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An indicative costed plan for the mitigation of global risks

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Abstract

An integrated risk management method is developed for the task of addressing global risks—those threatening the destruction of civilisation, humanity, life on Earth, or the entire planet. Use of the method produced four main results. First, the following risks were classified as global risks: an avian influenza pandemic; scientific experiments which change the fabric of the universe in ways not previously seen in nature; global-warming, especially either releasing methane from methane clathrates or causing a new ice age; biovorous nanoreplicators; computers or robots surpassing human accomplishment; super-eruption; nuclear exchange (full superpower arsenals); strike by large asteroid or comet; eruption of continental flood basalts; and a massive pulse of cosmic rays. Second, it was found that responses are capable of development for each risk. Third, a comprehensive scan for potential interactions between risks and responses found that solar and wind energy (mooted as an alternative to global-warming fossil fuels) would be greatly reduced or uncertain during a super-eruption winter. Two energy options both address global warming and are robust against super-eruption: geothermal and nuclear. Of these, geothermal energy seems lower-risk than nuclear. Finally, the full suite of required responses is estimated to cost approximately $67 trillion. Starting now but introduced over the multi-decade timeframes generally available, this budget would represent a surprisingly small 2.2 per cent of gross world product per year. By contrast, US expenditure on World War II in 1944 was 35 per cent of GNP.

1. Introduction

Global risks may be defined as those threatening the destruction of civilisation, humanity, life on Earth, or the entire planet.

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The range of potential types of global risk, as well as their apparent imminence, is significantly increasing. Illustrating this increase, Rees [1] concluded starkly that, if we do nothing, humanity has a 50 per cent chance of becoming extinct within the next century. A conclusion of similar gravity was drawn in an assessment by Wilson [2] of the state of the biosphere: that, due to human-induced change, the Earth is now in the early-to-middle stages of the sixth mass extinction since complex life began 2.1 billion years ago.

At the level of single global risks, the most studied has been climate change arising from global warming. Here, two pointed findings may be taken to illustrate the degree of threat. First, climate change which has been both severe and abrupt has occurred repeatedly in the past [3] (a Pentagon study has seriously explored a scenario of such abrupt climate change occurring within 15 years and resulting in widespread civilisation-threatening, resource wars [4]). Second, on a smaller but still pressing scale, there is evidence that summer heat waves, which killed tens of thousands in the 2003 Northern summer, will become increasingly frequent and severe [5].

How, then, might a robust plan to reduce global risks to safe levels be derived, and what might it look like? In such urgent risk situations, the use of the discipline of integrated risk management can contribute to responses to risks being planned more coherently, being implemented more rapidly, and having greater effectiveness. This paper reports an attempt to develop an integrated risk management framework and method for the task of addressing global risks. The framework is then populated with data to provide indicative answers to these questions: What is the full list of known global risks? When each risk is next expected? Are there means to mitigate these risks? If so, can we afford to implement them? Have we time to implement them? If so, how much time is there, and when should we start?

The standard integrated risk management approach, after [6], is to:

1. Define the system under consideration; scan the system to find all candidate risks;
2. Rank these risks in order of size and urgency;
3. In strict risk rank order:
   (a) diagnose the causes of each risk;
   (b) assess response options to reduce the risk to safe levels;
   (c) seek linkages and dependencies between risks and responses;
   (d) prescribe the most cost-effective responses in an integrated strategy which addresses both scale of response required and urgency;
4. Fund and implement prescribed responses in an integrated strategy;
5. Monitor progress and feed back results to assist in keeping implementation on target.

Given the evidence that time is short, the approach to information used in the present analysis is based on two concepts. The first is a management variant of Occam's razor: that approaches should be as simple as possible, consistent with doing justice to the issue, but no simpler. The second concept is more closely allied to the management/policy-development tradition than to the scientific tradition. The concept is that all required cells of the required assessment and planning framework must be filled in, certainly with highly precise data when that is available, but with less precise if it is not, even to the extent of using planner judgment if no other information has been found. The approach is a type of what is sometimes termed strawman planning, in which "a crude plan or document may serve as the strawman or starting point in the evolution of a project. The strawman is not expected to be the last word; it is (capable of being) refined until a final model or document is obtained that resolves all issues concerning the scope and nature of the project'' [7]. Such an approach contrasts with one version of the scientific approach, which would leave the uncertain cells in the planning framework blank until precise information was available, and no plan would be devised until then.

A further point is that, due to the range of topics assessed by the one author of this paper, a full knowledge of the literature in each field was not possible.

These variations in the information and knowledge used in the paper are addressed by the presentation of an explicit assessment of the quality of information used for each risk and response assessed.

Turning to existing practice, elements of the standard integrated risk management approach have been carried out in great detail for some risks (e.g., road safety [8], global warming [9] and disease prevention [10]). Tonn [11] outlines such an approach using many but not all of the steps of integrated risk management for all risks, but it was not Tonn's aim to attempt quantitative estimates. Posner [12] has assessed many of the significant risks, and made specific quantitative estimates, but has not brought these together in an integrated budget. For the economic, social and environmental risks arising from energy use, the UNDP and others in their World Energy Assessment [13] use the approach comprehensively, to the costing stage. For the climate change risk, Pacula and Socolow [14] assess the availability of greenhouse effect mitigation measures, but do not proceed to the costing stage or beyond. There has been no previous attempt at *all* stages of the method for *all* major hazards.

Attempts at the thorough implementation of the standard integrated risk management approach at whole-of-system level can lead to markedly improved outcomes. In the field of public health, the approach was introduced in the 1990s for road safety in the state of Queensland, Australia [8]. In that case, its use was associated with large improvements in coverage, efficiency and effectiveness, with major new programs markedly—40–50 times—more cost-effective than the practices they replaced [15,16]. As a result, accelerated and improved reduction in road crashes was seen at system level, in the state of Queensland. Analogously, therefore, such an integrated risk analysis and prescription at the level of global risks might, by providing better information, assist relevant participants—governments, groups, and individuals—to address global risks more coherently and quickly.

2. Method

2.1. Organising framework

As many commentators [for example, 17] point out, there are gaps, inconsistencies and unresolved differences concerning the approach to global risks at many levels, ranging from overall philosophical approach at one extreme to specific elements of the risk assessment process at the other. If integrated risk management provides a tested tool to address the question of the global risks themselves, what is a perspective from which to address these broader issues of gaps, inconsistency, and unresolved differences?

One starting point to an overall approach is provided by considering the basis of the scientific method. This can be seen [18] as "a cycle of hypothesising and verification embedded in a theoretical framework and tied to the 'real world'…". Using this definition, a further question is: what is the best ‘‘overall theoretical framework’’ and ‘‘definition of the real world’’ to use? To address this further question, one is drawn to philosophy, concerned as it is (according to the Oxford Dictionary [19]) with ‘‘ultimate reality and with the most general causes’’. Generally—for example, according to the Encyclopaedia Britannica [20]—a traditional view of (western) philosophy is considered to comprise:

- *the branches of metaphysics*: the study of the nature of reality;
- *epistemology*: the study of the nature of knowledge, including method for gaining knowledge;
- *logic*: the study of standards of correct argumentation;
- *ethics*: the study of nature of, and standards for, morality; and
- *aesthetics*: the study of the nature of beauty.

In terms, then, of the scientific method's ‘‘theoretical framework ‘‘and definition of the ‘‘real world’’, all branches of philosophy can be considered to relate to the scientific method's theoretical framework, and metaphysics to the scientific method's real world.

Summarised, perhaps too crudely, metaphysics concerns *what* is studied/considered, and known: space and time, matter and the energy within it, and the principles governing them. Epistemology concerns basically *how* we study/know. The remaining three branches can be considered to help us judge the quality of what is, and how we know it. Logic provides criteria for correct argumentation; ethics for moral behaviour; and aesthetics notes that some decisions are matters of taste. Of course, each branch of philosophy is open to checking by all the others. A decision suggested on grounds of taste might well be vetted against criteria from logic and ethics.

With this background, this study will use the full span of space and time as the formal, explicit framework and checklist, from which to derive the physical *scope* of the study. The integrated risk assessment process (expanded to included explicit tests for the adequacy of logical and ethical processes, and the role of aesthetics acknowledged) will be used, in deriving the *method* for the study. This approach is an attempt to make explicit the rationale for developing the method, and to reduce the risk of inadvertent conceptual gaps in it.

In this paper the adequacy of logic [21] is assessed using tests for logical fallacies. Lists of the categories of logical fallacies referred to can be found at [21].

Similarly, the adequacy of ethical behaviour [22] is assessed via a battery of three tests:

1. *The harm/beneficence test*:
   (a) Who/what are those affected by my action?
   (b) Is the impact harmful or beneficial?
   (c) What are the alternative actions?
   (d) Which action has the best benefit/harm ratio?
2. *The reversibility test*: Would this seem a good choice if I were affected by it, and its subset: what would be the outcome if everyone did this? And—
3. *The publicity test*: Would I be happy for my decision to be published?

It is noted that these ethical tests have a strong common theme of fairness.

2.2. Scope (of entities and time horizons)

The *scale* of risk in scope for this study, as mentioned in the Introduction, is any risk capable of destroying the planet, the biosphere, humanity, or civilisation. By this definition, both humans and all other living things are within the scope of the study. There are also ethical reasons for the inclusion of all life: for example in 2002, German basic law was amended so that animals, like humans, were given the right to be respected by the state and to have their dignity protected [23].

It can also be suggested that the anthropocentric and biocentric perspectives now amount to the same thing in terms of outcomes. This is for the following reasoning. The stocks at world level of other life required to provide the biospheric life support system which humans need can be calculated. When this is done, it is seen that populations of a certain and substantial size are needed. For *us* to get *our* requirements, then, these large populations must get *their* requirements, *just as if they had rights*. In other words, whether we take a biocentric view that all life has rights, or an (informed and enlightened) anthropocentric view based on self-interest, it amounts to the same thing.

For these ethical (biocentric) and pragmatic (enlightened anthropocentric) reasons, the biological *subject* of risk for the global risk assessment method is the entire biosphere.

The study is of global risks, so those causes of death below the scale of global risks, even if large, do not come within the scope of the assessment. Hence are excluded the many animal and plant species at risk of extinction, and people at risk of death through causes such as malnutrition, infectious and parasitic diseases (including HIV-AIDS), conflict, and terrorism, or disaster such as flood or storm.

The *source* of risks to these subject entities can be from anywhere in the realm of Nature—of matter, energy and their flows, ranging in scale from universal to sub-atomic.

2.3. Common measuring stick for the entities populating the framework

Given that a biocentric approach is taken in the study, the biota is standardly [24] characterised by biomes/species [25] and the common metric for biome/species quantification is tonnes of biomass [26]. Human populations are also quantified by number of persons.

2.4. Approach to risk

2.4.1. Overview

Concerning risk assessments, Rahmstorf and Zickfeld [27] make the distinction between risk assessment and outcome prediction: “In (outcome) prediction, the question is “What is most likely to happen?” In a risk assessment, the question is “What could go wrong, and what would the consequences be?” This assessment is considered to be a risk assessment as defined by Rahmstorf and Zickfeld [27]. The risks sought are those defined as global risks in Section 2.2.

The chance of a global risk coming about is considered in terms of the plausible worst-case scenario.

The chance of a worst-case-scenario event coming about is treated as consisting of (a) when the event is next expected, and (b) what its probability of happening is, when next expected. With this background, it is a fundamental tenet of the approach of this paper to global risks that if a proposed global risk has a non-zero probability, even if small, and could occur now, it should be assessed and planned for now—not have planning postponed because it has a relatively low probability. This is because, for global risks, even one global risk coming true, unforestalled, is one too many. Only the capacity to forestall any and all plausible global risks is sufficient to enable the conclusion that we have been fully prudent.

With this philosophy, the lower probability of a low-probability global risk influences this assessment only in terms of the phasing of implementation: if resources are short, and two risks are expected at the same time, the more probable risk should be treated first.

2.4.2. Scanning for risks

Risks were identified from a literature survey (for criteria for the survey, see Introduction), and quantified in terms of tonnes of biomass lost if the risk came about. Probability of risk coming about was taken from the literature or, as outlined in the Introduction, in specified cases where no literature was found, by author estimate or, in a few cases, author judgment.

The effect of risk was estimated in terms of biomass lost if the risk came about.

2.4.3. Quantification of the losses arising from risks

As mentioned in Section 2.4.1, only the capacity to forestall any and all plausible global risks is sufficient to enable the conclusion that we have been fully prudent. Hence the purpose of the quantification of candidate global risks is to assess that they are of sufficient scale to be considered global risks. Ranking of the scale of potential losses from global risks is carried out in this paper primarily for the purposes of structuring the analysis: this does not mean lower ranked global risks are less important.

Quantification of the losses arising from each risk was carried out as follows. Losses were estimated for the next occurrence of each risk. Non-human losses so caused were determined from the literature and expressed in billions of tonnes of biomass lost. Human losses from risks were determined from the literature initially in terms of number of lives lost. This was then translated into biomass loss equivalent.

2.5. Responses to risks

Interventions to reduce risks, their potential benefits, and their cost of implementation, were taken from literature survey. For each risk, the feasibility and cost of *full prevention* of the *worst-case* scenario is assessed (if this is affordable, even cheap, we will know we can be successful).

2.5.1. Benefit maximisation from response implementation

In conventional strategic planning, including strategic planning for risk management, cost–benefit analysis [28] is used to select between opportunities or risks to address so as to seek the maximum benefit from the funds available.

Where global risks are involved, the process of seeking to maximise benefits can be radically simpler. First, in the selection of projects, all candidate risks on the list must be addressed, each with a project which fully addresses the risk. In other words, there must be 100 percent coverage of each global risk. Miss even one risk, or address it only partially, and we are still exposed to disaster.

There are, however, dearer and cheaper ways to effectively meet each risk. So the selection of the projects which are best value for money to address each risk must still be made. Here arises the second simplification when the topic is global risks. The outcomes from the different risks always include loss of life and so are commensurate. For this reason cost-effectiveness analysis—lives (or tonnes of biomass) saved per dollar—can be used.

A further issue concerns the net present value of present and future outcomes. The current practice in benefit–cost analysis transfers a value assessment method based around individual humans in the present to the whole biota in perpetuity. This approach has been widely critiqued. Van den Burgh [29] provides a summary, noting that a society, as opposed to an individual, does not have a finite life, and hence no time preference. From the point of view of this paper's assessment framework for ethics and logic, the above use of benefit–cost analysis represents ethical unfairness, and the logical fallacy of the false analogy. Hence, in this study, the cost-effectiveness analysis method used treats future benefits as equal to present benefits; that is, a life saved now or at any time in the future is considered to have the same value. Hence no discount rate is used.

2.6. *Budget*

Intervention characterisation and quantification is carried out using the standard approach. This seeks for the largest risks the responses which most cost-effectively rectify existing loss to the greatest extent or prevent potential future loss. With the resources available for this study, scans for initiatives could not be exhaustive. The major candidates from the literature however, those which promise full mitigation or effective adaptation, were sought and characterised, and the cheapest initiatives of these used for budget estimates. Both one-off and recurring expenditure requirements are estimated. Expenditure required per year is derived by dividing total budget by years available for implementation. The affordability of this funding requirement is assessed at level of global capacity to pay by reference to annual gross world product (GWP).

Amounts are expressed in $US. Where the term trillion is used, it represents a thousand billion. In turn, billion represents a thousand million. For simplicity of expression, billion is abbreviated as bn, and trillion as tr.

2.7. *Response priorities*

The priority of implementation of each response is estimated by a multi-criterion analysis method, as follows. First, specific priority-related information for each criterion for each risk is tabulated (see format in Table 2). Second, to standardise the wide variety of information types involved in the tabulation, the information is translated into rankings (Table 3). An overall priority rank is then determined.

It is noted that the scale of consequence generated from an occurrence of the risk is not used as a criterion for priority. This is because, as outlined in Section 2.4.1, it is a fundamental tenet of the approach of this paper that if a proposed global risk has a non-zero probability, even if small, and could occur now, it should be assessed and planned for now—not have planning postponed because it has a relatively low probability. This is in turn because, for global risks, even one global risk coming true, unforestalled, is one too many. Only the capacity to forestall any and all plausible global risks is sufficient to enable the conclusion that we have been fully prudent.

The criteria used in the multi-criterion analysis were: risk imminence; risk likelihood; response technical feasibility; response affordability; and time available for adequate implementation (the less time available, the higher the priority). Because there were no specific reasons for giving specific weights to specific criteria, each criterion was weighted equally.

2.8. The method: summary of main features

The method developed in the foregoing sections for the present assessment has these main features. The method:

1. Uses sustainability principles, augmented by explicit ethical and logical process tests, and an expansion of scope to include extra-terrestrial threats.
2. Attempts to stand back far enough to see the question as a whole.
3. Uses a common measuring stick for the entities assessed.
4. Takes an insurance-like, not a certainty-based approach to risk, which scans for and assesses the opportunities for mitigating worst-case scenario risks.
5. Does not use benefit–cost analysis but estimates cost of 100 per cent coverage of risk by most cost-effective responses.
6. Uses as budget approval criterion the affordability or otherwise of the responses which can reduce worst-case scenario risks to safe levels.

It is considered that the foregoing method passes the logical and ethical process tests outlined in Section 2.1. This is primarily because it is considered that the scope of the study is set adequately wide, in two main ways. First, the study encompasses all biota entities, not just humans. Second, it seeks all risks, and does not simply focus on one or other risk, even if major.

In the next sections the method is used with available information to produce an indicative "first-cut" integrated global risk and response assessment.

3. Results

In reading this section, it should be noted that, while some details and references to fuller accounts are given, it is not the aim of this study to provide detailed descriptions of each risk and response scenario.

With the above caveat, quantified results and related discussion are presented in this section, in the following order:

1. Characterisation of the system subject to global risks.
2. The specific global risks identified.
3. A characterisation of each risk and the main responses to it.
4. Priority of responses.
5. Funding required for responses.

3.1. Characterisation of the biological system subject to global risks

So as to enable a common view of the extent of exposure to risk, life forms are measured by the common metric of biomass. From [25], the figure used for the Earth's total biomass is 1823.8 billion tonnes dry matter and the figure for the human population is 0.044 billion tonnes dry matter (1/22 000 of total biomass).

3.2. Global risks

From the scan of risks, 15 risks were classed as global risks. These risks are listed briefly in this section to enable in the next section an analysis of the information available for their assessment. This analysis is followed in Section 3.2.2 by the main characterisation and analysis of each risk and related responses.

The 15 risks resulting from the scan, listed in order of resulting likely loss at the next occurrence of the risk (if unmitigated), are as follows:

1. Scientific experiments which would change the fundamental fabric of the universe in a way not previously seen in Nature;
2. Asteroid/comet >10 km diameter;
3. DNA-based exponentially self-replicating nanomachines (green goo);
4. Computers, robots surpassing human accomplishment;
5. Biovorous nanoreplicators (grey goo);
6. Collapse of supermassive star causing intense pulse of γ-rays, cosmic rays and muon particles;
7. Eruption of continental flood basalts;
8. Anthropogenic global warming-induced release of methane from methane clathrates on the continental shelves and permafrost causing double-size global warming or oxygen depletion;
9. New ice age caused by natural cycle;
10. New ice age caused by abrupt climate change from reduced Atlantic thermohaline circulation;
11. Global warming (not causing methane release or ice age);
12. Nuclear exchange (full superpower arsenal), including resultant nuclear winter;
13. Asteroid/comet about 600 m diameter;
14. Super-eruption, most particularly Yellowstone; and
15. Avian influenza pandemic.

3.2.1. Characterisation of information found concerning risks and responses to risks

When the key dimensions of the 15 global risks and matching responses which were identified and quantified are grouped under five headings, an assessment table with some 75 cells is generated. Table 1 represents such a table and shows, for each of the 75 cells, the quality of information used in the identification and quantification process and, in particular, whether the cell was able to be populated by information from prior studies or was of necessity populated by estimates from the present author.

The table shows that information judged to be high quality (from published sources including refereed journals or books or reports from authoritative publishers or bodies)

Table 1
For each risk, quality and quantity of information used for estimates assessed by quality and quantity score[a]

Risk	Risk		Response			Per cent information from refereed journals, or books or reports from authoritative publishers or bodies
	Nomination	Date next expected	Nomination	Quantification of amount of response needed, and cost		
				Data	Calculation	
Scientific experiments which would change fundamental fabric of universe in a way not previously seen in Nature. Current case: killer strangelets	3	3	3	n.a.[b]	n.a.[b]	100
Asteroid/comet >10 km diameter	6	4	3	1	1	60
DNA-based exponentially self-replicating nanomachines (green goo)	3	3	3	n.a.[b]	n.a.[b]	100
Computers, robots surpassing human accomplishment	3	3	3	n.a.[b]	n.a.[b]	100
Biovorous nanoreplicators (grey goo)	3	3	3	n.a.[b]	n.a.[b]	100
Collapse of supermassive star causing intense pulse of gamma rays, cosmic rays and muon particles	3	3	1	n.a.[b]	n.a.[b]	67
Eruption of continental flood basalts	3	3	4	1	1	60
Anthropogenic global-warming induced release of methane from methane clathrates	4	4	4	4,1	1	67
New ice age caused by natural cycle	4	4	3	n.a.[b]	n.a.[b]	100
New ice age caused by abrupt climate change from reduced Atlantic thermohaline circulation	4	4	3	4,1	1	67
Global warming not causing methane release or ice age	6	3	3	4,1	1	67
Nuclear exchange (full superpower arsenal)	4	3	3	n.a.[b]	n.a.[b]	100
Asteroid/comet about 600 m diameter	4	4	3	1	1	60
Supereruption, most particularly Yellowstone	3	3	3,2	4,1	1	67
Infectious and parasitic diseases—Avian influenza	6	4	4	n.a.[b]	n.a.[b]	100
Per cent information from refereed journals, or books or reports from authoritative publishers or bodies	100	100	94	36	0	81

[a]Key: 6: Multiple published sources, including high-impact refereed journals or books or reports from authoritative publishers or bodies (representative sources used in this study); 5: Multiple published sources, including refereed journals, or books or reports from authoritative publishers or bodies (representative sources used in this study); 4: Only some published sources, but these include high-impact refereed journals or books or reports from authoritative publishers or bodies; 3: Only some published sources, but these include refereed journals or books or reports from authoritative publishers or bodies; 2: Only some published sources, these unrefereed; 1: No prior information found, so author estimate used.

[b]Not applicable (current required expenditure is negligible compared to other budget estimates in this assessment).

was available concerning the *identification* of all risks and almost all responses. *Quantification* was carried out not for the five relatively inexpensive responses or the responses to the two risks not currently expected but only for the seven costly, large-scale responses. For these responses high-quality information was available for only 36 per cent of the quantifications carried out, and pre-existing *calculations* of the global quantity of response required and its cost were found for no risks. For these cases, author estimates or calculations were used.

3.2.2. Risk diagnosis and response prescription

In order of resulting likely loss at the next occurrence of the risk (if unmitigated,) each of the following sections first describes and quantifies the specific risk in question. It then asks:

1. Have we interventions to comprehensively prevent the risk?
2. If the answer to this question is uncertain, what would a comprehensive approach to effective, thorough-going adaptation look like?
3. Can we afford, and have we the time required, to implement the interventions to the extent needed?

These questions are addressed in each case by calculating the cost of implementation of each response to the risk, if each response were introduced globally across the entire area of exposure of each risk.

Risk 1. *Scientific experiments which would change the fundamental fabric of universe in a way not previously seen in Nature, generating risks such as killer strangelets*

As Rees [1] notes, "some theorists have conjectured that certain types of experiment could conceivably unleash a runaway process that destroyed not just us but Earth itself." The main current potential such process could be the production of so-called strangelets as a byproduct of experiments on sub-atomic particles. In one scenario, strangelets escape and fuse with nuclei, producing larger strangelets in a runaway reaction that eventually consumes the Earth [30]. Loss: the Earth, and therefore all biota. Probability of occurrence: this risk may occur if relevant experiments are implemented [1,30].

One response to this risk, outlined by Rees [1], is that for each proposed experiment of this type, an investigation should be carried out of whether the probability of risk is below an acceptable threshold. This investigation should be conducted not by those with a vested interest in the proposal but by a panel involving not only experts but also representatives of the general public. In the process, "a 'Red Team' would try to think of the worst that might happen and a 'Blue Team' would try to think of antidotes or counter-arguments"[1]. Concerning the specific current issue of experiments which have the risk of producing killer strangelets, one series of heavy ion collision experiments is now under way at one site (Brookhaven in the US); experiments at a second site (CERN in Switzerland) are proposed [30]. A case has been made [30] that these experiments should not be conducted unless the risks are shown to be at least 10 million times less than they currently appear. Cost of response: negligible compared to that of larger responses assessed in this paper.

Risk 2. *Effect of asteroid/comet strike of diameter greater than* 10 km

The prior frequency of such asteroid strikes is about one in every 50–100 million years [31]; the last such was 65 million years ago, meaning one could be expected now. The 10 km-diameter comet risk is from parabolic-orbit comets [32]. While low-probability events, parabolic-orbit comets cannot fully be ruled out at any time, and can arrive with as little as 6 months' warning. Loss: for diameter greater than 10 km, 95 per cent of current biota and significant damage to the Earth [27,44]; for diameter around 600 m, one-quarter of humanity [31], and biota are expected to be lost.

An international conference sponsored by NASA [33] concerning this risk has recommended that a knowledge base be developed within 30 years enabling a comet/asteroid interception and deflection capability. The conference produced an initial indicative costing for this task of $5.5 bn. Published estimates of cost to implement actual capability were not found, but are estimated here as, say, a 100 times larger (= $0.5 tr).

Risks 3–5

Three risks rank equal third: an overwhelming, planet-wide spread of self-replicating nano-machines, either fully artificial (grey goo) or utilising DNA/chlorophyll (green goo); and computers/robots surpassing human accomplishment [1]. All three risks [1,34], in worst-case scenario form, would lead to the loss of all biota. All are considered plausible in 50 years [1].

The response proposed for these risks [34] is legislation preventing their development and a systematic inspection regime. Costs are considered negligible relative to the larger costs in this assessment.

Risk 6. *Collapse of supermassive star causing intense pulse of* $\gamma-$*rays, cosmic rays and muon particles*

If this risk event were to occur, the following sequence of events would be expected [35]. The arrival of the initial pulse of $\gamma-$rays would cause all organic material on the surface of the Earth to burn. The almost immediately following cosmic rays would produce destructive daughter particles called muons. These would affect all life they contact with lethal doses of radiation. As muons would penetrate hundreds of metres into the earth, there would be some protection possible, but for very few. Previous episodes are likely to have occurred approximately every 100 million years, a timescale comparable to that of some mass extinctions [35]. With this background, a loss of almost all biota is expected, say, 99 per cent, or 1806 bn tonnes. This risk event is expected extremely rarely (once every 100 million years [35]), but the next occurrence cannot presently be predicted, and so it must formally be considered possible at any time.

The situation concerning this risk is daunting, because, as mentioned, cosmic ray-produced muons penetrate the earth deeply [35]. But life has not vanished from the Earth during possible previous episodes so there is the possibility of muon-resistant shelters, if only for a representative cross-section of life (a cosmic-ray event is expected to last only days [35]). The cost of such shelters would be negligible compared to that for the larger responses assessed in this paper. Better yet, with future technology, an Earth-protecting space shield may be feasible within, say, 10 000 years, other risks permitting.

Risk 7: *Eruption of continental flood basalts*

Previous continental flood basalt events include those forming the Deccan and Siberian Traps, the creation of which is associated with mass extinctions [36]. A further similar eruption could lead to a similar mass extinction, of 95 per cent of biota, and pro rata for humanity. Four events have occurred in the last 380 million years [36]. Based on the previous pattern of timings [36] commencement of a new event now cannot be ruled out.

While associated with mass extinction events [36], each continental flood basalt eruption has occurred over time spans estimated to be from 55 000 to several million years. Ignoring, in global-risk terms, the smaller local damage due to the eruption itself, the main global-level risk is seen in the evidence that past eruptions have involved major CO_2 emissions. Accumulating in the atmosphere, there is evidence [36] that in the past these have triggered methane release from the above-mentioned clathrate deposits. Given the long periods of emission involved, it is considered that a comprehensive system for CO_2 capture from the air could prevent this CO_2 build-up (see next section for details of CO_2 capture from the air).

With this background it is considered that specific mitigation action is not currently needed.

Risks 8–11. *Anthropogenic global-warming induced risks and ice-age risks*

Because the one suite of measures addresses Risks 8–11, in the following sections the risks are each described first, and then the measures specified.

Risk 8. *Anthropogenic global-warming-induced release of methane from methane clathrates on the continental shelves or from permafrost*

This risk event causes double-size global warming or oxygen depletion [37–40]. There is evidence [40] that the last time this occurred in a full-blown way, 250 million years ago, 88 per cent of species became extinct (the late Permian mass extinction). Assuming this species extinction holds pro rata for biomass leads to an 88 per cent loss of biomass and pro rata, a human population loss of 5.4 bn.

The probability of this risk occurring is near certain on chemical grounds if the atmospheric temperature rises high enough; the probability that temperature will rise high enough is near certain on current emission trends; estimates of time to this state of affairs existing are as short as 100 years: "… estimates on the exact time lag before climate change would significantly affect the hydrates range from about 100 years to a few thousand years…" [39]

Risk 9. *A new ice age caused by the natural cycle*

The next such ice age appears not to be a current risk as it is either overdue, but being prevented by the early anthropogenic greenhouse effect [41,42], or not expected for 15 000 years [43]. Therefore no substantive action appears needed now.

Risk 10. *A new ice age caused by abrupt climate change from reduced Atlantic thermohaline circulation*

In contrast to the situation for an ice age from the natural cycle, a new ice age is considered possible from anthropogenic causes (greenhouse effect-induced reduction in Atlantic thermohaline circulation causing abrupt cooling sufficient to precipitate ice age [3]).

A new ice age would likely create an environment like that in the last ice age [44]: "Much more arid than at present almost everywhere, with desert and semi-desert occupying huge areas of the continents and forests shrunk back into refugia." This has been estimated to lead to 65 per cent of current land biomass being lost [45,46] (with, pro rata, a human population loss of 4 bn).

The probability of the thermohaline circulation failing is captured in the following statement [46]: "The concept of ... transitions between (thermohaline circulation) states is now commonly evoked as a mechanism to explain the abrupt climate changes that were characteristic of the last glaciation…Most, but not all, coupled GCM projections of the 21st century show a reduction in the strength of the Atlantic (thermohaline) circulation with increasing concentrations of greenhouse gases (GHGs)—if the warming is strong enough and sustained enough, a complete collapse cannot be excluded.''

Risk 11. *Global warming not causing methane release or ice age*

Although it does not cause the above catastrophes, modelling [47] suggests that global warming not causing methane release or ice age can still cause massive loss of biota through drought-induced deforestation (56 per cent loss of biomass). The occurrence of this risk is plausible within the next 100 years, based on a reading of [47].

Ironically, as outlined, the outcomes of the risks from global warming run the gamut from, at one extreme, triggering a new ice age, to generating deleterious warming effects just of itself, to, worst of all, causing double-size global warming (due to triggering the release of methane from continental shelf clathrate compounds).

The challenges therefore are two-fold: 1: To prevent further rise in GHG emissions, and, ideally, 2: To return the GHG level in the atmosphere to that before anthropogenic interference. This latter is likely to be worth doing to absolutely minimise the risk of triggering the worst outcome, of clathrate breakdown.

Interventions to meet these challenges are assessed in terms of amount required and cost as follows:

1: *Prevention of further rise in GHG emissions*. On current trends, world GHG emissions in 2020 are expected to be about 13 Gt CO_2 equivalent [48]. Reduction required per annum is 80 per cent, or 10.4 Gt [48]. To meet this target, interventions are: 1a: *Prevention of further deforestation*, which is emitting GHGs and removing a GHG sink; 1b: *Reafforestation*; and 1c: *Reduction of burning of fossil fuels*. The mix of the foregoing responses selected here is one which is guided by relative cost-effectiveness (see Section 3.6), maximises value for money, does not put all eggs in one basket, and does not set too extreme a target for reafforestation: hence 25 per cent of target is proposed to be met from forest measures, and 75 per cent from reduction in fossil fuel use.

2: *Returning the GHG level in the atmosphere to that before anthropogenic interference*: here the intervention is CO_2 capture from the air.

Response 1a: *Prevention of further net deforestation*. (2.4 per cent of total forest area per year is currently taken for timber [49]: this is ignored in this calculation.) Payment per year to avoid further net deforestation = \$50 per ha [49] × existing forest area (3.9 bn ha) [49] = \$0.20 tr.

Response 1b: *Reafforestation*. If 2.6 Gt per annum is absorbed by reafforestation, and average total absorption over the average (50 y) life of a reafforestation project is 150 tonnes/ha [49], then area of forest required = 2.6 gGt/150 T/ha × 50 = 0.87 bn ha. Existing world forest area = 3.9 bn ha [49]: hence extra forest required = 22.3 per cent of existing forest. Cost of reafforestation = land, \$1000/ha [50] plus establishment, \$800/ha [50] = \$1800/ha. Hence, one-off reafforestation cost = 0.87 bn ha × \$1800 = \$1.57 tr. Annual maintenance cost/forest services payment is estimated as \$50 per ha [49] × forest area (0.87 bn ha) [49] = \$0.04 tr.

Response 1c: *Reduction of fossil fuel use*. If the remaining 75 per cent of the 80 per cent GHG emission reduction target is met by a reduction in fossil fuel use and its substitution by non-carbon energy sources, fossil fuel use must decrease by .75 × 80 per cent = 60 per cent.

To reach this goal, two overall non-carbon scenario extremes are possible (each with optimised energy efficiency): all renewable, or all nuclear.

Resource availability is not a constraint: according to The World Energy Assessment [13], the technically available potential for each scenario is several orders of magnitude above current global energy use.

Similarly, cost is not a constraint for a range of energy options: on a levelised (full life-cycle cost) basis, current technology for baseload power for nuclear and some renewables (geothermal and wind) is comparable to coal (photovoltaics are currently higher in cost) [51,52].

Finally, capital requirements: as a share of GDP, energy sector investment in the 1990s was 1–1.5 per cent of global GDP, or $0.29–0.43 tr (average = $0.36 tr) [13]. To meet the GHG reduction target, 60 per cent of the output of this investment would need to be non-carbon energy. Assuming for convenience that output is proportional to input, 60 per cent of energy sector investment (or $0.22 tr) would have to be in non-carbon energy. Concerning costs, the World Energy Assessment [13] has estimated that the above non-carbon scenarios are actually cheaper (by around 50 per cent) than investments expected for a business-as-usual carbon scenario.

At, then, conservatively, 30 per cent not 50 per cent lower, capital requirements for non-carbon-scenario packages of (a) nuclear, (b) wind, and (c) geothermal are each costed at $0.22 tr × 0.7 = $0.15 tr per year, or $0.07 tr per year less than the business as usual case.

Disaggregated fuel and other elements of levelised costs [13] are hard to source, and so they are not specified in this estimate (that is, they are considered to be incurred similarly for each scenario). Given this treatment favours dearer non-carbon energy generation, such treatment is conservative.

With this background, the total non-carbon energy budget increase/decrease required compared to business as usual is negative $0.07 tr. per year.

Response 2: *Return GHG level in the atmosphere to that before anthropogenic interference*. Not only stabilisation of, but also reduction from, the current GHG content of the atmosphere is preferable because reaching the present level has already committed the Earth from 50 to 100 years of warming and several centuries of sea-level rise [53]. To go further and restore atmosphere to long-term background (pre-industrial) level requires CO_2 capture from the air [54]. It has been estimated that such removal can be achieved, for example using a calcium hydroxide approach, and for $200/tonne of carbon [54]. Weight of atmosphere is 4.4 million billion tonnes [55]. CO_2 level now is 367 ppm, up from 280 ppm in 1750 [48]. The difference, 87 ppm, is the amount to be removed, and equals 382.8 bn tonnes of CO_2, or 104.5 bn tonnes of carbon. This represents a total cost of 104.5 bn tonnes C × $200 per tonne = $20.9 tr.

Risk 12. *Full nuclear exchange*

A nuclear exchange involving full superpower arsenals, including resultant nuclear winter [56,57], could result in 2 bn person deaths (30% of world population) [56,57]. Pro rata, this is equivalent to an all-biota loss of 547 bn tonnes biomass. The cumulative risk during 40 years of Cold War of this occurring was seen by some as much as 50 per cent [1]. In the next century, a realignment leading to a new standoff as dangerous as the Cold War cannot be ruled out [1].

Here a reasonable response would be to continue, strengthen and accelerate reduction of nuclear arsenals of US and former USSR, and prevent new arsenal development. (Cost: negligible compared to that of larger responses.)

Risk 13: *Asteroid or comet approximately* 600 m *diameter*

The next such asteroid is not expected for about 800 years [31]. But parabolic-orbit comets [32] cannot fully be ruled out at any time. Atkinson et al. [31] suggest one quarter of humanity would be lost; equivalently, one quarter of biota. Response: as for Risk 2.

Risk 14. *Super-eruption, most particularly Yellowstone*

There are about 40 super-volcano sites worldwide, from which it has been estimated [58] that there is a probability of eruption of one about every 100 000 years. The main risk from a super-volcano eruption is the likely resulting super-volcano winter, which could last between 5 and 7 years [59]. This would reduce solar energy reaching the Earth's surface: "even the minimum estimate of stratospheric loading (by super-eruption) would have reduced sunlight to about 1/10 of a cloudless day at high noon] [59], causing a great reduction in photosynthesis. Further, "all above-ground tropical vegetation (would be) killed by sudden hard freezes [60] and a 50 per cent die-off of temperate forest is predicted from hard freezes during the growing season [58].

The expected super-volcano winter could thus produce climate change on a global scale approaching that of the greenhouse effect [58] (an estimate of a super-volcano winter human death toll of 1 bn has been made [59,67]. Pro rata, this would translate to one-sixth of total biota. The probability of eruption from the full complement of potential super-volcanoes has been estimated as once in every 100 000 years [58]. Yellowstone eruptions have been approximately estimated as once in every 600 000 years, with the last occurring 630 000 years ago [60]: while the statistics for estimating next events are not necessarily this simple [32], on this basis one may now be overdue.

The main risk from a super-volcano eruption is the likely resulting super-volcano winter [61,62], which could be expected to last between 5 and 7 years. This would reduce solar energy reaching the Earth's surface, vitiating photovoltaic energy systems during this period, making wind energy systems uncertain, and causing a great reduction in photosynthesis.

This catastrophic prospect has two major implications. First, it suggests that the move away from fossil fuels for anti-global warming reasons should neither be to super-volcano-vulnerable solar or wind power, nor to nuclear, which has other risks, but to (similar cost—see global warming assessment above) geothermal power. Second, research into super-eruption prevention, for example via geo-engineering safe pressure reduction, would seem imperative. The potential benefit from such research gains further salience, when the following very initial costings of comprehensive adaptation to life after an eruption are considered.

The following characterisation is of a basic life support system to enable the human population to survive the super-volcano winter, if mitigation did not occur. The system is considered for humans only. If other biota were to be included, the costs would increase by orders of magnitude. Such a system could consist of:

1. Infrastructure to produce food supplies by non-solar means;
2. Robust building stock and transport infrastructure;
3. Geothermal energy source (for rationale for geothermal see Section 3.3.2) with robust (underground) power reticulation.

Element 1. *Using geothermal energy to produce a maximally input-energy-efficient food supply for humans*. World plant food production in 2002 was 2.77 bn metric tonnes [63].

With average plant food energy content at 16 KJ/g [64] = 4.43 Exajoules (EJ). Assuming plants with high edible: total mass are chosen, and that inedible mass is used for further food feedstock or energy, a total plant energy *content* requirement of 6 EJ per year emerges. Given that energy efficiency of typical food plants is 1.61 per cent [65], this means an energy *input* to the system from geothermal sources of 6/0.0161 = 373 EJ per year. This compares with a figure for current annual world energy use [13] of 400 EJ. Given that the currently accessible geothermal resource base is 600 000 EJ [13], there is no issue with energy availability from geothermal sources. *Cost:* In one scenario modelled by the World Energy Assessment [13] it was estimated that the 2.73-fold increase in energy infrastructure expected by 2050 would require (in constant 1990 dollars) an extra $0.30 tr per year. Hence it is assumed pro rata that the extra 0.93-fold increase in energy supply to provide the non-solar food supply would cost a further extra $0.10 tr per year. Continuing to assume that these expenditures are being made around the 2050 period, for which the World Energy Assessment [13] assumes a middle-growth GWP of $75 tr, the extra $0.10 tn for the non-solar food supply equals a small 0.13 per cent of 2050 GWP.

Element 2. *Building stock of adequate strength to withstand volcanic winter weather, and with adequate heating and cooling; and air and water filters to manage volcanic winter air and water quality*. World population of 6 bn: 1.5 bn habitations at 4 people per habitation. Of these, 1 bn new at, say, $20 000 each; 0.5 bn upgraded at, say, $10 000 each = total of $25 tr. Other buildings (offices, factories) assumed (author judgment) to cost half that of habitations: $12 tr. Grand building stock total = $37 tr.

Research into *mitigation*, including via geo-engineering, possibly by safe prevention. While there is opinion that pressure reduction is infeasible [32], such research would still seem worthwhile. Given the high potential cost of adaptation indicated above, if prevention is at all achievable, $37 tr could be spent before it was dearer than adaptation. In other words, a budget even of tens of trillions of dollars to achieve super-eruption prevention would be money well spent.

The foregoing comparison of prevention and adaptation costs concerning super-volcanoes suggests that, if a means can be found to prevent the 40 or so [58] potential super-volcanoes erupting at a what is only a very small percentage of the Earth's entire surface—admittedly, this would be by geo-engineering on a larger scale than humans have so far attempted—the very large costs of effective adaptation can be avoided. So also, the loss of life on Earth, and the destruction of our civilisation as we know it. Further, if it ends up that sites can be made safe by depressurisation, the process may be a valuable input into the world geothermal energy system, the need for which is indicated by the both the global warming and super-volcano winter analysis. It is ironic to consider the source of a risk contributing to risk responses, including its own!

Risk 15. *Avian influenza pandemic*

Avian influenza would appear to be the one current case of an infectious disease which could threaten civilisation. This is because a large proportion (50 per cent) of the entire human population could potentially be infected [66]; and because avian influenza has a very high mortality. In 2004–2005 the mortality of those infected was 70 per cent [67]. These figures translate to potential global total deaths of 2.8 bn people. There are also risks to others not infected due to pandemic-generated shutdown of transport and food-processing plants [66]. There is a current outbreak: this may become a pandemic [66].

The main response here [66] is the development and full global deployment of a vaccine. (Cost negligible compared to that of larger responses.)

3.2.3. Overarching processes for responses

The overall plan for the mitigation of the full complement of global risks should also contain some further overarching processes concerning information and governance. These processes are not costed here, but would be small compared to those assessed in the plan, and would include:

1. Adequate information to citizens via mass media on risks and effective response options;
2. Participatory decision-making, which means elections, a free press, and free speech.
3. Family planning for those who seek it, in order to reduce pressure on the biosphere and on other people.

3.3. Overview of results

3.3.1. Risks: scales of global risks and other risks compared

The foregoing assessment enables a comparison between several specific hazards which have been put forward as either large or the largest risks to civilisation, humanity, life on Earth or the entire planet. As mentioned, global warming is increasingly seen as the largest such hazard. For example, the Prime Minister of the UK, Tony Blair, has stated [68] that he cannot think of "any bigger long-term question facing the world community". In contrast, a group consisting mainly of economists (the Copenhagen Consensus [69]) has rated HIV-AIDS the highest priority problem for action, and global warming much lower. As outlined, just considering potential human deaths, at some point in the next 100 years, global warming unchecked is likely to reach a point where, in the methane-release worst-case-scenario, it has generated a total of 5.4 bn human deaths. HIV-AIDS in the single year of 2001 killed 2 866 000 [70]. Assuming, for the sake of illustration, no change in annual rate, this represents a total over the 100 years of 286 600 000, or 0.286 bn, deaths. Hence, while fully acknowledging the scale of the HIV-AIDS tragedy, the worst-case scenario risk from global warming to humans over the century is 5.4 bn/0.286 bn = 18.9 times greater than the HIV-AIDS risk. The ratio only increases further if the impacts on other biota are included.

3.3.2. Responses: overview of availability of candidates

The analysis made the overall finding that, with two exceptions, measures either exist, or are at least feasible enough to explore developing, to mitigate the 15 global risks assessed in this paper. The first exception is for the Earth experiencing an intense pulse of γ-rays, cosmic rays and muon particles. Fortunately (see Section 3.2.2), this is estimated to happen very infrequently, and, if the past apparent frequency pattern is maintained, is not one of the more currently expected risks. Even here, deep refuges could provide protection for some life. The second exception is the geological risk of super-volcano. There is no current proven *prevention* measure for a super-eruption; but development of advance warning systems [32] would underpin other options. Exploring the option of geo-engineering prevention is feasible: the issue of thoroughgoing adaptation to super-eruption via robust life-support for the human population is explored, in part to underscore the great benefit if super-eruption prevention could be achieved. A further adaptation option is the development of evacuation plans and food supply reserves [32].

3.3.3. Risks and responses: interactions

Using an integrated risk management approach to global risks enabled a scan of the full range of risks and responses for potential interactions, either beneficial (to exploit) or deleterious (to avoid).

When responses are sought which are robust against a variety of risk combinations, a major deleterious case in point becomes apparent. As outlined in Section 3.2.2, research suggests there is more than enough solar, wind, nuclear and geothermal energy to replace global warming-inducing carbon fuels, and to meet human energy needs. As mentioned in Section 3.3.1 however, a volcanic ash-induced winter of at least 5–7 years is expected to follow a super-eruption. Solar and wind energy sources would be greatly reduced or uncertain during this period. Hence only the nuclear and geothermal options are robust against *both* global-warming and super-volcano risks. Of these, geothermal energy has a lower overall risk profile and higher public acceptability than nuclear energy, and so appears to be the more feasible option.

A further interaction has been pointed out [71,72] in which super-volcanism and ice ages positively feed back between each other. In other words, a super-volcano, via a super-eruption winter, can bring forward an ice age if one is drawing nearer cyclically; and an ice age, by crustal loading, can precipitate a vulnerable super-volcano. Unfortunately, Yellowstone seems geographically positioned to be vulnerable to such a process.

A further impression from the side-by-side comparison of the major atmospheric risks is that the precipitating events, i.e. anthropogenic GHG emissions, and super-eruptions, are triggers for the further, much graver risks of methane release from clathrates, and super-volcano winter. Super-volcano winter is, in total atmosphere energy-budget terms, a low-energy event. It just happens to produce a sulphuric acid aerosol cloud, which is positioned to almost exquisitely interfere with a further relatively low-energy event, but one which meets a fundamental biosphere need, photosynthesis.

Both the link of the triggers to the graver events, and the evidence of positive feedback between parallel trigger-risk sequences only underline how beneficial it will be to keep the triggers inactivated by a wide margin.

3.4. Priority of responses

For each risk, Table 2 provides data concerning the relative urgency of the responses required to address risks. This data is both on when the risk is next expected and the time required for response implementation. (It is noted that consideration of the optimal phasing and geographical location of specific responses is beyond the scope of this paper.)

Comparison of the estimated time of the next occurrence of each risk with the time required for response implementation indicates how pressing the time available for implementation is. (In reading this information, a negative number in the time available column means that, on the estimates made, the risk event may occur before the preventative response has had time to be implemented. The implication then is that options for an accelerated effort should be assessed.)

In Table 3, information is taken from Table 2 for those risks which are current or untreated (that is, excluding the risk of a new ice age due to the natural cycle—see Section 3.2.2). In Table 3, information is translated into ranks and used to provide a multi-criterion assessment of the relative priority of the responses required to address the risks. This assessment is made for each risk by assembling information on when the risk is next expected, the technical feasibility of the response, its affordability, and how pressing time is concerning implementation. The multi-criterion assessment ranks higher those responses which are needed soon, and/or are relatively low-cost and/or are more technically feasible. Conversely, responses to risks which are lower in probability, or are technically more difficult to currently achieve are ranked lower. In reading the ranking in Table 3, however, it is reiterated that all global risks require treatment: a lower ranking does not imply that a response should be seen in any way as optional.

Table 3 suggests that the four highest priority risks are so ranked because the risks are imminent and likely, and the responses are highly feasible and (relatively) low cost. These risks—of scientific experiments changing the fabric of the universe, nanoreplicators, and computers, and robots surpassing human accomplishment—all require only relatively feasible and low-cost inspection regimes. Avian influenza is the risk assessed as having the highest likelihood, and once developed, the distribution of a vaccine is, given the political will, highly technically feasible; cosmic ray shelters for a cross-section of life are feasible and low-cost.

The next three risks, all generated by global warming, so rank because of their high likelihood and response feasibility, despite their high cost. Modelling of the time-scales required for global implementation of a major plank of the global-warming response, CO_2 removal from the air, has been carried out [54]. A reading of [54] suggests that, with an apparently feasible acceleration of the effort modelled, the global-warming risk can be mitigated in time—if the full-scale effort required is started now.

Super-eruption mitigation, ranked next, is where time is most pressing (see Table 2). While 10–100 years' warning may be available before an eruption, if the (author-only) estimate of 100 years to develop and implement prevention is true, options for a super-accelerated effort will be required.

The remaining risks, some of which are very low probability, seem to be capable of mitigation with time to spare, but only if full-scale action is started when it should be.

3.5. Cost-effectiveness analysis, budget requirement per year, and affordability

For each response estimated to be currently required, Table 4 provides estimates of total cost, cost-effectiveness in terms of tonnes of biomass saved per thousand dollars, as well as affordability in terms of expenditure required per year.

Cost-effectiveness information is primarily required to assist in choosing between costed response options for the same risk. (If only one response is available for a global risk, the cost question becomes simply whether the response can be afforded.) In this study, alternative response options existed only for global warming, and concerned CO_2 capture from the air, either in forests or via chemical means. Here Table 4 shows that each CO_2 capture option has a cost-effectiveness of the same order of magnitude. With relative cost-effectiveness therefore not a major determinant in this case, the amount of forest initiatives in the proposed package of CO_2 capture measures was influenced by the amount of reafforestation which was feasible (author judgement: 22 per cent extra forest) and the remainder made up of chemical CO_2 capture from the air. This package was considered to have the benefits both of diversification with little cost penalty, as well as the outcomes of the other ecological services generated by forests.

With the time available for implementation estimated, and cost information from Section 3.2.2, an estimate of budget requirement per year is made. Table 4 contains

Table 2
Responses to risks: assessment of factors influencing urgency[a]

Risk (and specific response where needed for clarity)	Years between occurrences	Range of possible dates (years from present) at which conditions for next risk event expected (0 = happening now)	Prudent best-guess number of years from now at which potentially precipitating event for risk must be expected. (Author estimate based on previous column) (a)	Probability of risk event in next 100 years, if not prevented	Amount of warning (yrs) (0 = happening now or no warning) (b)	Time after event starts when severe outcomes occur (yrs) (c)	Time window for action to start before risk arrives (a + c) (d)	Response measure/package (Source: Section 3.2.2)	Time required for global implementation of measure/most crucial element of package (yrs) (e)	Is there enough time for implementation of most crucial measure[b] Difference between time-window for action and time required for implementation of action (yrs) (e–d) (f)
Experiments changing fundamental fabric of universe [1,47]	No precedent	5	5	Not zero, but very low [47]	0.01	0	5	Risk analysis committee	1[reading of 1]	4
Asteroid > 600 m diameter [44]	70 000	800 [45]	800	Asteroid not expected for 800 years	1	0	800	Deflection capability	20 [reading of 33]	780
Comet > 600 m diameter [44]	70 000	1 [45]	1	Comet, although low probability, may appear at any time	1	0	1	Deflection capability	20 [reading of 33]	−20
Nanoreplicators, computers, robots [1]	No precedent	50–500 [1]	50	Clearly possible on current trend	2	0 [48]	50	Prevention laws and inspection program	10	92
Cosmic rays (shield) [49]	100 m [49]	1–10 m	0	Not zero, but very low[49]	0.01	0.01	0.01	Space-based protective shield	1000	−999
Cosmic rays (shelters) [49]	100 m [49]	1–10 m	0	Not zero, but very low[49]	0.01	0.01	0.01	Deep shelters for cross-section of life	5	−5
Continental flood basalts [50]	62 m [50]	1–3 m [50]	0	Not zero, but very low [42]	100	10 000	10 000	CO_2 removal from the air	40 [54]	10 061
Global-warming-induced release of methane from methane clathrates [51–53]	No precedent for anthropogenesis	50–100 [51–53]	50	Clearly possible on current trend	1	0	50	CO_2 removal from the air; geothermal energy; reafforestation	40 [54]	11
	100 000 [55]		0		0 [55]	0	0		0	0

Next ice age caused by natural cycle, if currently prevented by early anthropogenic greenhouse effect [55]		0 [55] (Under this scenario, conditions for the risk event are already in place)		Under this scenario, conditions for risk are already in place				Maintain CO_2 concentration of the air at target level		
Next ice age caused by natural cycle, if due in 15 000 years [57]	100 000 [57]	15 000 [57]	15 000	0	15 000	0	15 000	Increase CO_2 concentration of the air to target level	200	4800
New ice age caused by abrupt climate change [60,61]	No precedent for anthropogenesis	50–100 [60,61]	50	Clearly possible on current trend	1	0	50	CO_2 removal from the air; geothermal energy; reafforestation	40 [83]	11
Global warming damaging, but not causing ice age or methane release from clathrates [62]	No precedent for anthropogenesis	50–100 [62]	50	Clearly possible on current trend	1	0	50	CO_2 removal from the air; geothermal energy; reafforestation	40 [83]	11
Nuclear exchange (full superpower arsenals), including resultant nuclear winter [63,64]	No precedent	30 [1]	30	n.k.	5	0	30	Reduction of existing arsenals and prevention of development of new arsenals	5	25
Super-eruption [65,66] (prevention)	600 000 (Yellowstone) [66]; 50 000 (worldwide) [65]	1–30 000 [65]	1	Clearly possible given years since last event	From 10 to 100 years [45]	0.01	10 (based on minimum likely warning period)	Safe super-volcano pressure release	100	–90
Super-eruption [65,66] (adaptation)	600 000 (Yellowstone) [66]; 50 000 (worldwide) [65]	1–30 000 [65]	1	Clearly possible given years since last event	From 10 to 100 years [45]	0.01	10 (based on minimum likely warning period)	Evacuation plans, and food and other resource reserves	30	20
Avian influenza pandemic [68]	Several per century [68]	0.5 [68]	1	An influenza pandemic is overdue given past frequency	0	0.1	0.5	Development and full global deployment of vaccine	1 [from reading of 68]	–0.4

[a] If reference is not given, estimate is by author.

[b] A negative number means that the risk event may occur before the preventative response as currently conceived has had time to be implemented. In policy terms, this means speedier interventions should be sought.

Table 3
Untreated current risks: response priority dimensions, and responses ranked by grand priority rank

Risk	Mitigation measure/package (Source: Section 3.2.2)	Risk event imminence rank (base data: Table 2)	Risk event likelihood rank (base data: Table 2)	Response technical feasibility rank (base data: Table 2)	Response affordability rank (base data: Section 3.2.2)	Time available for implementation of most crucial response[a] (base data: Table 2)	Grand rank
Experiments changing fabric of universe	Risk analysis committee	4	2	1	1	6	1
Avian influenza pandemic	Development and full global deployment of vaccine	3	1	3	3	5	2
Cosmic rays (shelter)	Deep shelters	1	13	2	4	4	3
Nanoreplicators, computers, robots	Prevention laws and inspection program	8	6	4	2	12	4
Global warming: clathrates	Forest, non-fossil fuel and CO_2 removal from the air initiatives	8	3	6	9	7	5
Global warming: new ice age	As for clathrates above	8	3	6	9	7	6
Global warming	As for clathrates above	8	3	6	9	7	7

Asteroid/comet approximately 600 m diameter	Deflection capability	7	11	10	7	3	8
Super-eruption (prevention)	Safe super-volcano pressure release (if found to be feasible)	5	7	14	13	2	9
Nuclear exchange (full superpower arsenals)	Verifiable reduction of existing arsenals and prevention of development of new arsenals	12	9	5	5	11	10
Cosmic rays (shield)	Space-based protective shield	1	13	13	14	1	11
Super-eruption (adaptation)	Robust infrastructure, evacuation plans and food sources	5	7	12	12	10	12
Asteroid/ comet > 10 km diameter	Deflection capability	13	10	9	9	13	13
Continental flood basalts		14	12	11	8	14	14

[a]Less time available generates higher rank.

Table 4
Major responses to current risks: analysis of budget requirement per year[a]

Risk	Mitigation measure/package (largest/most time-sensitive measure listed first) (source: Section 3.2.2)	Time required for global implementation of measure/most crucial element of package (yrs) (a) (Source: Table 2)	Cost (from Section 3.2.2) ($tr)			Biomass saved (source: Section 3.2.2) (when worst outcome possible prevented) (c)	Cost-effectiveness[b] (c/b)	Comment on relative cost-effectiveness	Cost/year ($tr) (b/a)
			One-off	Annually recurring (over period of time required for implementation (a))	Total cost over period (b)				
Experiments changing fabric of universe	Risk analysis committee	1	Negligible[a]			1834	>3498	Highly cost-effective	n.a.[c]
Asteroid/comet >600 m diameter	Deflection capability	20	0.5		0.5	1749	3498	Highly cost-effective due to large effect resulting from small energy investment (in deflection)	0.025
Nanoreplicators, computers, robots	Prevention laws and inspection program	10	Negligible[a]			1824	>3498	Highly cost-effective	n.a.[c]
Cosmic rays	Space-based protective shield	1000	Not feasible to estimate			1806		n.a.[c]	n.a.[c]
	Deep shelters	5	Negligible[a]			1806	>3498	Highly cost-effective	n.a.[c]
Global warming (methane release from clathrates)	Prevention of deforestation	40		0.2	8				0.2
	Reafforestation	40	1.57	0.04	3.17			Of same order of magnitude as CO_2 removal initiatives	0.08
	Non-fossil fuel energy	40		−0.07	−2.8	1203	See Comment	Lower cost than business as usual energy options	−0.07
	CO_2 removal from the air	40	20.9		20.9	1605	76.8	Of same order of magnitude as forestry initiatives	0.52
Nuclear exchange (full superpower arsenals)	Verifiable reduction of existing arsenals and prevention of development of new arsenals	5	Negligible[a]			547	>3498	Highly cost-effective	n.a.[c]

Super-eruption	Safe super-volcano pressure release (if found to be feasible) or fabricating robust infrastructure, evacuation plans and food sources	100	37	37	352	9.5	Costliest response per tonne biomass saved	0.37
Avian influenza pandemic	Development and full global deployment of vaccine	1	Negligible[a]		0.034 (humans only)	>3498	Highly cost-effective	n.a.[c]
Total				66.77				1.125

[a]Cost negligible against scale of other estimates in this table.
[b]Tonnes biomass saved per thousand dollars.
[c]Not applicable.

estimates of expenditure required over the expected implementation period for each response. The table suggests that the total funding requirement for mitigation of the 15 global risks assessed—including a worst-case scenario requiring adaptation to a super-volcano winter—is of the order of $67 tr. Multi-decade timeframes, however, are generally available for implementation (while it is stressed that the evidence is that major implementation for many responses must be started now). This analysis suggests that required expenditure per year could be around $1.1 tr, or 2.2 per cent of projected annual GWP.

Further, if super-volcano eruptions can be prevented (see Section 3.4) the total requirement of $67 tr would drop by $27 tr, which is the amount of the adaptation cost of $37 tr, minus the cost of the super-eruption prevention, say, $10 tr. This would produce a requirement of ''only'' $40 tr or, roughly pro rata, an annual $0.66 tr, or 1.3 per cent of projected GWP.

The costs of specific interventions have several notable features. Firstly, the CO_2 mitigation cost estimate of a *saving* of $1.65 tr (over the business-as-usual scenario) differs from the estimates derived by others using different means, of $5.1 tr [73]; of no more than 1 per cent of GWP [74]; and 0.5–2.0 per cent of GWP [75]. The result however, is consistent with the view of Lovins and Lovins [76] who have shown that the full use of energy efficient infrastructure saves more in energy cost reductions than it costs. Further, once renewable energy systems are in place, their energy source is nearly free. So, for energy, the funding required is akin to an investment with an eventual net positive return, even excluding its prime disaster-prevention goal.

And in terms of national commitment to meet strategic threats, US expenditure on World War II in 1944 was 35 per cent of GNP [77].

3.6. Implementation of prescribed responses in an integrated strategy

The first principle of the United Nations Framework Convention on Climate Change (UNFCCC) [78], states that ''The Parties should protect the climate system for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities. Accordingly, the developed country Parties should take the lead in combating climate change and the adverse effects thereof.'' A similar approach could be taken for the full suite of global risks.

3.7. Progress monitoring, and public feedback

Systems theory states that all regulators detect discrepancies from some expectation, and feed back information to make adjustments that reduce the discrepancy [79]. Communities, governments, groups, and individuals all seek such information to guide, justify, and motivate action. A plan of the type outlined above could be used as the framework for a monitoring tool to provide such information by assessing the net movement towards its goals of disparate actions worldwide, and, via reporting results, perhaps enhance such actions.

An integrated risk management method was used by the author in the field of road safety in the state of Queensland, Australia. In order to maintain and improve agreed effective interventions, it included provision of feedback to service deliverers. The use of the system was associated with improved road crash reduction, which led to the halving of road deaths in the state [8,15,16]. In 2001, the state attained a road death rate per vehicle-kilometre bettered by no country in the OECD [80].

In the above case, the systems information was provided to output areas, which were command and control in nature, i.e., traffic police and road constructers. An empirical study concerning pollution control [81], however, has shown that even where command and control is not involved, information alone, in the form of public disclosure, can create "additional and strong incentives" for action.

For the present requirement, a web-based global risk and response information centre could be the source of information, both directly to users and via re-publication.

4. Discussion

This paper commenced by noting that there is increasing evidence that the number of global risks is increasing, and that some are likely to be imminent, and that the use of an integrated risk management approach could contribute to the response to this situation being planned more coherently, being implemented more rapidly, and having greater effectiveness.

Concerning the availability of information to enable the population of such an integrated risk management framework for global risks, adequate information was available, in the opinion of the present author, for the greater part of the framework at a quality sufficient for management or policy decision-making (Table 1). There were, however, even by this criterion, significant information gaps and uncertainties.

Concerning gaps in our collective knowledge, Table 1 suggested that high quality information was most lacking in the area of amount and cost of responses to fully mitigate risks. This area in particular would benefit from further specialist research to produce more and better estimates.

Turning to uncertainties, one example concerns whether the timing of the next ice age is overdue [41,42] or not expected for some thousands of years [43]. In either case, responses were not considered necessary at present. Another example concerns whether a super-volcano winter would be severe [61,62] or mild [32]. Here the worst-case, severe, scenario was assessed.

For a larger number of risks, while prevention options have begun to be considered in the literature, an agreed approach to address them is far from settled—examples here in include the risks from experiments which may alter the fabric of the Universe in ways not seen in nature [1,30], and from nano-technology developments [1]. For some further risks, no substantial specialist research has yet been carried out on prevention. Perhaps the greatest of these risks is that from the super-volcano, concerning options both for mitigation and adaptation. Here again, in the present analysis initial strawman author estimates were attempted.

With the above caveats, 15 global risks were identified, and a priority order for response proposed based on a multi-criterion analysis. It is noted that the scale of consequence generated from an occurrence of the risk was not used as a criterion in the analysis of priority because it was considered that for full prudence the capacity to forestall any and all plausible global risks is required.

The study drew attention to the potential problem of focusing only on the largest risks and being caught unaware by a lesser but still lethal threat. One major benefit of the integrated risk management approach is that it enables a comprehensive scan for potential interactions between the full range of risks and the full range of responses. The main finding from this scan concerned the effect of the super-eruption risk on responses to the global warming risk. The scan drew attention to the fact that sources of solar and wind energy would be greatly reduced or uncertain during a super-eruption winter and hence not robust against the super-eruption risk. Given this, two energy options were identified which both address global warming and are robust against super-eruption: geothermal energy and nuclear energy. Of these, geothermal energy seemed lower-risk than nuclear.

The study estimated that costs of response implementation to address all the risks assessed are affordable. An integrated budget was drawn up, suggesting a requirement, in worst-case expenditure scenario, of the expenditure of about 2.2 per cent of our wealth (GWP) per year over the next few decades. The best-case expenditure scenario was 1.3 per cent per year over the same period. The study emphasised that, for what is at stake, these costs are surprisingly low.

Finally, if there is further development leading to a convincing and accepted plan, the next question will be: will we act? Or will it be true that, as Kurt Vonnegut [82] put it, "We could have saved the Earth, but we were too damned cheap."

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