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Abstract: A recent paper published in this journal (Goes, Tuana, and Keller 2011; GTK) examined the economic benefit, "or lack thereof," of aerosol geoengineering. GTK concluded that geoengineering fails a cost-benefit test over a wide range of scenarios regarding (i) the probability that such a program would be aborted and (ii) the economic damages caused by geoengineering itself. In this paper, we demonstrate that GTK's conclusions are a result of their framing of the conditions under which geoengineering would/could be used. Specifically, they equate geoengineering with a decision to forgo (highly optimized) emissions controls now and forever (beginning with a 25% reduction in global CO_2 emissions in 2015). In this paper, we consider other, and we believe more reasonable, geoengineering usage scenarios. In so doing, we demonstrate that geoengineering can pass a cost-benefit test over almost the entire range of scenarios considered by GTK.

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Reexamining the economics of aerosol geoengineering

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Abstract

A recent paper published in this journal (Goes, Tuana, and Keller 2011; GTK) examined the economic benefit, "or lack thereof," of aerosol geoengineering. GTK concluded that geoengineering fails a cost-benefit test over a wide range of scenarios regarding (i) the probability that such a program would be aborted and (ii) the economic damages caused by geoengineering itself. In this paper, we demonstrate that GTK's conclusions are a result of their framing of the conditions under which geoengineering would/could be used. Specifically, they equate geoengineering with a decision to forgo (highly optimized) emissions controls now and forever (beginning with a 25% reduction in global CO_2 emissions in 2015). In this paper, we consider other, and we believe more reasonable, geoengineering usage scenarios. In so doing, we demonstrate that geoengineering can pass a cost-benefit test over almost the entire range of scenarios considered by GTK.

Keywords: geoengineering, solar radiation management, economics

1. Introduction

The recent paper by Goes, Tuana, and Keller (2011, hereafter GTK), published in this journal, analyzed the economic benefit, "or lack thereof," of aerosol geoengineering (GEO).[1] Their paper and the model presented therein provide a useful framework for understanding and exploring the differing perspectives surrounding research into and possible deployment of geoengineering. GTK found that GEO fails a cost-benefit test over a wide range of scenarios regarding (i) the probability that such a program would be aborted and (ii) the damages caused by its implementation (see their Fig. 7).

In this paper, we reconsider these arguments and demonstrate that GTK's conclusions are based on their framing of the GEO use decision, rather than on the underlying concept itself. This framing excludes several possible motivations for geoengineering research and potential deployment: (i) a concern that emissions reductions may not materialize or that they may not materialize in time (Crutzen 2006), (ii) uncertainty regarding the climate sensitivity and the possibility that climate may be more sensitive to greenhouse gasses (GHG) than some fear[2], and (iii) a belief that the climate system may contain tipping points beyond which significant and irreversible damages may occur (Lenton et al. 2008).

Specifically, GTK's primary assumptions regarding the use of GEO or emissions controls biased their results against GEO:

1. They assumed that a decision to use GEO is a decision to pursue a policy of no emissions controls. They compared this policy of no controls to a policy of "optimal" and strong emissions controls (e.g., GTK's abatement strategy called for a 25% reduction in global CO_2 emissions by 2015 and 40% by 2025). Since a policy of no controls is, by definition, economically worse than optimal controls, especially given

[1] In fact, GTK modeled a generic, free, and globally-deployed solar radiation management program (SRM), but considered aerosol geoengineering as a canonical example. Following GTK, we will refer to this implementation of SRM as geoengineering (GEO), but neither our results nor theirs are necessarily limited to aerosol geoengineering.

[2] Bickel, J. Eric. 2010. "The Climate Engineering Option: Economics and Policy Implications." American Enterprise Institute. http://www.aei.org/docLib/Bickel%20paper-The%20Climate%20Engineering%20Option.pdf

GTK's assumptions, burdening a decision to use GEO with the decision to pursue no controls biases the results against the use of GEO.

2. While they allowed for discontinuities in the deployment of GEO, GTK assumed that emissions controls would continue in perpetuity and that the climate system itself contains no discontinuities or tipping points (Lenton et al. 2008).
3. GTK assumed that society cannot react to an aborted GEO program by implementing emissions controls, for example.
4. While GTK accounted for the damage that may be related to GEO deployment (e.g., the economic costs of a reduction in precipitation), they assumed that emissions reductions do not generate any negative externalities and that their total cost is completely described by the direct costs of abatement. This assumption may not be justified, since emissions controls might alter trading relationships between nations, create opportunities for rent seeking, etc. (Barrett 2008; Bickel and Lane 2010). Our point is not that GEO will cause no damage or that these damages should not be assessed, but rather that all responses to climate change should be held to the same analytic standard.

This paper does not argue either for or against geoengineering deployment. Rather, our aim is to show that GTK's results, which appear to argue strongly against geoengineering, are a result of their framing of the issue. A different, and possibly more reasonable, framing, using GTK's own assumptions and model formulation, demonstrates that GEO passes a cost-benefit test over the wide range of scenarios that they considered.

This paper is organized as follows. In the next section, we summarize GTK's methods, results, and analysis. In §3, we reframe the use of GEO and show how this results in different conclusions than those reported by GTK. Finally, we conclude in §4.

2. GTK Methods, Results, and Analysis

GTK used the Dynamic Integrated model of Climate and the Economy (DICE-07) (Nordhaus 2008) but made four changes to this model. These changes may be summarized as follows. First, they included a term in DICE's radiative forcing equation to account for the quantity of SRM deployed, measured in W m^{-2} (see their Equation 14). This technique was also employed by Bickel and Lane (2010). Second, they altered the term structure of discount rates (see their Fig. 1) by using the framework presented by Newell and Pizer (2004), which is based on Weitzman (1998). Third, they replaced DICE's climate model with an implementation of DOECLIM (Kriegler 2005), which they argued is better able to capture the fast response of atmospheric temperatures to the presence of aerosols (see discussion in their §2.3). Finally, they replaced DICE's damage function (see their Equation 15), which is a function of temperature change, with a damage function developed by Lempert et al. (2000). This new damage equation is a function of both the temperature change since pre-industrial times and the rate of temperature change. In addition, they added a component to this function that accounts for the economic damages caused by the use of GEO. Specifically, they defined a parameter θ, which is the damage caused by GEO, as a percent of gross world product (GWP), when GEO offsets radiative forcing equal to a doubling of CO_2 concentrations.

In this paper, we too use DICE-07 and implement all of the modifications detailed above. Our results, given the same assumptions and framing, closely match those of GTK. We then analyze other GEO usage scenarios and test the sensitivity of GTK's results, as well as our own, to assumptions regarding discounting.[3]

GTK considered two policy alternatives: optimal abatement of CO_2 emissions beginning in 2015 (Abate) and business-as-usual (BAU), the latter's being a policy of no controls. They allowed for the use of GEO in the BAU case, also beginning in 2015, and assumed that this program either will be aborted 50 years later (intermittent GEO) or will continue indefinitely (continuous GEO). "Intermittent GEO" may not the most appropriate name for the scenario GTK considered, since it connotes a cycling between the use and non-use of GEO. In fact, GTK

[3] GTK used the discounting framework detailed in Newell and Pizer (2004). As Gollier and Weitzman (2010) have recently shown, this framework assumes there is an immediate and permanent dislocation in the return to capital. Gollier (2009) proved that if uncertainty in returns is transitory, for example, if it follows Geometric Brownian Motion, as assumed by Newell and Pizer (2004), then the term-structure of interest rates should be flat, as originally assumed by Nordhaus (2008).

analyzed an aborted GEO program, after which society has *no ability to respond*, including no ability to implement abatement.

GTK considered the uncertainty in three important model parameters: climate sensitivity, abatement costs, and climate damages. Their paper further discussed and supported these assessments (see their §2.4). Following GTK, we discretize these uncertainties, yielding 6300 States of the World (SOW), 50 possible outcomes for climate sensitivity, 7 for abatement costs, and 18 for damages.

2.1 Base Case Results

We begin by verifying GTK's base-case results, which are based on best-guess estimates for each of the three uncertainties described above and an assumption that deployment of GEO does not cause any economic damages (i.e., $\theta = 0$). Given our use of the same models and assumptions, our results closely match GTK. For example, Fig. 1 presents the radiative forcing and temperature changes for BAU, optimal abatement, continuous GEO, and intermittent GEO. As highlighted by GTK, we see that once GEO is aborted, atmospheric temperature increases rapidly, returning after about 40 years to the level that would have been obtained under BAU. This issue has, of course, been raised by several authors including Wigley (2006) and Matthews and Caldeira (2007).

Fig. 2 presents the economic damages (climate damage and abatement costs) and abatement rate for our implementation of the GTK model. Damages increase above the BAU scenario when GEO is aborted, slightly exceeding 6% of GWP.[4] BAU damages exceed 2% of GWP in 2075, and total damages under abatement surpass 2% of GWP around 2055.

We have included in Fig. 1 and Fig. 2, DICE-07's estimates of the optimal radiative forcing, temperature change, total costs, and abatement (i.e., these values under a policy of optimal abatement). GTK's modification of DICE-07 has significantly increased climate damages and therefore the optimal level of abatement. For example, under DICE-07 the maximum

[4] Our damages are slightly higher than those reported by GTK; these estimates are highly sensitive to the damage equation parameters and differences in temperatures. These differences, however, do not alter (i) our ability to closely match GTK's results or (ii) our conclusions.

temperature change reaches 3.5K, whereas GTK's model implements a level of abatement sufficient to hold temperature changes below 2K.[5]

As a point of reference, Fig. 3 explores the effect of GTK's modeling changes on the optimal level of emissions controls. The GTK line is the emissions profile used by GTK and in this paper. DICE-07 is the optimal emissions profile obtained from the base-case DICE-07 model (inputs at their mean or "best-guess" values), as reported by Nordhaus (2008). DICE-07 + LEM is the effect of replacing DICE's damage function with the one used by GTK, which is based on Lempert et al. (2000). DICE-07 + LEM + DOE is the effect of replacing DICE's damage function with the one used by GTK and replacing DICE's climate model with DOECLIM. Finally, DICE-07 + LEM + DOE + NP is the effect of making the previous two changes and also replacing DICE-07's discounting with the Newell and Pizer (2004) methodology used by GTK. The difference between DICE-07 + LEM + DOE + NP and GTK is that the former is based on mean input values whereas the latter has been optimized under uncertainty. While there is some difference between these strategies, they are rather close. The primary difference between DICE-07 and the GTK model, in this base case, is the change to the discounting framework. While the other modeling changes (DOECLIM and the Lempert damage function) do not produce a major difference here, they will play a larger role in the case where GEO is aborted.

Fig. 4 adds to GTK's analysis reported in Fig. 2 by presenting the cumulative discounted total costs under each of their scenarios. Immediately apparent is that the cumulative costs of GTK's aborted GEO program are less than the costs of BAU, assuming GEO causes no additional damage. This suggests that adding GEO to a BAU policy could be better than BAU even if the GEO program is later aborted. GTK did not analyze such strategies, since they equated GEO with BAU. It is also interesting to note that the total costs of an aborted GEO program are lower than optimal abatement through 2150—almost 100 years after the GEO termination date. We explore these issues further in §3, including consideration of cases where GEO itself causes damages.

[5] GTK's model estimates that climate damages from following a policy of no controls are almost $115 trillion (all $ are 200-year present values in 2005 $), compared to $22.5 trillion in the standard DICE model (Nordhaus 2008). Their optimal control policy imposes over $60 trillion in abatement costs, compared to $2 trillion in the standard DICE model.

2.2 Probabilistic Results

As mentioned above, GTK considered 6300 equally likely SOW. Since they were comparing two alternatives, those need to be understood. Fig. 5 displays a schematic decision tree representing GTK's framing of the GEO decision. They assumed that society can choose either Optimal Abatement (Abate) or BAU with GEO (BAU_GEO). The expected utility of the Abate alternative is

$$EU[Abate] = \sum_{i=1}^{6300} \frac{1}{6300} U(SOW_i, Abate), \quad (1)$$

where SOW_i is the *i*-th SOW and U is the utility assigned to each SOW given that an abatement strategy is in place.

If, on the other hand, society chooses BAU_GEO, then GEO is used to completely offset any and all energy imbalances created by greenhouse gas emissions (and land use changes). Under this alternative, GEO will be aborted after 50 years (in 2065) with probability p and continued indefinitely with probability 1-p. If GEO is aborted, the expected utility is EU[BAU_GEO_INT, θ], where we have included θ to emphasize that the value of this outcome depends upon the damages caused by GEO. If GEO is continued indefinitely, the expected utility is EU[BAU_GEO_CONT, θ], where the expectations are take with respect to the SOW, as in Equation (1). The expected utility of BAU_GEO is then

$$EU\left[\text{BAU\_GEO},\theta\right] = p\,EU\left[\text{BAU\_GEO\_INT},\theta\right] + \left(1 - p\right)EU\left[\text{BAU\_GEO\_CONT},\theta\right]. \quad (2)$$

GTK then solved for the breakeven probability, p^*, that would make society indifferent between Abate and BAU_GEO, or when EU[Abate] = EU[BAU_GEO, θ], which is given by

$$p^*(\theta) = \frac{EU[\text{BAU\_GEO\_CONT},\theta] - EU[\text{Abate}]}{EU[\text{BAU\_GEO\_CONT},\theta] - EU[\text{BAU\_GEO\_INT},\theta]}. \quad (3)$$

This probability is a function of θ, the damage caused by the use of GEO. The numerator of p^* measures how much better off society is under a continuous GEO program than it would have been otherwise, where GTK assume that "otherwise" is optimal abatement. The denominator measures how much worse off society would be under an aborted GEO program compared to a continuous GEO program. There are, of course, many reasons that GEO could fail such a test. For example, if one assumes, as GTK did in many cases, that the damages caused by a continuous GEO program are worse than the damages caused by abatement (climate damages and abatement costs), then GEO would be a clearly unreasonable choice.

It is important to emphasize that p^* is not the breakeven probability of “geoengineering,” as the title of GTK’s paper suggests. Rather, it is instead the breakeven probability between *BAU with GEO* and abatement. These are clearly different and, as Equation (3) makes clear, the baseline to which one compares the use of GEO will significantly affect these breakeven probabilities.

Fig. 6a presents a scenario map for this breakeven probability and the level of economic damages, θ, caused by GEO, using GTK discounting. These results are very close to those of GTK (see their Fig. 7). If $p^* = 0$ (GEO will not be aborted), then any level of GEO damages above about 0.75% of GWP would result in optimal abatement being preferred to BAU with GEO. Increasing the probability that GEO will be aborted decreases the level of tolerable damages. GEO is not preferred for any level of damages if the probability that GEO is aborted is greater than about 0.15. Based on the very small region where GEO passes the cost-benefit test, GTK concluded that substituting GEO for abatement fails a cost-benefit test “rather close to the most optimistic assumptions, and…for most of the explored parameter combinations.”

Fig. 6b presents this same scenario map under DICE discounting.[6] The dashed line labeled “GTK Region” signifies the region in which GTK found that GEO passed a cost-benefit test (Fig. 6a). The region in which GEO passes a cost-benefit test is considerably enlarged. For example, a continuous GEO program passes as long as θ is less than about 1.4%. An aborted GEO program passes as long as θ is less than about 0.5%. In other words, if the damages related to GEO are less than 0.5% of GWP then GEO passes a cost-benefit test even if society knew the program would be aborted, but could do nothing, either now or in the future, to deal with that scenario. Like many results in climate-change economics, we see that GTK’s results are highly sensitive to the discount rate.

[6] The emissions control strategy for this case was obtained using best-guess parameters and is the policy labeled “DICE-07+LEM+DOE” in Fig. 3. That fact that this policy is not optimized under uncertainty only strengthens our results.

Several questions naturally arise regarding GTK's analysis:

1. GTK's normative recommendations rely on a descriptive model of the emissions-control policy process. Specifically, they assumed that if we do not choose BAU with GEO, we *can* choose and implement *optimal* abatement. How well does this model describe what is likely in the real world?
2. Has GTK modeled the decision that society faces? Do we really face a choice between optimal abatement *or* complete substitution of geoengineering for emissions controls? This will certainly affect the results, as Equation (3) makes clear; the breakeven probability strongly depends on the baseline to which GEO is compared.
3. Why should we assume that society cannot respond when the GEO program is aborted? If society can choose abatement now, why can't it choose abatement 50 years from now after it has learned that its GEO program has ended?
4. Given the potential difficulties in securing a global agreement regarding greenhouse gas emissions and the incentive to defect, why should one assume that abatement continues indefinitely? Why couldn't the very same factors that GTK posited will interrupt a GEO program (e.g., a war or a breakdown in an international agreement) also result in the abandonment of emissions controls?

We address the first question here and then turn to the others in the next section.

There are at least two primary issues regarding GTK's descriptive model of the policy process. First, GTK compared BAU_GEO to the most economically efficient abatement strategy. A better comparison might be to compare to an abatement strategy that is likely to unfold in reality. It seems unlikely that it would be (i) optimal and (ii) as strict as GTK assumed. Referring back to Fig. 3, GTK's abatement strategy requires about 25% emissions reductions by 2015 and almost 40% by 2025. We are uncertain of the prospects for emissions controls, but a 25% reduction in global emissions by 2015 seems unlikely. If so, then it is unfair to compare BAU_GEO to this standard.[7]

[7] One could also argue that GEO will not be ready for deployment in 2015. It is for this reason that Bickel and Lane (2010) assumed GEO could not be deployed before 2025.

3. Reframing the Use of Geoengineering

In this section, we reframe GTK's use of GEO by considering several deployment scenarios. The cases we consider are not the only possible uses of GEO. Rather, we consider canonical usage scenarios by relaxing GTK's assumptions that GEO can be used only under BAU, that abatement cannot be interrupted, and that society is unable to respond in the event of an aborted GEO program. Reality is certainly more complex than the stylized examples presented below.

3.1 Slight Modifications to GTK's Framing

We now make minor modifications to GTK's framing of GEO use. We still assume that the choice is between BAU with GEO or optimal abatement. However, in this section we first allow society to respond to an aborted GEO program. Next, we relax the assumption that emissions controls, once started, are certain to continue indefinitely and that only GEO is subject to being abandoned.

3.1.1 Responding to an Aborted Geoengineering Program

GTK assumed that if society chooses to pursue BAU along with GEO, it has no ability to respond in the event that GEO is aborted (see Fig. 5). We see no prima facie reason why this would be the case. Indeed, the political incentive to implement emission controls might be very strong under such circumstances and the technology to implement these reductions may be more affordable.

Fig. 7 displays the schematic decision tree for this case. The initial choice is still between Abate and BAU_GEO, but we now allow for the option to respond to an aborted GEO program. To facilitate our analysis, we simply assume that society can choose GTK's abatement policy, but shift its start date to 2065 (e.g., 25% emissions reductions in 2065, 40% emissions reductions in 2075, etc.). We do not claim that this response is optimal. Rather, we are simply providing a framework that we believe is (minimally) consistent with GTK's assumption that the choice is between BAU and optimal abatement.

Our scenario map, with GTK's discounting, appears in Fig. 8a. The point of indifference when $p^* = 0$ is the same as in Fig. 6a, since GEO is continued indefinitely in this case and society does not need to respond. Again, we also display GTK's original breakeven range. This single change has considerably expanded the region in which GEO passes a cost-benefit test: instead of

GEO failing for any probability of abortment greater than 0.15, the new threshold is 0.89. Fig. 8b presents this scenario map under DICE discounting. Again, the acceptable region is increased. In this case, GEO passes a cost-benefit test for any probability of abortment as long as θ is less than 0.9%.

3.1.2 Aborting Emissions Controls

Although GTK allowed GEO to be aborted, they assumed that abatement is not subject to this risk. Again, we see no reason that this assumption must hold. Let p_A and p_G be the probabilities that abatement and geoengineering, respectively, are aborted. One could create a three-dimensional scenario map that would show the breakeven surface for θ, p_A, and p_G. However, to facilitate communication, we assume there is some exogenous uncertainty (e.g., a war) that would end a program of emissions controls or a geoengineering. Thus, we assume that $p_A = p_G = p$. In this case, the breakeven probability formula becomes

$$p^*(\theta) = \frac{EU[\text{BAU\_GEO\_CONT},\theta] - EU[\text{Abate}]}{\Delta EU[\text{BAU\_GEO},\theta] - \Delta EU[\text{Abate}]}, \tag{4}$$

where $\Delta EU[\text{BAU\_GEO},\theta]$ is the difference in expected utility between a continuous GEO program and an intermittent GEO program, and $\Delta EU[\text{Abate}]$ is the difference in expected utility between a continuous abatement program and an intermittent abatement program. GTK, in effect, assumed that $\Delta EU[\text{Abate}] = 0$.

In the case of an aborted program of emissions controls, we assume that emissions controls are phased out as installed capital stock is retired. The specifics of such a transition are clearly uncertain. As an illustrative example, we assume that emissions reductions decrease linearly from their 2055 level to 0% over 40 years.

Fig. 9a presents the scenario map for this case. Again, the acceptable region is increased relative to that presented by GTK. In fact, as long as θ is less than about 0.11%, GEO passes a cost-benefit test for all values of p. The use of a higher discount rate (Fig. 9b) enlarges this area still further.

3.2 The Addition of Geoengineering to BAU or Emissions Controls

Geoengineering does not present an either/or choice; geoengineering and emissions controls are not mutually exclusive. Rather, GEO could be added to many strategies. Thus, the proper test of GEO's cost-benefit is an *incremental* one. The economic question is whether the addition of GEO to a particular strategy results in a Pareto-optimal improvement. In the next two sections, we consider the addition of GEO to either a policy of BAU or a policy of optimal controls.

3.2.1 GEO under BAU

We now assume that society faces a choice between BAU or BAU_GEO. The schematic decision tree is omitted, since its structure is identical to GTK's framing (Fig. 5), except that Abate is replaced with BAU. In this case, society does not respond to an aborted GEO program with emissions controls, nor have we assumed that emissions controls could be aborted. This is not meant to convey that we don't think such cases are possible. Rather, we are investigating only the incremental addition of GEO to BAU. One could certainly analyze a strategy that allows society to respond with emissions reductions in the event that GEO is aborted. This would only increase the attractiveness of BAU with GEO when compared to BAU alone.

Fig. 10a presents the scenario map for this case. Here, GEO passes a cost-benefit test over almost the entire range of values investigated by GTK. As discussed in §2.1, this result was hinted at in Fig. 4, which showed that cumulative discounted costs of an aborted BAU_GEO program are lower than the costs of BAU, based on GTK's assumptions and modeling changes. In this case, use of DICE discounting reduces the acceptable region (Fig. 10b). This is because high values of θ (greater than the damages under BAU) impose a cost in the near term for the possibility of a future benefit (if GEO is not aborted). These future benefits are not valued as highly under DICE discounting. Thus, changing the discount rate can make GEO more or less attractive.

3.2.2 GEO under Emissions Controls

Several authors (Wigley 2006; Bickel and Lane 2010) have suggested that the use of geoengineering in conjunction with emissions controls may present an economical and possibly less risky strategy than pursuing emissions reductions alone. For example, GEO might be used to stabilize temperatures while emissions controls are used to reduce CO_2 concentrations. In order to test this strategy, we assume that society agrees to adopt a GEO strategy where 1 W m^{-2} of negative forcing is provided via aerosol injection, for example, which we refer to as GEO1. We note, by referring to Fig. 1, that GEO1 offsets approximately half of the radiative forcing under GTK's abatement policy.

In the interest of space, we do not consider other levels of GEO use. In particular, we do not attempt to solve for the "optimal" level of GEO use because this requires estimates of the economic damage caused by GEO, which we take to be a variable to which we will test sensitivity. Furthermore, given the many uncertainties that remain, it seems premature to compute the optimal use of geoengineering. Our test is more difficult in that we will be overusing GEO in those cases where it causes significant economic damages (greater than those under abatement).

Based on the knowledge that GEO1 will be implemented, society chooses an emissions trajectory, which will be lower than the one that would be selected under a policy of emissions controls without GEO. We further assume that society chooses this emissions control strategy under the belief, perhaps mistaken, that its GEO1 program will be in place indefinitely. In Fig. 11, we compare the GEO1 emissions profile to GTK's emissions control profile. We found this level of emissions reductions by assuming mean values for the parametric uncertainties. As discussed in §2.1 and shown in Fig. 3, we believe this trajectory is close to the optimal profile one would find by optimizing over the SOW but do not claim that it is optimal. Rather, GEO1 should simply be viewed as a possible emissions control strategy. In this case, we again assume that if GEO1 is aborted, then society cannot increase its abatement. Relaxing this assumption or computing the optimal emissions control profile would only strengthen our results, which are presented in Fig. 12a.

Again, GEO passes a cost-benefit test over a wide range of scenarios considered by GTK. For example, as long as the economic damages caused by GEO are less than 0.7% of GWP, adding GEO1 to an emissions control strategy would pass a cost-benefit test even if society knew that its GEO1 program would be aborted ($p^* = 1$) and could do nothing to prepare for or react to that eventuality. DICE discounting enlarges the acceptable region (Fig. 12b).

As mentioned in §1, GTK assumed that emissions reductions do not produce any costs other than the direct costs of abatement. One could relax this assumption by assuming there is some external cost, like GTK's θ, that quantifies any negative externalities that would accompany emissions reductions. In the interest of space, we have not done this. Increasing the cost of abatement would only strengthen our conclusions and increase the region in which GEO passes a cost-benefit test.

3.3 The Ethics of Geoengineering

We do not address the ethics of geoengineering here and instead refer the interested reader to Svoboda, Keller, Goes, and Tuana (Forthcoming) and Bickel and Bonevac[8] which discuss these issues at length. However, some of the conclusions on which GTK based their ethical analysis are overturned by a reframing of the GEO use decision. An aborted GEO program could indeed harm future generations, possibly resulting in more damage at the termination date, but perhaps lower overall, than BAU or optimal abatement. In this sense, choosing to use GEO is a risk-based decision to transfer some risk into the future. At the same time, a decision *not* to use GEO is a decision to accept the risk of crossing a tipping point, for example, which could be very near; this also passes a risk to future generations. Thus, the choice is not as simple as avoiding actions that impose risks on others--that alternative no longer exists, if it ever did. The choice is not between geoengineering and a world without climate change. Rather the choice is between geoengineering and the world that will obtain without geoengineering (Bickel and Lane 2010).

4. Conclusion

As stated at the outset, this paper has made no attempt to argue for the deployment of geoengineering. Instead, we have demonstrated that framing the use of geoengineering is critical to determining its cost-benefit. All of our changes to GTK's analysis have resulted in a much larger region in which GEO passes a cost-benefit test, because they positioned GEO in almost the worst possible way: Society can either (i) implement an optimally designed abatement policy (beginning with 25% reductions just four years from now) that produces no negative externalities

[8] Bickel, J. Eric and Daniel Bonevac, "The Ethics of Geoengineering." A draft is available from the first author by request.

and that will proceed uninterrupted for the next several hundred years, or (ii) implement geoengineering that completely substitutes for emissions reductions and if things go badly (50 years from now), society must simply suffer the consequences and is not permitted to choose emissions reductions later. Given this choice, it is not surprising that GTK found only a very small region in which the use of GEO would be economic. Differing and we believe more reasonable framings of geoengineering use result in nearly the opposite conclusion: GEO can pass a cost-benefit test over a wide range of scenarios regarding (i) the probability it would be abandoned, and (ii) the economic damage caused by its use.

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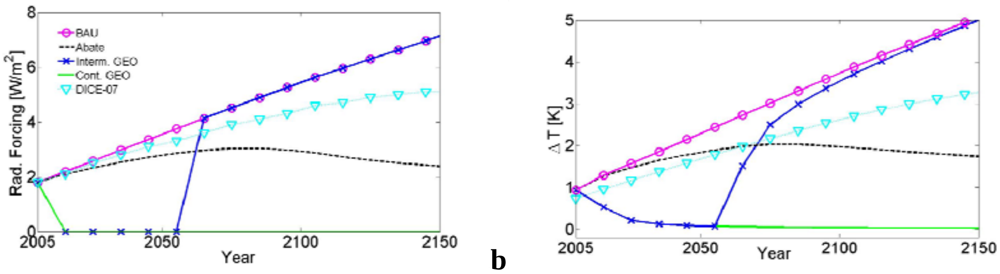
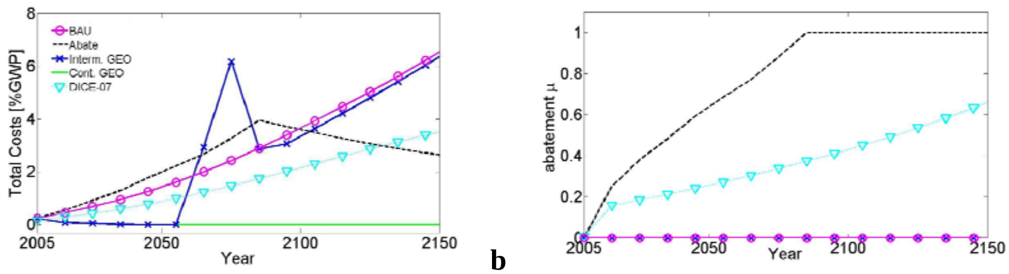
Figures



a **b**

Fig. 1 Radiative forcing (panel **a**), and global mean surface temperature change (panel **b**), for BAU (circles), optimal abatement (dashed line), continuous geoengineering (solid line), and intermittent geoengineering (crosses). DICE-07 results (triangles) are added as a reference. These results are based on mean inputs (not averaged over all 6300 SOW) and neglect potential economic damages due to aerosol geoengineering forcing.



a **b**

Fig. 2 Total costs of climate change (abatement costs plus climate damages), (panel **a**) and fraction of CO_2 abatement (panel **b**), for BAU (circles), abatement (dashed line), intermittent geoengineering (crosses), and continuous geoengineering (solid line). DICE-07 results (triangles) are added as a reference. These results are based on mean inputs (not averaged over all 6300 SOW) and neglect potential economic damages due to aerosol geoengineering forcing.

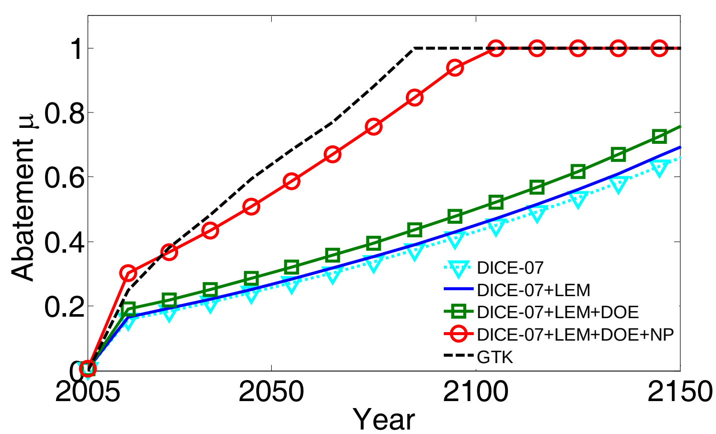


Fig. 3 Effect of GTK modeling changes on the optimal level of emissions controls. The difference between GTK's and DICE-07's abatement strategies is dominated by GTK's change to DICE-07's discounting.

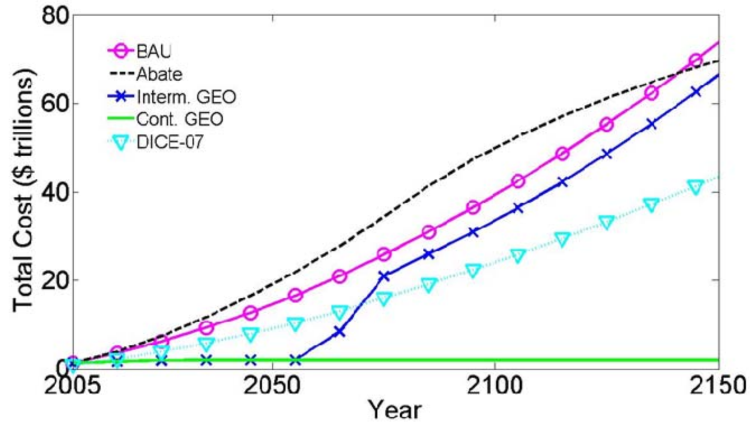


Fig. 4 Cumulative discounted total costs of climate change (abatement costs plus climate damages) for BAU (circles), abatement (dashed line), intermittent geoengineering (crosses), and continuous geoengineering (solid line). These results are based on best-guess inputs (not averaged over all 6300 SOW) and neglect potential economic damages due to aerosol geoengineering forcing. Cumulative damages under an aborted GEO strategy are lower than BAU and optimal abatement (through 2150).

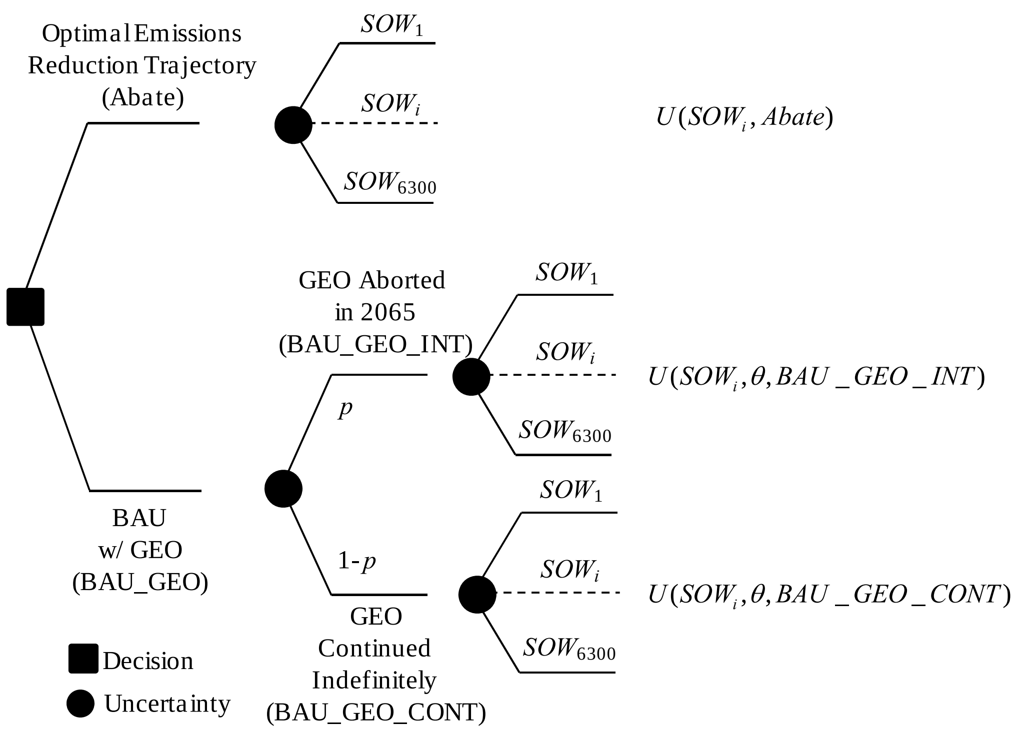


Fig. 5 Schematic decision tree detailing GTK's framing of the aerosol geoengineering deployment decision. Choosing GEO requires selection of BAU in the GTK framework.

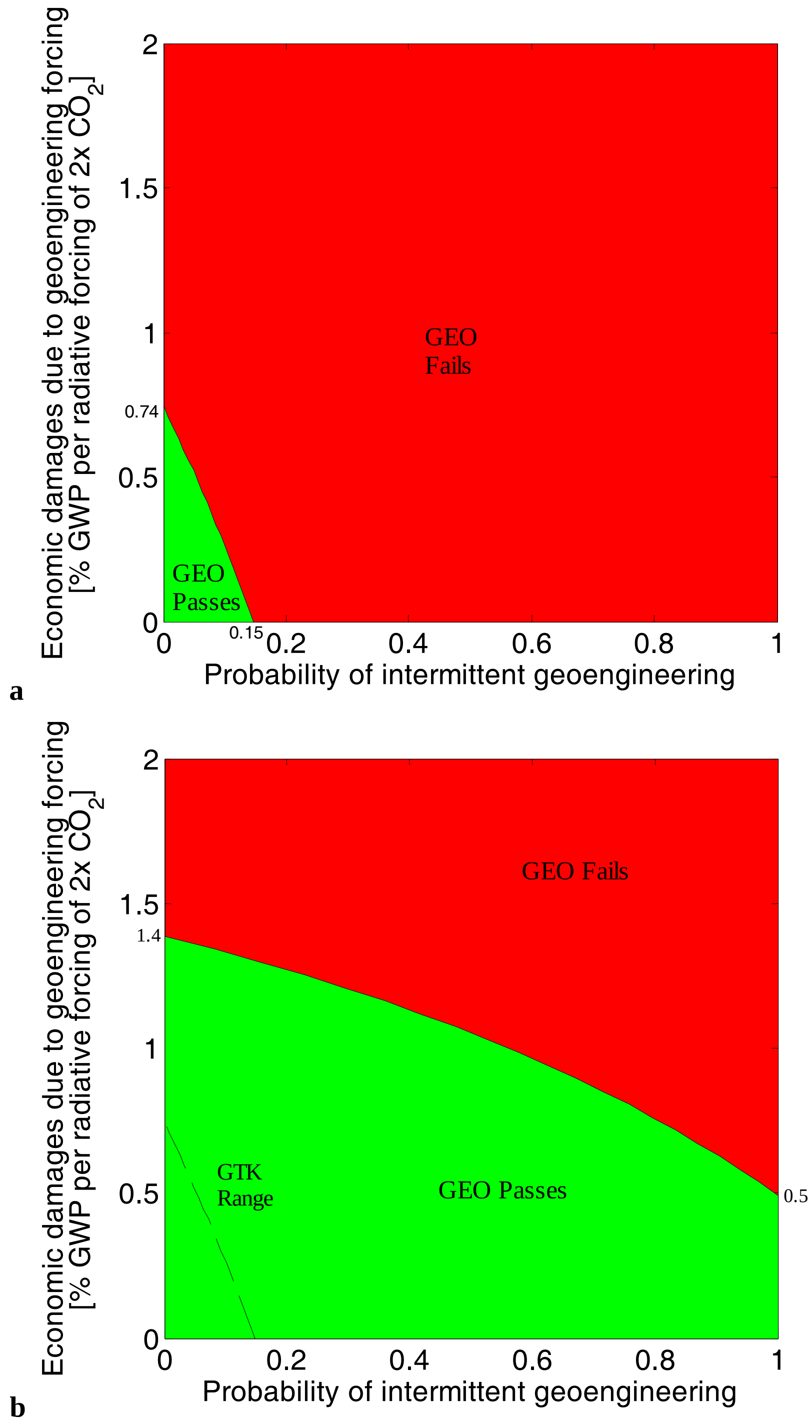


Fig. 6 Scenario map for the cost-benefit test to substitute geoengineering for CO_2 abatement as a function of the probability of aborted geoengineering and the estimated damages due to geoengineering radiative forcing under GTK discounting (panel **a**) or DICE discounting (panel **b**). The change in discounting greatly increases the region in which GEO passes a cost-benefit test.

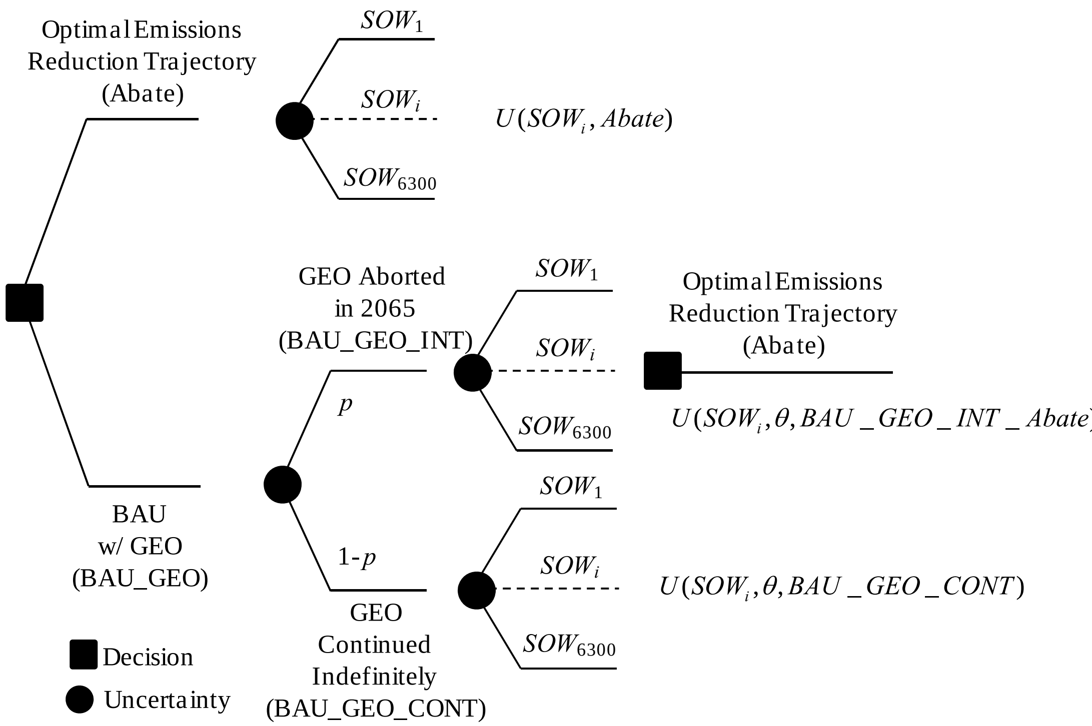


Fig. 7 Schematic decision tree for GEO decision that allows society to respond to an aborted GEO program by implementing abatement.

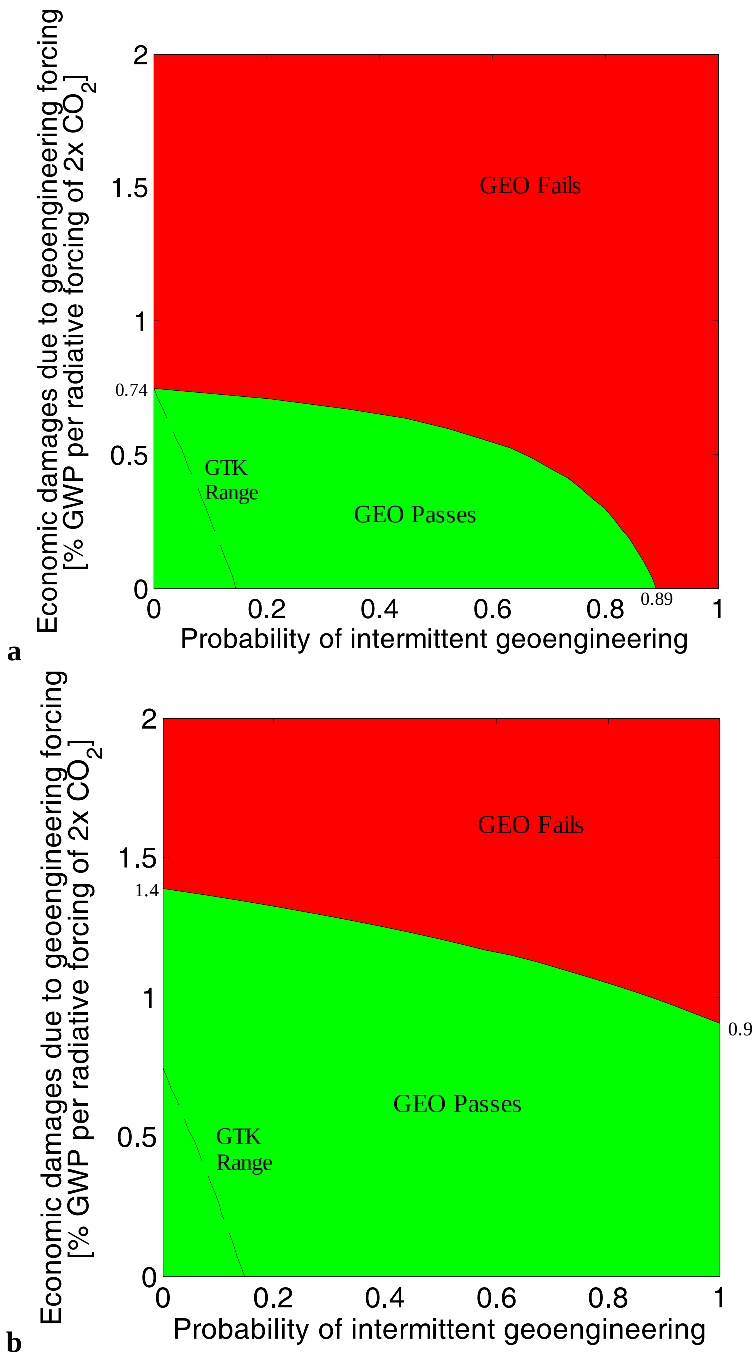


Fig. 8 Scenario map for the cost-benefit test to substitute geoengineering for CO_2 abatement, including the option to implement emissions reductions if the geoengineering program is aborted, as a function of the probability of aborted geoengineering and the estimated damages due to geoengineering radiative forcing under GTK discounting (panel **a**) or DICE discounting (panel **b**). Allowing society to respond to an aborted GEO program greatly increases the region in which GEO passes a cost-benefit test.

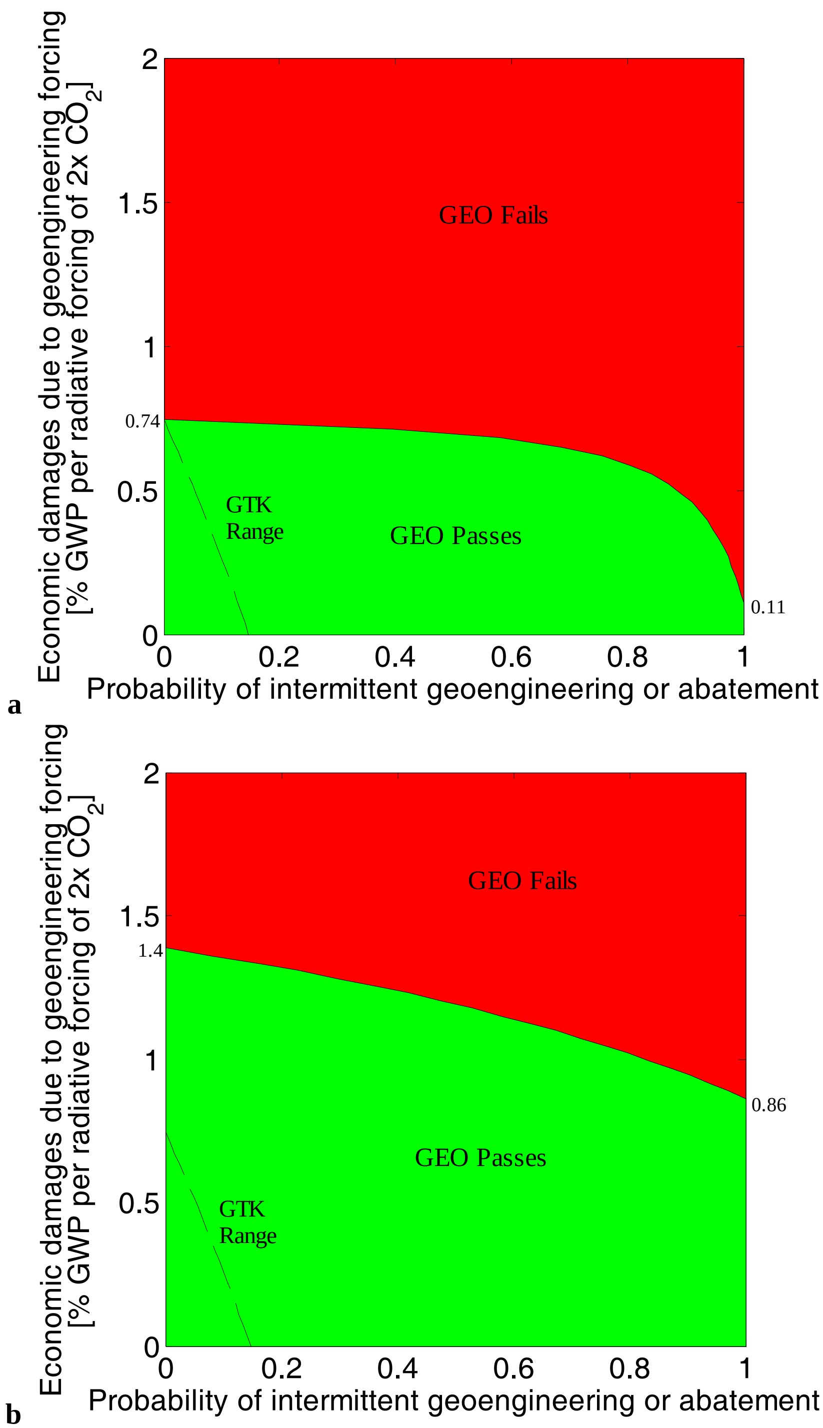
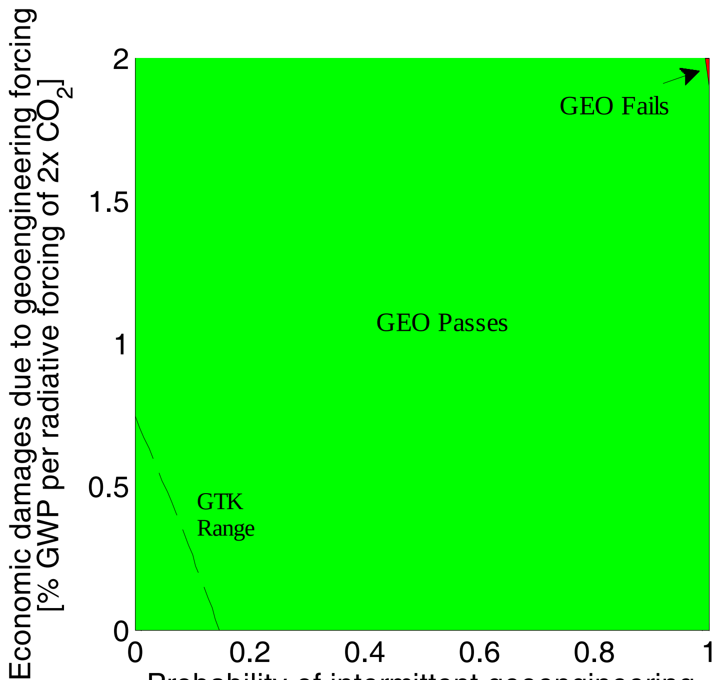
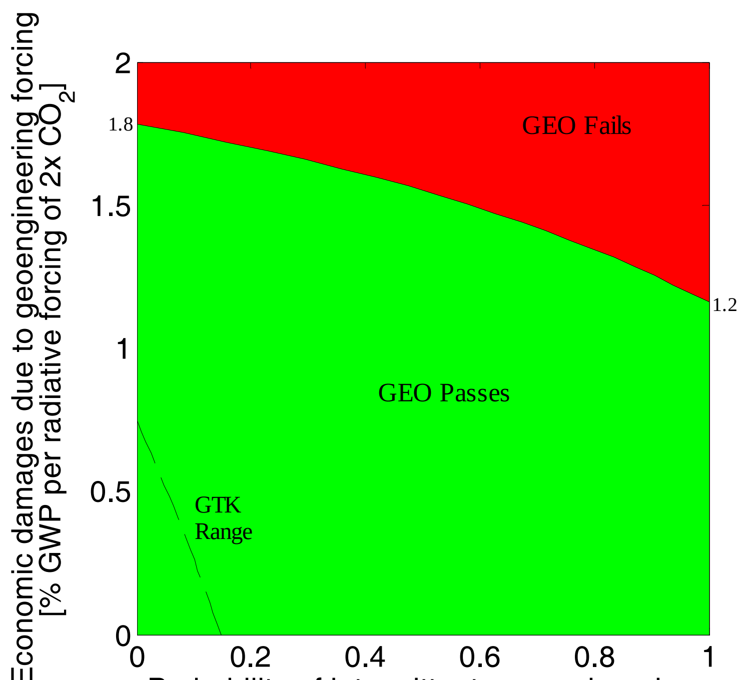


Fig. 9 Scenario map for the cost-benefit test to substitute geoengineering for CO_2 abatement, assuming that both geoengineering and emissions controls could be aborted under GTK discounting (panel **a**) or DICE discounting (panel **b**). Allowing for the fact that abatement may not continue indefinitely increases the region in which GEO passes a cost-benefit test.



a



b

Fig. 10 Scenario map for the cost-benefit test to add geoengineering to a BAU policy under GTK discounting (panel **a**) or DICE discounting (panel **b**).Geoengineering now passes the cost-benefit test for almost the entire range of values tested by GTK (panel **a**). Viewing GEO as an incremental policy change greatly enlarges the region in which is passes a cost-benefit test, compared to GTK's conclusions.

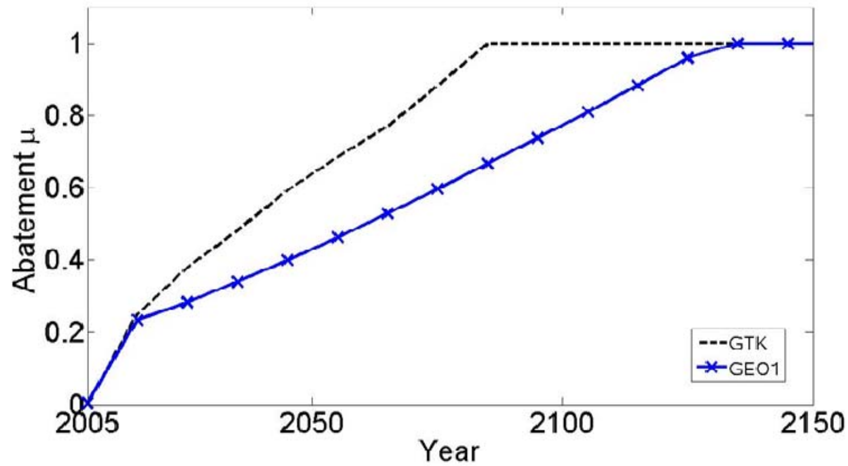


Fig. 11 Comparison of emissions control trajectories under GTK's optimal control case and under GEO1. GEO1 assumes that society deploys 1 W m^{-2} of geoengineering and alters its emissions reductions accordingly.

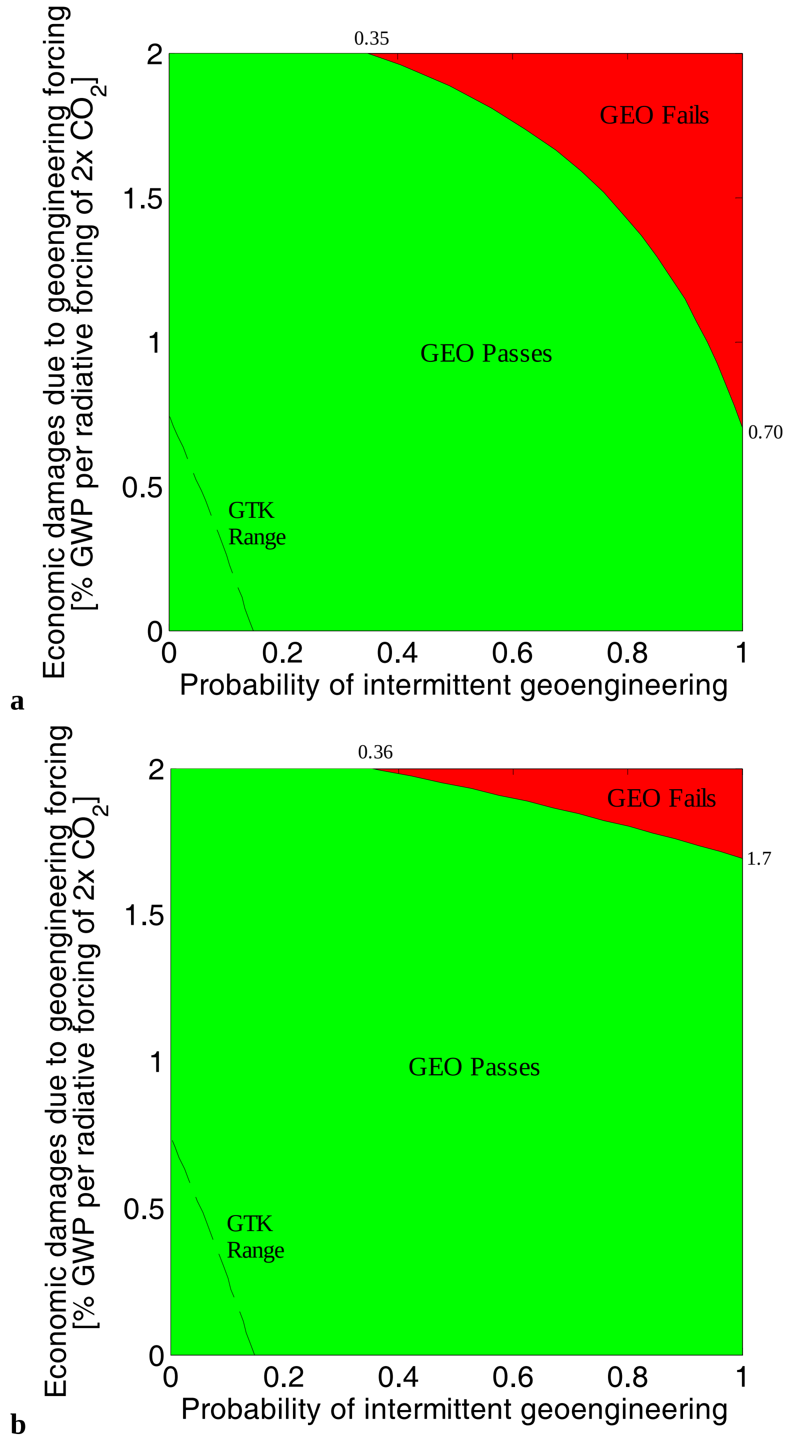


Fig. 12 Scenario map for the cost-benefit test to add geoengineering to a policy emissions reductions under GTK discounting (panel **a**) or DICE discounting (panel **b**). Geoengineering now passes the cost-benefit test over a wide range of values tested by GTK.