But, again, to be clear, this is an argument applied to *justify* use of Bayes and is not something that Bayes itself expresses in its method. Given the very nature of anthropogenic climate change, therefore, it is reasonable to ask whether it makes sense to "firm up the science" with regard to the climate sensitivity range along these lines (drawing on a method rooted in classical probability, summing to 1 etc.; see Gillies, 2000).

Consider, as a final point, what use of Bayes suggests about any defined range and its upper threshold. While Sherwood et al. (2020) state they are "unable to rule out that the sensitivity could be above 4.5 °C per doubling of carbon-dioxide level" (Sherwood et al., 2020, p.1), in terms of the application of Bayes the edge of each confidence range is a cut-off and values beyond this have a *zero* "prior" probability. While Sherwood et al., therefore, cannot rule out an outcome above the range *as a possibility*, the revised range does exactly that in probabilistic terms. Though experts in the field may be aware of this limitation it is less clear what the findings convey to the public and policymakers and this too is not irrelevant, given the nature of anthropogenic climate change and this brings us to the second step in our two-stage argument. Narrowing the climate sensitivity measure may have counterproductive consequences.

4. Bayes, firming up the science and counterproductive consequences

Pushing the lower threshold of the climate sensitivity range upwards seems likely to induce greater urgency in addressing the anthropogenic causes of climate change – though this does not in itself address the issue of how this is achieved via Bayes. However, narrowing the range and conveying greater confidence to policymakers regarding the upper part of the range may have unintended counterproductive consequences. Though changes to the climate sensitivity measure do not eliminate the need for decarbonisation, narrowing the range and lowering the upper value may have implications for the urgency and stringency of mitigating actions that *could* have been implemented if known or relied on previously. This is important because climate change is high impact and its context is one of enduring effects and irreversibility, including in its spillover consequences (loss of biodiversity, extinction events etc.). Moreover, stringent action to prevent harm can be adjusted downwards, whereas, insufficiently stringent action due to a lack of certainty about its need cannot be retrospectively adjusted upwards. As such, there is an asymmetry to *precaution* in the presence of known unknowns and surprise that can influence multiplicative effects with irreversible impact (Taleb, 2020; Derbyshire, 2022). In the context of climate change, therefore, it is essential to place a premium on prudential conduct that allows for degrees and types of uncertainty and facets of *fundamental* uncertainty. The "precautionary principle", of course, is a well-recognized aspect of climate policy. Article 3 (3) of the 1992 United Nations Framework Convention on Climate Change (UNFCCC) states:

> The Parties should take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects. Where there are threats of serious or irreversible damage, **lack of full scientific certainty should not be used as a reason for postponing such measures** … policies and measures should take into account different socio-economic contexts, be comprehensive, cover all relevant sources, sinks and reservoirs of greenhouse gases and adaptation, and comprise all economic sectors. Efforts to address climate change may be carried out cooperatively by interested Parties [emphasis added].
>
> (UNFCCC, 1992: 4)

There is, for example, fundamental uncertainty associated with many of the new technologies being developed to facilitate a green economy and to enable mitigation (Rueda et al., 2021; Workman et al., 2021; Dyke et al., 2021; Morgan, 2020). Are they possible in principle, scalable, commercial and (given the urgency of the carbon budget problem) timely? To reiterate, there is an asymmetric payoff from climate change mitigation because of its irreversibility (Aldred, 2013). What *may* later be deemed excessive mitigation has relatively little present negative impact, and has ancillary positive impacts. For example, better air quality. Whereas, by contrast, inadequate mitigation now is potentially catastrophic in the future because it cannot be retrospectively adjusted upwards.

It is also highly relevant that what humanity does in terms of government policy, corporate responses and individual and group behaviour are not separate issues from whether in fact climate change responses are effective. These are by definition internal or performative when addressing *anthropogenic* change to the climate. It is, of course, stating the obvious to suggest adjustments to the climate sensitivity range provide a resource for this activity. But this is highly significant

[7] Consider what all this means, if future updates implied a climate sensitivity outturn beyond 3.9 °C or 4.5 °C per doubling of carbon emissions, thus requiring the upper bound to be increased, the introduction of this new state of nature would have a destabilising effect on decision-making. It would be attributed a zero posterior probability based on its absence as a prior. This reveals a primary issue in terms of the concept of uncertainty that stands behind method.

insofar as it speaks to the potential for complacency and delay and there is a long tradition of this (some of it malicious some of it inadvertent) in regard of climate change (Franta, 2021; Lamb et al., 2020; Oreskes and Conway, 2010).[8] There is, of course, a balance to be struck insofar as scientists want to project that results are in some sense "objective" rather than compromised or politicised in some pejorative sense, but this is different from understanding the impact of climate science for policy and thinking carefully about communicative consequences and efficacy. In the past (with notable exceptions such as James Hansen) climate scientists as a community have been relatively reticent in stressing the urgency and importance of the issues (though this has not prevented manufactured or misrepresented scandals, such as "Climategate" in 2009). This, of course, has started to change now we have organisations such as the Alliance of World Scientists and a declared "climate emergency" because of the failure of powerful actors to move beyond "business-as-usual".

In any case, it is uncontroversial to suggest that "messaging matters" for if and how we solve climate emergency – though quite how to achieve effective messaging and how to inform and educate policymakers and the public remain matters of contention (e.g. Lakoff, 2010; Røpke, 2020). It should, however, be uncontentious that a better understanding of the nature of scientific method and use and meaning of evidence would be beneficial. A great deal of confusion is created by the expectation of certainty from science, since the continual modification of claims and outcomes creates a lay sense of scepticism. Varieties of scientific realism, for example, suggest the point of science is to explore causal mechanisms and how they evolve as ways of acting of "powerful particulars" (though there are various terminologies for this). It typically requires experimental intervention to isolate parts of processes and induce regular outcomes, and yet the "laws" of nature do not cease to exist because they are operative in combination in uncontrolled situations. It is the significance of this difference that requires science to design experiments and to propose and test principles of ways of acting of things that may confound our most-informed understandings of what is going on (despite that our explanations of ways of working are basic to both our view of an ordered reality and our technological societies). Greater understanding of this would surely foster more consistent attitudes towards science and provide a more supportive framework for combinations of statements along the lines "We cannot be certain and yet the evidence suggests we need to be cautious and avoid possible worst cases". This, in turn, has further implications for specifics.

Clearly, climate change can be framed in ways that foreground a negative outcome or in ways that foreground the same outcome positively. Communication can motivate and empower or not. Communication is more than mere conveyance of information, it is more than merely true or false, it is also persuasive, plausible and motivating or antithetical to these. For example, "It is 20 % likely that global warming of 2 °C will make a quarter of all species extinct" or "It is 80 % likely that global warming of 2 °C will *not* make a quarter of all species extinct" have quite different registers. Drawing on his longstanding and influential work on metaphor and cognition (notably his *Philosophy in the Flesh*) Lakoff (2010) makes the point that effective communication and messaging in the context of public understanding requires more than relentless facts. It requires a discursive strategy that creates continuity of experience and awareness of ongoing events and which maps this to an emotively effective sense of efficacy. Concomitantly, Morton et al. (2011) find that uncertainty can exacerbate feelings of powerlessness. However, if conjoined with a sense of self-efficacy it may improve motivation.

Research then, suggests that increasing certainty about climate change uncertainty has an uncertain effect on mitigation planning and activity (Aldunce et al., 2016; Milfont, 2012; Morton et al., 2011; Spence and Pidgeon, 2010). This and the first step in our two stage argument suggests there is a case for evidence-informed management of uncertainty which also allows for communicative efficacy directed at those whose actions are required in order to solve the problem at hand. The approach should be one that does not require a full conception of all possible states of the world for it to be explanatorily effective and for learning to occur. We would further argue that stimulating prudential action (mitigation etc.) to prevent harm would benefit from a "prospective" perspective based on if-then conditional thinking rather than prediction (Seligman et al., 2013).[9] This if-then conditional thinking is the basis of Intuitive Logics scenario planning. Appropriate framing of climate change uncertainty may depend on the stakeholders involved and the specific nature of each policy context. This implies a role for flexible tools for this purpose, tools, moreover, that facilitate the management of degrees of uncertainty and fundamental uncertainty; tools which encourage prudential activity, subject to the precautionary principle and with due consideration to the high impact and irreversible nature of climate change (see Workman et al., 2021, 2020). We would argue that scenario planning has this potential, although much of the work done so far using scenario planning (beyond that previously referenced) has not been particularly sensitised to the required foci.

5. Scenario building and the case for intuitive logics scenario planning

We have argued that applying Bayesian updating to climate sensitivity measures requires numerical values to be assigned to beliefs and does not allow for what lies outside the decision set. As such it does not allow for surprise and fundamental uncertainty. Furthermore, it may despite good intentions have counterproductive consequences. If climate sensitivity measures "firm up the science" this can readily influence policy and behaviour, and in some cases this may lead to an under-response, since what is outside the range may not now be under consideration for the purposes of decision-making. Given the problem under scrutiny is anthropogenic change to the climate, this is an important tension. The precautionary principle, and the accelerating and irreversible nature of climate change, suggests we should far prefer a type I precautionary 'error' of overresponse over a type II of underresponse (Derbyshire, 2022). However, uncertainty itself can have different effects and these depend in part on how evidence and argument

[8] And this is to say nothing regarding the role economic theory and research has played in inducing delay because of "Integrated Assessment Models" (IAMs), such as the "Dynamic Integrated model of Climate and the Economy" (DICE). These have been used to inform IPCC scenario pathways for socioeconomic policy re mitigation and adaptation. They have, however, proved controversial in terms of the use by economists of, and compatibility with, Earth system science and have proved increasingly controversial among social scientists and policymakers in terms of the claims made and inferences drawn from these DICE models. For example, DICE models focus on the "social cost of carbon" (SCC) and are built around the Ramsey formula, which calculates a monetary discount rate which is then applied to cost-benefit analysis. The rate has profound influence on how the needs of the future are valued in relation to the present based on a "social rate of time preference". As the well-publicised dispute between Nicholas Stern and William Nordhaus highlights, models are calibrated and discount rates are essentially chosen rather than unequivocally rooted in climate and ecological science. Nordhaus received the "Sveridges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel" (jointly with Paul Romer) in 2018. Over the years Nordhaus and various colleagues have argued against significant and early attempts to reduce emissions and have suggested different "optimal warming rates" from the point of view of economic growth over the rest of the century and into the next. Though Nordhaus recognises the need for major change, for example, built around carbon pricing, the calculations in his Nobel lecture still allow for an optimal warming trajectory of 3 °C by end of the century and a further trend increase to 4 °C by 2150. There are numerous critiques (Asefi-Najafabady et al., 2021; Keen, 2021; Gills and Morgan, 2021; Spash, 2002).

[9] Though to be clear there are severe limits on prospect theory in behavioural economics as an adequate approach.

are framed. The implication then, is that there is a role for a more deliberative and flexible approach to decision-making in the context of climate emergency. And one might add a further point here: subjective probability axiomatized via Savage as subjective expected utility is unable to adequately accommodate differences of framing and thus the need for carefully considered and potentially diverse rationales, which might be deployed for the purposes of decision-making. From a subjective probability perspective considering the same problem using multiple decision-making approaches and rationales is irrational (Bermúdez, 2020, 2009, 2018a). They may conflict with each other leading to ambivalence (Bermúdez, 2020, 2009, 2018b). In contrast, decision-making aids that have the ability to frame climate-change's uncertain impact in alternative ways may be preferable (for some issues see Holden et al., 2018; Rickards et al., 2014a, Rickards et al., 2014b) when one considers that the "stakeholders" in a climate emergency are ultimately everyone, and so the approach must be able to accommodate to difference.

There is a great deal of relevant work within philosophy on the justification of pluralism and diversity which we do not have the space to discuss here (classically Rescher, 1993) but to be clear, we are not advocating an anti-science, anti-truth or "anything goes" attitude to evidence and argument. Such an approach would be self-defeating, since it would imply a type of ontological relativism, which could embrace climate-denial and undermine the very point of enhancing recognition of the urgency of the situation. The point rather is to enhance understanding of the available evidence and also the nature of and potential severity of uncertain consequences. Given the wide variety of stakeholders involved in responding adequately to climate change, we would argue decision-making tools used must be able to stimulate what Bermúdez refers to as "frame-sensitive reasoning" and "reflexive decentring" (Bermúdez, 2020). The former encourages decision-makers to consider alternative perspectives on the same problem, and the latter encourages awareness of the effect of framing on one's present perspective. As Bermúdez notes, rather than being irrational, the ability to consider the same situation from alterative perspectives is an indicator of good decision-making (Bermúdez, 2018b: 179, 2020). Moreover, it is a highly effective way to address deeply-entrenched and potentially conflictual problems. To appreciate the relevance of this one need only consider the fractious argument surrounding the financing of climate transition and the asymmetric distributional implications for currently rich and poor countries of absolute reductions in total resource and energy use on a global scale (if this proves necessary, which seems likely given the continued failure of the various metrics of "decoupling", e.g., Parrique et al., 2019; Hickel and Kallis, 2020).

As Urueña notes in a recent paper which decomposes and explores the philosophical underpinnings of scenarios in the context of Futures Studies, there is an inherent contingency and complexity (in the sense of complicated, rather than chaotically stable, which is what it means to Earth scientists) to systems and this implies that classically based prediction can be insufficient and/or inappropriate, especially when addressing issues which have scope for or intend one to affect future outcomes, notably socio-political activity (Urueña, 2019; see also Patomäki, 2006). Scenarios are an "antidote" against perspectives "in which – intentionally or not – the agential power of social actors to influence development pathways remains unproblematized" (Urueña, 2019: 16). Building scenarios creates evidence-based modal narratives that:

> attempt to describe future horizons to develop an inclusive space for enhanced flexible decision-making processes. Broadly, creating scenarios can be understood as a socio-epistemic practice, the main purpose of which is to construct conjectural and non-deterministic representations of future states of affairs to explore and illuminate the human condition and provide practical or *phronetic* knowledge to regulate praxis.
>
> (Urueña, 2019: 16)

Urueña decomposes scenario building in various ways to explore their modality (highlighting key elements, and then distinctions between types of reasoning or inference and selection according to criteria and whether the scenario is possible, probable or plausible for the subset of desirable states of affairs), but the important point for our purposes is that "the purpose is not to know the future, but first to 'open it'… and then to 'close it down' by guiding the decision-making processes" (Urueña, 2019: 18). As such, scenario planning is a decision aid able to frame climate change's uncertainty and impact in alternative ways.

Scenario planning has the potential to change perspectives on the possible extremity of an impact and the high degree of uncertainty associated with it. Since its basis is plausibility, not classical probability (which can inadvertently present the future as a *fait accompli*), it can readily accommodate key features of the climate change problematic as they appear to governments and populations – matters that are irreducible to probabilistic risk and resulting from multiplicative and exponential effects leading to accelerating impacts. Still, while having a long history (Derbyshire, 2020b), scenario planning remains a nascent field (Workman et al., 2021, 2020), though it is growing in prominence.

Scenarios represent if-then conditional "predictions" but not as traditionally understood. We place the word "predictions" in inverted commas here because, given this very different nature, it may not even be appropriate to call scenarios "predictions". Such if-then scenario predictions broaden perspective on the range of possible outturns well beyond probabilistic confines. Furthermore, if-then scenario predictions allow for the performative dynamic in decision-making. They can be designed to alter the future by changing our perspective on its alternative possibilities (Seligman et al., 2013). Deliberation can thus stimulate action. As such, the approach emphasizes reality's inherent openness, and humans' inherent reflexivity. Bayesian updating designed to increase scientific certainty, by contrast, places emphasis on present knowledge as a means to predict the future, even though this present knowledge may be a very partial representation of all relevant knowledge revealed over time. This difference is fundamental to scenario planning's usefulness as a device for highlighting and considering the full extent of the future's uncertainty.

There are several versions of scenario planning and the Intuitive Logics approach is only one variant among these (Derbyshire, 2020b). Its basic format has an eight-stage process (Table 1), which we summarise here based on the work of Cairns and Wright (2018) and Cairns et al. (2016) (see also Derbyshire and Giovannetti, 2017):

A deliberative, reflexive and iterative approach is taken to and throughout the eight stages. In stage 1, a focal issue is identified for the scenario exercise. This issue may be initially explored using structured interviews with key decision-makers and other stakeholders, thus uncovering present understandings and existing perceptions of it. In stage 2, a range of driving forces related to this focal issue are identified. Driving forces are the causes that are expected to contribute, individually or in combination, to bringing about a change in relation to the focal issue. They are sometimes identified by grouping them under the PESTEL dimensions: political, economic, social, technological, environment and legal (Cairns and Wright, 2018; Cairns et al., 2016). In stage 3, driving forces are categorised as causally related and "clustered" and these are depicted in "influence diagrams", representing the cause-and-effect relationship between them. Discussions are then directed to achieve a specific "resolved outcome" for that cluster. Given there may be many clusters/influence diagrams, a small number of these clusters are selected as "higher-level factors", which represent the broad and most critical causal driving forces of change in relation to the focal issue identified in stage 1.

Stages 4, 5 through 8 apply method to uncertainty. In stage 4, two extreme values are attributed to each higher-level factor, respectively representing an extremely positive and an extremely negative, and yet still plausible, outturn in relation to their designated "resolved outcome". In stage 5, each higher-level factor is then ranked in terms of the uncertainty of the extent of its impact on the focal issue using a 2 × 2 matrix in which one dimension represents its impact and the other its uncertainty. The two higher-level factors with the greatest perceived uncertainty as to the extent of their impact (on the focal issue) are labelled Factor A and Factor B. In stage 6, these are then used to create a final 2 × 2 matrix that frames the scenario writing. In stage 7, drawing on discussions that took place throughout the exercise, descriptors are added to each quadrant of this 2 × 2 matrix in order to aid scenario writing. In stage 8, four narrative scenarios are then written based on the resulting combination of extreme outturns for each of the two selected higher-level factors – one scenario for each of the four resulting quadrants of the final 2 × 2 matrix created in stage 7 (A1/B1, A1/B2, A2/B1 and A2/B2).

6. Scenario planning as an approach for considering multiplicative, accelerating and exponential effects and irreversible and incommensurable impacts

It is relatively straightforward to adapt Intuitive Logics scenario planning to emphasise multiplicative, accelerating and exponential effects leading to irreversible and incommensurable (i.e., qualitatively different) impacts, and therefore an asymmetric payoff from precaution (Derbyshire, 2022). Higher-level factors are compared and ranked in terms of their relative uncertainty and impact (on the focal issue) in stages 5 and 6 (see Table 1). This selection leads to the framing of the final 2 × 2 matrix on which four scenarios are based and is therefore critical to the whole exercise. A simple set of heuristics, as captured in Table 2, can be used by stakeholder participants in order to rank higher-level factors in terms of the extent of their uncertainty and impact. Use of this heuristic renders IL scenario planning highly congruent with precautionary decision-making.

The presence of *multiplicative*, *accelerating*, *exponential* and *second-order* effects gives rise to fundamental uncertainty about both the full extremity of a higher-level factor's outcome (i.e., its uncertainty) and the extent of its impact on the focal issue. We previously noted, for example, that it took two-hundred years for the figure for parts per million (ppm) atmospheric CO_2 to increase by 25 %, but just the last thirty years for it to increase by 50 %. The rate of change of ppm is thus accelerating. Second- and higher-order effects are important but only considered in a limited way in IL scenario planning currently. There is little attentiveness to the interaction and knock-on effects between the outcome from *different* higher-level factors.

At its simplest, *irreversibility* reflects the fact that some outcomes have the characteristic of *finality*, representing an extremity that should be avoided at all costs. Finality is therefore representative of an *incommensurability* between extreme outcomes. Incommensurability may, therefore, be a feature of the gains and losses associated with higher-level factors in stage 4, if they are qualitatively different and incomparable in their desirability, and therefore do *not* simply represent different gradations or valences of an outcome of the same type. For example, there is a qualitative difference between two extreme (yet plausible) outcomes attributed to a higher-level factor where the positive represents a 10 % increase in a species' numbers year-on-year, and yet the negative represents outright extinction.

Asymmetry in the pay-off from strategic (mitigating) actions is a characteristic related to that of *irreversibility* and *incommensurability*. The way to conceptualise this is to think in terms of the type I and type II precautionary errors discussed by Aven (2020) and by considering the different outcomes from over- and under-responding to a potential extreme outcome in terms of the above incommensurability. If an ecological species is under threat, and one among the primary higher-level factors causing this threat is human-related – e.g., the use of a harmful chemical fertiliser – then precautionary asymmetry through the 'omission' (Taleb, 2012) of that cause must be considered. Omitting use of a particular chemical, or substituting it for a less damaging and more natural alternative, may reduce the production of a crop to an extent, but this economic effect, which may be perceived negatively by some stakeholders, is incomparable to (i.e., qualitatively different from) the extinction of the focal species. The cost of *over-responding* in terms of eliminating the use of a chemical that may subsequently be proven to be harmless is minimal. Yet, if a causal link between it and harm is eventually proven, yet no action was taken because there was previously an absence of *certain* evidence about the chemical's negative effect, the cost of *under-responding* is potentially catastrophic and irreversible in terms of the species' extinction.

Similar reasoning applies to carbon emissions and such asymmetry in the pay-off from precautionary action, as the discussion in this paper has shown, is ever present both in relation to climate change's local manifestations and impacts, and in relation to planetary-scale climate change. At the grand scale of global climate change, and in terms of reducing carbon emissions, the cost of over-responding by implementing extremely stringent mitigating actions now pales into insignificance compared to the potential cost of *under-responding*, which could be catastrophic and irreversible. As a final point, though IL scenario planning may seem abstract when set out in brief, it is a *participatory process* and thus quite different than the experience of being a passive recipient of a presentation by experts. It is not merely a source of information but

Table 2
Questions for assessing, ranking and then selecting higher-level factors in stages 5 and 6 of IL scenario planning based on the uncertainty and impact of their designated extreme outcomes.

Aspect of uncertainty/ impact assessment considered	What are we trying to assess?	Example questions designed to aid its consideration:
Uncertainty in terms of extremity of outcome	Are potentially **multiplicative**/ **accelerating**/**exponential**/ **second-order** effects present, or anticipated to be present, leading to fundamental uncertainty about the full extremity of the cluster's designated outcome and its impact on the focal issue?	• Is the combined effect of the higher-level factor's causes on a key variable associated with its resolved outcome (as captured in the extreme values attributed in stage 4) additive or multiplicative? • Is the length of time needed for this key variable to double and then further double expected to decrease over time, implying acceleration? • Is there positive feedback from a circular relationship between the designated resolved outcome and its causes (as captured within the higher-level factor's cluster diagram)? • Is there a knock-on effect on the designated outcome of other higher-level factors?
Impact on focal issue	Are potentially **irreversible** and **incommensurable** impacts present giving rise to an **asymmetric** pay-off from action and inaction?	• Does the higher-level factor's designated outcome have the potential characteristic of finality? • Is there a cut-off point beyond which harm from it cannot possibly exceed and is it acceptable? • Are its extreme negative and positive outcomes (as attributed in stage 4) incomparable due to their incommensurability (i.e. are they qualitatively different)? • Is there incommensurability in terms of the gains and losses from any mitigating actions taken in response and is the pay-off from them convex or concave (see Derbyshire, 2022)?

rather a deliberative process which requires engagement, encourages ownership and facilitates learning as one makes links and explores options and reasoning. As such, through a pedagogy IL scenario planning speaks to Lakoff's concern with communicative efficacy that facilitates taking responsibility. In the case of climate emergency that means understanding that one's own actions may seem insignificant in isolation but the combination of those actions is vital and their confluence is powerful. Moreover, underpinning the application is the insight that a key aspect of uncertainty is our responses and thus effective management of uncertainty is married to our own commitment to efficacious conduct in order to help realise one possible future and close down another. This deliberative dynamic is common to SFDF approaches, as Workman et al. (2021) also emphasise.

7. Conclusion: scenario planning, a nascent field whose time has come?

As stated in the introduction, tackling climate change has become one of the most important policy issues of our time and the climate sensitivity measure is a key aspect of the science. It has implications for all aspects of society. We have pursued a two-stage argument regarding the significance and use of the climate sensitivity measure. First, we have argued that there is a methodological problem associated with using Bayesian updating to "firm up the science". There is a problem of known unknowns and the potential for surprise which sits awkwardly with Bayes. Second, narrowing the range may have counterproductive consequences depending on what this conveys to the public and policymakers. If narrowing the range invites under-responses then this may undermine the "precautionary principle". Stringent action to prevent *anthropogenic* climate change can be adjusted downwards, whereas, insufficiently stringent action due to a lack of certainty about its need cannot be retrospectively adjusted upwards. Such an asymmetry places a premium on being wrong in the right way: we should far prefer the error of over-responding to that of under-responding. This is a preference for what Aven (2020) calls a "type I precautionary error" over that of a "type II precautionary error" (Derbyshire, 2022). As such, there is great scope to apply some version of scenario focused decision frameworks, such as Intuitive Logics, since these work with uncertainty and can facilitate iterative evidence-informed learning, "opening up" future (desirable) possibilities, rather than undermining them (inadvertently or otherwise). As a final point, however, it must be emphasised here that the scale and urgency of climate emergency and ecological breakdown demand of us significant transformations in the way and to what ends economies are provisioned (O'Neill et al., 2018; Gills and Morgan, 2020; Spash, 2021).

Credit authorship contribution statement

The authors would like to confirm that they are joint and equal co-authors of this article.

Declaration of competing interest

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